Ground-Water Recharge to and Storage in the Regolith-Fractured Crystalline Rock Aquifer System, Guilford County, North Carolina

By Charles C. Daniel, III, and Douglas A. Harned

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Thomas J. Casadevall, Acting Director

For additional information write to:

District Chief
U.S. Geological Survey
3916 Sunset Ridge Road
Raleigh, NC 27607

Copies of this report can be purchased from:

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CONVERSION FACTORS, RELATION OF RECHARGE RATES, TEMPERATURE, AND DEFINITIONS

CONVERSION FACTORS:

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
square mile (mi^2)	259	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
gallon (gal)	3.785	liter
	Flow Rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003784	cubic meter per day

RELATION OF RECHARGE RATES:

Unit depth per year	Volume			
1 inch (in.) is equal to:	74.59 gallons per day per acre [(gal/d)/acre]	47,738 gallons per day per square mile [(gal/d)/mi^2]	6,365 cubic feet per day per square mile [(ft^3/d)/mi^2]	70 cubic meters per day per square kilometer [(m^3/d)/km^2]

EQUATIONS FOR TEMPERATURE CONVERSION between degrees Celsius (°C) and degrees Fahrenheit (°F):

$$°C = 5/9\ (°F - 32)$$
$$°F = 1.8\ (°C + 32)$$

DEFINITIONS:

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

Water year: In U.S. Geological Survey reports, a water year is defined as the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends.

Abbreviations and Acronyms:

GIS	Geographic Information System
HYSEP	Hydrograph Separation Program
USGS	U.S. Geological Survey

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ABSTRACT

Quantitative information concerning recharge rates to aquifers and ground water in storage is needed to manage the development of ground-water resources. The amount of ground water available from the regolith-fractured crystalline rock aquifer system in Guilford County, North Carolina, is largely unknown. If historical patterns seen throughout the Piedmont continue into the future, the number of ground-water users in the county can be expected to increase. In order to determine the maximum population that can be supplied by ground water, planners and managers of suburban development must know the amount of ground water that can be withdrawn without exceeding recharge and(or) overdrafting water in long-term storage. Results of the study described in this report help provide this information. Estimates of seasonal and long-term recharge rates were estimated for 15 selected drainage basins and subbasins using streamflow data and an analytical technique known as hydrograph separation. Methods for determining the quantity of ground water in storage also are described.

Guilford County covers approximately 658 square miles in the central part of the Piedmont Province. The population of the county in 1990 was about 347,420; approximately 21 percent of the population depends on ground water as a source of potable supplies. Ground water is obtained from wells tapping the regolith-fractured crystalline rock aquifer system that underlies all of the county.

Under natural conditions, recharge to the ground-water system in the county is derived from infiltration of precipitation. Ground-water recharge from precipitation cannot be measured directly; however, an estimate of the amount of precipitation that infiltrates into the ground and ultimately reaches the streams of the region can be determined by the technique of hydrograph separation. Data from 19 gaging stations that measure streamflow within or from Guilford County were analyzed to produce daily estimates of ground-water recharge in 15 drainage basins and subbasins in the county. The recharge estimates were further analyzed to determine seasonal and long-term recharge rates, as well as recharge duration statistics.

Mean annual recharge in the 15 basins and subbasins ranges from 4.03 to 9.69 inches per year, with a mean value of 6.28 inches per year for all basins. In general, recharge rates are highest for basins in the northern and northwestern parts of the county and lowest in the southern and southeastern parts of the county. Median recharge rates in the 15 basins range from 2.47 inches per year (184 gallons per day per acre) to 9.15 inches per year (681 gallons per day per acre), with a median value of 4.65 inches per year (346 gallons per day per acre) for all basins.

The distribution of recharge rates in the county suggests a correlation between recharge rates and hydrogeologic units (and derived regolith). The highest recharge estimates occur in the northwestern part of Guilford County in basins underlain by felsic igneous intrusive rocks and lesser areas of metasedimentary rocks. Recharge estimates in this area range from 6.37 to 9.33 inches per year. Basins in the southwestern, central, and northeastern parts of the county are underlain primarily by metaigneous rocks of felsic and intermediate compositions, and recharge estimates range from 5.32 to 5.51 inches per year. In the extreme southern and southeastern parts of the county, the lower Deep River subbasin and the lower Haw River subbasins have the lowest estimated recharges at 4.15 and 4.03 inches per year, respectively. Although the areas of these subbasins that lie within Guilford County are underlain primarily by metaigneous rocks of felsic and intermediate compositions, the larger part of these

subbasins lies south and southeast of Guilford County in areas underlain by hydrogeologic units of metavolcanic origin.

The distribution of recharge rates in the study area is almost the reverse of the distribution of precipitation across the study area. Average annual precipitation varies across the study area from 43 to 48 inches. The lowest rainfall occurs in the northern and northwestern parts of the study area; the highest rainfall occurs in the southern and southeastern parts of the study area. Within Guilford County, annual rainfall varies from less than 44 inches in the northwest to about 46 inches in the southeast. The fact that the highest recharge rates occur in the areas of lowest rainfall and the lowest recharge rates occur in the areas of highest rainfall, further supports the conclusion that recharge rates are highly dependent on hydrogeologic conditions, particularly differences in the infiltration capacities of regolith.

Recharge duration statistics also were determined for the same 15 basins and subbasins. Recharge duration statistics provide information needed by planners for evaluating the availability of ground water at different levels of demand so that overuse, or overdrafting, can be prevented, or other sources of water can be made available during periods of low recharge. Use of water from ground-water storage is one option during periods of low recharge. Methods for determining the amount of ground water available from storage are described, and two examples describing the use of recharge and storage data for planning and ground-water management are presented.

The first example illustrates the use of estimates of average annual recharge and the area of impervious cover to arrive at minimum lot sizes for single family dwellings that will be supplied by individual wells and serviced by on-site septic systems for wastewater treatment. The second example illustrates the use of recharge duration statistics, test data from wells, and knowledge of the quantity of ground water in long-term storage to develop a community water system for a planned cluster development containing multiple homes with on-site wastewater treatment. In order to have the highest possible recharge rates in the capture area, the wells that supply water to the development are to be located in an area of forest and old pasture that will be set aside as a recreational area; the houses with their septic systems will be clustered on another part of the tract. In the second example, the ground-water based community system could have 100 percent backup against pump or well failure by having at least two wells.

INTRODUCTION

Growth of population and industry in Guilford County, North Carolina, has resulted in increased demand for water. Ground water has commonly been overlooked as a potential water-supply source because of the uncertainty of obtaining adequate yields from wells tapping the county's bedrock aquifers. Furthermore, the amount of ground water available in Guilford County for potable supplies is largely unknown. According to the U.S. Bureau of the Census (1992), ground water is used by about 21 percent of the population in Guilford County. This is less than half the approximately 47 percent of the population in the North Carolina Piedmont that relies on ground water for potable supplies; however, if historical patterns seen throughout the Piedmont continue into the future (Daniel, 1992, fig. 2), the number of ground-water users can be expected to increase as total population increases.

Planners and managers of suburban development can benefit from additional knowledge of ground-water resources in Guilford County. In order to determine the maximum population density that can be supplied water by a well or group of wells, the planner must know the amount of water that can be withdrawn without overdrafting water in long-term storage. This yield is approximately equal to the recharge that can be captured in the source area supplying water to a pumped well.

In response to the expected increase in ground-water use, the U.S. Geological Survey (USGS), in cooperation with the Guilford County Health Department and the Guilford Soil and Water Conservation District, began a study in 1996 to assess the availability and chemical quality of ground-water from the regolith-bedrock aquifer system in the county. As part of this study, ground-water recharge was estimated for selected drainage basins using streamflow data and an analytical technique known as hydrograph separation. The recharge estimates were analyzed and the results were used to produce hydrographs illustrating the seasonal variation of ground-water recharge, statistical summaries of long-term recharge rates, and recharge duration tables. The selected drainage basins for which recharge characteristics were determined are shown in figure 1.

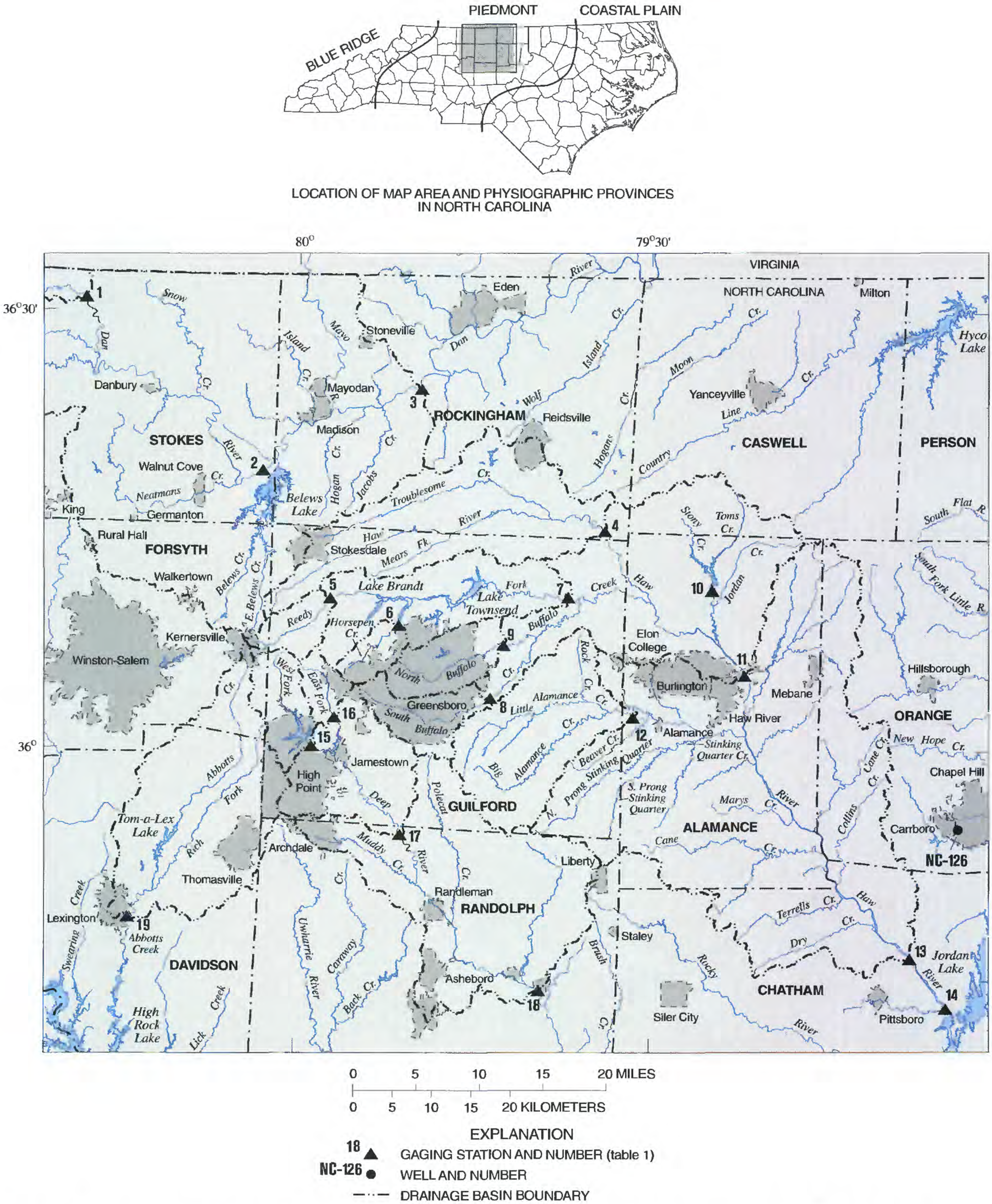

Figure 1. Regional setting of the Guilford County study area in the Piedmont physiographic province of North Carolina, selected drainage basins, and locations of gaging stations used in the ground-water recharge analysis.

Location and Background

The area of this investigation includes Guilford County, North Carolina, and areas in adjacent counties extending to the basin boundaries of streams that receive streamflow from Guilford County (fig. 1). The area of investigation in and around Guilford County can be considered fairly typical of the central Piedmont of North Carolina. The Piedmont of North Carolina is part of the Piedmont physiographic province, as described by Fenneman (1938), that extends from New Jersey to Alabama and lies between the Blue Ridge and Coastal Plain Provinces. The topography of the area consists of low, rounded hills and long, northeast-southwest trending ridges with up to a few hundred feet of local relief. The rolling topography is the result of streams acting on rocks of unequal resistance. Isolated hills with summit elevations standing above the upland surface are remnants of extremely erosion-resistant rock. In contrast to the topography of the crystalline-rock terrane typical of most of the Piedmont, erosion has produced lowlands in the soft sedimentary rocks of the Triassic basins that are downfaulted into the crystalline rocks. Triassic sedimentary rocks are not found within Guilford County; however, the Danville Triassic basin crosses Rockingham and Stokes Counties and underlies part of the Dan River Basin that drains the northwest corner of Guilford County.

The amount of ground water available in Guilford County for potable supplies and other uses is unknown. However, the number of people who can be supported by ground water is ultimately limited by the availability of this resource. In Guilford County, ground water is available from wells tapping the regolith-bedrock aquifer system that is present throughout much of the Piedmont. Under high pumping rates and(or) during periods of no recharge, wells extract water from long-term storage in the regolith-bedrock aquifer system, but the amount of water in storage is limited. Long-term use of ground water is dependent upon recharge to the ground-water system from infiltration of precipitation. Recharge to the system replaces ground water that seeps out of storage in the aquifer to springs, streams, lakes, and pumping wells. In order to wisely plan for future growth, the sustained yield of the ground-water system—here defined as the amount of ground water that can be removed from the ground-water system without exceeding recharge and(or) depleting long-term storage—needs to be evaluated. Understanding the sustained yield of the ground-water system depends upon knowledge of recharge areas and recharge rates.

The Guilford County Health Department, during meetings held in 1995 and early 1996, proposed that ground-water availability and chemical quality be evaluated throughout the county. In mid 1996, a two-phase study was begun to evaluate ground-water availability and quality. The analysis of ground-water availability was completed during the first phase, and results of the analysis are described in this report. Availability depends on rates of recharge to the regolith-bedrock aquifer system and the amount of ground water in long-term storage. Because ground-water flow is not constrained by county boundaries, it was further proposed that the area of investigation extend beyond county boundaries to adjacent natural hydrologic boundaries. In regolith-bedrock aquifer systems, these boundaries are typically determined by the location of drainage basin boundaries.

Specific objectives regarding ground-water availability included: (1) evaluation of long-term ground-water recharge rates and storage throughout Guilford County based on available data, (2) refinement of the long-term estimates of ground-water recharge by evaluation of possible differences in recharge rates between drainage basins, (3) further refinement of the estimates by determining seasonal changes in recharge rates resulting from seasonal climatic changes (changes in precipitation and evapotranspiration), and (4) production of a report describing ground-water recharge rates in different drainage basins throughout the county and an evaluation of the amount of ground water in storage. In addition to the report about recharge and storage, electronic data bases of non-map products, such as recharge-duration tables and hydrographs of monthly recharge estimates, were to be prepared to accompany a Geographic Information System (GIS) version of a watershed map showing basins and subbasins to which recharge estimates apply.

Purpose and Scope

The purpose of this report is to present the results of the investigation and describe the methods used to estimate recharge to the regolith-fractured crystalline bedrock aquifer system in Guilford County, North Carolina. Also described in the report are methods for evaluating quantities of ground water in storage beneath tracts of land. Examples illustrating use of the recharge estimates, in conjunction with ground-water storage data, for ground-water management and planning also are presented.

Nearly all of the data used in this evaluation were derived from base-flow analysis of streamflow records collected at 19 streamflow gaging stations located within and outside of Guilford County (fig. 1; table 1). Estimates of recharge on a regional scale are based on assumptions

Table 1. Gaging stations that record streamflow within and from Guilford County, N.C.

[mi^2, square miles; ft^3/s, cubic feet per second]

Site number (fig. 1)	Station number	Station name	Latitude	Longitude	Drainage area (mi^2)	Period of record[a]
		Roanoke River Basin				
1	02068500	Dan River near Francisco	36°30'53"	80°18'11"	129	1928–87, 1992–95
2	02069000[b]	Dan River at Pine Hall	36°19'09"	80°03'01"	501	1987–90
3	02071000	Dan River near Wentworth	36°24'45"	79°49'35"	1,035	1940–95
		Cape Fear River Basin				
4	02093500[b]	Haw River near Benaja	36°15'06"	79°33'55"	168	1929–71
5	02093800	Reedy Fork near Oak Ridge	36°10'22"	79°57'12"	20.6	1956–95
6	02094000[b]	Horsepen Creek at Battle Ground	36°08'34"	79°51'24"	16.4	1926–31, 1935–59
7	02094500[c]	Reedy Fork near Gibsonville	36°10'31"	79°37'01"	131	1929–95
8	02095000[b, d]	South Buffalo Creek near Greensboro	36°03'36"	79°43'33"	34.1	1929–58
9	02095500[b, e]	North Buffalo Creek near Greensboro	36°07'13"	79°42'30"	37.1	1929–90
10	02096000[b]	Stony Creek near Burlington	36°11'00"	79°24'50"	44.2	1953–59
11	02096500[f]	Haw River at Haw River	36°05'13"	79°22'02"	606	1929–95
12	02096700[b]	Big Alamance Creek near Elon College	36°02'21"	79°31'29"	116	1958–80
13	02096960	Haw River near Bynum	35°45'48"	79°08'02"	1,275	1974–95
14	02097000[b]	Haw River near Pittsboro	35°42'19"	79°05'00"	1,310	1929–73
15	02098500[b]	West Fork Deep River near High Point	36°00'15"	79°58'42"	32.1	1924–26, 1929–58
16	02099000[b]	East Fork Deep River near High Point	36°02'15"	79°56'46"	14.8	1929–93
17	02099500[g]	Deep River near Randleman	35°54'12"	79°51'10"	125	1929–95
18	02100500[h]	Deep River at Ramseur	35°43'34"	79°39'20"	349	1924–95
		Yadkin-Peedee River Basin				
19	02121500[i]	Abbotts Creek at Lexington	35°48'23"	80°14'05"	174	1941–57, 1989–95

[a]Complete water years. Water year as used by the USGS is defined as the period from October 1 through September 30 and is identified by the calendar year in which it ends.

[b]Discontinued.

[c]Water transferred out of the basin for Greensboro, N.C., municipal water supply; between 1935 and 1995, the combined transfer from three reservoirs averaged 28.7 ft^3/s.

[d]Wastewater discharges into South Buffalo Creek upstream of station reported by the USGS (1929–58); discharge rate not given.

[e]Wastewater discharges into North Buffalo Creek upstream of station reported by the USGS (1929–90); discharge rate not given.

[f]Water pumped from reservoir on Stony Creek upstream of gaging station for Burlington, N.C., municipal water supply; about one-half is returned as wastewater to the Haw River upstream of the gage; about one-half is discharged below the gage. Between 1952 and 1995, the average withdrawal from Stony Creek was 10.8 ft^3/s; discharge below the gage averaged 5.5 ft^3/s.

[g]High Point, N.C., withdraws water from the Deep River for municipal water supply. Approximately three-fourths is returned as treated wastewater upstream of the gage near Randleman, N.C.; about one-fourth is transferred to the Abbotts Creek Basin. Between 1951 and 1995, this transfer averaged 4.0 ft^3/s.

[h]Asheboro, N.C., withdraws water from the Uwharrie River Basin for municipal water supply; treated wastewater is discharged into the Deep River upstream of the gage near Ramseur, N.C. Between 1951 and 1995, the transfer of water to the Deep River averaged 4.2 ft^3/s.

[i]High Point, N.C., withdraws water from the Deep River Basin and transfers part of this water, as treated wastewater, to the Abbotts Creek Basin. Between 1951–57 and 1989–95, this transfer averaged 4.3 ft^3/s. Water is withdrawn from Abbotts Creek by Lexington for municipal water supply and is returned as treated wastewater below the gage. Between 1942–57 and 1989–95, the diversion of water past the gage averaged 3.7 ft^3/s.

of uniform conditions within the underlying aquifers as well as uniform conditions in the drainage basins with respect to factors such as soils, topography, land use, and land cover, which affect infiltration. Because conditions in drainage basins are rarely uniform throughout the entire basin, the estimates may not precisely quantify recharge in all areas.

Statistical summaries of annual recharge, monthly recharge, and recharge duration estimates are presented for 15 selected drainage basins and subbasins. Presentation and discussion of the estimates is organized by drainage basin to better define the areal distribution of these characteristics within the county.

Previous Investigations

There have been no previous investigations to evaluate the sustainable yield of the regolith-fractured crystalline rock aquifer system in Guilford County, North Carolina. The yields to wells tapping the various hydrogeologic units in the county have been investigated in several studies. Guilford County was included in a multicounty study by Mundorff (1948); as part of this study 377 wells were inventoried, and the yields were statistically analyzed to identify relations between well yields, rock units, and topographic settings of well sites. Wells in Guilford County were included in a study of ground-water resources in the upper Cape Fear River Basin by Daniel and Sharpless (1983). Included in that study is an assessment of ground-water recharge based on hydrograph separation analysis that demonstrated the seasonality of ground-water recharge to the regolith-fractured crystalline rock aquifer system of the study area.

Harned and Daniel (1987) also described the seasonality of recharge to the Piedmont ground-water system; included in this paper is a description of the ground-water component of Piedmont streams and the implications for ground-water supply systems and land-use planning. According to these authors, the average amount of ground-water discharge for 10 streams in the North Carolina Piedmont is 44 percent of total streamflow. The range of values for the 10 streams is 24 to 65 percent. If it is assumed that there is no long-term change in ground-water storage, the values determined for ground-water discharge are equal to ground-water recharge.

The hydrogeologic units in Guilford County were mapped by Daniel and Payne (1990) as part of a study to map hydrogeologic units in the Piedmont and Blue Ridge Provinces of North Carolina. A statistical analysis relating well yields to construction practices and siting of wells in various hydrogeologic units and topographic settings in the Piedmont and Blue Ridge Provinces of North Carolina was made by Daniel (1989). Results from this regional study are considered applicable to Guilford County.

Ground-water resources in Guilford County were evaluated by Floyd and Peace (1974) and McKelvey (1994) as part of studies of ground-water resources in the upper Cape Rear River Basin. McKelvey (1994) evaluated the application of geomorphic and statistical analysis to site-selection criteria for high-yield water wells in the area; included in this study is an evaluation of the relation between well yields, well locations, and fracture traces that demonstrated the relation between high yields to wells and intensity of bedrock fracturing.

Description of the Study Area

The Guilford County study area in North Carolina includes Guilford County and surrounding areas in Alamance, Caswell, Chatham, Davidson, Forsyth, Orange, Randolph, Rockingham, and Stokes Counties which contain parts of drainage basins receiving runoff from Guilford County (fig. 1). Guilford County covers approximately 658 square miles (mi^2) in the central part of the Piedmont Province. The major population centers in Guilford County are Greensboro, High Point, and Stokesdale. The county population in 1990 was about 347,420 people; of the total population, about 272,960 people obtained water from public water systems which were dependent upon surface water as the raw water source. The remaining 74,460 residents (21.4 percent of the total population) obtained water from individual wells and ground-water based community systems (U.S. Bureau of the Census, 1992). Residents who rely on ground water as their source of potable water live almost exclusively in rural areas of the county.

The topography of the study area consists of low, rounded hills and long, rolling northeast-southwest trending ridges. The upper surfaces of some ridges and interstream divides are relatively flat and may be remnants of an ancient erosional surface of low relief. More recent erosion and downcutting by streams has dissected this ancient erosional surface, creating a local topographic relief of 100 to 200 feet (ft) between stream bottoms and ridge tops. Summit altitudes of ridges in the northwestern part of Guilford County are generally greater than 900 ft above sea level, but summit altitudes decrease to about 750 ft along the eastern side of the county. The lowest altitudes occur along valleys of rivers that flow out of the county on the east and south; altitudes at the county line are less than 600 ft along the Haw River, less than 550 ft along Stinking Quarter Creek, and less than 660 ft along the Deep River. Summit altitudes in downtown Greensboro, N.C., are greater than 850 ft, and greater than 900 ft in downtown High Point, N.C. A few isolated mountains in the county rise above the general Piedmont surface.

The climate of the Guilford County study area is moderate and can be typed as humid-subtropical. The area is characterized by short, mild winters and long, hot, humid summers. Mean minimum January temperatures range from 31 to 33 degrees Fahrenheit (°F), whereas mean maximum July temperatures range from 87 to 89 °F. Average annual precipitation varies across the area from 43 to 48 inches (in.). The lowest rainfall occurs in the northern and northwestern parts of the study area; the highest rainfall occurs in the southern and southeastern parts of the study area (Kopec and Clay, 1975, fig. 5.15). Prevailing winds are from the southwest with a mean annual windspeed of about 9 miles per hour. The average length of the freeze-free season in the area lasts approximately 190 to 210 days, with the last date of freezing temperature occurring between April 1 and April 21. The average first date of freezing temperature occurs between October 30 and November 9 (Kopec and Clay, 1975).

Acknowledgments

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HYDROGEOLOGIC SETTING OF GUILFORD COUNTY

The hydrogeologic setting of Guilford County is defined by the intricate relation between the streams and rivers that convey runoff from the county and the regolith-fractured crystalline rock aquifer system that (1) stores ground water, and (2) functions as a conduit to route ground water from recharge areas to discharge areas. Ground-water discharge to streams, rivers, and other surface-water bodies is an important component of total streamflow in Guilford County. Rates of recharge to the ground-water system vary from drainage basin to drainage basin depending upon several factors, including precipitation, topography, soil, and land use. The quantity of ground water in storage is not only a function of recharge, but the hydraulic and hydrogeologic characteristics of the aquifer system as well. The hydraulic and hydrogeologic characteristics of the aquifer system are, to a greater or lesser extent, functions of the lithology, tectonic history, and susceptibility to weathering of the various hydrogeologic units that lie beneath the county. Hydrogeologic conditions and processes that are important to the evaluation of ground-water recharge and availability presented in this report are described in the sections that follow.

Rivers, Streams, and Drainage Basins

Rivers and streams draining Guilford County are part of a regional drainage network that flows in a generally southeasterly direction across the Piedmont and Coastal Plain Provinces before flowing into the Atlantic Ocean. Most of the streams flowing out of Guilford County belong to two major river systems—the Deep River Basin in the west and the Haw River Basin in the east (fig. 1). The Deep River and Haw River join in Chatham County below Jordan Lake to form the Cape Fear River which flows to the coast southeast of Wilmington, N.C. East Belews Creek and Hogan Creek, which drain the northwestern corner of Guilford County, flow to the north-northeast into western Rockingham County where they join the Dan River. The Dan River continues in a northeasterly direction across Rockingham County into Virginia where it joins the Roanoke River, another major river system that flows to the southeast across the Piedmont and Coastal Plain Provinces of Virginia and North Carolina. Rich Fork, a tributary to Abbotts Creek, drains the southwestern corner of Guilford County. Abbotts Creek flows into High Rock Lake, one of several reservoirs along the Yadkin River. The Yadkin River continues to the southeast across the North Carolina Piedmont, and becomes the Pee Dee River as it flows into the Coastal Plain of South Carolina.

Tributaries of the Haw River that drain northern, central, and eastern Guilford County include Troublesome Creek, Reedy Fork, Buffalo Creek, and Big Alamance Creek (fig. 1). The Haw River begins in western Guilford County, flows to the east-northeast into Rockingham County where it turns to the southeast before crossing northeastern Guilford County. The Haw River continues to the southeast across Alamance County into Chatham County where, southeast of Pittsboro, N.C., the B. Everett Jordan Dam on the Haw River impounds water in the Haw River and New Hope River valleys to form Jordan Lake.

Average annual runoff from the unregulated streams draining Guilford County ranges between 12.29 and 18.85 inches per year (in/yr) (U.S. Geological Survey, 1924–95) and averages about 14.48 in/yr (time-weighted average). Data from gaging stations 02094500 (site 7), 02095000 (site 8), 02095500 (site 9), 02096500 (site 11), 02099500 (site 17), 02100500 (site 18), and 02121500 (site 19) (fig. 1) are not included in this evaluation because of regulation and return flows from wastewater-treatment plants. Stations 02068500 (site 1), 02069000 (site 2), and station 02096000 (site 10) (fig. 1) are not included because they do not measure flow within or from Guilford County (data from these three stations are used in the recharge analysis to define subbasin boundaries).

The Regolith-Fractured Crystalline Rock Aquifer System

Metamorphic and igneous crystalline rocks underlie nearly all of the Piedmont Province. However, large rift basins, extending from New Jersey to South Carolina within the Piedmont crystalline rocks, have been filled with sedimentary deposits of Triassic age (Smoot and Robinson, 1988). One of these rift basins, the Danville Triassic basin, crosses Rockingham and Stokes Counties to the north and northwest of Guilford County. However, no sedimentary rocks of Triassic age occur in Guilford County. Metamorphic and igneous crystalline rocks underlie all of Guilford County.

In Guilford County, the metamorphic and igneous crystalline rocks are mantled by varying thicknesses of regolith. An idealized sketch of the ground-water system (fig. 2) shows the following components of the system: (1) the unsaturated zone in the regolith, which generally contains the organic layers of the surface soil, (2) the saturated zone in the regolith, (3) the lower regolith which contains the transition zone between saprolite and bedrock, and (4) the fractured crystalline bedrock system.

Collectively, the uppermost layer is regolith, which is composed of saprolite, alluvium, and soil (Daniel and Sharpless, 1983). Thickness of the regolith throughout the study area is extremely variable and ranges from zero to more than 150 ft. The regolith consists of an unconsolidated or semiconsolidated mixture of clay and fragmental material ranging in grain size from silt to boulders. Because of its porosity, the regolith provides the bulk of the water storage within the Piedmont ground-water system (Heath, 1980).

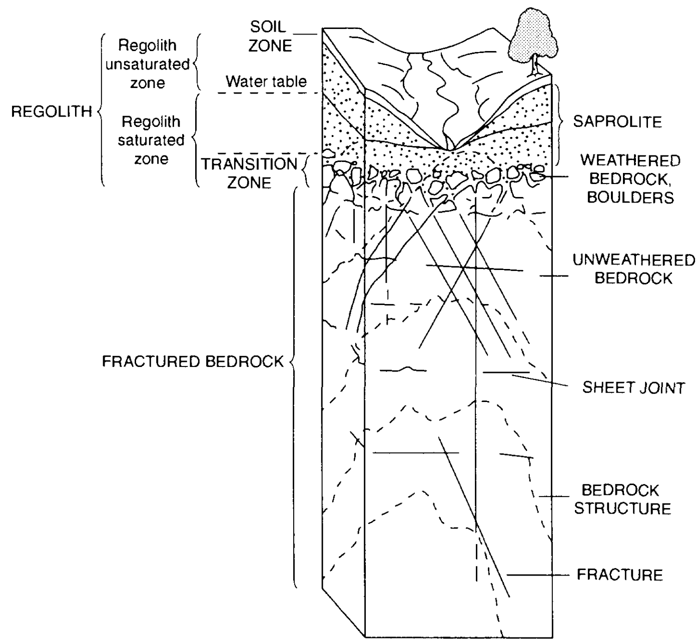


Figure 2. Principal components of the ground-water system in the Piedmont physiographic province of North Carolina (from Harned and Daniel, 1992).

Saprolite is the clay-rich, residual material derived from in-place weathering of bedrock. Saprolite is often highly leached and, being granular material with principal openings between mineral grains and rock fragments, differs substantially in texture and mineral composition from the unweathered crystalline parent rock in which principal openings are along fractures. Because saprolite is the product of in-place weathering of the parent bedrock, some of the textural features of the bedrock are retained and can be observed in outcrops. Saprolite is usually the dominant component of the regolith, in that alluvial deposits are restricted to locations of active and former stream channels and river beds; soil is generally restricted to a thin mantle on top of both the saprolite and alluvial deposits.

In the transition zone, unconsolidated material grades into bedrock. The transition zone consists of partially weathered bedrock and lesser amounts of saprolite. Particles range in size from silts and clays to large boulders of unweathered bedrock. The thickness and texture of this zone depend a great deal on the texture and composition of the parent rock. The best defined transition zones are usually those associated with highly foliated metamorphic parent rock, whereas those of massive igneous rocks are poorly defined with saprolite present between masses of unweathered rock (Harned and Daniel, 1992). It is thought that the incipient planes of weakness produced by mineral alignment in the foliated rocks facilitate fracturing at the onset of weathering, resulting in numerous rock fragments. The more massive rocks do not possess these planes of weakness, and weathering tends to progress along fractures such as joints. The result is a less distinct transition zone in the massive rocks.

In the Piedmont of North Carolina, 90 percent of the records for cased bedrock wells indicate combined thicknesses of 97 ft or less for the soil, saprolite, and transition zones of the regolith (Daniel, 1989). The average thickness of regolith was reported by Daniel (1989) to be 52 ft. The thickness of regolith in Guilford County is thought to be similar to that of the Piedmont as a whole.

Augering of three wells in Guilford County northwest of Greensboro indicated that the transition zone over a highly foliated mafic gneiss was approximately 15 ft thick (Harned and Daniel, 1992). This zone was reported in Georgia by Stewart (1962) and in Maryland by Nutter and Otton (1969). They describe this zone as being more permeable than the upper regolith and slightly more permeable than the soil zone. This observation is substantiated by reports from well drillers of so-called "first water" in drillers' logs (Nutter and Otton, 1969).

The high permeability of the transition zone is probably a result of less advanced weathering in the lower regolith relative to the upper regolith. Chemical alteration of the bedrock has progressed to the point that expansion of certain minerals causes extensive minute fracturing of the crystalline rock, yet has not progressed so far that the formation of clay has clogged these fractures. The presence of a zone of high permeability on top of the bedrock may create a zone of concentrated flow within the ground-water system. Well drillers may find water at relatively shallow depth, yet complete a dry hole after setting casing through the regolith and transition zone and into unweathered bedrock. If this happens, the ground water probably is present and moving primarily within the transition zone, but there is probably poor connection between the regolith reservoir, the bedrock fracture system, and the well.

The regolith contains water in pore spaces between rock particles. The bedrock, on the other hand, does not have any significant intergranular porosity. It contains water, instead, in sheetlike openings formed along fractures in the otherwise "solid" rock. Porosity and ground-water storage are the major differences in the water-bearing characteristics of the regolith and bedrock (fig. 3). The porosity of regolith is typically about 35 to 55 percent in the soil and saprolite, but decreases with depth in the transition zone as the degree of weathering decreases (Stewart, 1962; Stewart and others, 1964). Porosity in fractured bedrock ranges from 1 to 10 percent (Freeze and Cherry, 1979, table 2.4), but porosities of 10 percent are atypical. Values of 1 to 3 percent are much more representative of the North Carolina Piedmont.

As a general rule, the abundance of fractures and size of fracture openings decreases with depth. At depths

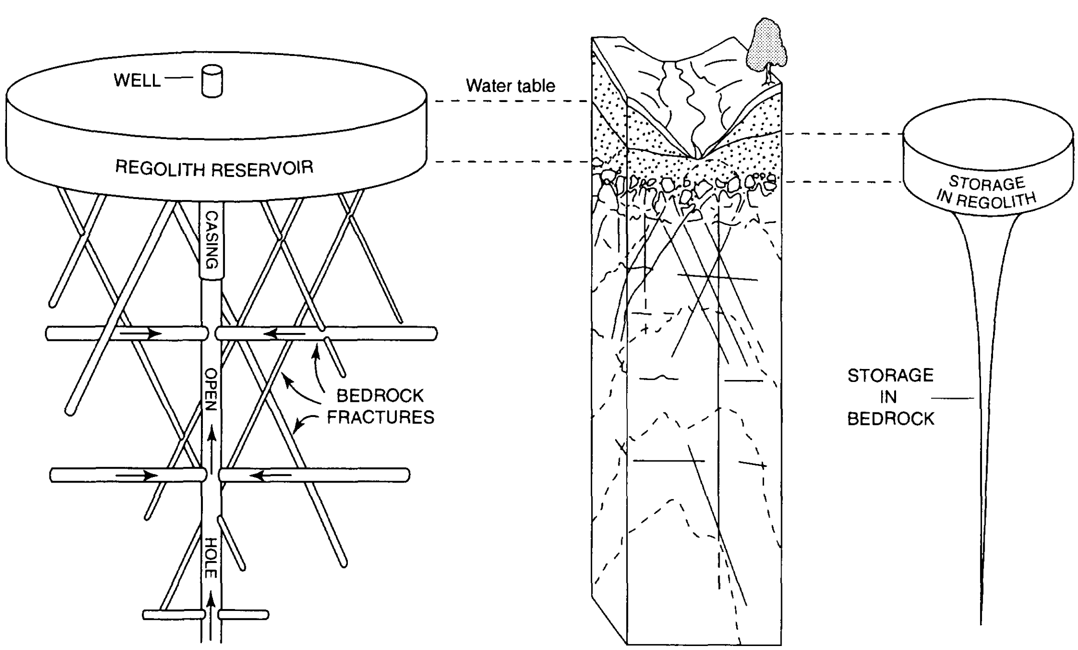


Figure 3. The reservoir-pipeline conceptual model of the Piedmont ground-water system and the relative volume of ground-water storage within the system (modified from Heath, 1984).

approaching 600 ft and greater, the pressure of the overlying material, or lithostatic pressure, holds fractures closed, and the porosity can be less than 1 percent (Daniel, 1989). Because of its larger porosity, the regolith functions as a reservoir that slowly feeds water downward into fractures in the bedrock (fig. 3). These fractures serve as an intricate interconnected network of pipelines that transmit water to springs, wetlands, streams, or wells.

Small supplies of water adequate for domestic needs can be obtained from the regolith through large-diameter bored or dug wells. However, most wells, especially where moderate supplies of water are needed, are relatively small in diameter and are cased through the regolith and finished with open holes in the bedrock. Bedrock wells generally have much higher yields than regolith wells because, being deeper, they have a much larger available drawdown.

Hydrogeologic Units

The geologic framework of Guilford County is very complex (Carpenter, 1982); beneath much of the county the bedrock consists of folded, fractured, and metamorphosed sedimentary and igneous basement rocks. In the northwestern part of the county, the metamorphic rocks are cut by an elongate, northeast trending, granite pluton that extends across several counties; this porphyritic granite is considered correlative with the Churchland Pluton of Davidson County (Butler and Ragland, 1969; Stromquist and Sundelius, 1975). Also intruded into the metamorphic rocks are lesser bodies of slightly metamorphosed or unmetamorphosed igneous rocks. Typical bedrock lithologies include granite, diorite, slate, tuff, and schist. Bedrock in the county is overlain nearly everywhere by unconsolidated material termed regolith. The characteristics of bedrock and regolith and the hydrologic relation between them influence the water-supply potential of the ground-water system in the county.

Within the Piedmont and Blue Ridge physiographic provinces, there are hundreds of rock units that have been defined and named by various conventions more in keeping with classical geologic nomenclature than hydrologic terminology. The geologic nomenclature does little to reflect the water-bearing potential or hydrologic properties of the different units. To overcome this shortcoming and to reduce the number of rock units to the minimum necessary to reflect differences in water-bearing potential and hydrologic properties, a classification scheme based on origin (rock class igneous, metamorphic, or sedimentary; or subclass metaigneous, metavolcanic, or metasedimentary), composition (mafic, intermediate, felsic), and texture (foliated, massive) was devised by Daniel (1989). The number of hydrogeologic units resulting from this classification of rocks in the Piedmont and Blue Ridge Provinces of North Carolina is 21. Of the 21 units described by Daniel (1989), 9 occur within Guilford County (table 2; fig. 4).

The rationale behind the hydrogeologic units shown in table 2 is the hypothesis that origin, composition, and texture can be linked not only to a rock's primary porosity but also to its susceptibility to the development of secondary porosity in the form of fractures and solution openings. The composition and texture would also determine, in part, the rate and depth of weathering of these units and the water-bearing properties of the resulting regolith.

Using this classification scheme and the most recent geologic maps available, Daniel and Payne (1990) compiled a hydrogeologic unit map for the Piedmont and Blue Ridge physiographic provinces of North Carolina. Well location maps were superimposed on this hydrogeologic unit map, and units corresponding to the well locations were coded and entered into a computerized data file for analysis to determine hydrologic characteristics of each unit. Summaries of these characteristics are presented by Daniel (1989). The Guilford County area of the hydrogeologic unit map is shown in figure 4.

Ground-Water Source and Occurrence

The continuous movement of water in the Earth system is referred to as the hydrologic cycle (Meinzer, 1942; Chow, 1964) and quantification of the various components of the hydrologic cycle is referred to as a water budget. The water budget of an area can be expressed by the following general form of a mass balance equation:

$$\text{precipitation} = \text{evaporation} + \text{transpiration} + \text{streamflow} \pm \text{change in storage} \qquad (1)$$

Under natural conditions, precipitation represents 100 percent of the input to surface-water and ground-water supplies. Part of the precipitation is returned to the atmosphere by evaporation from soil, wet surfaces, and surface-water bodies and by transpiration by vegetation. These return paths to the atmosphere are collectively referred to as evapotranspiration.

Streamflow has two components: (1) ground-water discharge, and (2) surface runoff consisting of overland flow from areas that cannot absorb precipitation as fast as it falls and precipitation that falls directly upon bodies of

Table 2. Classification, lithologic description, and area of hydrogeologic units in Guilford County, N.C. (from Daniel, 1989, table 1)

[mi^2, square miles]

Map symbol (fig. 4)	Hydrogeologic unit	Lithologic description	Area (mi^2)
		Igneous Intrusive Rocks	
IFI	Igneous, felsic intrusive	Light-colored, mostly granitic rocks, fine- to coarse-grained, some porphyritic, usually massive, locally foliated; includes granite, granodiorite, quartz diorite, quartz monzonite.	145
IMI	Igneous, mafic intrusive	Dark-greenish-gray to black, medium- to coarse-grained intrusive bodies; primarily gabbroic in composition, includes closely associated gabbro and diorite where they are too closely associated to be mapped separately, ultramafic rocks, diabase.	0.5
		Metamorphic Rocks	
		Metaigneous Rocks (Intrusive)	
MIF	Metaigneous, felsic	Light-colored, massive to foliated metamorphosed bodies of varying assemblages of felsic intrusive rock types; local shearing and jointing are common.	329
MII	Metaigneous, intermediate	Gray to greenish-gray, medium- to coarse-grained, massive to foliated, well-jointed, metamorphosed bodies of dioritic composition.	85
MIM	Metaigneous, mafic	Massive to schistose greenstone, amphibolite, metagabbro, and metadiabase, may be strongly sheared and recrystallized; metamorphosed ultramafic bodies are often strongly foliated, altered to serpentine, talc, chlorite-tremolite schist and gneiss.	3
		Metavolcanic Rocks (Extrusive-Eruptive)	
MVF	Metavolcanic, felsic	Chiefly dense, fine-grained, light-colored to greenish-gray felsic tuffs and felsic crystal tuffs, includes interbedded felsic flows. Felsic lithic tuffs, tuff breccias, and some epiclastic rocks; recrystallized fine-grained groundmass contains feldspar, sericite, chlorite, and quartz. Often with well-developed cleavage, may be locally sheared; phyllitic zones are common throughout the Carolina slate belt.	14
MVM	Metavolcanic, mafic	Grayish-green to dark-green, fine- to medium-grained andesitic to basaltic tuffs, crystal tuffs, crystal-lithic tuffs, tuff breccias and flows; pyroclastic varieties may contain lithic fragments; usually exhibits prominent cleavage; alteration minerals include chlorite, epidote, calcite, and tremolite-actinolite.	31
		Metasedimentary Rocks	
GNM	Gneiss, mafic	Mainly biotite hornblende gneiss; fine- to coarse-grained, dark-gray to green to black rock, commonly with distinct layering and foliation, often interlayered with biotite and hornblende gneisses and schists, and occasional amphibolite layers.	43
SCH	Schist	Schistose rocks containing primarily the micas muscovite or biotite or both, occasional sericite and chlorite schists; locally interlayered with hornblende gneiss and schist, commonly with distinct layering and foliation.	7

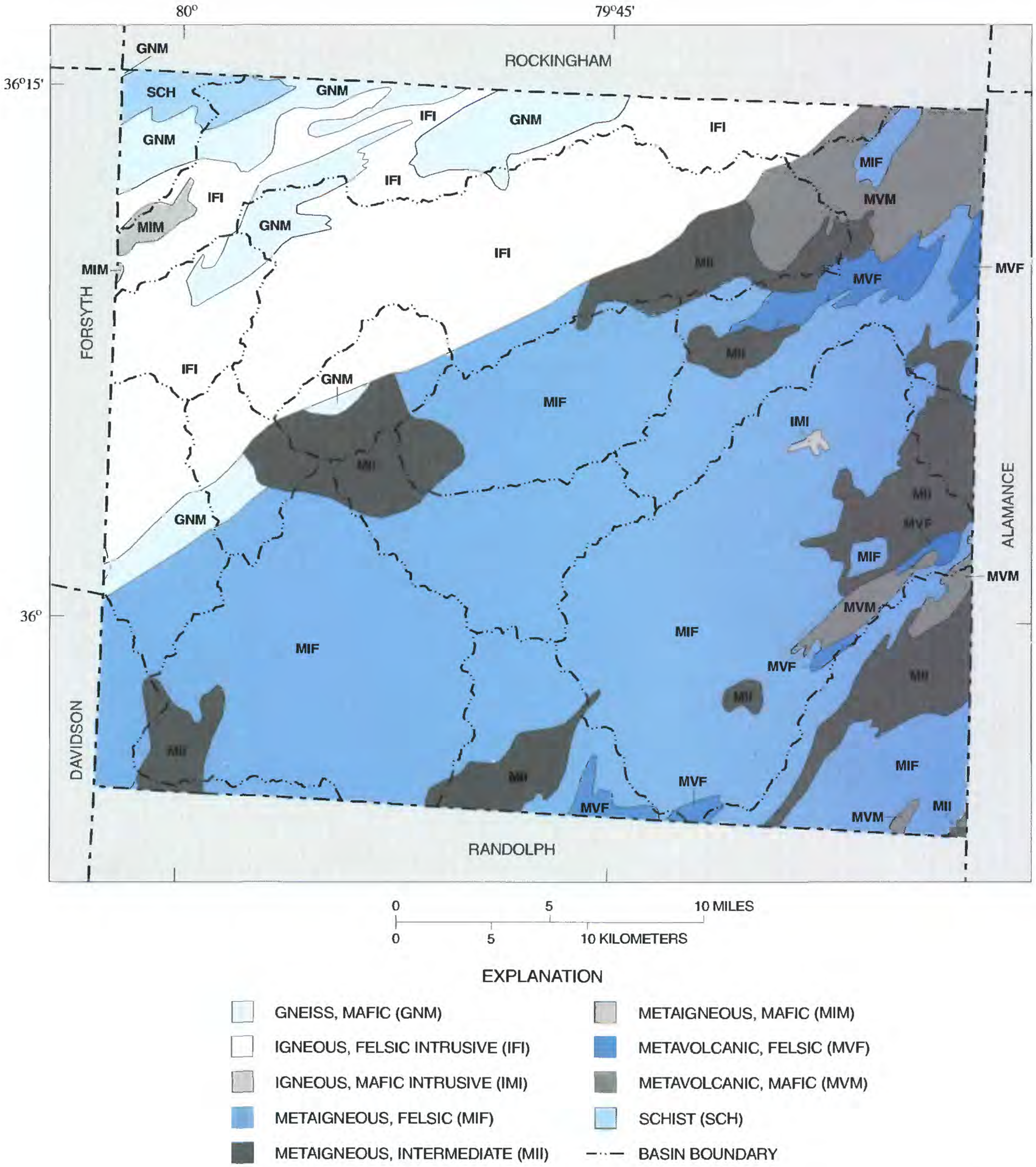


Figure 4. Hydrogeologic unit map of Guilford County, N.C. (from Daniel and Payne, 1990).

water. Storage has two components: (1) water stored in surface-water bodies, and (2) water stored in the ground.

When these components of the water budget are analyzed on a monthly basis, a pronounced pattern, or seasonality, is apparent with higher ground-water recharge occurring during the cooler, nongrowing season during the months of January through March, and the lowest ground-water recharge occurring at the height of the growing season during the months of June through September (Daniel and Sharpless, 1983, fig. 7). The seasonality in ground-water recharge is primarily a result of seasonal variation in evapotranspiration. Seasonal patterns in precipitation have less effect on recharge. In fact, long-term records indicate that precipitation is rather evenly distributed during the year and that the wettest months are often June and July—near the low point of seasonal ground-water recharge.

The components of the water budget that are important to this study are (1) water that is stored in the ground, and (2) rates of recharge to and discharge from the ground-water system that result in changes in ground-water storage. When changes in ground-water storage are small, ground-water recharge is roughly equal to ground-water discharge. To account for seasonal variation in components of the water budget resulting from variation in precipitation, evaporation, and transpiration, it is useful to express components of the water budget on a yearly basis because the year-to-year variation tends to be small. Over longer periods, perhaps a decade or more, net changes in the water budget as a result of seasonal changes tend to be near zero. For this report, data will be analyzed and results presented on a water-year basis. Duration statistics for the various drainage basins will be based on the entire period of record, in water years.

Recharge to and Discharge from the Ground-Water System

The ground-water system serves two hydraulic functions: (1) it stores water to the extent of its porosity, and (2) it transmits water from recharge areas to discharge areas. Thus, the ground-water system serves as both a reservoir and a conduit. In most hydrogeologic settings, ground-water systems are more effective as reservoirs than as conduits.

Under natural conditions (no major ground-water withdrawals or artificial recharge), ground water in the intergranular pore spaces of the regolith and bedrock fractures is derived from infiltration of precipitation. Water enters the ground-water system in recharge areas, which generally include all of the interstream land surface at elevations above streams and their adjoining flood plains. Streams and flood plains are, under most conditions, discharge areas. After infiltration, water slowly moves downward through the unsaturated zone to the water table, which is the top of the saturated zone. Water moves laterally through the saturated zone, discharging as seepage springs on steep slopes and as bank and channel seepage into streams, lakes, or swamps. In the regolith, ground-water movement is primarily by intergranular flow; in the bedrock, ground-water flow is by fracture flow, and the flow paths from recharge areas to discharge areas are often much more circuitous than in the regolith.

Recharge rates are generally expressed in terms of volume (such as cubic feet or gallons) per unit of time (such as day or year) per unit of area (such as a square mile, or an acre), which is referred to as unit area recharge. When these units are reduced to their simplest forms, the result is recharge expressed as an average depth of water on the land surface per unit of time, which is referred to as the equivalent uniform depth. Recharge varies from month to month and year to year, depending on amounts of precipitation, seasonal distribution, evaporation, transpiration, land use, and other factors.

Another important aspect of recharge and discharge involves timing. Recharge occurs during and immediately following periods of precipitation and, thus, is intermittent. Discharge, on the other hand, is a continuous process as long as ground-water levels are above levels at which discharge occurs. However, between periods of recharge, ground-water levels decline, and the rate of discharge also declines. Most recharge of the ground-water system occurs during late fall, winter, and early spring, when plants are dormant and evaporation rates are small.

The depth to the water table varies from place to place depending on topography, climate, season of the year, and properties of the water-bearing materials. However, the climate throughout Guilford County is relatively uniform and the water-bearing properties of the different bedrock lithologies and regoliths are similar. Therefore, topography probably has the greatest influence on the depth to the water table in a specific area. In stream valleys and areas adjacent to ponds and lakes, the water table may be at or very near land surface. Beneath slopes, upland flats, and broad interstream divides, the water table generally ranges from a few feet to a few tens of feet beneath the surface, but beneath hills and rugged ridge lines, the water table may be at considerably greater depths. In effect, the water table is a subdued replica of the land surface.

Ground-Water Storage

Nearly all ground-water storage in the Piedmont ground-water system is in the regolith. The quantity stored in the bedrock is small by comparison. Ground-water levels vary seasonally, declining during the summer and early fall when atmospheric conditions enhance evaporation and plants transpire significant quantities of water, and rising during the winter and early spring when plants are dormant. The seasonal range of water-level change is about 4–12 ft (fig. 5A); thus, the average saturated thickness of the regolith can vary by 4–12 ft. However, year-to-year variations are usually small, and on an annual basis, ground-water storage in the study area is probably relatively stable. Data shown in figure 5 are from a long-term observation well located east of Guilford County in southeastern Orange County. Another long-term observation well (NC-142; Smith and others,

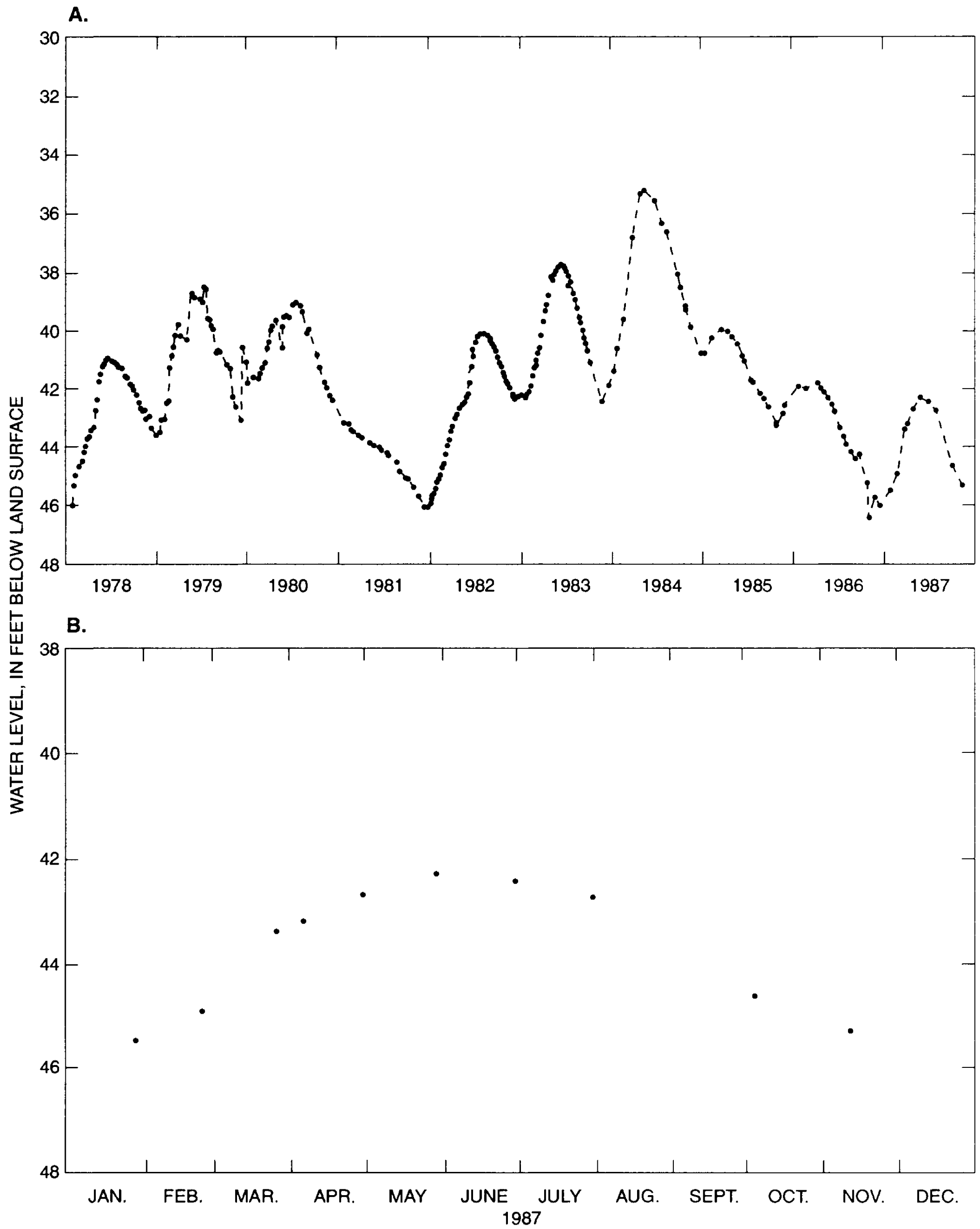


Figure 5. Water level in observation well NC-126, Orange County, N.C., (from Coble and others, 1989). (A) Decade hydrograph for the period 1978–87; (B) Annual hydrograph for the year 1987.

1996) is located west of Guilford County in Davie County. Both wells exhibit similar seasonal water-level fluctuations and are considered representative of ground-water conditions in the area of the Piedmont that includes Guilford County. Because of their similarity, only the hydrograph from observation well NC-126 in Orange County is shown (fig. 5).

Although higher rates of ground-water recharge typically occur during the months of January through March (Daniel and Sharpless, 1983), the water table usually does not reach its greatest height until May or June (fig. 5B). The 2- to 3-month lag between the time of maximum ground-water recharge and the time of highest water table is attributed to the time required for recharge to move through the unsaturated zone between land surface and the water table. A similar lag has been reported by Daniel and others (1997) for 36 wells tapping regolith and bedrock in the southwestern Piedmont of North Carolina. However, peak recharge in that region usually occurs during the months of February through April and the highest ground-water levels often occur in July or August. The occurrence of these events about a month later than in the eastern Piedmont is attributed to the higher elevation, cooler climate, and later start to the growing season in the southwestern Piedmont.

Because nearly all ground-water storage is in the regolith, the amount of water in storage can be estimated from the saturated thickness of regolith. The depth of well casing used in drilled open-hole wells approximates the regolith thickness at a given well. By subtracting the depth to water from the depth of casing, an estimate of the saturated thickness of regolith is obtained. If the water level in the well is below the bottom of the casing, the saturated thickness of regolith is set equal to zero. Daniel (1989, table 5) presented a statistical summary of data on depth of well casing, depth to water, and estimated saturated thickness of regolith for wells in different topographic settings in the Piedmont. The average depth of well casing for all wells is 52.0 ft. The average depth to water is greatest beneath hills and ridges and least beneath valleys and draws. Consequently, the saturated thickness of regolith is least beneath hills and ridges (average 20.4 ft) and greatest beneath valleys and draws (average 33.6 ft). The saturated thickness of regolith beneath slopes (average 24.6 ft) is intermediate to these extremes. The average saturated thickness of regolith for all wells is 24.0 ft.

The quantity of ground water available from storage in Guilford County can be estimated from the following general relationship:

$$\text{available ground water in storage} = \text{saturated thickness of regolith} \times \text{specific yield} \qquad (2)$$

The specific yield to be used in the above storage computation can be derived from the relation for northeastern Georgia shown in figure 6A. Stewart (1962) and Stewart and others (1964) tested saprolite cores from the Georgia Nuclear Laboratory area for several properties, including porosity and specific yield. They found that porosity, although variable, changes only slightly with depth through the saprolite profile until the transition zone is reached, where porosity begins to decrease.

Specific yield is the ratio of the volume of water a saturated rock (or other Earth material) will yield by gravity, to the total volume of rock. The distinction between porosity and specific yield is important; porosity indicates the total volume of pore space in the rock whereas specific yield refers to the volume of water that can be drained from the saturated rock. The two values are not equal because some water is retained within openings by surface tension and as a film on the rock surfaces. The ratio of the volume of water retained to the total volume of rock is the specific retention. Based on average thicknesses of saturated regolith presented by Daniel (1989) and the relations in figure 6B, the average quantity of available water in storage is 0.55 million gallons per acre (Mgal/acre) beneath hills and ridges, 0.77 Mgal/acre beneath slopes, and 1.22 Mgal/acre beneath valleys and draws. The average quantity of water available beneath all sites is 0.73 Mgal/acre.

Where a discrete transition zone is present between the saprolite and unweathered bedrock (Harned and Daniel, 1992), the relations between porosity and depth and specific yield and depth are nonlinear. Consequently, equation (2) given in the preceding paragraph will be nonlinear, and a plot of this relation will be nonlinear as shown in figure 6B. The quantity of water available from storage can be estimated from figure 6B. However, it is worth noting that the water table throughout much of the central Piedmont of North Carolina appears to be in the saprolite, as determined from water levels in bored and hand-dug wells (Mundorff, 1948; LeGrand, 1954; Bain, 1966). Few, if any, of these wells penetrate the transition zone, the top of which is the point of refusal for most well-boring equipment. Although water levels fluctuate

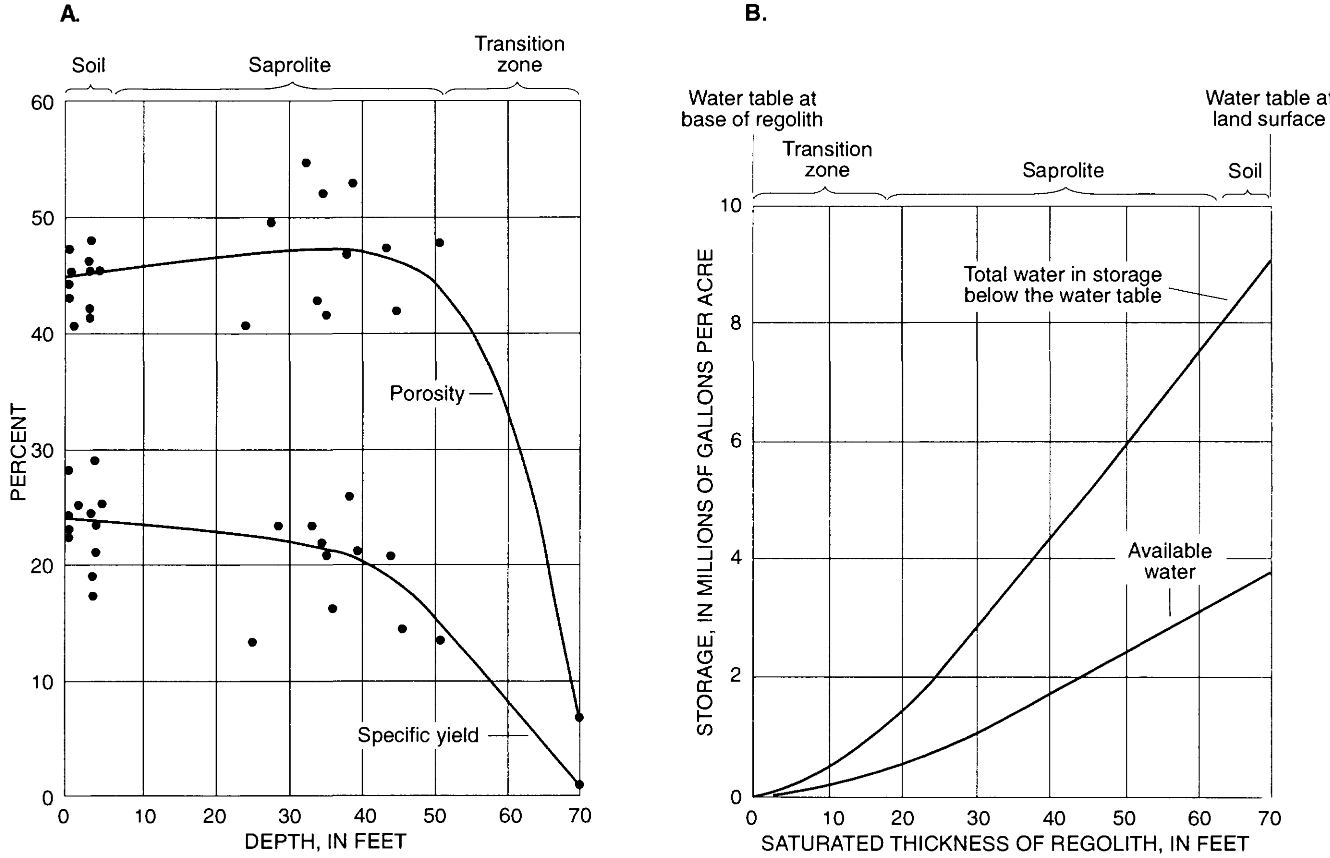


Figure 6. Relation of porosity and specific yield to total ground-water storage and available water in the regolith. (A) Variation of porosity and specific yield with depth in the regolith (from Stewart, 1962); (B) Total ground water in storage below the water table and water available by gravity drainage.

seasonally in these wells, few go dry, indicating that for the most part, seasonal fluctuation of the water table occurs within the saprolite. As shown in figure 6B, water available from storage in the saprolite follows a more or less linear part of the relation with a specific yield of about 0.20 (fig. 6A). Therefore, the contribution to base flow from storage in the saprolite can be estimated by the linear equation:

$$\text{water from storage} = 0.20 \times \text{change in water table} \qquad (3)$$

Based on this equation and a 4- to 12-foot natural annual variation in the water table, the quantity of water in storage can increase or decrease by 0.8–2.4 cubic feet per square foot (ft^3/ft^2) of aquifer area (0.31–0.89 Mgal/acre) in a year's time.

Sufficient similarities exist between the Piedmont of northeastern Georgia and the central Piedmont of North Carolina that this information can be used with reasonable limits of confidence. The depth of weathering, lithology of the underlying bedrock, and geologic structures are similar in both areas. Furthermore, Daniel and Sharpless (1983) report that dewatering of saprolite during a pumping test in a similar hydrogeologic setting in Guilford County could be explained by a specific yield of 0.20.

HYDROGRAPH SEPARATION METHODS AND ESTIMATION OF RECHARGE

Ground-water recharge from precipitation is difficult to measure directly; however, an estimate of the amount of precipitation that infiltrates into the ground and ultimately reaches the streams of the region as base flow can be determined by the technique of hydrograph separation (Rorabaugh, 1964; Daniel, 1976; Pettyjohn and Henning, 1979; Daniel, 1990b; Rutledge, 1993). Hydrograph separation entails dividing the streamflow graph (hydrograph) into two components—ground-water discharge and overland runoff—and then adding up the flow determined to be ground-water discharge over the hydrograph period. Under the assumption that there has been no long-term change in ground-water storage, ground-water discharge is equal to the ground-water recharge.

The hydrograph separation method employed in this study is the local-minimum method of Pettyjohn and Henning (1979) that estimates values of daily mean base flow. The method is executed by the USGS computer program HYSEP (Sloto, 1991) that reads data files of daily mean streamflow obtained from USGS records. HYSEP, which is executed in FORTRAN-77, is an implementation of hydrograph separation algorithms originally developed by Pettyjohn and Henning (1979) for use on Ohio streams. Pettyjohn and Henning (1979) developed three algorithms for performing hydrograph separations—the local minimum, the fixed interval, and sliding-interval methods. The local-minimum method of hydrograph separation was chosen for this study because it provides the lowest (most conservative) daily mean base-flow estimate of the three algorithms implemented in HYSEP. Although this method produces estimates of daily mean ground-water discharge, use of the small time scale (1 day) may result in substantial errors in short-term recharge estimates. Therefore, statistics for longer periods (monthly, annually, period of record) are reported in the hydrographs and summary tables that are discussed in later sections.

Comparison of Methods

The Pettyjohn-Henning local-minimum method (Pettyjohn and Henning, 1979) belongs to a category of hydrograph separation techniques known as base-flow record estimation (Rutledge, 1993). Results from this method include the effects of riparian evapotranspiration (loss of ground water to vegetation and evaporative losses on the flood plain) and, therefore, are usually lower than estimates produced by the hydrograph separation technique of recession-curve displacement (Rutledge, 1993). Estimates of ground-water recharge produced by base-flow record estimation are sometimes called effective (or residual) ground-water recharge because the estimates represent the difference between actual recharge and losses to riparian evapotranspiration.

The recession-curve displacement method, often referred to as the Rorabaugh or the Rorabaugh-Daniel method (Rorabaugh, 1964; Daniel, 1976), is more theoretically based as compared to base-flow record estimation and is much less affected by riparian evapotranspiration. Development of the computer program RORA to perform the recession-curve displacement (Rorabaugh-Daniel) method has been described recently by Rutledge (1993) and Rutledge and Daniel (1994), but several changes to the program have been made since its development was first reported (A.T. Rutledge, U.S. Geological Survey, written commun., 1995, 1996). Prior to development of RORA, the recession-curve displacement method was performed manually, and manual application apparently still produces the best results under certain conditions such as periods of high evapotranspiration. However, manual application of the recession-curve displacement method has the disadvantage of the time required to apply all the steps necessary to calculate recharge for each storm event. Because of efficiency of application and general acceptance of the technique of base-flow record estimation, the computerized Pettyjohn-Henning local-minimum method was the method of choice to analyze more than 800 years of available streamflow record from 19 gaging stations that measure streamflow within and from Guilford County.

Results from selected hydrograph separation techniques, including the Pettyjohn-Henning local-minimum method and the Rorabaugh-Daniel method, were compared by Daniel (1990b). Results of the comparison for 161 water years of record from 16 stations in four States (Georgia, North Carolina, Tennessee, and Pennsylvania) showed that the Pettyjohn-Henning local-minimum method produced results that averaged 21 percent lower than the Rorabaugh-Daniel recession-curve displacement method. This suggests the possibility that riparian evapotranspiration may consume, on average, as much as 21 percent of ground-water recharge before it discharges to streams as base flow.

Knowledge of differences between estimates of ground-water recharge produced by different hydrograph separation techniques—and the magnitude of these differences—is important for the development and use of ground-water management strategies. The Rorabaugh-Daniel method may produce better estimates of total recharge on interstream uplands (recharge areas), but the Pettyjohn-Henning local-minimum method seems to account for the ground water used by riparian vegetation in discharge areas. Therefore, estimates of ground-water recharge produced by the Pettyjohn-Henning method, which accounts for riparian losses, are conservative estimates of the quantity of ground water potentially available to wells. However, maintaining riparian vegetation as buffers along streams can help ensure good water quality in streams. Use of conservative estimates of recharge also will help ensure that sufficient ground water is available for riparian vegetation. This was another reason for choosing the Pettyjohn-Henning local-minimum method of hydrograph separation.

The Recharge Hydrograph

A hydrograph is a graph showing stage, flow, velocity, or other characteristics of water with respect to time (Langbein and Iseri, 1960). The recharge hydrographs presented in this report show monthly values of ground-water recharge during the water year, as well as mean and median values for the period of record. Estimates of daily mean recharge were subset by months and the mean recharge was computed for each month. The monthly means of recharge were then analyzed to determine the maximum monthly value, minimum monthly value, and mean of those monthly values for each month.

A water year is a continuous 12-month period selected to present data pertaining to hydrologic or meteorologic phenomena during which a complete annual hydrograph cycle normally occurs (Paulson and others, 1991). The hydrographs in this report are for the water year that runs from October 1 through September 30.

The Duration Table

The duration table is a tabular arrangement of flow-duration data that shows the percentage of time during which specified flows were equaled or exceeded during a given period; it combines in one table the flow characteristics of a stream (or other hydrologic characteristic) throughout the range of discharge, without regard to the sequence of occurrence (Searcy, 1959). The duration curve, which is a graphic illustration derived from the cumulative-frequency data in the duration table, also is the integral of the frequency diagram. For ease of interpretation, duration curves are not presented in this report; only the duration tables are presented.

The duration tables in this report contain estimates of ground-water recharge and the percentages of time that specified estimates of recharge were equaled or exceeded. In a strict sense, the flow-duration data apply only to the period for which data were used to develop the frequency distribution. If flow during the period on which the duration table is based represents the long-term flow of the stream, the curve may be considered a probability curve and used to estimate the percentage of time that a specified discharge will be equaled or exceeded in the future.

The duration data provide a convenient means for studying flow characteristics of streams and for comparing one basin with another (Koltun, 1995). Duration tables are presented for each of the basins that are discussed in the following section.

GROUND-WATER RECHARGE IN SELECTED DRAINAGE BASINS

Nineteen gaging stations were selected to provide nearly complete coverage of streamflow conditions in Guilford County. Station names, station numbers, drainage areas, and periods of streamflow record collected at each of the stations are given in table 1. Locations of the gaging stations and all, or most, of the associated drainage basin boundaries are shown in figure 1. These 19 stations represent all the continuous-record gaging stations that have been used to measure streamflow within or from Guilford County. Nine of the stations were active in 1995; data collection at 10 stations has been discontinued. These stations have continuous streamflow record of sufficient length to define the base-flow characteristics of the individual basins. Streamflow in most basins has not been appreciably affected by human activities; in basins where effects of such activities could be identified and quantified, adjustments were made to the streamflow record to compensate for these human activities.

The boundary for each of the drainage basins was delineated using USGS 1:24,000-scale topographic maps. The boundaries were digitized and entered into a computerized geographic information system (GIS) so that drainage-basin areas could be determined and comparisons made between hydrologic and hydrogeologic conditions in individual drainage basins.

When multiple gaging stations occur along the same stream or within the same drainage system, the drainage basins defined by the gaging stations overlap. When periods of data collection at stations also overlap, it is possible to estimate the ground-water contribution to streamflow from the intervening area between stations. This is accomplished by subtracting the base flow at the upstream station from the base flow at the downstream station. The difference is considered the contribution from the subbasin area between the stations. In subbasins defined by three or more gaging stations, the base-flow record from all stations may not overlap for the entire period of record. In this case, the period of record for the subbasin is determined by the period of overlapping record between the downstream station and the upstream station with the largest drainage area. Using data from the

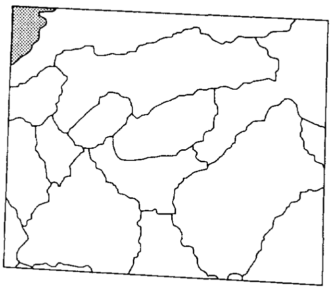
19 gaging stations, it was possible to analyze 15 basin and subbasin areas in Guilford County. Drainage areas for the parts of the 15 basins and subbasins that lie within the boundaries of Guilford County are given in table 3.

Descriptions of the individual basins and subbasins are presented in the following sections. Statistical summaries of recharge estimates for the basins and subbasins are presented in tables. Hydrographs of monthly recharge estimates are presented to illustrate the seasonal variation in recharge during a water year. The hydrographs of monthly recharge estimates present three sets of data: (1) the maximum monthly estimates of recharge during the period of record, (2) the means of monthly estimates of recharge for the period of record, and (3) the minimum monthly estimates of recharge during the period of record. The monthly means define a systematically changing seasonal hydrograph with higher recharge during the late fall and spring and lower recharge during the summer and early fall. However, the monthly maximums and minimums, although generally exhibiting the same seasonal pattern, are subject to variations resulting from floods and droughts that occurred some time during the period of record. This is especially apparent in some hydrographs of maximum monthly estimates of recharge where floods or extremely wet periods result in irregular hydrographs with multiple peaks. Finally, the recharge estimates for the different basins and subbasins are compared and discussed in terms of hydrogeologic conditions that may account for similarities and differences between the recharge estimates.

Table 3. Drainage areas of 15 basins and subbasins within the boundaries of Guilford County, N.C.

[mi^2, square miles; —, unnumbered]

Site no. (fig. 1)	River or stream name and extent of basin or subbasin within Guilford County	Drainage area (mi^2)
3	Dan River subbasin between station 02068500 near Francisco, N.C. (site 1, fig. 1), and station 02071000 near Wentworth, N.C.	11.5
4	Haw River Basin upstream from station 02093500 near Benaja, N.C.	64.8
5	Reedy Fork Basin upstream from station 02093800 near Oak Ridge, N.C.	17.8
6	Horsepen Creek Basin upstream from station 02094000 at Battle Ground, N.C.	16.4
7	Reedy Fork subbasin between station 02093800 near Oak Ridge, N.C. (site 5, fig. 1), station 02094000 at Battle Ground, N.C. (site 6, fig. 1), and station 02094500 near Gibsonville, N.C.	94.5
8	South Buffalo Creek Basin upstream from station 02095000 near Greensboro, N.C.	34.1
9	North Buffalo Creek Basin upstream from station 02095500 near Greensboro, N.C.	37.1
11	Upper Haw River subbasin between station 02093500 near Beneja, N.C. (site 4, fig. 1), station 02094500 near Gibsonville, N.C. (site 7, fig. 1), station 02095500 near Greensboro, N.C. (site 9, fig. 1), station 02095000 near Greensboro, N.C. (site 8, fig. 1), and station 02096500 at Haw River, N.C.	64.7
12	Big Alamance Creek Basin upstream from station 02096700 near Elon College, N.C.	115
13	Lower Haw River subbasin between station 02096500 at Haw River, N.C. (site 11, fig. 1), station 02096700 near Elon College, N.C. (site 12, fig. 1), and station 02096960 near Bynum, N.C.	46.6
15	West Fork Deep River Basin upstream from station 02098500 near High Point, N.C.	26.1
16	East Fork Deep River Basin upstream from station 02099000 near High Point, N.C.	14.8
17	Upper Deep River subbasin between station 02098500 near High Point, N.C. (site 15, fig. 1), station 02099000 near High Point, N.C. (site 16, fig. 1), and station 02099500 near Randleman, N.C.	76.2
18	Lower Haw River subbasin between station 02099500 near Randleman, N.C. (site 17, fig. 1), and station 02100500 at Ramseur, N.C.	29.4
19	Abbotts Creek Basin upstream from station 02121500 at Lexington, N.C.	8.45
—	Ungaged area on the Uwharrie River	0.45
	Total area in county	657.64



Dan River Subbasin

The Dan River subbasin is the 906-mi^2 part of the Dan River Basin that lies between gaging station 02068500 (site 1, fig. 1) near Francisco, N.C., and gaging station 02071000 (site 3, fig. 1) near Wentworth, N.C. Tributaries to the Dan River, such as Belews Creek, East Belews Creek, and Hogan Creek, extend southward from the Dan River and receive runoff from the northwestern part of Guilford County. The area of the Dan River subbasin within Guilford County is 11.5 mi^2, or 2 percent of the land area of the county.

Discharge records for gaging station 02068500 (site 1, fig. 1) near Francisco, N.C., and gaging station 02069000 (site 2, fig. 1) at Pine Hall, N.C., were analyzed by hydrograph separation, and the daily estimates of recharge were combined to make a composite record spanning 55 water years in the period from 1940 to 1995. Station 02068500 was discontinued in 1987 and reactivated at the beginning of the1992 water year. Records from station 02069000 were used for the 1988 through 1990 water years. Station 02071000 near Wentworth has been in continuous operation since the 1940 water year (table 1). The composite estimates of recharge at 02068500 were subtracted, on a daily basis, from the record for the Dan River near Wentworth to produce daily estimates of recharge for the intervening area between the stations.

The daily estimates were further analyzed to produce the results presented in tables 4 and 5 and figure 7. Annually, estimated mean recharge in the Dan River subbasin is 8.45 in., or 630 gallons per day per acre ([gal/d]/acre). The median recharge is 576 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 4 and figure 7.

Table 4. Statistical summary of recharge estimates for the Dan River subbasin between station 02068500 near Francisco, N.C., and station 02071000 near Wentworth, N.C.

[Analysis includes data from station 02069000 (site 2, fig. 1)]

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
55	8.45	2.22	4.71	14.21	59.7

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	55	422	158	854
November	55	526	244	1,020
December	55	608	276	1,230
January	55	697	300	1,300
February	55	845	503	1,690
March	55	941	496	1,910
April	55	915	456	1,640
May	55	751	381	1,390
June	55	593	246	953
July	55	489	128	998
August	55	413	128	849
September	55	359	88.7	846
All months	660	630	88.7	1,910

Table 5. Ground-water recharge duration statistics for the Dan River subbasin between station 02068500 near Francisco, N.C., and station 02071000 near Wentworth, N.C.

[Analysis includes data from station 02069000 (site 2, fig. 1)]

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time							
Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	2,670						
1	1,570	26	779	51	569	76	402
2	1,400	27	770	52	563	77	394
3	1,310	28	759	53	558	78	387
4	1,250	29	749	54	552	79	380
5	1,200	30	739	55	546	80	373
6	1,160	31	730	56	540	81	365
7	1,120	32	720	57	533	82	358
8	1,090	33	709	58	526	83	350
9	1,070	34	699	59	519	84	343
10	1,040	35	689	60	514	85	336
11	1,020	36	681	61	507	86	328
12	994	37	672	62	500	87	320
13	970	38	663	63	494	88	311
14	950	39	655	64	486	89	301
15	931	40	647	65	479	90	290
16	912	41	638	66	473	91	278
17	895	42	630	67	466	92	267
18	880	43	624	68	459	93	254
19	866	44	618	69	453	94	243
20	853	45	610	70	445	95	229
21	840	46	603	71	438	96	215
22	829	47	596	72	430	97	196
23	816	48	589	73	422	98	175
24	802	49	583	74	415	99	134
25	791	50	576	75	409	100	0.00

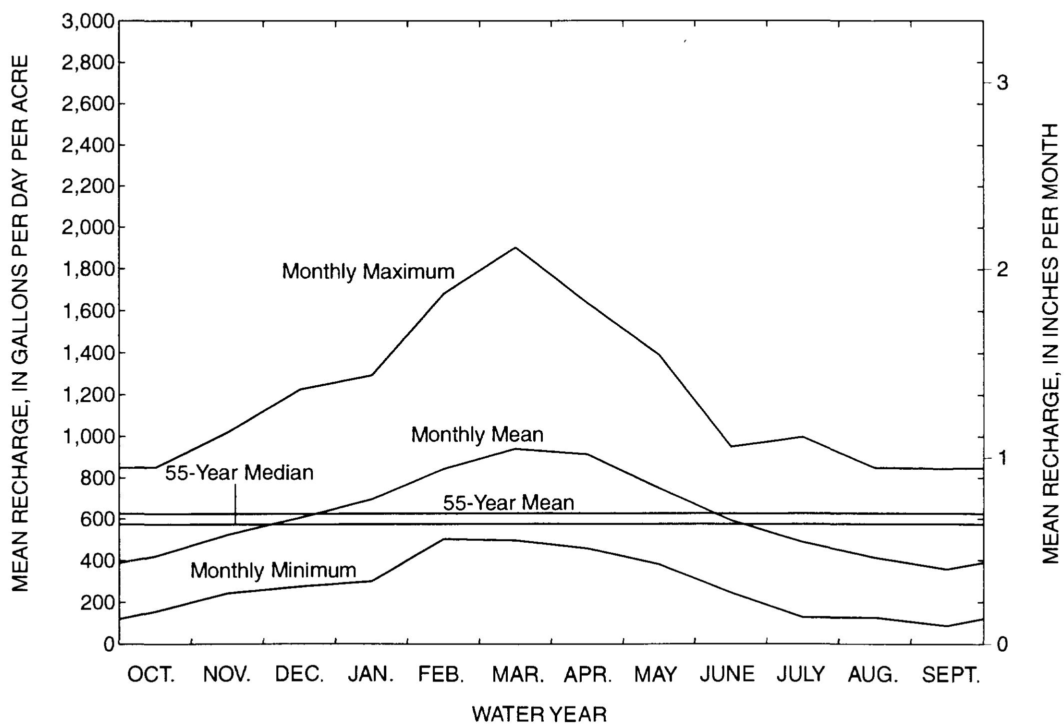
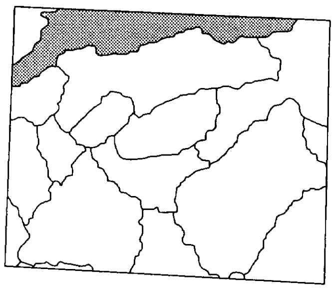


Figure 7. Variation of monthly mean ground-water recharge in the Dan River subbasin between station 02068500 near Francisco, N.C., and station 02071000 near Wentworth, N.C.



Haw River Basin Upstream from Benaja, N.C.

The part of the Haw River Basin that lies upstream from gaging station 02093500 (site 4, fig. 1) near Benaja, N.C., has a drainage area of 168 mi^2. The Haw River originates in the extreme east-central part of Forsyth County and flows in an east-northeasterly direction across northern Guilford County into southern Rockingham County where it turns to the southeast, crosses northeastern Guilford County, and flows into Alamance County. The area of the Haw River upstream from station 02093500 that lies within Guilford County is 64.8 mi^2, or 10 percent of the land area of the county.

Discharge records for gaging station 02093500 were analyzed by hydrograph separation to give daily estimates of recharge for the 43-year period between 1929 and 1971. Station 02093500 was discontinued in 1971. The daily estimates of recharge were further analyzed to produce the results presented in tables 6 and 7 and figure 8. Annually, estimated mean recharge in the Haw River Basin is 6.71 in., or 501 (gal/d)/acre. The median recharge is 418 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 6 and figure 8.

Table 6. Statistical summary of recharge estimates for the Haw River Basin upstream from station 02093500 near Benaja, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
43	6.71	1.63	4.18	10.15	55.6

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	43	288	64.8	654
November	43	430	136	1,390
December	43	535	261	982
January	43	682	307	1,240
February	43	857	361	1,980
March	43	870	456	1,460
April	43	777	324	2,200
May	43	481	276	976
June	43	340	164	639
July	43	278	67.2	816
August	43	268	55.7	787
September	43	211	19.1	667
All months	516	501	19.1	2,200

Table 7. Ground-water recharge duration statistics for the Haw River Basin upstream from station 02093500 near Benaja, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time							
Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	5,820						
1	1,740	26	661	51	409	76	245
2	1,450	27	649	52	401	77	240
3	1,290	28	633	53	394	78	233
4	1,190	29	619	54	388	79	226
5	1,110	30	607	55	382	80	218
6	1,050	31	597	56	375	81	212
7	999	32	587	57	368	82	204
8	957	33	578	58	361	83	196
9	931	34	568	59	355	84	190
10	905	35	558	60	347	85	182
11	881	36	547	61	340	86	174
12	858	37	538	62	333	87	168
13	838	38	530	63	325	88	161
14	818	39	520	64	319	89	154
15	804	40	510	65	313	90	147
16	789	41	499	66	306	91	138
17	776	42	488	67	300	92	132
18	764	43	479	68	294	93	123
19	751	44	469	69	286	94	117
20	737	45	457	70	280	95	108
21	723	46	450	71	273	96	100
22	713	47	443	72	266	97	90.2
23	702	48	434	73	260	98	73.2
24	688	49	427	74	255	99	52.6
25	673	50	418	75	249	100	3.61

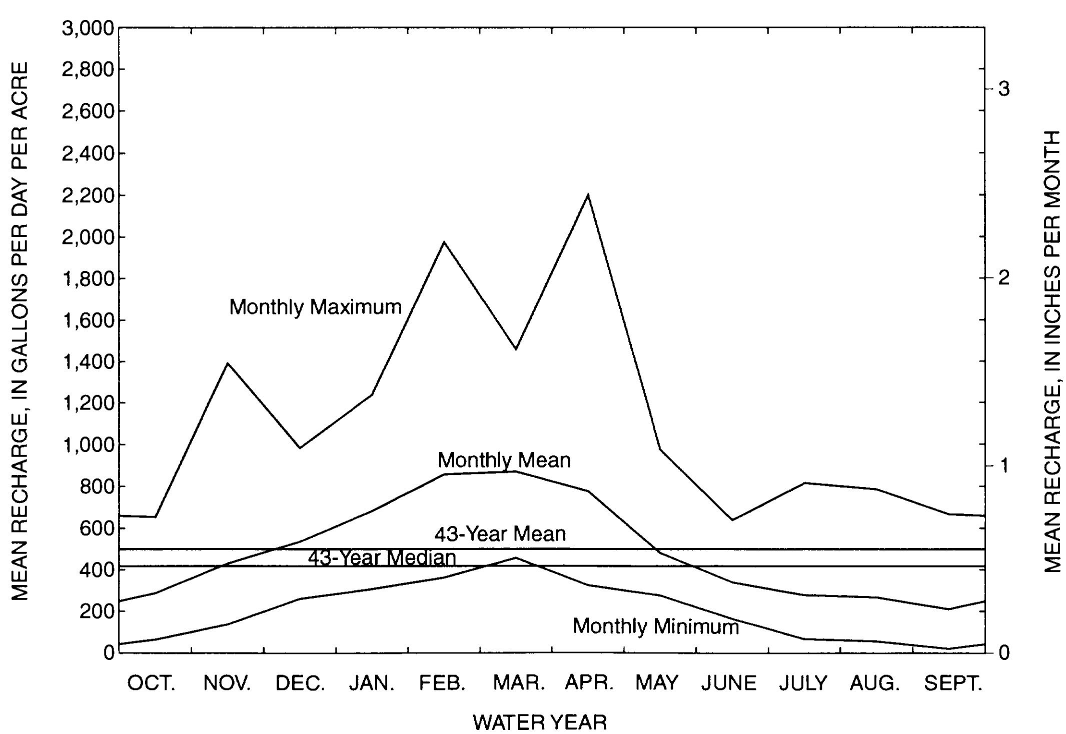
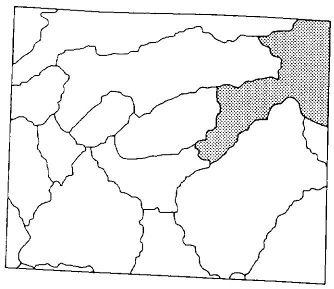


Figure 8. Variation of monthly mean ground-water recharge in the Haw River Basin upstream from station 02093500 near Benaja, N.C.



Upper Haw River Subbasin

The upper Haw River subbasin is the 236-mi^2 part of the Haw River Basin that lies between gaging stations 02093500 (site 4, fig. 1) near Benaja, N.C., 02094500 (site 7, fig. 1) near Gibsonville, N.C., 02095500 (site 9, fig. 1) near Greensboro, N.C., 02095000 (site 8, fig. 1) near Greensboro, N.C., and gaging station 02096500 (site 11, fig. 1) at Haw River, N.C. The area of the upper Haw River subbasin in Guilford County is 64.7 mi^2, or 10 percent of the land area of the county.

Discharge records from the five stations were analyzed by hydrograph separation, and daily estimates of recharge were generated for the 67 water years between 1929 and 1995. Discharge records from the five stations do not overlap for the entire 67-year period (table 1); however, there is sufficient overlap that the recharge estimate is considered representative of the intervening area between these stations. Discharge records from a sixth station, 02096000 (site 10, fig. 1), on Stony Creek near Burlington, N.C., were collected for 7 water years between 1953 and 1959. Estimates of recharge for this site were included in the computation of recharge for the Haw River subbasin between 1953 and 1959, but because of the much longer period of record at the other five stations, the area of Stony Creek upstream of 02096000 is included in the upper Haw River subbasin, and the 67-year estimate of recharge is considered representative of the larger area.

Water is diverted by Greensboro from reservoirs on Reedy Fork upstream of station 02094500; however, this water is returned as wastewater upstream of stations 02095500 and 02095000. Thus, these diversions are balanced by wastewater discharges and no adjustments to inflow to the upper Haw River subbasin were made for these three stations. Water also is diverted from reservoirs on Stony Creek upstream of station 02096500 by Burlington, N.C. About half of this water is returned as treated wastewater upstream of the station and about half is returned downstream of the station. Therefore, discharge past station 02096500 was adjusted by adding the net difference between annual average diversions and wastewater returns upstream of the station to daily average streamflow before conducting the hydrograph separation. During the water years between 1952 and 1995, net annual average reduction in flow above station 02096500 ranged from 0.4 ft^3/s to 8.2 ft^3/s, and averaged 5.5 ft^3/s. Estimates of recharge for stations 02093500, 02094500, 02095500, 02095000, and 02096000, when available, were subtracted on a daily basis from estimates of recharge for station 02096500 to produce daily estimates of recharge for the intervening area between these stations.

The daily estimates of recharge were further analyzed to produce the results presented in tables 8 and 9 and figure 9. Annually, estimated mean recharge in the upper Haw River subbasin is 5.36 in., or 401 (gal/d)/acre. The median recharge is 298 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 8 and figure 9.

Table 8. Statistical summary of recharge estimates for the upper Haw River subbasin between station 02093500 near Benaja, N.C., station 02094500 near Gibsonville, N.C, station 02095500 near Greensboro, N.C., station 02095000 near Greensboro, N.C., and station 02096500 at Haw River, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
67	5.36	1.93	1.68	9.62	43.3

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	67	197	0.00	896
November	67	276	0.00	1,220
December	67	431	3.01	1,360
January	67	631	19.1	1,760
February	67	713	73.8	1,690
March	67	768	174	2,270
April	67	593	154	1,770
May	67	354	63.0	1,210
June	67	272	8.44	1,050
July	67	229	0.99	867
August	67	188	0.00	878
September	67	156	0.00	658
All months	804	401	0.00	2,270

Table 9. Ground-water recharge duration statistics for the upper Haw River subbasin between station 02093500 near Benaja, N.C., station 02094500 near Gibsonville, N.C, station 02095500 near Greensboro, N.C., station 02095000 near Greensboro, N.C., and station 02096500 at Haw River, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	7,080						
1	1,880	26	535	51	291	76	143
2	1,450	27	523	52	284	77	138
3	1,280	28	509	53	277	78	132
4	1,170	29	497	54	269	79	125
5	1,090	30	486	55	264	80	118
6	1,020	31	473	56	258	81	111
7	959	32	461	57	252	82	104
8	910	33	450	58	247	83	95.8
9	877	34	439	59	240	84	87.6
10	846	35	428	60	233	85	79.2
11	815	36	418	61	228	86	69.5
12	786	37	408	62	222	87	58.2
13	763	38	397	63	215	88	47.7
14	739	39	388	64	210	89	35.7
15	719	40	378	65	204	90	23.6
16	698	41	369	66	198	91	5.70
17	679	42	361	67	192	92	0.00
18	662	43	353	68	186	93	0.00
19	644	44	345	69	181	94	0.00
20	625	45	337	70	176	95	0.00
21	608	46	329	71	171	96	0.00
22	591	47	321	72	166	97	0.00
23	576	48	313	73	160	98	0.00
24	562	49	306	74	155	99	0.00
25	549	50	298	75	149	100	0.00

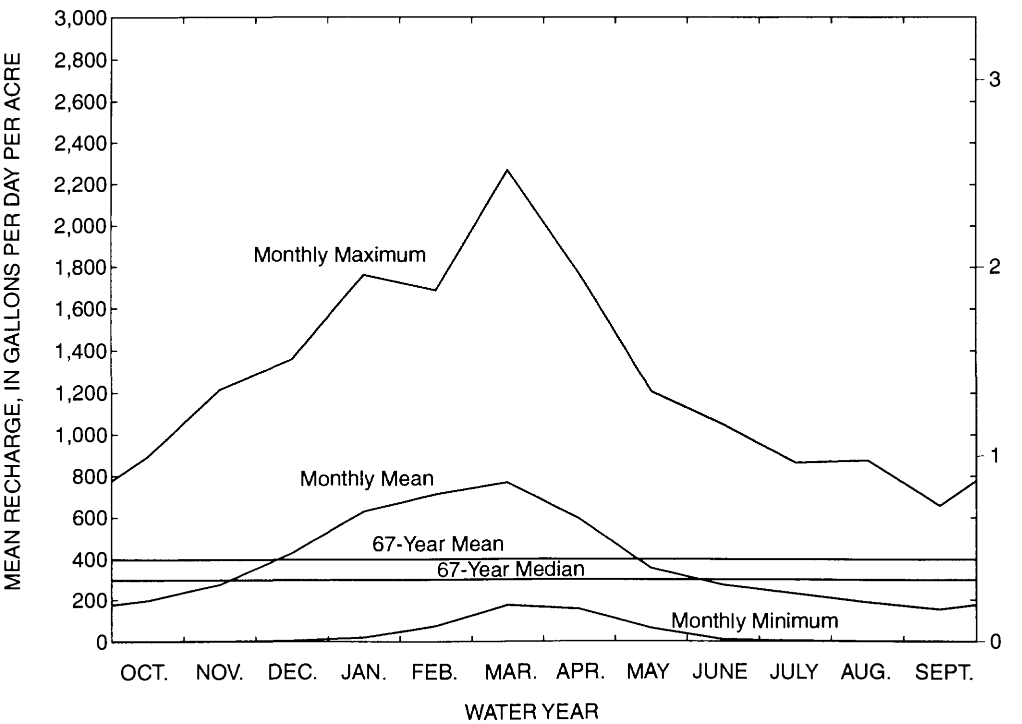
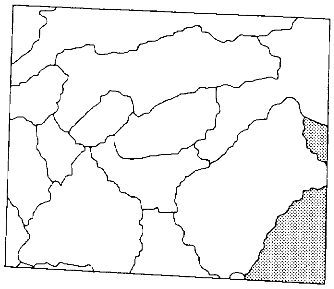


Figure 9. Variation of monthly mean ground-water recharge in the upper Haw River subbasin between stations 02093500 near Benaja, N.C., 02094500 near Gibsonville, N.C., 02095500 near Greensboro, N.C., 02095000 near Greensboro, N.C., and station 02096500 at Haw River, N.C.



Lower Haw River Subbasin

The lower Haw River subbasin is the 553-mi^2 part of the Haw River Basin that lies between gaging station 02096500 (site 11, fig. 1) at Haw River, N.C., station 02096700 (site 12, fig. 1) near Elon College, N.C., and gaging station 02096960 (site 13, fig. 1) near Bynum, N.C. Big Alamance Creek and several of its tributaries, such as Stinking Quarter Creek and Beaver Creek, receive runoff from the eastern and southeastern parts of Guilford County. Big Alamance Creek flows in an easterly direction into central Alamance County where it joins the Haw River. The area of the lower Haw River subbasin within Guilford County is 46.6 mi^2, or 7 percent of the land area of the county.

Discharge records for gaging station 02097000 (site 14, fig. 1) near Pittsboro, N.C., and gaging station 02096960 (site 13, fig. 1) near Bynum, N.C., were analyzed by hydrograph separation, and the daily estimates of recharge were combined to make a composite record spanning 67 water years from 1929 to 1995. Station 02097000 was discontinued in 1973 and replaced by 02096960 the same year. Gaging station 02096500 has been in continuous operation since the 1929 water year (table 1). Water is diverted from reservoirs on Stony Creek upstream of station 02096500 by Burlington, N.C. About half of this water is returned as treated wastewater upstream of the station and about half is returned downstream of the station. Therefore, discharge past station 02096500 was adjusted by adding the net annual average diversion to daily average streamflow before conducting the hydrograph separation. During the water years between 1952 and 1995, net annual average diversions above station 02096500 ranged from 0.4 ft^3/s to 8.2 ft^3/s, and averaged 5.5 ft^3/s. Station 02096700 was in operation for 23 water years from 1958 through 1980 (table 1). Estimates of recharge at 02096500 and 02096700 (for the water years from 1958 through 1980) were subtracted, on a daily basis, from the composite record for the Haw River near Bynum to produce daily estimates of recharge for the intervening area between the stations.

The daily estimates were further analyzed to produce the results presented in tables 10 and 11 and figure 10. Annually, estimated mean recharge in the lower Haw River subbasin is 4.03 in., or 302 (gal/d)/acre. The median recharge is 184 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 10 and figure 10.

Table 10. Statistical summary of recharge estimates for the lower Haw River subbasin between station 02096500 at Haw River, N.C., station 02096700 near Elon College, N.C., and station 02096960 near Bynum, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
67	4.03	1.63	1.35	9.33	37.0

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	67	92.6	0.00	828
November	67	160	0.00	892
December	67	293	0.06	1,050
January	67	523	28.4	1,540
February	67	665	69.9	1,850
March	67	678	119	2,000
April	67	510	15.5	1,270
May	67	275	10.2	1,060
June	67	151	6.18	741
July	67	128	0.00	497
August	67	91.7	0.00	383
September	67	59.2	0.00	395
All months	804	302	0.00	2,000

Table 11. Ground-water recharge duration statistics for the lower Haw River subbasin between station 02096500 at Haw River, N.C., station 02096700 near Elon College, N.C., and station 02096960 near Bynum, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time							
Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	2,840						
1	1,540	26	428	51	175	76	37.3
2	1,260	27	415	52	167	77	32.5
3	1,130	28	402	53	160	78	27.7
4	1,050	29	387	54	153	79	23.8
5	983	30	376	55	146	80	19.9
6	932	31	364	56	140	81	15.8
7	884	32	353	57	134	82	11.4
8	837	33	343	58	128	83	7.42
9	800	34	332	59	122	84	3.40
10	768	35	320	60	116	85	0.00
11	741	36	309	61	110	86	0.00
12	713	37	298	62	106	87	0.00
13	684	38	286	63	101	88	0.00
14	656	39	277	64	95.8	89	0.00
15	628	40	267	65	91.3	90	0.00
16	605	41	258	66	85.7	91	0.00
17	581	42	249	67	80.7	92	0.00
18	561	43	240	68	76.0	93	0.00
19	543	44	233	69	71.0	94	0.00
20	525	45	226	70	65.7	95	0.00
21	509	46	217	71	60.8	96	0.00
22	493	47	209	72	56.2	97	0.00
23	476	48	200	73	51.1	98	0.00
24	460	49	192	74	46.4	99	0.00
25	443	50	184	75	41.6	100	0.00

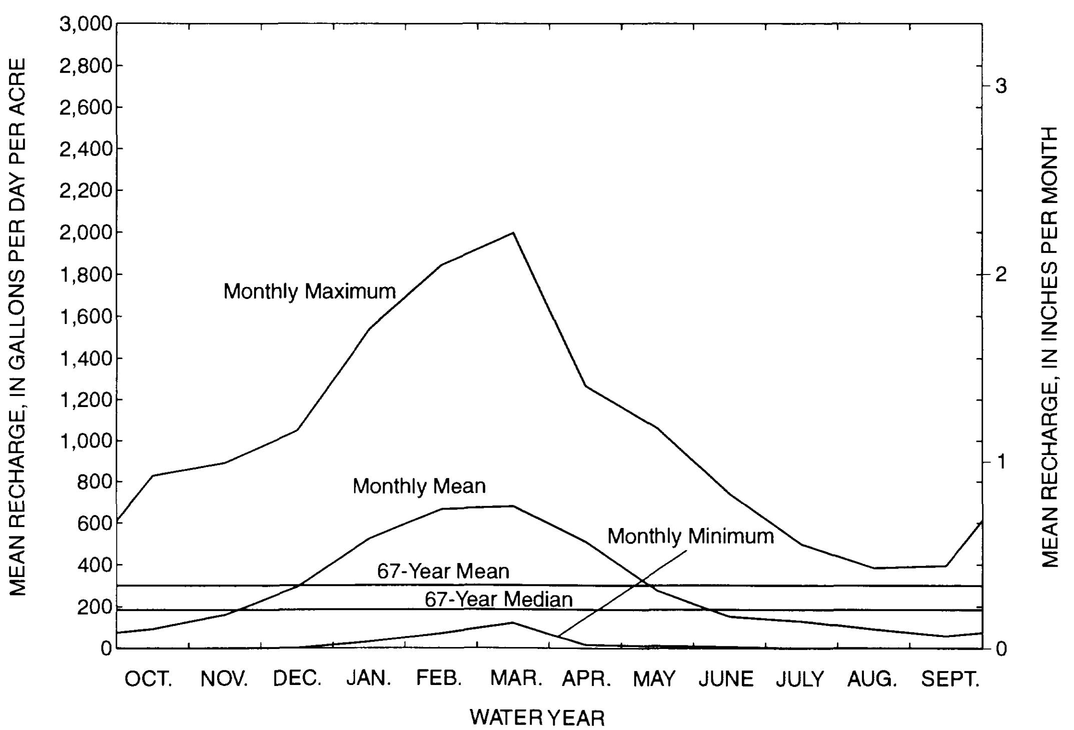
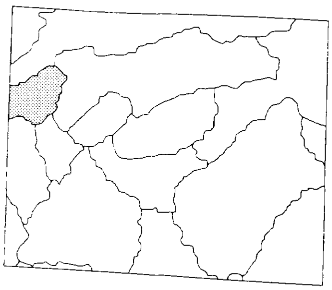


Figure 10. Variation of monthly mean ground-water recharge in the lower Haw River subbasin between station 02096500 at Haw River, N.C., station 02096700 near Elon College, N.C., and station 02096960 near Bynum, N.C.



Reedy Fork Basin Upstream from Oak Ridge, N.C.

The part of the Reedy Fork Basin that lies upstream from gaging station 02093800 (site 5, fig. 1) near Oak Ridge, N.C., has a drainage area of 20.6 mi^2. Reedy Fork originates in east-central Forsyth County at Kernersville, N.C., and flows in a northeasterly direction into Guilford County to a point just west of Oak Ridge where it turns to the east. Reedy Fork then continues across northern Guilford County into northwestern Alamance County where it joins the Haw River. The area of the Reedy Fork Basin within Guilford County is 17.8 mi^2, or 3 percent of the land area in the county.

Discharge records for gaging station 02093800 were analyzed by hydrograph separation, and daily estimates of recharge were generated for the 40-year period between 1956 and 1995. The daily estimates of recharge were further analyzed to produce the results presented in tables 12 and 13 and figure 11. Annually, estimated mean recharge in the Reedy Fork Basin is 9.33 in., or 696 (gal/d)/acre. The median recharge is 612 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 12 and figure 11.

Table 12. Statistical summary of recharge estimates for the Reedy Fork Basin upstream from station 02093800 near Oak Ridge, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
40	9.33	2.29	5.81	13.24	60.7

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	40	502	198	1,490
November	40	588	271	1,080
December	40	705	409	1,160
January	40	908	401	1,620
February	40	1,010	621	1,680
March	40	1,040	546	1,950
April	40	935	378	1,880
May	40	714	362	1,320
June	40	588	211	1,400
July	40	502	151	1,330
August	40	461	180	1,950
September	40	396	145	782
All months	480	696	145	1,950

Table 13. Ground-water recharge duration statistics for the Reedy Fork Basin upstream from station 02093800 near Oak Ridge, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	9,510						
1	2,160	26	834	51	592	76	417
2	1,780	27	833	52	589	77	409
3	1,630	28	823	53	588	78	403
4	1,470	29	804	54	588	79	397
5	1,390	30	786	55	585	80	390
6	1,320	31	784	56	564	81	385
7	1,270	32	783	57	553	82	377
8	1,230	33	763	58	540	83	368
9	1,180	34	750	59	540	84	362
10	1,150	35	736	60	539	85	353
11	1,120	36	735	61	539	86	344
12	1,080	37	735	62	522	87	334
13	1,080	38	714	63	513	88	324
14	1,040	39	702	64	500	89	314
15	1,030	40	687	65	491	90	304
16	996	41	687	66	490	91	293
17	980	42	686	67	483	92	281
18	960	43	676	68	476	93	270
19	933	44	661	69	469	94	260
20	929	45	647	70	461	95	250
21	905	46	638	71	452	96	236
22	884	47	637	72	446	97	221
23	882	48	637	73	439	98	199
24	870	49	621	74	432	99	172
25	852	50	612	75	422	100	83.3

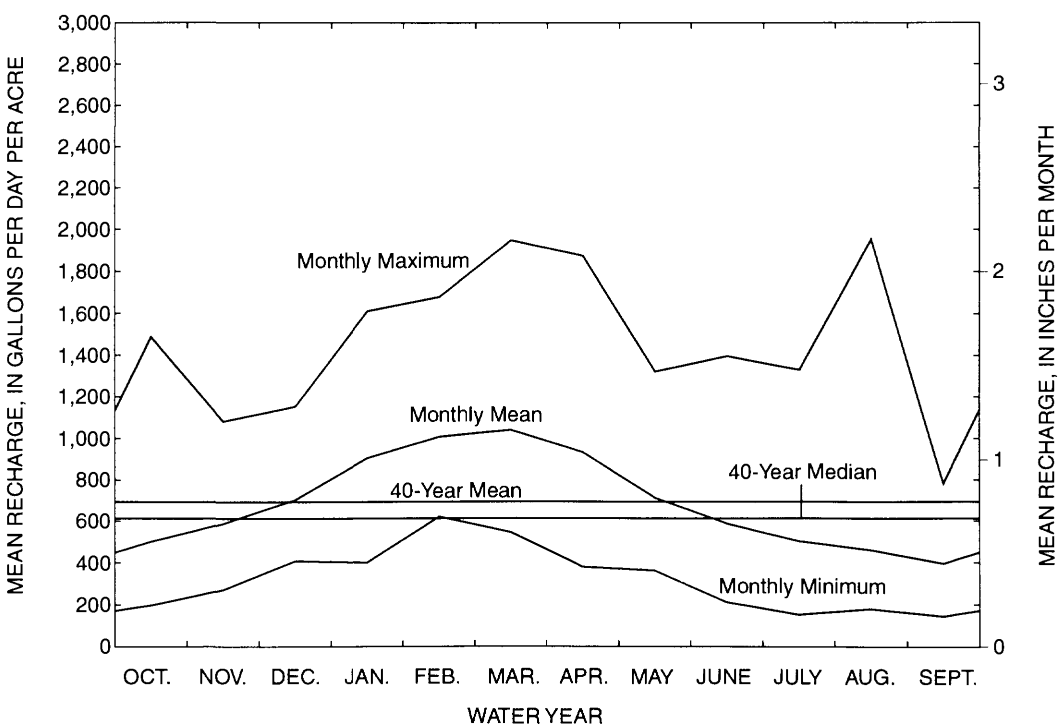
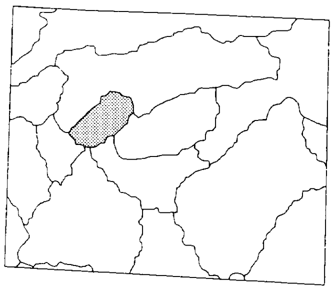


Figure 11. Variation of monthly mean ground-water recharge in the Reedy Fork Basin upstream from station 02093800 near Oak Ridge, N.C.



Horsepen Creek Basin

The Horsepen Creek Basin is the 16.4-mi^2 area that lies upstream from gaging station 02094000 (site 6, fig. 1) at Battle Ground, N.C. Horsepen Creek originates in west-central Guilford County; it flows in a northeasterly direction into Lake Brandt, the westernmost of two reservoirs on Reedy Fork. From Lake Brandt, Reedy Fork flows to the east into Lake Townsend. From Lake Townsend, Reedy Fork continues to the east across northern Guilford County into northwestern Alamance County where it joins the Haw River. The area of the Horsepen Creek Basin is 2 percent of the land area in the county.

Discharge records for gaging station 02094000 were analyzed by hydrograph separation, and daily estimates of recharge were generated for 31 water years of the period between 1926 and 1959. Station 02094000 was in operation for 6 water years from 1926 through 1931 (table 1). No measurements were made during the 1932 to 1934 water years. The gage was reactivated at the beginning of the 1935 water year and continued in operation until the end of the 1959 water year. Measurements at the gage were discontinued in 1959.

The daily estimates of recharge were further analyzed to produce the results presented in tables 14 and 15 and figure 12. Annually, estimated mean recharge in the Horsepen Creek Basin is 6.39 in., or 478 (gal/d)/acre. The median recharge is 394 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 14 and figure 12.

Table 14. Statistical summary of recharge estimates for the Horsepen Creek Basin upstream from station 02094000 at Battle Ground, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
31	6.39	1.50	3.95	11.43	51.9

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	31	343	124	1,900
November	31	398	151	743
December	31	516	206	1,600
January	31	649	252	1,730
February	31	753	324	1,330
March	31	727	401	1,050
April	31	655	326	1,320
May	31	462	255	790
June	31	334	155	683
July	31	307	102	1,200
August	31	340	113	1,500
September	30	246	57.9	692
All months	371	478	57.9	1,900

Table 15. Ground-water recharge duration statistics for the Horsepen Creek Basin upstream from station 02094000 at Battle Ground, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	15,400						
1	1,840	26	572	51	384	76	252
2	1,450	27	566	52	381	77	248
3	1,240	28	560	53	374	78	242
4	1,100	29	552	54	366	79	240
5	1,020	30	545	55	359	80	235
6	955	31	534	56	351	81	229
7	920	32	525	57	347	82	223
8	889	33	515	58	340	83	218
9	849	34	508	59	334	84	214
10	826	35	502	60	330	85	206
11	804	36	492	61	323	86	203
12	770	37	484	62	318	87	197
13	762	38	477	63	315	88	191
14	736	39	469	64	311	89	184
15	708	40	460	65	306	90	178
16	699	41	454	66	299	91	171
17	697	42	447	67	294	92	162
18	671	43	445	68	288	93	156
19	650	44	434	69	284	94	147
20	636	45	427	70	279	95	140
21	630	46	420	71	273	96	133
22	616	47	413	72	267	97	126
23	604	48	407	73	261	98	114
24	592	49	400	74	259	99	91.5
25	581	50	394	75	255	100	31.8

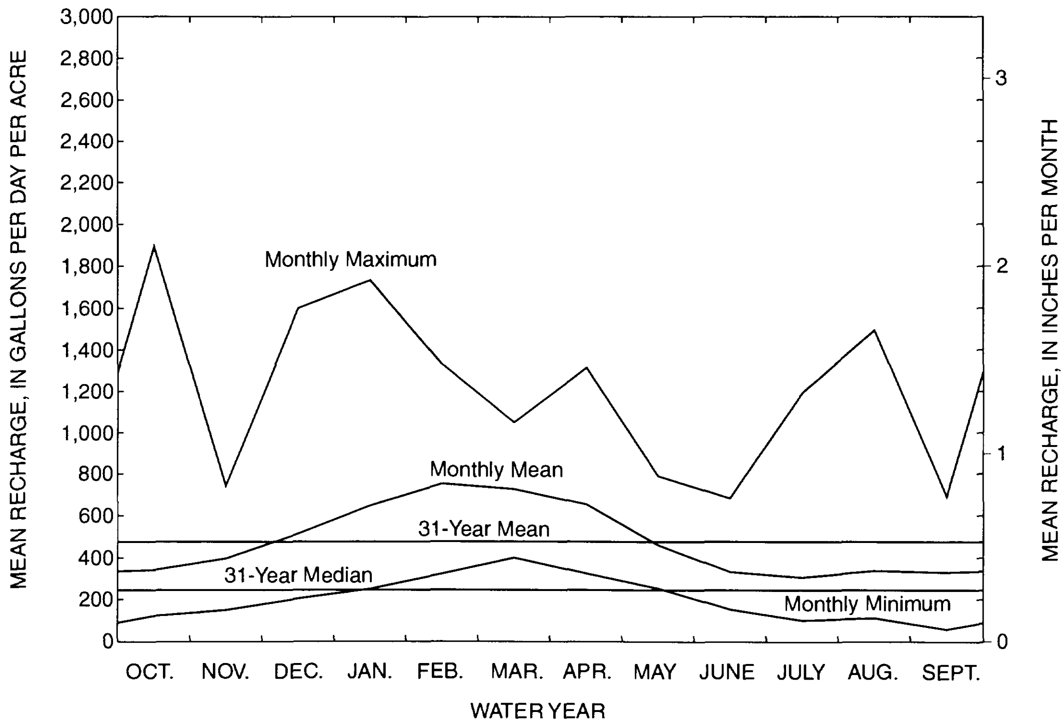
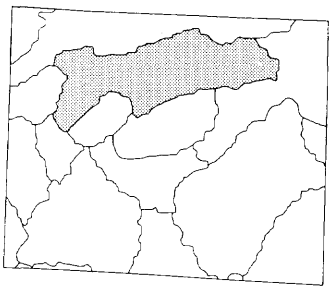


Figure 12. Variation of monthly mean ground-water recharge in the Horsepen Creek Basin upstream from station 02094000 at Battle Ground, N.C.



Reedy Fork Subbasin

The Reedy Fork subbasin is the 94.5-mi^2 area that lies between station 02093800 (site 5, fig. 1) near Oak Ridge, N.C., station 02094000 (site 6, fig. 1) at Battle Ground, N.C., and station 02094500 (site 7, fig. 1) near Gibsonville, N.C. Reedy Fork originates in east-central Forsyth County at Kernersville, N.C., and flows in a northeasterly direction into Guilford County to a point just west of Oak Ridge near station 02093800 where it turns to the east. Reedy Fork flows to the east into Lake Brandt. East of Lake Brandt, Reedy Fork flows into Lake Townsend. A third water-supply reservoir, Richland Lake, is located on a tributary to Lake Townsend. From Lake Townsend, Reedy Fork continues to the east across northern Guilford County, past station 02094500, into northwestern Alamance County where it joins the Haw River. The area of the Reedy Fork subbasin is 14 percent of the land area in the county.

Discharge records from the three stations were analyzed by hydrograph separation, and daily estimates of recharge were generated for 64 water years of the period between 1926 and 1995. Discharge records from the three stations do not overlap for the entire 64-year period (table 1); however, there is sufficient overlap that the recharge estimate is considered representative of the intervening area between these stations. Discharge at station 02094500 is affected by diversions from Lake Brandt, Lake Townsend, and, until 1981, Richland Lake. Annual average diversions from Lake Brandt between 1935 and 1995 ranged from 8.1 to 29.7 ft^3/s and averaged 18.7 ft^3/s. Annual average diversions from Lake Townsend between 1970 and 1995 ranged from 11.8 to 28.1 ft^3/s and averaged 20.3 ft^3/s. Annual average diversions from Richland Lake between 1953 and 1981 ranged from 0.7 to 5.5 ft^3/s and averaged 2.9 ft^3/s. These diversions were added to the discharge records at station 02094500 before conducting the hydrograph separation. Station 02094000 was operated during the water years from 1926 through 1931 and, later, from 1935 through 1959. Measurements at the gage were discontinued in 1959. Station 02093800 has been in operation since the beginning of the 1956 water year. Estimates of recharge for stations 02094000 and 02093800 were subtracted, on a daily basis, from estimates of recharge for station 02094500 for the period between 1926 and 1931 and the period between 1935 and 1995 to obtain daily estimates of recharge for the intervening area between the three stations.

The daily estimates of recharge were further analyzed to produce the results presented in tables 16 and 17 and figure 13. Annually, estimated mean recharge in the Reedy Fork subbasin is 6.37 in., or 475 (gal/d)/acre. The median recharge is 397 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 16 and figure 13.

Table 16. Statistical summary of recharge estimates for the Reedy Fork subbasin between station 02093800 near Oak Ridge, N.C., station 02094000 at Battle Ground,N.C., and station 02094500 near Gibsonville, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
64	6.37	1.42	3.60	10.06	38.0

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	64	349	35.1	1,120
November	64	400	103	896
December	64	479	207	1,050
January	64	627	267	1,520
February	64	684	179	1,740
March	64	679	237	1,270
April	64	639	254	1,940
May	64	461	233	990
June	64	378	72.4	1,820
July	64	340	101	1,010
August	64	346	32.7	854
September	64	317	23.0	723
All months	768	475	23.0	1,940

Table 17. Ground-water recharge duration statistics for the Reedy Fork subbasin between station 02093800 near Oak Ridge, N.C., station 02094000 at Battle Ground, N.C., and station 02094500 near Gibsonville, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	5,450						
1	1,850	26	528	51	393	76	302
2	1,450	27	521	52	389	77	296
3	1,230	28	514	53	385	78	291
4	1,100	29	508	54	381	79	286
5	1,010	30	501	55	378	80	282
6	946	31	495	56	374	81	277
7	886	32	489	57	371	82	274
8	830	33	484	58	368	83	269
9	794	34	479	59	365	84	263
10	764	35	474	60	361	85	258
11	740	36	469	61	359	86	250
12	717	37	465	62	355	87	243
13	693	38	461	63	352	88	234
14	672	39	456	64	349	89	225
15	650	40	451	65	346	90	216
16	635	41	446	66	343	91	206
17	620	42	440	67	339	92	198
18	606	43	434	68	336	93	191
19	593	44	428	69	332	94	181
20	583	45	422	70	329	95	169
21	573	46	417	71	325	96	155
22	563	47	412	72	320	97	140
23	553	48	406	73	315	98	119
24	545	49	401	74	311	99	83.0
25	536	50	397	75	307	100	0.00

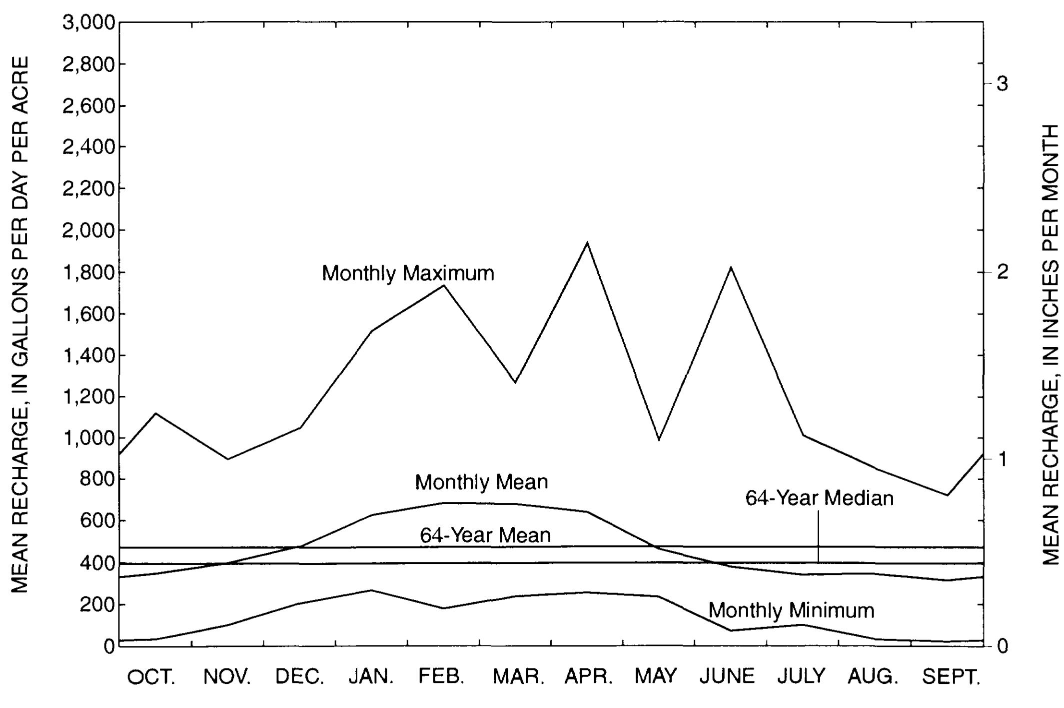
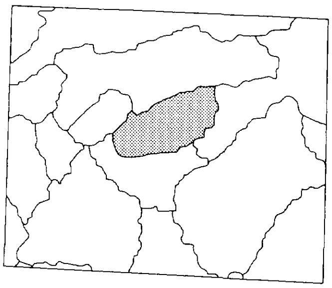


Figure 13. Variation of monthly mean ground-water recharge in the Reedy Fork subbasin between station 02093800 near Oak Ridge, N.C., station 02094000 at Battle Ground, N.C., and station 02094500 near Gibsonville, N.C.



North Buffalo Creek Basin

The North Buffalo Creek Basin is the 37.1-mi^2 area that lies upstream from gaging station 02095500 (site 9, fig. 1) near Greensboro, N.C. North Buffalo Creek originates in central Guilford County within the city of Greensboro, N.C., and flows in a northeasterly direction until it is joined by South Buffalo Creek to form Buffalo Creek. Buffalo Creek continues into northeastern Guilford County where it joins Reedy Fork. The area within the North Buffalo Creek Basin upstream from station 02095500 is 6 percent of the land area of the county.

Discharge records for gaging station 02095500 were analyzed by hydrograph separation to produce daily estimates of recharge for the 62-year period between 1929 and 1990. Station 02095500 was discontinued in 1990 (table 1). Wastewater was discharged into North Buffalo Creek upstream of the gaging station during this period and contributed to total streamflow; however, records of wastewater discharge are unavailable and no adjustment has been made to the recharge estimates. Thus, the estimates of recharge are probably somewhat higher than would have been obtained for natural conditions. The daily estimates of recharge were further analyzed to produce the results presented in tables 18 and 19 and figure 14. Annually, estimated mean recharge in the North Buffalo Creek Basin is 9.69 in., or 723 (gal/d)/acre. The median recharge is 681 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 18 and figure 14.

Table 18. Statistical summary of recharge estimates for the North Buffalo Creek Basin upstream from station 02095500 near Greensboro, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
62	9.69	2.60	4.62	14.68	47.2

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	62	536	133	1,140
November	62	604	174	1,140
December	62	740	227	1,440
January	62	902	325	1,530
February	62	1,020	385	1,880
March	62	1,020	519	1,750
April	62	899	399	1,540
May	62	707	310	1,570
June	62	609	190	1,280
July	62	561	171	1,200
August	62	556	136	1,130
September	62	522	174	1,070
All months	744	723	133	1,880

Table 19. Ground-water recharge duration statistics for the North Buffalo Creek Basin upstream from station 02095500 near Greensboro, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	4,760						
1	1,880	26	871	51	674	76	486
2	1,620	27	861	52	666	77	472
3	1,480	28	848	53	657	78	463
4	1,390	29	844	54	653	79	451
5	1,330	30	830	55	650	80	437
6	1,280	31	817	56	640	81	436
7	1,230	32	817	57	632	82	420
8	1,200	33	803	58	626	83	408
9	1,170	34	790	59	623	84	399
10	1,140	35	789	60	612	85	382
11	1,110	36	778	61	602	86	379
12	1,090	37	768	62	599	87	363
13	1,060	38	762	63	594	88	354
14	1,050	39	755	64	585	89	341
15	1,030	40	746	65	575	90	328
16	1,010	41	735	66	572	91	318
17	988	42	734	67	564	92	303
18	974	43	725	68	555	93	295
19	956	44	716	69	545	94	276
20	946	45	708	70	544	95	262
21	929	46	708	71	532	96	239
22	920	47	700	72	522	97	219
23	903	48	690	73	517	98	198
24	893	49	681	74	504	99	169
25	880	50	681	75	490	100	92.6

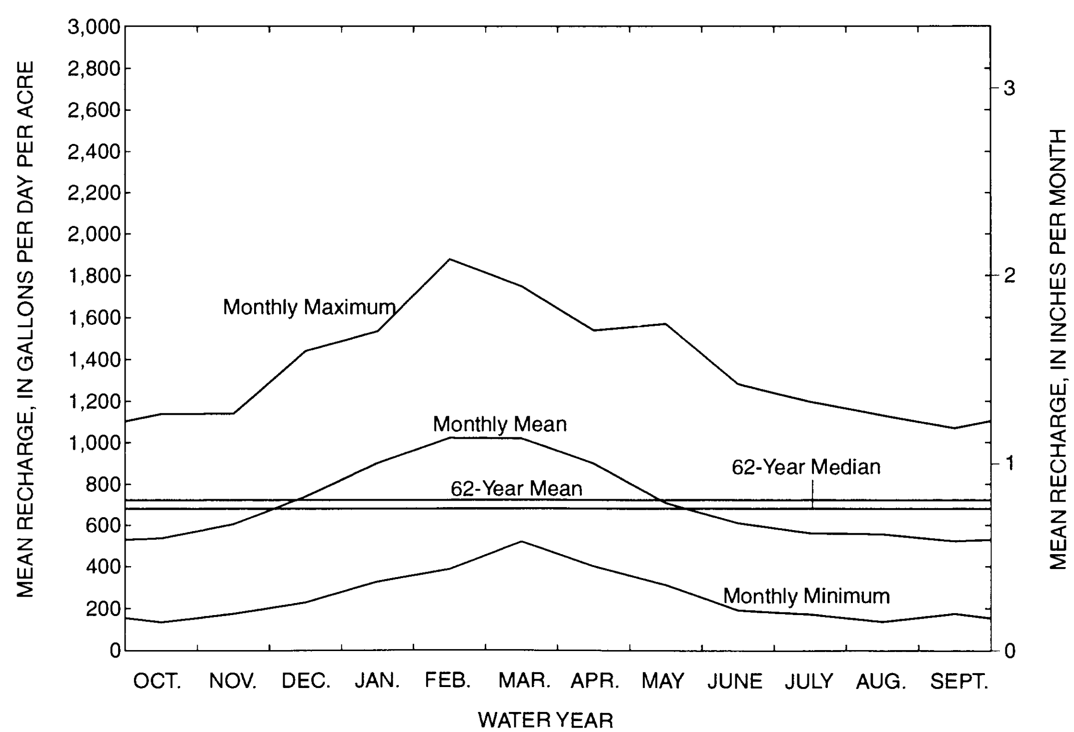
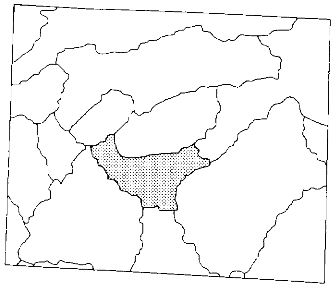


Figure 14. Variation of monthly mean ground-water recharge in the North Buffalo Creek Basin upstream from station 02095500 near Greensboro, N.C.



South Buffalo Creek Basin

The South Buffalo Creek Basin is the 34.1-mi^2 area that lies upstream from gaging station 02095000 (site 8, fig. 1) near Greensboro, N.C. South Buffalo Creek originates in west-central Guilford County within the city limits of Greensboro and flows in an east-southeasterly direction into southern Greensboro where it turns to flow in a northeasterly direction until it is joined by North Buffalo Creek to form Buffalo Creek. Buffalo Creek continues into northeastern Guilford County where it joins Reedy Fork. The area within the South Buffalo Creek Basin upstream from station 02095000 is 5 percent of the land area of the county.

Discharge records for gaging station 02095000 were analyzed by hydrograph separation to produce daily estimates of recharge for the 30-year period between 1929 and 1958. Station 02095000 was discontinued in 1958 (table 1). Wastewater was discharged into South Buffalo Creek upstream of the gaging station during this period and contributed to total streamflow; however, records of wastewater discharge are unavailable and no adjustment has been made to the recharge estimates. Thus, the estimates of recharge are probably somewhat higher than would have been obtained for natural conditions. The daily estimates of recharge were further analyzed to produce the results presented in tables 20 and 21 and figure 15. Annually, estimated mean recharge in the South Buffalo Creek Basin is 5.51 in., or 412 (gal/d)/acre. The median recharge is 305 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 20 and figure 15.

Table 20. Statistical summary of recharge estimates for the South Buffalo Creek Basin upstream from station 02095000 near Greensboro, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
30	5.51	1.31	2.98	8.90	36.5

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	30	212	22.8	404
November	30	348	90.2	1,100
December	30	481	130	1,470
January	30	629	177	1,550
February	30	770	187	1,360
March	30	719	370	1,390
April	30	579	278	1,060
May	30	338	179	685
June	30	270	83.7	1,540
July	30	242	46.7	1,010
August	30	179	37.0	409
September	30	177	33.7	476
All months	360	412	22.8	1,550

Table 21. Ground-water recharge duration statistics for the South Buffalo Creek Basin upstream from station 02095000 near Greensboro, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	8,570						
1	1,850	26	510	51	301	76	175
2	1,410	27	494	52	295	77	171
3	1,200	28	482	53	284	78	167
4	1,090	29	480	54	277	79	163
5	1,020	30	468	55	271	80	158
6	949	31	456	56	264	81	153
7	902	32	451	57	256	82	150
8	865	33	442	58	251	83	147
9	836	34	431	59	246	84	142
10	803	35	421	60	241	85	137
11	776	36	421	61	237	86	133
12	751	37	411	62	232	87	128
13	721	38	401	63	228	88	124
14	693	39	391	64	222	89	120
15	671	40	391	65	218	90	116
16	655	41	381	66	214	91	111
17	631	42	372	67	211	92	106
18	618	43	362	68	207	93	99.2
19	601	44	361	69	203	94	90.5
20	589	45	348	70	199	95	87.2
21	571	46	338	71	195	96	79.0
22	556	47	331	72	191	97	67.6
23	541	48	330	73	186	98	60.1
24	532	49	317	74	183	99	39.4
25	514	50	305	75	180	100	15.0

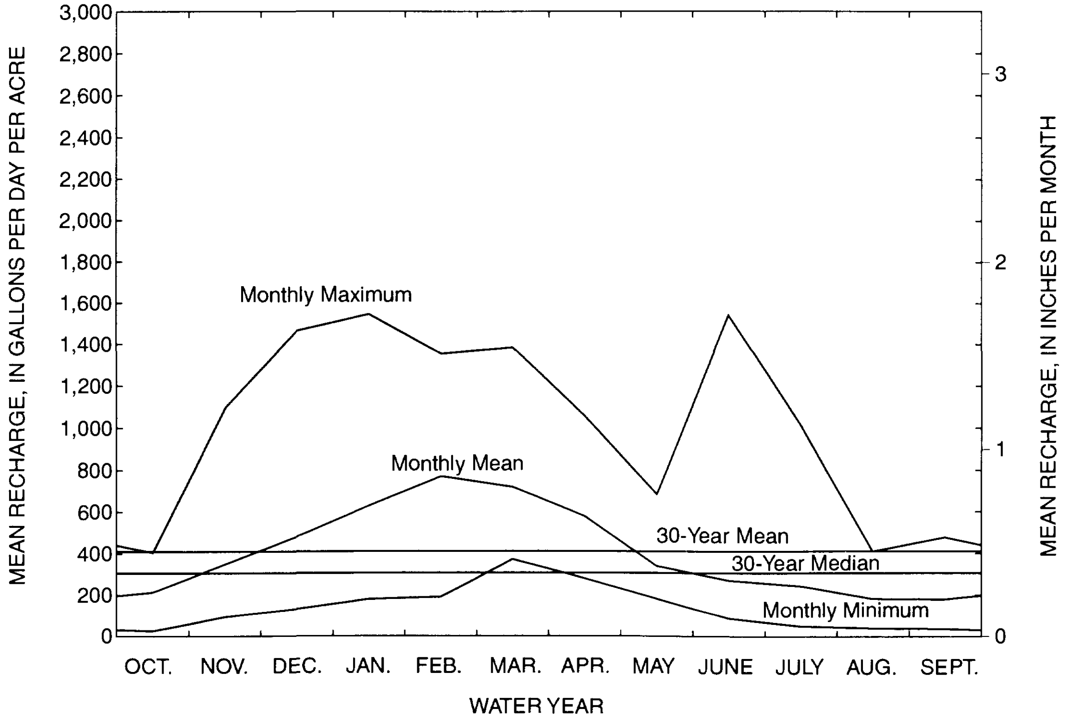
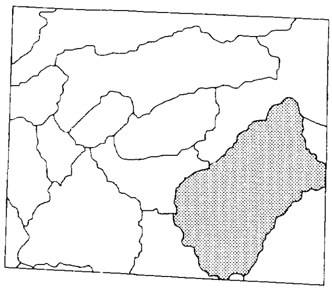


Figure 15. Variation of monthly mean ground-water recharge in the South Buffalo Creek Basin upstream from station 02095000 near Greensboro, N.C.



Big Alamance Creek Basin

The Big Alamance Creek Basin is the 116-mi^2 area that lies upstream from gaging station 02096700 (site 12, fig. 1) near Elon College, N.C. Big Alamance Creek originates in the south-central part of Guilford County and flows in a northeasterly direction into east central Guilford County where it is joined by Little Alamance Creek before turning to the east near the Alamance County line. Big Alamance Creek continues its eastward course across central Alamance County until it joins the Haw River southeast of Graham, N.C. The area of Big Alamance Creek within Guilford County is 114.8 mi^2, or 17 percent of the land area of the county.

Discharge records for gaging station 02096700 were analyzed by hydrograph separation to produce daily estimates of recharge for the 23-year period between 1958 and 1980. Station 0209670 was discontinued in 1980 (table 1). The daily estimates of recharge were further analyzed to produce the results presented in tables 22 and 23 and figure 16. Annually, estimated mean recharge in the Big Alamance Creek Basin is 5.51 in., or 412 (gal/d)/acre. The median recharge is 296 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 22 and figure 16.

Table 22. Statistical summary of recharge estimates for the Big Alamance Creek Basin upstream from station 02096700 near Elon College, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
23	5.51	1.68	2.41	9.24	42.4

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	23	180	23.4	501
November	23	266	59.7	783
December	23	411	166	987
January	23	704	281	1,630
February	23	798	384	1,560
March	23	877	367	1,580
April	23	638	218	1,170
May	23	412	137	1,170
June	23	233	66.6	548
July	23	179	18.8	475
August	23	130	35.8	356
September	23	116	10.1	321
All months	276	412	10.1	1,630

Table 23. Ground-water recharge duration statistics for the Big Alamance Creek Basin upstream from station 02096700 near Elon College, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	4,180						
1	1,790	26	566	51	284	76	128
2	1,510	27	548	52	275	77	122
3	1,340	28	531	53	267	78	114
4	1,220	29	515	54	258	79	111
5	1,130	30	504	55	250	80	105
6	1,060	31	492	56	244	81	99.9
7	1,010	32	479	57	235	82	95.8
8	970	33	469	58	229	83	89.2
9	933	34	453	59	223	84	86.8
10	893	35	442	60	216	85	82.5
11	856	36	431	61	209	86	78.9
12	827	37	420	62	201	87	75.0
13	797	38	410	63	198	88	72.0
14	772	39	401	64	192	89	67.9
15	754	40	390	65	187	90	63.5
16	736	41	379	66	183	91	56.9
17	715	42	369	67	177	92	52.2
18	696	43	358	68	174	93	49.6
19	680	44	349	69	167	94	47.0
20	663	45	340	70	162	95	41.6
21	647	46	331	71	157	96	35.6
22	630	47	321	72	153	97	31.9
23	611	48	311	73	147	98	25.2
24	599	49	305	74	139	99	17.6
25	580	50	296	75	133	100	3.40

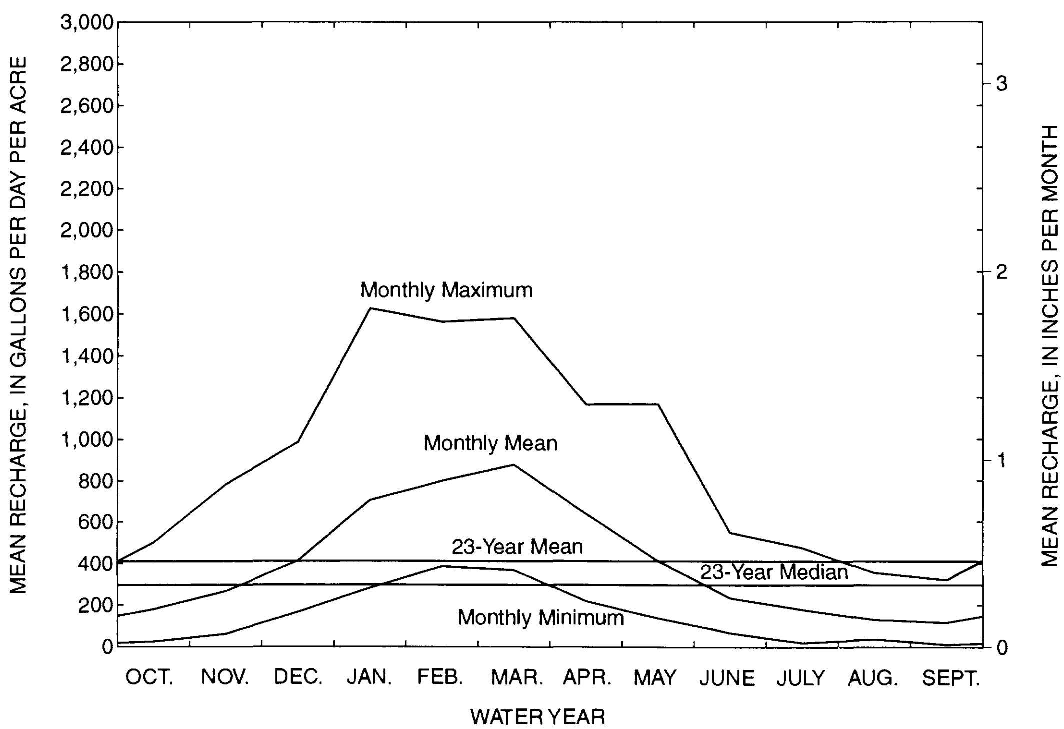
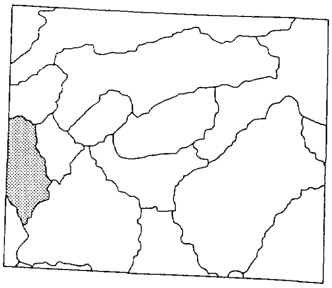


Figure 16. Variation of monthly mean ground-water recharge in the Big Alamance Creek Basin upstream from station 02096700 near Elon College, N.C.



West Fork Deep River Basin

The West Fork Deep River Basin is the 32.1-mi^2 area that lies upstream from gaging station 02098500 (site 15, fig. 1) near High Point, N.C. West Fork Deep River originates in the west-central part of Guilford County near the Forsyth-Guilford county line and flows in a south-southeasterly direction until it joins East Fork Deep River at High Point, N.C., to form the Deep River. The Deep River flows to the southeast into northern Randolph County. The area of the West Fork Deep River Basin within Guilford County is 26.1 mi^2, or 4 percent of the land area of the county.

Discharge records for gaging station 02098500 (site 15, fig. 1) were analyzed by hydrograph separation, and daily estimates of recharge were generated for 33 water years in the period between 1924 and 1958. The station was not in operation during the 1927 and 1928 water years; the station was discontinued in 1958. The daily estimates of recharge were further analyzed to produce the results presented in tables 24 and 25 and figure 17. Annually, estimated mean recharge in the West Fork Deep River Basin is 5.39 in., or 402 (gal/d)/acre. The median recharge is 346 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 24 and figure 17.

Table 24. Statistical summary of recharge estimates for the West Fork Deep River Basin upstream from station 02098500 near High Point, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
33	5.39	1.03	3.24	7.52	40.9

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	33	234	78.4	468
November	33	336	123	742
December	33	442	175	906
January	33	588	204	1,370
February	33	661	303	1,020
March	33	665	434	1,030
April	33	595	324	1,160
May	33	395	219	671
June	33	264	177	507
July	33	237	103	604
August	33	226	82.2	499
September	33	187	51.8	450
All months	396	402	51.8	1,370

Table 25. Ground-water recharge duration statistics for the West Fork Deep River Basin upstream from station 02098500 near High Point, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	3,460						
1	1,270	26	519	51	337	76	210
2	1,080	27	507	52	329	77	205
3	966	28	503	53	318	78	199
4	911	29	494	54	315	79	194
5	854	30	482	55	311	80	189
6	826	31	472	56	305	81	186
7	793	32	472	57	299	82	180
8	765	33	462	58	295	83	176
9	734	34	453	59	289	84	170
10	712	35	443	60	283	85	165
11	692	36	441	61	281	86	160
12	674	37	439	62	277	87	157
13	661	38	429	63	272	88	152
14	649	39	419	64	266	89	147
15	633	40	409	65	261	90	142
16	623	41	409	66	255	91	137
17	608	42	403	67	252	92	132
18	598	43	393	68	249	93	127
19	583	44	385	69	243	94	123
20	569	45	378	70	237	95	115
21	566	46	375	71	232	96	109
22	555	47	364	72	227	97	102
23	544	48	354	73	221	98	94.4
24	535	49	346	74	218	99	76.1
25	532	50	346	75	214	100	18.9

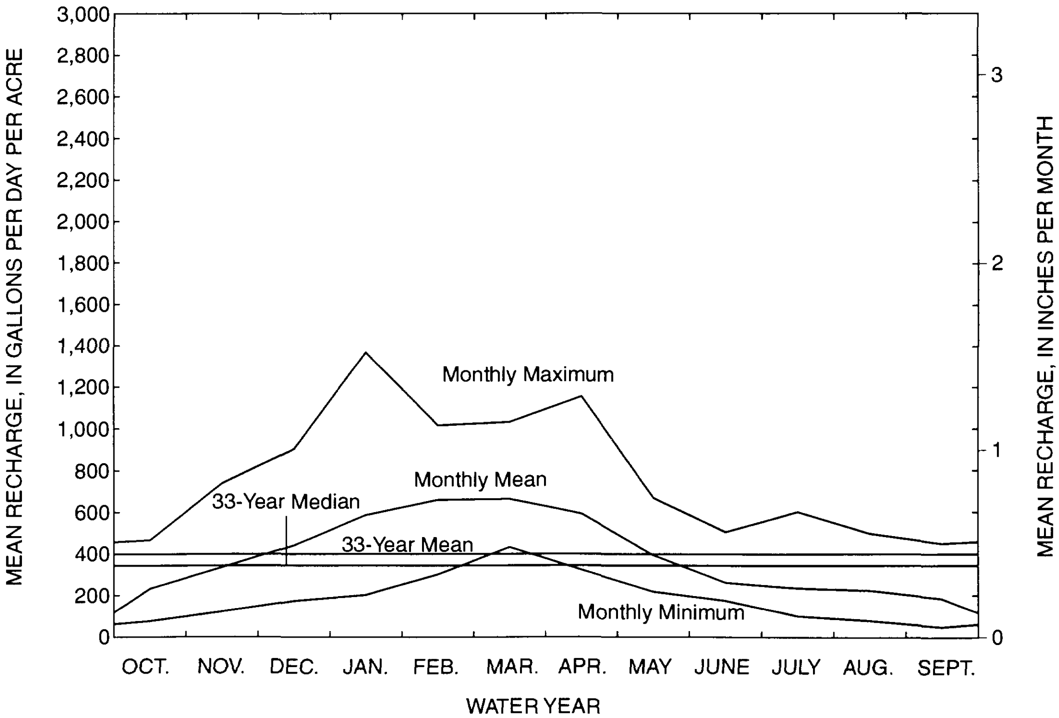
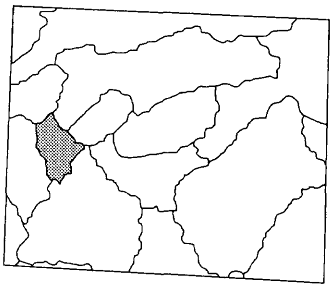


Figure 17. Variation of monthly mean ground-water recharge in the West Fork Deep River Basin upstream from station 02098500 near High Point, N.C.



East Fork Deep River Basin

The East Fork Deep River Basin is the 14.8-mi^2 area that lies upstream from gaging station 02099000 (site 16, fig. 1) near High Point, N.C. East Fork Deep River originates in the west-central part of Guilford County and flows in a southerly direction until it joins West Fork Deep River at High Point, N.C., to form the Deep River. The Deep River flows to the southeast into northern Randolph County. The area within the East Fork Deep River Basin upstream from station 02099000 is 2 percent of the land area of the county.

Discharge records for gaging station 02099000 were analyzed by hydrograph separation to give daily estimates of recharge for the 65-year period between 1929 and 1993. Station 02099000 was discontinued in 1993. The daily estimates of recharge were further analyzed to produce the results presented in tables 26 and 27 and figure 18. Annually, estimated mean recharge in the East Fork Deep River Basin is 6.71 in., or 501 (gal/d)/acre. The median recharge is 406 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 26 and figure 18.

Table 26. Statistical summary of recharge estimates for the East Fork Deep River Basin upstream from station 02099000 near High Point, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
65	6.71	1.55	3.95	11.55	45.4

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	65	319	123	805
November	65	405	156	1,050
December	65	521	184	1,940
January	65	692	218	1,850
February	65	777	311	1,620
March	65	786	407	2,060
April	65	658	340	1,210
May	65	490	274	996
June	65	394	190	932
July	65	360	133	1,770
August	65	318	146	952
September	65	289	102	1,470
All months	780	501	102	2,060

Table 27. Ground-water recharge duration statistics for the East Fork Deep River Basin upstream from station 02099000 near High Point, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	13,800						
1	1,840	26	585	51	401	76	287
2	1,440	27	574	52	396	77	283
3	1,260	28	566	53	389	78	280
4	1,160	29	553	54	383	79	274
5	1,060	30	543	55	378	80	272
6	1,000	31	534	56	374	81	267
7	955	32	525	57	368	82	262
8	908	33	519	58	362	83	259
9	882	34	512	59	359	84	253
10	838	35	504	60	355	85	248
11	819	36	496	61	349	86	246
12	796	37	485	62	343	87	240
13	762	38	480	63	341	88	235
14	751	39	472	64	335	89	232
15	738	40	465	65	328	90	226
16	710	41	459	66	327	91	219
17	683	42	451	67	321	92	215
18	682	43	444	68	318	93	208
19	667	44	439	69	314	94	205
20	655	45	433	70	310	95	198
21	641	46	429	71	307	96	190
22	630	47	422	72	303	97	179
23	617	48	416	73	300	98	169
24	607	49	410	74	294	99	138
25	594	50	406	75	291	100	75.1

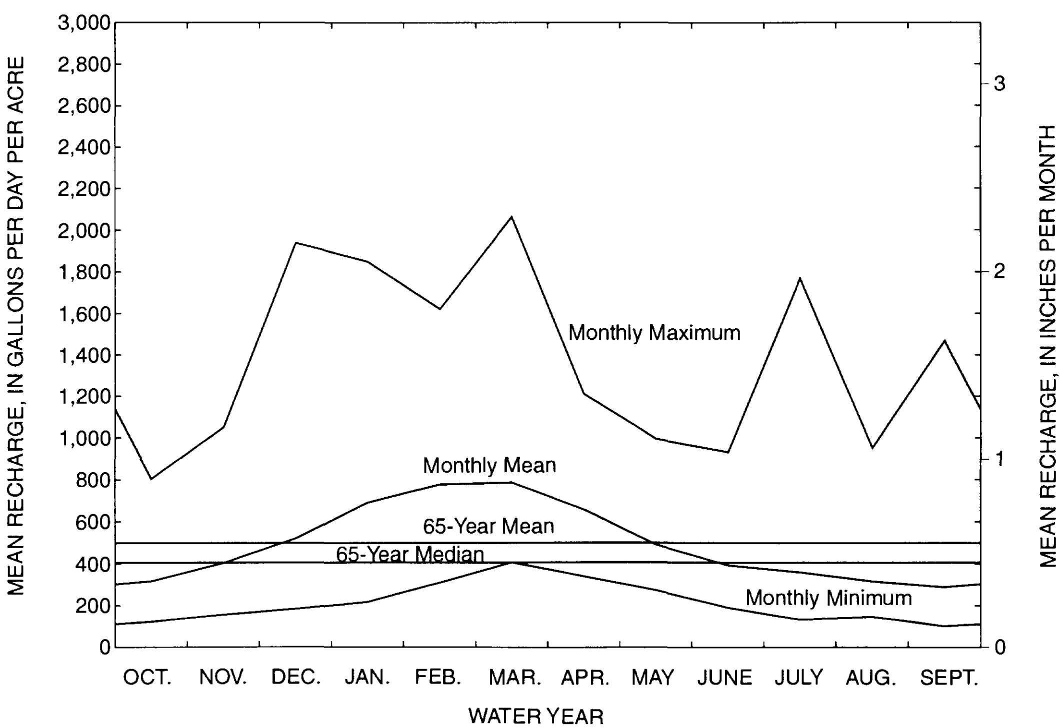
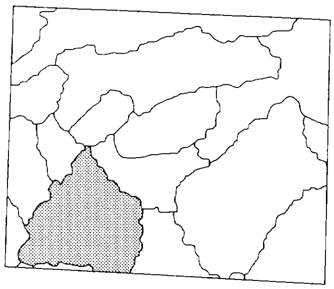


Figure 18. Variation of monthly mean ground-water recharge in the East Fork Deep River Basin upstream from station 02099000 near High Point, N.C.



Upper Deep River Subbasin

The upper Deep River subbasin is the 168-mi^2 part of the Deep River Basin that lies between gaging station 02098500 (site 15, fig. 1) near High Point, N.C., gaging station 02099000 (site 16, fig. 1) near High Point, N.C., and gaging station 02099500 (site 17, fig. 1) near Randleman, N.C. The area of the upper Deep River subbasin in Guilford County is 76.2 mi^2, or 12 percent of the land area of the county.

Discharge records from the three stations were analyzed by hydrograph separation, and daily estimates of recharge were generated for the 65 water years between 1929 and 1993. Discharge records from the stations do not overlap for the entire 65-year period (table 1); however, there is sufficient overlap that the recharge estimate is considered representative of the intervening area between these stations. Station 02098500 was first operated between 1924 and 1926, and no data were collected in 1927 and 1928; it was reactivated at the beginning of the 1929 water year and remained in service through 1958, when it was discontinued (table 1). Station 02099000 was in operation for 65 water years from 1929 through 1993 (table 1). Station 02099500 has been in continuous operation since the 1929 water year (table 1). The City of High Point diverts water upstream of station 02099500 for municipal water supply; part of the water is returned to the Deep River as treated wastewater and part is discharged into Rich Fork Creek, a tributary of Abbotts Creek. The transfer of wastewater to the Abbotts Creek Basin results in a reduction in flow in the Deep River. During the water years between 1951 and 1993, the net difference between annual average diversions and wastewater returns upstream of station 02099500 ranged from less than 1 ft^3/s to 9.4 ft^3/s, and averaged 4.1 ft^3/s. Therefore, the net differences were added to streamflow before conducting the hydrograph separation. Estimates of recharge at 02098500 (for the water years from 1929 through 1958) and 02099000 (for the water years from 1929 through 1993) were subtracted, on a daily basis, from the record for the Deep River near Randleman to produce daily estimates of recharge for the intervening area between the stations.

The daily estimates of recharge were further analyzed to produce the results presented in tables 28 and 29 and figure 19. Annually, estimated mean recharge in the upper Deep River subbasin is 5.32 in., or 398 (gal/d)/acre. The median recharge is 250 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 28 and figure 19.

Table 28. Statistical summary of recharge estimates for the upper Deep River subbasin between station 02098500 near High Point, N.C., station 02099000 near High Point, N.C., and station 02099500 near Randleman, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
65	5.32	1.96	1.89	10.59	39.1

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	65	160	0.00	876
November	65	267	0.23	2,250
December	65	428	0.00	1,420
January	65	655	32.5	2,300
February	65	760	109	1,580
March	65	810	245	2,970
April	65	599	168	2,010
May	65	351	13.2	1,230
June	65	219	0.07	1,130
July	65	201	0.00	1,040
August	65	184	10.5	699
September	65	139	0.20	681
All months	780	398	0.00	2,970

Table 29. Ground-water recharge duration statistics for the upper Deep River subbasin between station 02098500 near High Point, N.C., station 02099000 near High Point, N.C., and station 02099500 near Randleman, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	15,000						
1	2,110	26	501	51	244	76	124
2	1,690	27	485	52	238	77	118
3	1,450	28	468	53	232	78	113
4	1,320	29	454	54	227	79	109
5	1,210	30	441	55	221	80	104
6	1,120	31	427	56	215	81	97.8
7	1,060	32	414	57	209	82	92.5
8	995	33	402	58	204	83	87.1
9	948	34	391	59	199	84	81.4
10	906	35	380	60	194	85	73.7
11	866	36	369	61	189	86	66.7
12	832	37	358	62	185	87	60.6
13	797	38	349	63	181	88	53.4
14	761	39	338	64	177	89	45.4
15	733	40	329	65	173	90	38.0
16	705	41	320	66	169	91	29.7
17	680	42	311	67	166	92	21.6
18	658	43	302	68	162	93	13.1
19	635	44	292	69	158	94	4.78
20	613	45	285	70	153	95	0.00
21	592	46	277	71	148	96	0.00
22	572	47	270	72	143	97	0.00
23	554	48	263	73	138	98	0.00
24	535	49	256	74	133	99	0.00
25	519	50	250	75	129	100	0.00

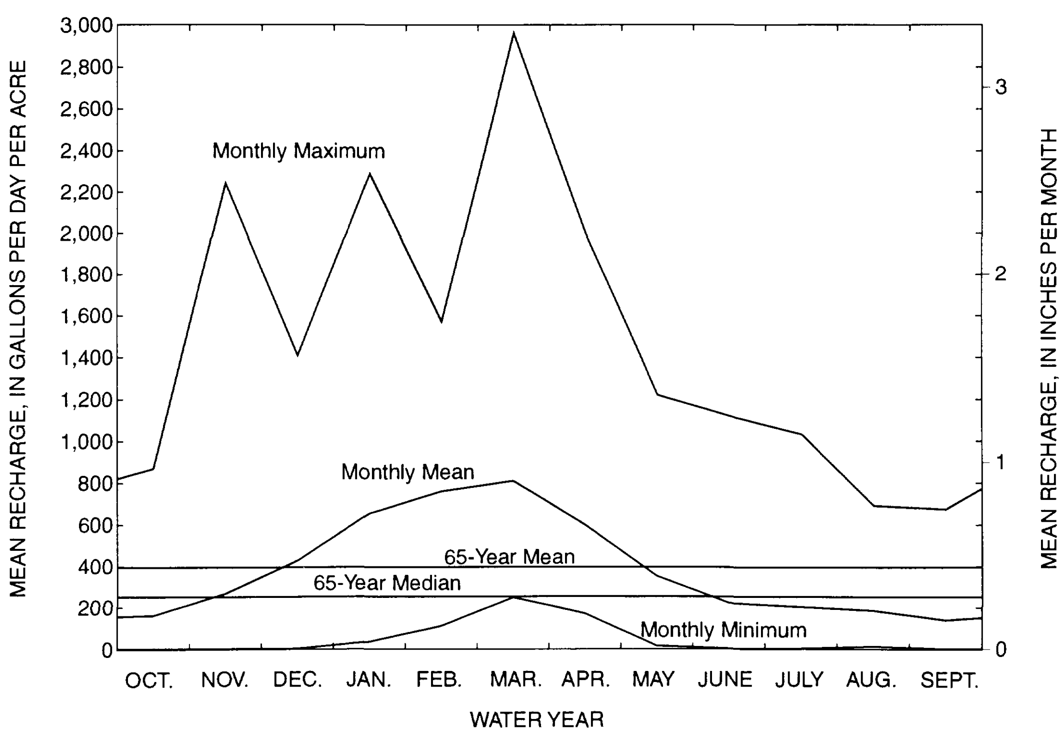
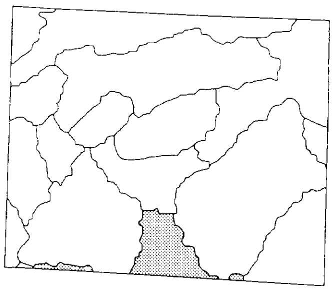


Figure 19. Variation of monthly mean ground-water recharge in the upper Deep River subbasin between station 02098500 near High Point, N.C., station 02099000 near High Point, N.C., and station 02099500 near Randleman, N.C.



Lower Deep River Subbasin

The lower Deep River subbasin is the 224-mi^2 part of the Deep River Basin that lies between gaging station 02099500 (site 17, fig. 1) near Randleman, N.C., and gaging station 02100500 (site 18, fig. 1) at Ramseur, N.C. West Fork Deep River and East Fork Deep River originate in west-central Guilford County and flow in a southeasterly direction to a point on the east side of High Point where they join to form the Deep River. The Deep River continues on a southeasterly course across Randolph County, passing through Randleman, Franklinville, and Ramseur along the way. The area of the lower Deep River subbasin within Guilford County is 29.4 mi^2, or about 4 percent of the land area of the county.

Discharge records for gaging station 02099500 (site 17, fig. 1) near Randleman, N.C., and gaging station 02100500 (site 18, fig. 1) at Ramseur, N.C., were analyzed by hydrograph separation, and daily estimates of recharge were generated for the 67-year period between 1929 and 1995. Station 02099500 has operated continuously since the 1929 water year (table 1). Gaging station 02100500 has operated continuously since the 1924 water year (table 1). Water is diverted from the Deep River upstream of station 02099500 for High Point's municipal water supply. Part of this diverted water is returned upstream of the station as treated wastewater; part of the wastewater is diverted out of the basin into Rich Fork, a tributary of Abbotts Creek. The transfer of wastewater to the Abbotts Creek Basin results in a reduction in flow in the Deep River that affects stations 02099500 and 02100500 equally. Therefore, no adjustment was made for the wastewater discharges to Rich Fork. Water is withdrawn by Asheboro, N.C., from reservoirs on Back Creek (in the Uwharrie River Basin) for municipal water supply; treated wastewater is discharged into the Deep River upstream of station 02100500 at Ramseur. The transfer of water from the Uwharrie River Basin into the Deep River results in an increase in flow past station 02100500. During the water years between 1951 and 1995, the annual average wastewater discharge ranged from about 1 ft^3/s to 7.9 ft^3/s, and averaged 4.2 ft^3/s. The annual average wastewater discharges were added to daily streamflow at station 02100500 before conducting the hydrograph separation. Estimates of recharge at 02099500 were subtracted, on a daily basis, from the record for the Deep River at Ramseur for the period between 1929 and 1995 to produce daily estimates of recharge for the intervening area between the stations.

The daily estimates of recharge were further analyzed to produce the results presented in tables 30 and 31 and figure 20. Annually, estimated mean recharge in the lower Deep River subbasin is 4.15 in., or 310 (gal/d)/acre. The estimated median recharge is 199 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 30 and figure 20.

Table 30. Statistical summary of recharge estimates for the lower Deep River subbasin between station 02099500 near Randleman, N.C., and station 02100500 at Ramseur, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
67	4.15	1.67	0.80	7.74	33.6

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	67	113	0.00	659
November	67	160	0.28	513
December	67	286	0.00	910
January	67	470	0.00	1,630
February	67	643	70.0	1,410
March	67	672	75.3	1,570
April	67	523	110	1,190
May	67	282	23.6	934
June	67	182	3.16	636
July	67	162	8.94	641
August	67	131	0.00	557
September	67	102	0.00	578
All months	804	310	0.00	1,630

Table 31. Ground-water recharge duration statistics for the lower Deep River subbasin between station 02099500 near Randleman, N.C., and station 02100500 at Ramseur, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	3,310						
1	1,390	26	440	51	192	76	71.5
2	1,210	27	425	52	186	77	68.1
3	1,100	28	411	53	179	78	64.3
4	1,020	29	398	54	171	79	61.4
5	962	30	387	55	164	80	57.8
6	910	31	375	56	158	81	54.2
7	863	32	365	57	152	82	50.4
8	816	33	352	58	147	83	46.4
9	777	34	342	59	142	84	42.5
10	750	35	331	60	137	85	37.7
11	717	36	321	61	131	86	33.0
12	689	37	310	62	127	87	28.5
13	665	38	299	63	123	88	24.2
14	644	39	291	64	119	89	19.3
15	623	40	281	65	115	90	14.1
16	603	41	272	66	110	91	8.57
17	583	42	262	67	106	92	1.53
18	565	43	253	68	102	93	0.00
19	549	44	244	69	98.2	94	0.00
20	532	45	236	70	94.3	95	0.00
21	517	46	229	71	90.6	96	0.00
22	501	47	222	72	86.7	97	0.00
23	485	48	215	73	82.2	98	0.00
24	471	49	207	74	78.5	99	0.00
25	455	50	199	75	74.9	100	0.00

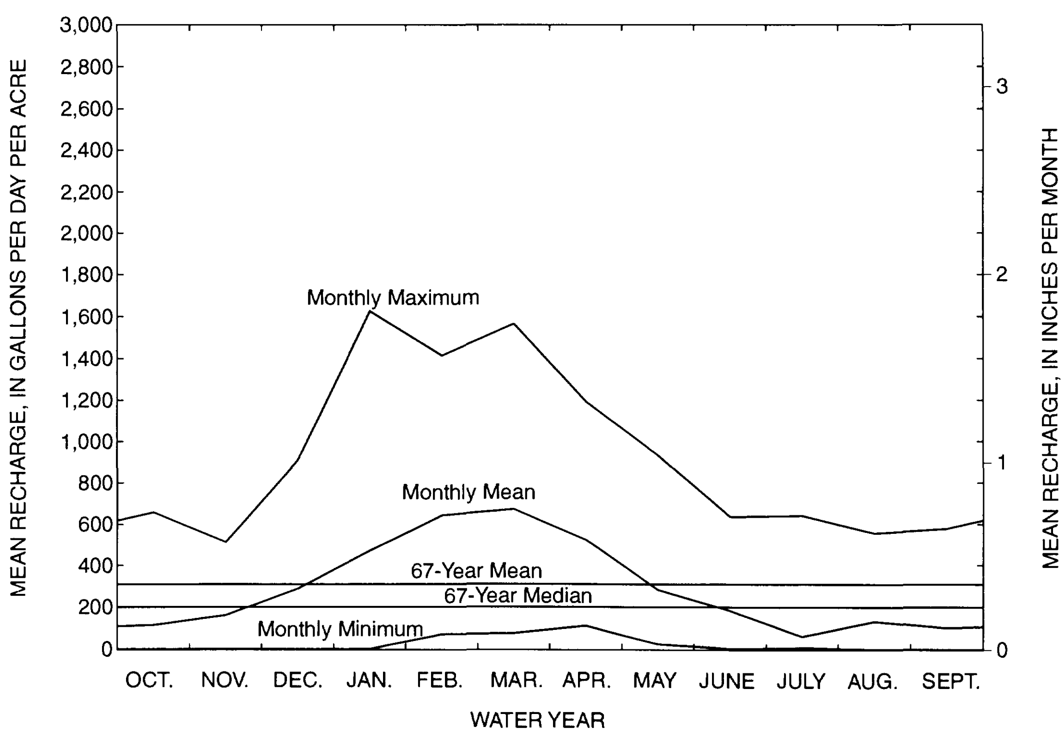
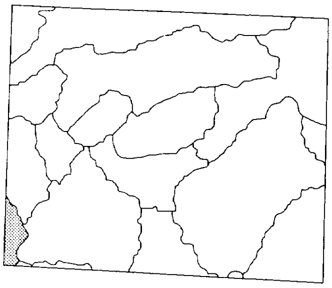


Figure 20. Variation of monthly mean ground-water recharge in the lower Deep River subbasin between station 02099500 near Randleman, N.C., and station 02100500 at Ramseur, N.C.



Abbotts Creek Basin

The part of the Abbotts Creek Basin that lies upstream from gaging station 02121500 (site 19, fig. 1) at Lexington, N.C., has a drainage area of 174 mi^2. Abbotts Creek originates in east-central Forsyth County at Kernersville, N.C., and flows in a southerly direction into northwestern Davidson County. West of High Point, Abbotts Creek turns to the west-southwest, continues through central Davidson County past Lexington, and flows into High Rock Lake, one of several reservoirs along the Yadkin River. Rich Fork, a tributary of Abbotts Creek, originates on the west side of High Point, N.C., and receives runoff from the southwestern part of Guilford County. The area of the Abbotts Creek Basin within Guilford County is 8.45 mi^2, or about 1 percent of the land area in the county.

Discharge records for gaging station 02121500 were analyzed by hydrograph separation, and daily estimates of recharge were generated for 24 water years of the period between 1941 and 1995. Station 02121500 was in operation for 17 water years from 1941 through 1957. Measurements at the gage were discontinued in 1957. The station was reactivated at the beginning of the 1989 water year and has been in operation since that time (table 1). Lexington, N.C., withdraws water from Lake Tom-a-Lex on Abbotts Creek upstream of station 02099500 for municipal water supply. Part of this water is returned to Abbotts Creek downstream of the station as treated wastewater; part of the wastewater is diverted out of the basin into Swearing Creek. The withdrawal of water from Lake Tom-a-Lex results in a reduction in flow at station 02121500. During the water years between 1942 and 1957, and between 1989 and 1995, the annual average withdrawals ranged from about 2.0 ft^3/s to 6.0 ft^3/s, and averaged 3.7 ft^3/s. Treated wastewater is discharged by High Point, N.C., into Rich Fork, a tributary of Abbotts Creek. The transfer of water from the Deep River Basin into the Abbotts Creek Basin results in an increase in flow past station 02121500. During the water years between 1951 and 1957, and between 1989 and1995, the annual average wastewater discharge ranged from about 1.5 ft^3/s to 7.4 ft^3/s, and averaged 4.3 ft^3/s. The annual average withdrawals from Lake Tom-a-Lex were added to daily streamflow at station 02121500, and the annual average wastewater discharges into Rich Fork were subtracted from daily streamflow at station 02121500, before conducting the hydrograph separation.

The daily estimates of recharge were further analyzed to produce the results presented in tables 32 and 33 and figure 21. Annually, estimated mean recharge in the Abbotts Creek Basin is 5.33 in., or 398 (gal/d)/acre. The median recharge is 280 (gal/d)/acre. Monthly mean recharge varies seasonally as shown in table 32 and figure 21.

Table 32. Statistical summary of recharge estimates for the Abbotts Creek Basin upstream from station 02121500 at Lexington, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
24	5.33	1.29	3.48	7.70	40.9

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
October	24	178	34.9	517
November	24	277	68.6	931
December	24	411	98.5	1,080
January	24	621	163	1,250
February	24	732	265	1,770
March	24	818	439	2,150
April	24	605	234	1,150
May	24	376	145	957
June	24	276	104	1,090
July	24	210	47.2	680
August	24	151	46.0	387
September	24	124	28.2	312
All months	288	398	28.2	2,150

Table 33. Ground-water recharge duration statistics for the Abbotts Creek Basin upstream from station 02121500 at Lexington, N.C.

Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time

Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre	Percent of time	Recharge (gal/d)/acre
0	4,120						
1	1,910	26	505	51	271	76	137
2	1,590	27	493	52	263	77	132
3	1,310	28	482	53	255	78	128
4	1,130	29	470	54	247	79	123
5	1,060	30	459	55	240	80	117
6	996	31	449	56	234	81	112
7	942	32	437	57	229	82	106
8	903	33	430	58	222	83	101
9	862	34	418	59	217	84	97.9
10	833	35	410	60	211	85	93.0
11	801	36	402	61	207	86	91.2
12	778	37	393	62	203	87	87.1
13	746	38	383	63	197	88	81.5
14	723	39	375	64	194	89	75.5
15	701	40	365	65	188	90	72.3
16	685	41	357	66	183	91	67.2
17	657	42	349	67	177	92	62.6
18	637	43	342	68	172	93	58.1
19	615	44	332	69	166	94	54.2
20	594	45	325	70	162	95	50.2
21	575	46	315	71	157	96	44.4
22	554	47	308	72	154	97	38.9
23	540	48	298	73	150	98	32.1
24	527	49	290	74	145	99	23.5
25	516	50	280	75	141	100	5.22

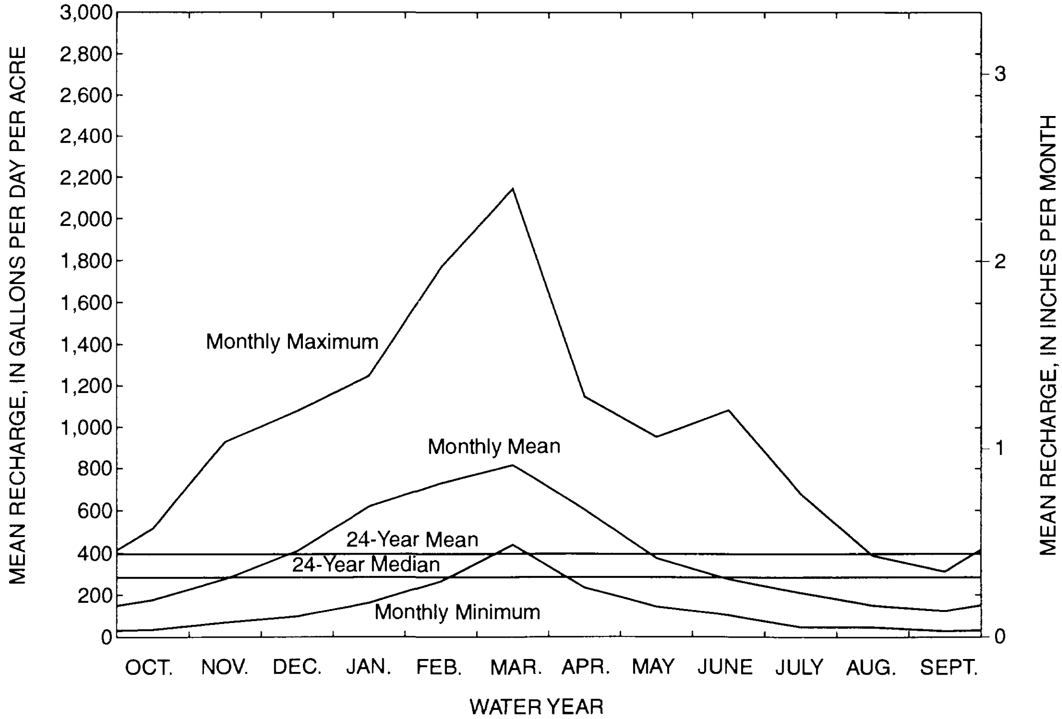


Figure 21. Variation of monthly mean ground-water recharge in the Abbotts Creek Basin upstream from station 02121500 at Lexington, N.C.

Comparison of Basins

Ground-water recharge in 15 Guilford County drainage basins and subbasins is compared in figure 22. The box plots summarize the recharge duration characteristics of the 15 basins and subbasins. Recharge rates that will be equaled or exceeded 90-, 75-, 50-, 25-, and 10-percent of the time are shown. The mean ground-water recharge also is shown for comparison to the duration characteristics.

Mean ground-water recharge in the 15 drainage basins and subbasins ranges from 4.03 in/yr

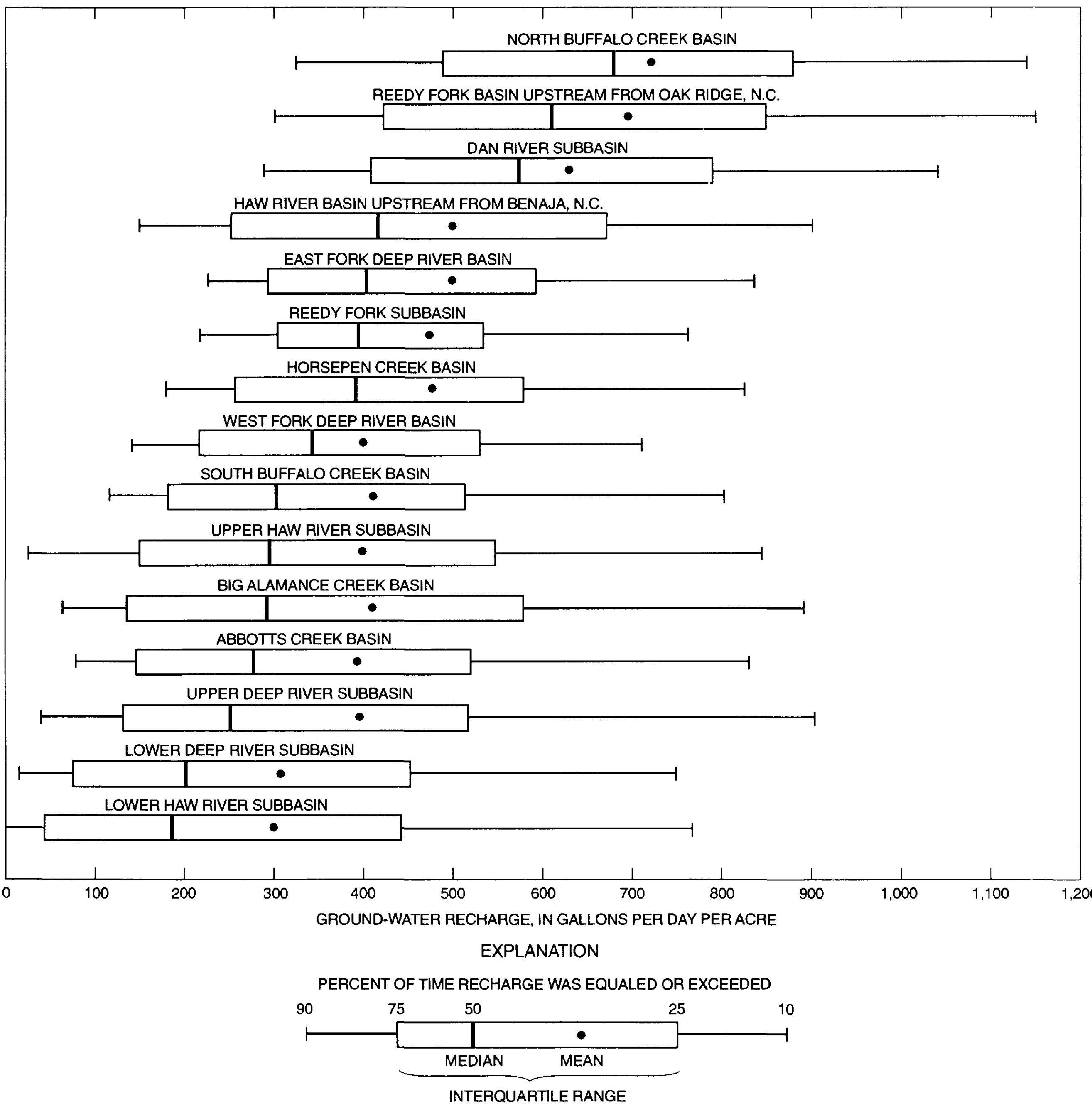


Figure 22. Box plots showing selected ground-water recharge duration characteristics and mean recharge in 15 basins and subbasins in Guilford County, N.C.

(302 (gal/d)/acre) in the lower Haw River subbasin to 9.69 in/yr (723 (gal/d)/acre) in the North Buffalo Creek Basin. The mean recharge for the 15 basins is 6.28 in/yr (469 (gal/d)/acre). In general, recharge rates are highest for basins in the northern and northwestern parts of the county and lowest in the southern and southeastern parts of the county.

Median ground-water recharge (recharge that will be equaled or exceeded 50-percent of the time) in the 15 drainage basins and subbasins ranges from 2.47 in/yr (184 (gal/d)/acre) in the lower Haw River subbasin to 9.15 in/yr (681 (gal/d)/acre) in the North Buffalo Creek Basin. The median recharge for the 15 basins is 4.65 in/yr (346 (gal/d)/acre).

The distribution of recharge rates in the county suggests a correlation between recharge rates and hydrogeologic units (and derived regolith). Although none of the 15 basins and subbasins that were studied are sufficiently small to characterize recharge rates according to individual hydrogeologic units, several basins are underlain predominantly by one hydrogeologic unit and some basins are underlain by no more than two. Recharge rates also depend on other factors which vary from basin to basin. An important factor is the infiltration capacity of the soil which depends not only on soil properties derived from weathering of the bedrock, but on land use and land cover. When land use and land cover are considered independent of other factors, the highest recharge rates and infiltration capacities are in forested areas; the lowest are in urban areas. Agricultural land uses typically are intermediate. Topography is also important, because gentle slopes reduce runoff rates and allow more time for infiltration.

Nearly all of Guilford County is underlain by hydrogeologic units consisting of igneous and metaigneous rocks of several types. MIF (metaigneous, felsic), MII (metaigneous, intermediate), and IFI (igneous, felsic intrusive) predominate (fig. 4; table 2). More than half (63 percent) of the county is underlain by metaigneous rocks which have similar weathering properties, and more than a fifth (22 percent) of the county is underlain by intrusive igneous rocks of felsic composition. The remainder of the county (15 percent) is underlain by metasedimentary and metavolcanic rocks of various types. The occurrence of IFI is limited exclusively to a single large plutonic body that underlies much of the northwestern third of the county; nearly all of the metaigneous rocks occur southeast of this pluton (fig. 4).

Recharge estimates for the North Buffalo Creek Basin, Reedy Fork basin upstream from Oak Ridge, and Dan River subbasin, are higher than any other basin or subbasin in Guilford County. Ground water also constitutes a higher percentage of total streamflow in Reedy Fork upstream from Oak Ridge (60.7 percent), and the Dan River subbasin (59.7 percent), than in any other streams in the county. Four other basins, Haw River upstream from Benaja, East Fork Deep River, Reedy Fork subbasin, and Horsepen Creek, have similarly high recharge estimates. Six of these seven basins and subbasins generally lie to the north and northwest of an imaginary line that extends from the northeast corner of Guilford County to the southeast corner of Forsyth County. The seventh basin, North Buffalo Creek, is crossed by this imaginary line, but generally lies southeast of the line. The presence of large areas of regolith derived from the IFI (igneous, felsic intrusive) hydrogeologic unit may explain the high recharge estimates (base-flow rates) in the six basins and subbasins northwest of this line. This unit tends to weather deeply and produce a deep, sandy, porous regolith with high infiltration capacity. The soil and saprolite resulting from the weathering of IFI is typically light colored and sandy, and is classified in the Cecil-Madison soil association (U.S. Department of Agriculture, 1977). However, most of the North Buffalo Creek Basin is underlain by MIF (metaigneous, felsic) and the remainder is underlain by MII (metaigneous, intermediate); none of the basin is underlain by IFI. The high recharge estimate for the North Buffalo Creek Basin may be due to reported, but unaccounted for, wastewater discharges upstream of station 02095500 (U.S. Geological Survey, 1929–90).

North Buffalo Creek and South Buffalo Creek are in adjacent basins and both are underlain by MIF and MII, yet the estimated annual recharge in the North Buffalo Creek Basin is 4.18 in/yr higher than the annual recharge in South Buffalo Creek Basin (5.51 in/yr). The 4.18 in/yr difference is equivalent to 11.4 ft^3/s. It is possible that this is due to the contribution of wastewater discharges to total streamflow. Although the rate of wastewater discharges to North Buffalo Creek is unknown, some indication of the amount of water used in Greensboro can be had from the reported diversions of water from reservoirs on Reedy Fork. Beginning in 1935, annual diversions from Lake Brandt were reported to be 8.1 ft^3/s; by 1990, the last year of discharge measurements at station 0209550, total annual diversions from Lake Brandt and Lake Townsend (diversions from Lake Townsend began in 1970) had increased to 51.7 ft^3/s (U.S. Geological Survey). For the period between 1929 and 1990 (the 62-year period of streamflow records used for recharge estimates), the average diversion from reservoirs on Reedy Fork for water supply was 24.0 ft^3/s. If only half of this water was returned as treated wastewater to North Buffalo Creek, the high recharge estimate could be explained. On the other hand, a wastewater treatment plant is also located on South Buffalo Creek, and recharge estimates for the South Buffalo Creek Basin, like the North Buffalo Creek Basin, are not adjusted for wastewater discharges. Yet, the recharge estimate for the South Buffalo Creek Basin (5.51 in/yr) is comparable to recharge estimates for the upper Deep River subbasin, Big Alamance Creek Basin, and upper Haw River subbasin that have similar hydrogeology.

South and southeast of the imaginary line described previously are eight basins and subbasins that have the lowest base flows in the county. Six of these, West Fork Deep River, South Buffalo Creek, upper Haw River subbasin, Big Alamance Creek, Abbotts Creek, and upper Deep River subbasin, are underlain primarily by the MIF (metaigneous, felsic) hydrogeologic unit. Weathering of this unit tends to produce a deep regolith with moderate infiltration capacity. The soil and saprolite resulting from the weathering of MIF varies in color from light to darker shades of tan, buff, and red. Although locally sandy, this soil often has high proportions of fine sand, silt, and clay. Much of the soil is classified in the Enon-Mecklenburg soil association (U.S. Department of Agriculture, 1977). Base flows in these six basins are slightly higher than base flows in the lower Haw River subbasin and lower Deep River subbasin.

Base flows in the lower Haw River subbasin, at 4.03 in/yr, and the lower Deep River subbasin, at 4.15 in/yr, are the lowest of the 15 basins and subbasins. Base flow in the lower Deep River subbasin, as a percentage of total streamflow, at 33.6 percent, is the lowest of the 15 basins and subbasins. Base flow in the lower Haw River subbasin, as a percentage of total streamflow, at 37.0 percent, is the third lowest. Much of the area drained by the lower Haw River subbasin and lower Deep River subbasin lies, respectively, to the east-southeast and south of Guilford County. Large areas of both subbasins are underlain by hydrogeologic units of metavolcanic origin; the MVF (metavolcanic, felsic) hydrogeologic unit predominates (Daniel and Payne, 1990). These data suggest that in areas underlain by MVF there is less recharge to the ground-water system, and that the quantity of ground water retained in storage is lower than in other hydrogeologic units in the county. However, most of the area underlain by MVF in these two subbasins lies outside of Guilford County; only 2 percent of Guilford County is underlain by MVF.

The areas of the lower Haw River subbasin and lower Deep River subbasin that lie within Guilford County are underlain primarily by the hydrogeologic units MIF and MII. Comparison of recharge estimates for these subbasins with recharge estimates for adjacent basins that are predominantly or entirely underlain by MIF and MII suggests that the recharge estimates for the entirety of the lower Deep River (4.15 in.) and lower Haw River (4.03 in.) subbasins may not be representative of the areas of these subbasins within Guilford County. Based on this comparison, it seems plausible that recharge in the Guilford County portions of the lower Deep River and lower Haw River subbasins may be as much as 1.15 in. to 1.50 in. higher than recharge for the subbasins as a whole.

Topographic relief may affect recharge estimates based on base-flow estimates. Broad valleys with shallow stream channels tend to have lower base-flow rates than deeper channels in the same hydrogeologic setting. This is apparent in the headwaters of streams and their tributaries near drainage divides where channels are not deeply incised into the landscape; these streams tend to be intermittent streams—that is, they are dry part of the year. However, farther downstream where a stream channel is more deeply incised and the relief between stream and divide is greater, flow occurs year round—that is, the stream is a perennial stream. When a stream is deeply incised into the underlying aquifer system, base flow will be maintained by ground water draining out of storage, even during droughts. Thus, deeply incised streams may have higher base flows than streams with shallower channels, and the resulting estimates of recharge will be higher for the deeply incised streams.

Daniel (1996, table 28) reported that estimates of recharge (base-flow rates) in the Morgan Creek Basin, Cane Creek Basin, and Eno River Basin in nearby Orange County increased in the downstream direction. This increase was attributed to higher topographic relief and greater depth of channel incision in the downstream direction. Within the Morgan Creek Basin, the presence of large areas of regolith derived from the MIF (metaigneous, felsic) hydrogeologic unit were thought to magnify the effects of topographic relief and channel incision. However, in Orange County nearly all of the county is underlain by hydrogeologic units consisting of metamorphic rocks of several types (metavolcanic rocks predominate), and the fact that most of these metamorphic rocks have similar weathering properties contributes to the narrow range in recharge rates among most basins and subbasins in that county. Thus, it is more likely that differences in recharge estimates resulting from effects of topographic relief can be distinguished from the effects due to differences in hydrogeology. In contrast with Orange County, differences in recharge estimates in Guilford County appear to be correlated with hydrogeologic units, or groups of units. The recharge estimates exhibit little or no apparent correlation with topographic relief. If relief plays a part in any of the estimates in Guilford County, any differences resulting from topographic relief are probably masked by the greater magnitude of differences in recharge resulting from differences among hydrogeologic units and infiltration capacities of the derived regolith.

Excluding the high recharge estimates in the North Buffalo Creek Basin, which may be due to unaccounted for wastewater discharges, the highest recharge estimates occur in the northwestern part of Guilford County in basins underlain by IFI and lesser areas of meta-sedimentary rocks. Recharge estimates in this area range from 6.37 in/yr (475 (gal/d)/acre) to 9.33 in/yr (696 (gal/d)/acre). Basins in the southwestern, central, and northeastern parts of the county are underlain primarily by the hydrogeologic units MIF and MII and recharge estimates range from 5.32 in/yr (398 (gal/d)/acre) to 5.51 in/yr (412 (gal/d)/acre). In the extreme southern and southeastern parts of the county, the lower Deep River subbasin and the lower Haw River subbasin have the lowest estimated recharges at 4.15 in/yr (310 (gal/d)/acre) and 4.03 in/yr (302 (gal/d)/acre), respectively. Although the parts of these subbasins that lie within Guilford County are underlain primarily by the units MIF and MII, the larger part of these subbasins lies south and east-southeast of Guilford County in areas underlain by hydrogeologic units of metavolcanic origin. These units extend to the northeast into Orange County (Daniel and Payne, 1990). Recharge rates in the lower Deep River subbasin and the lower Haw River subbasin are similar to recharge rates in basins throughout Orange County (Daniel, 1996) that are underlain by hydrogeologic units of metavolcanic origin.

DETERMINATION OF THE QUANTITY OF GROUND WATER AVAILABLE FROM STORAGE

An earlier discussion of ground-water storage described how the quantity of water available from storage is a function of the saturated thickness of the regolith and the specific yield (drainable porosity) of the regolith. The quantity of water available from the fractured bedrock is small in comparison to the quantity available from the regolith; therefore, determination of the quantity of water stored in the bedrock is not considered here. In order to determine the quantity of water available from storage in the regolith beneath any site, several hydrologic characteristics need to be measured. These characteristics include: (1) the depth to the top of bedrock, (2) the depth to the water table, and (3) the specific yield of the regolith. If a distinct transition zone is present beneath a site, the accuracy of the storage determination will be improved by determining the thickness of the transition zone and the specific yield of the partially weathered rock in the transition zone.

The thickness of saturated regolith can be expected to vary with topographic setting and susceptibility of the bedrock to weathering. The specific yield of the regolith will depend on several factors, but among the more important are grain size and effective porosity. Both of these factors are influenced by the mineralogy of the parent bedrock as well as that of the byproducts of weathering, especially the authigenic clays and iron-aluminum oxides and hydroxides. The intensity of weathering also decreases with depth; therefore, total porosity and specific yield vary with depth.

The determination of ground-water availability from storage in regolith derived from weathered metamorphic rocks is described by Stewart (1962) and Stewart and others (1964). The determination of the total thickness of the regolith, the thickness of the transition zone, and the saturated thickness of the regolith is described by Daniel and Sharpless (1983), Daniel (1990a), and Harned and Daniel (1992).

The total thickness of the regolith can be determined by drilling test wells or estimated from the depth of well casings installed in existing wells. The depth of casings used in water supply wells in the Piedmont is a reliable indicator of the total thickness of regolith (Daniel, 1990a). If new test wells are being drilled for this purpose, then it will be necessary to use equipment capable of drilling through the partially weathered rock in the transition zone. Typically, an air rotary drill rig would be used, although the percussion drilling method (commonly referred to as the cable-tool method) might be used (Driscoll, 1986; Heath, 1989). By keeping a detailed drilling log and geologist's log, including samples of well cuttings, it is possible to identify the base of the transition zone during drilling with an air rotary rig. The air rotary drill will easily cut through the soil and saprolite. The saprolite is usually completely weathered except for the possibility of a few residual boulders or fragments of unweathered rock. Unlike the soil and saprolite, cuttings from the transition zone will contain abundant rock fragments. However, faces of the fragments often will show evidence of weathering along pre-existing fractures. There also may be saprolitic material in the transition zone, but typically it is much less abundant than partially weathered rock. When fresh, unweathered rock is encountered, faces of the cuttings will not show evidence of weathering. This is the base of the regolith.

The top of the transition zone can be identified by use of an auger drill rig based on the depth of auger refusal. The auger will easily pass through the soil and saprolite, but the partially weathered rock of the transition zone is often sufficiently competent that an auger will not penetrate past the saprolite-transition zone boundary. The top of the transition zone can also be identified during drilling with an air rotary rig, but the power of the air rotary rig demands that care be exercised so as not to miss the change from saprolite to partially weathered rock. Slow drilling and careful attention to the cuttings will be necessary if the hydrogeologist is to identify the top of the transition zone using an air rotary rig.

Cores can be collected during drilling and analyzed for total porosity and specific yield. Representative samples need to be collected of the entire column of regolith, from land surface to the top of unweathered bedrock. Once the specific yield of the regolith is known, curves can be generated that indicate the quantity of water available to wells in relation to the saturated thickness of the regolith.

The saturated thickness of the regolith can be determined as the difference between the depth to the water table and the depth to the base of the regolith. The depth to the water table can best be determined from shallow wells or test holes that tap the regolith. The saturated thickness of regolith can also be estimated as the difference between the depth of casing in a drilled open-hole well and the static water level in the well (Daniel, 1989; Daniel, 1990a). However, wells that tap the bedrock may have static water levels that are several feet above the water table in discharge areas (channels and valley floors of perennial streams) and several feet below the water table in recharge areas (interstream uplands). Water levels from wells tapping bedrock should be used with caution to avoid overestimating or underestimating the quantity of available water in storage.

The depth to the water table and, as a result, the saturated thickness of regolith vary seasonally due to seasonal changes in evapotranspiration and recharge rates. Seasonal changes in recharge rates are well illustrated by the water-year recharge hydrographs presented in the individual basin and subbasin descriptions of this report. Water level data from observation wells in the central Piedmont, including Guilford County (Mundorff, 1948; LeGrand, 1954; Bain, 1966; Coble and others, 1989), indicate that ground-water levels typically vary as much as 4 to 12 ft during a year depending on the topographic setting of the well and other conditions—for example, the water-level hydrographs in figure 5 are based on water levels in a dug well tapping saprolite on a hilltop in southern Orange County. Fluctuations in the water table of this magnitude, when compared to the average saturated thickness of regolith, represent large changes in the volume of ground water in storage. Therefore, the time of year that water levels are measured needs to be recorded. Estimates of the quantity of ground water in long-term storage are most reliable when based on average annual water levels, which are not likely to change much from year to year under natural (unpumped) conditions. If data from a nearby long-term observation well are available, water-level measurements from wells at a site under evaluation can be adjusted to account for the date of the measurements.

When projected demands on the ground-water system are not great in comparison to generally accepted figures for ground-water availability, data from individual test wells or existing wells may suffice, especially for individual users. On the other hand, when demand is likely to reach the limits of availability, or is actually projected to reach these limits based on availability, detailed evaluation of the quantity of ground water in storage beneath a large tract of land may be necessary. Detailed areal evaluation is best achieved by generating isopach maps of the thickness of regolith and the saturated thickness of regolith. Generation of isopach maps requires well data from a number of sites on a tract. The sites should be selected and arranged in a manner that is representative of topographic settings and hydrogeologic conditions on the tract.

If changes in land use are also anticipated, the new land uses need to be considered with regard to their effect on ground-water recharge and the quantity of ground water in storage. Changes in land use that will reduce the infiltration capacity of the soil around a well site will increase surface runoff and reduce recharge to the ground-water system that would otherwise replace ground water removed by pumping and the natural flow of ground water to discharge areas. Over time, changes in land use that reduce infiltration capacity will almost certainly reduce well yields. The highest infiltration capacities typically occur in areas of mature forests (Chow, 1964). Therefore, from the standpoint of planning ground-water based supply systems, it might be best to locate wells in forested areas that can be set aside from development. On a given tract, these forested areas might also be used as parks, greenways, or wildlife habitat.

USE OF RECHARGE AND STORAGE DATA FOR GROUND-WATER MANAGEMENT PLANNING

Knowledge of ground-water recharge rates and quantities of ground water in storage can be used for ground-water management planning. Planning is especially important when ground water is being considered for large users, whether the use is for commercial or industrial supply, municipal supply, or individual residential supply in densely developed tracts. These users may extract ground water from one or more large wells, or a large number of individual supply wells. Whatever the method of extraction, the ultimate limit on ground-water availability in Guilford County, as well as other counties in the Piedmont, is the rate of recharge to the regolith-fractured crystalline rock aquifer system. Ground water in long-term storage will sustain well yields during the normal dry periods between recharge events and even during short droughts, but continued pumping at rates in excess of long-term average recharge can eventually deplete the water in long-term storage and well yields will decline until pumping comes into equilibrium with recharge. If little or no ground water is in storage within the regolith, then the ground-water system will have little carry-over capacity during dry periods. In order for the ground-water system to have good carry-over capacity, wells must be located in areas with thick saturated thicknesses of regolith.

When a well is pumped and water begins to move from an aquifer into a well, a cone of depression develops around the pumped well. As pumping continues, water is removed from storage in the vicinity of the well, and the cone of depression expands outward from the pumped well. If and when recharge equals the rate of withdrawal, a new balance can be established in the aquifer and expansion of the cone of depression will cease. For a given pumping rate, the shape and extent of the cone depends on the hydraulic properties of the aquifer material, whether the aquifer is confined or unconfined, and rates of recharge to the aquifer (Heath, 1989). If it can be assumed that the areal extent of a cone of depression will eventually reach equilibrium with recharge, then the areal extent of a cone of depression can be estimated from the recharge and pumping rates.

Because recharge to the aquifer system in Guilford County is derived from the infiltration of precipitation and can be assumed to be areally distributed, knowledge of recharge rates can be balanced with projected demands on the ground-water system to make an estimate of the recharge area necessary to support the demand. If little or no information is available about the quantity of ground water in long-term storage beneath a well site, then certain assumptions may have to be made about the ground water in storage, and recharge areas can be estimated based solely on pumping rates and recharge rates. If studies are made to determine the quantity of ground water in storage beneath a well site, then recharge duration statistics may be used, in conjunction with the ground-water storage data, to determine the percentage of time that recharge will meet a certain level of demand and the percentage of time that ground water in storage will help meet the remaining demand. In the absence of storage data, the estimate of recharge area should be conservative, and resultant recharge areas would be larger than might be necessary when data are available on the quantity of ground-water in long-term storage.

Hydrograph separation is a rapid and efficient method of estimating recharge in a drainage basin. However, it should be remembered that the recharge estimate obtained from hydrograph separation is an areal average of a range of recharge rates that varies depending on a variety of hydrogeologic factors, as well as land use and land cover, within a basin. Therefore, use of areal average recharge estimates to estimate local ground-water availability may not work in every case, especially for small tracts. The applicability of areal average recharge estimates should be weighed with regard to hydrogeologic and other conditions of a particular tract and whether they are similar or dissimilar to typical conditions within the entire drainage basin.

Two examples are presented in the following sections that illustrate procedures for estimating the size of a recharge area needed to satisfy a water demand. The first example is for a situation in which no site-specific data are available about the quantity of ground water available from long-term storage, and water is needed for single family dwellings that will be supplied by individual wells. The second example is for a situation in which site-specific data are available or can be determined as part of the ground-water development process for a community water system. These are hypothetical examples that illustrate how the areal average recharge estimates presented in previous sections might be used for ground-water management planning based on the assumption that conditions that affect recharge—such as geology, land use, and topography—on smaller tracts of land are typical of an entire basin. It is also worth noting that these are just two examples; other styles of development and combinations of hydrogeologic data may lead to other methods for estimating recharge areas. And conditions on a particular tract may not be typical of an entire basin. Thus, the combination of methods or approaches that are best suited for development of water systems on particular tracts is best determined by local authorities.

Example 1: Using Estimated Mean Annual Recharge to Determine Recharge Area

Use of recharge data for management planning can be as simple as using the estimated mean annual recharge to determine the recharge area necessary to meet a projected demand, or as complex as using recharge duration statistics in conjunction with a detailed analysis of long-term ground-water storage to estimate the required recharge area. In either case, the determination of recharge area begins with an estimate of projected demand based on the planned use for the water. If the recharge area contains impervious cover, the amount of impervious cover also needs to be known. Other adjustments may be necessary if certain land uses are considered unacceptable for inclusion in a recharge area. An example of the simplest case using estimated average annual recharge is presented first.

The first example is an analysis of the ground-water recharge area needed for a single family dwelling that will be supplied by an individual well and serviced by an on-site septic system for wastewater treatment. This type of analysis can be critical in areas of dense homebuilding to determine the maximum housing density (minimum lot size) that can be supported by recharge to the ground-water system.

The area chosen for this example is the Big Alamance Creek Basin upstream from gaging station 02096700 near Elon College, N.C. (site 12, fig. 1). The mean annual recharge for 23 years of record is 5.51 in/yr, or 412 (gal/d)/acre (table 22). Based on minimum design standards acceptable to the Federal Housing Administration (FHA) for water distribution systems (Linaweaver and others, 1967, p. 3), a minimum of 400 gallons per day (gal/d) per dwelling unit should be available. This figure is based on the assumption of an average annual per capita use of 100 gal/d and four persons per dwelling unit. Actual per capita water use in North Carolina, based on data from public systems with metered services, is about 67 gal/d (Terziotti and others, 1994, p. 15). Per capita use from self-supplied sources (wells and springs) may be less than from public-supply systems, but data for these sources are not available. Therefore, the actual per capita use in Guilford County is assumed to be 67 gal/d or 268 gal/d per dwelling unit. If a safety factor is desired, then the design criteria should be higher than the actual 67 gal/d per capita. The 100 gal/d per capita established by the FHA is 50 percent higher than measured per capita use and seems to be a reasonable margin of safety. Thus, 400 gal/d per household is used as the design standard for this example.

The next consideration is the area of the house and driveway as impervious cover. Even if a driveway is not paved, a hard-packed, typically gravel-surfaced driveway has very low infiltration capacity. For this example, assume the house has an 1,800-ft^2 floor area with a 2-car garage or carport of 600 ft^2; the total impervious area of the house is 2,400 ft^2. Assume the driveway is 10 ft wide and 100 ft long from road to garage for an additional 1,000 ft^2 of impervious area.

A further consideration is the use of on-site septic systems. If wastewater is removed from a homesite through a sewer system and treated at a wastewater treatment plant that discharges to a stream, the wastewater will have to be accounted for in the water budget of a homesite as a loss from recharge. On-site septic systems return wastewater to the ground-water system. However, most septic systems are installed with the drain field shallow enough that part of the wastewater is returned to the atmosphere by soil-moisture evaporation and transpiration by plants. More water will be returned to the atmosphere during the spring and summer when temperatures are warmer and plants are growing than in the fall and winter when temperatures are cooler and many plants are dormant. Regardless of the seasonal variation in losses to the atmosphere, the amount of wastewater returned to the atmosphere annually is thought to be low in relation to the total quantity of wastewater. In this example, an on-site septic system is used and it is assumed that all wastewater is returned to the ground-water system.

Use of the long-term mean annual recharge assumes that demand during the period of below-average recharge in the summer and fall months will be partially or entirely met by withdrawal from long-term storage, and that any water removed from long-term storage will be replenished during the period of above-average recharge in the winter and spring months. Thus there would be no net loss from long-term storage. To maintain this balance, recharge will have to satisfy demand. At the example homesite, the total impervious area is 3,400 ft^2, eliminating 3,400 ft^2 from the recharge area. The recharge area needed to satisfy a demand of 400 gal/d is:

$$\text{demand / recharge = recharge area, or} \qquad (4)$$

$$\text{400 gal/d / 412 (gal/d)/acre = 0.971 acres.}$$

One acre is 43,560 ft^2, and 0.971 acres is 42,297 ft^2. The area of the house, garage, and driveway is added to the recharge area to determine the minimum land area necessary for each housing unit. The total minimum land area is 45,697 ft^2, or about 1.05 acres.

An additional adjustment for the effect of changes in land use on infiltration capacity may be necessary. Forests and old permanent pasture (ungrazed or lightly grazed) have higher infiltration capacities than heavily grazed, permanent pasture (Chow, 1964, fig. 12-7). If heavily grazed, permanent pasture and landscaped, maintained lawns have similar infiltration capacities, then conversion from forest or old permanent pasture to maintained lawns would reduce infiltration capacity by 50 to 60 percent, and the recharge area would need to be increased accordingly. For example, assume that a home is to be built in an old permanent pasture and that when the home is completed, it will be surrounded by a landscaped, maintained lawn. Based on mass infiltration rates measured for a group of Piedmont soils (Chow, 1964, fig. 12-7), and the assumption that heavily grazed, permanent pasture and landscaped, maintained lawns have similar infiltration capacities, the mass infiltration rate on the lawn after one hour of rainfall will be 57 percent less than the infiltration rate on the old pasture. To obtain the same predevelopment rate of recharge per homesite, the recharge area in the example would have to be increased from 0.971 acres to 2.258 acres. Including the impervious area of the house, garage, and driveway, the minimum land area for the example housing unit would be about 2.34 acre.

In reality, the adjustment for a change in land use described above probably increases the land area per homesite more than is warranted. The example analysis assumes that the land use on the entire tract will change. This may not happen. More importantly, it should be noted that the recharge estimates for the Big Alamance Creek Basin, as well as the other basins and subbasins in the county, represent average conditions for the entire basin, which contains a variety of land uses. None of the basins studied have land use that is limited to forests and old permanent pasture. All the rural basins have large areas of tilled fields, grain fields, and heavily grazed pasture that have lower infiltration capacities than forests and old permanent pasture, as well as some impervious cover. The urban basins have large areas of impervious cover. Thus, adjustments for changes in land use need to be carefully evaluated in terms of overall land use in a basin when basin-wide recharge estimates are used to determine recharge areas for homesites.

Example 2: Using Recharge-Duration Statistics and Ground-Water Storage to Determine Recharge Area

Use of recharge-duration statistics in conjunction with a detailed analysis of long-term ground-water storage to estimate the recharge area necessary to meet projected demand is more complex than the previous example that is based on mean annual recharge and the assumption that ground water in long-term storage will be sufficient to meet demand during the dry summer and fall months. Application of this analytical procedure may also necessitate a detailed analysis of the quantity of available ground water in storage beneath a site or tract of land.

The quantity of water that actually can be withdrawn from long-term storage will depend on several factors; among these are the hydraulic characteristics of the aquifer system, including the transmissivity and storage coefficient, the lateral extent and thickness of the aquifer, the available drawdown in a well tapping the aquifer, the rate of extraction from the well, and the length of time that the well is pumped. All of these factors influence the shape of the cone of depression that develops around a pumped well.

When a well pump is turned on, a cone of depression begins to develop around the well. With continued pumping, the cone of depression deepens and expands outward from the well. The maximum drawdown occurs at the center of the cone of depression but is limited by the depth of the pump intake. In a laterally extensive aquifer, the cone of depression will expand until recharge equals discharge from the well or the drawdown in the well reaches the level of the pump intake. At the outer limit of the cone of depression, the drawdown is zero. Although the surface area of a cone of depression can be quite large, only a fraction of the water in storage beneath the cone of depression can be removed by pumping. Only with multiple wells and overlapping cones of depression can most of the water in long-term storage be extracted; however, this will have the undesired effect of dewatering the aquifer and depleting base flow to streams.

The shape of the cone of depression around a pumped well can be determined by an aquifer test with multiple observation wells (at different distances from the pumped well) and a distance-drawdown analysis of the drawdowns in the observation wells. Aquifer coefficients can also be determined from the test data. Once the aquifer coefficients are determined, distance-drawdown behavior can be predicted for different pumping rates and different pumping periods (Driscoll, 1986). Drawdown around the pumped well will be inversely proportional to the logarithm of the distance from the pumped well. The proportionality will be a function of the coefficient of storage, coefficient of transmissivity, pumping time, and pumping rate. After the shape of the cone of depression has been analyzed, the quantity of water that actually can be removed from long-term storage in the regolith (under water-table conditions) can be estimated. In this example, it will be assumed that 15 percent of the available water in storage beneath the area of the cone of depression can be removed under equilibrium pumping conditions. This number is reasonable based on limited data from other areas of the Piedmont. However, due to the variability of hydrogeologic conditions, site-specific data are preferred for planning purposes. It should be remembered that pumping in excess of equilibrium conditions will eventually dewater the ground-water system as water is removed from long-term storage in excess of recharge rates.

This example is for a planned cluster development containing multiple homes that will be supplied by a community water system; wastewater treatment will be handled by on-site septic systems. The ground-water based community system is to have 100 percent backup against pump or well failure by having at least two wells. The wells that supply water to the development are to be located in an area of forest and old pasture that can be set aside as a recreational area; the houses and their septic systems are to be clustered on another part of the tract. The recreational area also serves as the recharge area and wellhead-protection area (occasionally equated with the capture area around a well) for the community water system. Locating the wells in an area of forest and old pasture that will remain largely unchanged following development ensures that the highest possible recharge rates occur in the capture area. Assuming that well sites can be identified and wells of sufficient capacity to supply the community can be drilled, planners must then determine the area to set aside as capture/recreation/wellhead-protection area. The long-term sustainable yield from the wells also should be estimated in order to determine the maximum number of housing units that can be supported by the ground-water system and how much land is available for these units. Restrictions on land use and housing density may allow some housing units to be located in the outer limits of the capture area without seriously affecting recharge or ground-water quality.

The area chosen for this example is the same as the first example, Big Alamance Creek Basin upstream from gaging station 02096700 near Elon College, N.C. The design standard for houses in the development also is the same, 400 gal/d per household.

Soil borings and other tests at the well sites indicate that conditions are typical of the Piedmont of North Carolina. The average thickness of regolith is 52 ft, the depth to the water table is 31 ft, and the specific yield of the regolith is about 20 percent in the soil and saprolite, but decreases across the transition zone to near zero at the base of the zone (Daniel and Sharpless, 1983; Daniel, 1989; Harned, 1989). Based on these data, the average saturated thickness of regolith is 21 ft. The available water curve in figure 6B is considered representative of the well sites. Given 21 ft of saturated regolith, the available water in long-term storage beneath the well sites is approximately 590,000 gal/acre.

Two wells are drilled on the property. They are drilled far enough apart to avoid drawdown interference. When the two wells are put into production, only one of the wells is to be pumped in a 24-hour period, and that well is to be pumped no more than 12 hours per day. This schedule provides 100-percent backup for the water-supply system in case one well or pump fails. Production tests of wells in the Piedmont indicate that wells are less efficient when pumped continuously than when pumped in short cycles of 18 hours per day or less (Daniel, 1990a; Heath, 1992). Yield tests and distance drawdown analysis indicate that the two wells each produce 35 gallons per minute (gal/min) and the two cones of depression cover a total of 74 acres after 12 hours of pumping. Based on these data, it appears that the system can furnish 35 gal/min for 12 hours a day, or 25,200 gal/d. But, is this a sustainable yield?

A daily production of 25,200 gal/d from 37 acres is 681 (gal/d)/acre. Inspection of recharge duration statistics for the Big Alamance Creek Basin (table 23) indicates that recharge will satisfy this level of demand only about 19 percent of the time. For 81 percent of the time, or about 9.7 months a year, some water will have to be pumped out of long-term storage to meet demand. The most accurate method for using the duration statistics to determine the quantity of water that will be removed from storage is to integrate the volume of recharge beneath the duration curve; however, for simplicity, the quantity of water that would be removed from storage can be expressed in terms of average annual conditions. Comparison with the mean annual recharge of 412 (gal/d)/acre indicates that average recharge on 37 acres (the surface area of one cone of depression) is 15,244 gal/d. To produce 25,200 gal/d, the well will have to extract, on average, 9,956 gal/d from storage. If the quantity of ground water in long-term storage, based on field tests, is approximately 590,000 gal/acre, about 15 percent, or 8,971 gal/d (for 365 days) is available from 37 acres under equilibrium pumping conditions. On average, an additional 985 gal/d will have to be removed from long-term storage. Thus, a pumping rate of 35 gal/min is out of equilibrium with average annual conditions, and the yield will eventually decline over time as long-term storage is depleted.

If the pump installation was designed to pump at 35 gal/min, but pumping for 12 hours per day will deplete long-term storage, then the pumping period needs to be reduced so that the amount of water pumped will be in equilibrium with recharge. To continue this example, a pumping period sufficient to remove water equal to the average annual recharge will be evaluated to determine the suitability of that pumping period. As shown above, average annual recharge of 412 (gal/d)/acre on the surface of the cone of depression is 15,244 gal/d. At a pumping rate of 35 gal/min, this amount of water can be extracted in 7.26 hours. Inspection of table 23 indicates that recharge will satisfy a demand of 412 gallons per minute 38 percent of the time. Water in long-term storage will have to satisfy part of the demand 62 percent of the time, or about 226 days a year (7.4 months). Inspection of figure 16 indicates that these months will most likely be October, November, the first two weeks of December, the last two weeks of May, June, July, August, and September. Integration of the duration data (table 23) for the lower 62 percent of recharge indicates that recharge during this period will total about 40,000 gallons per year per acre ([gal/yr]/acre) or 177 (gal/d)/acre. Recharge during the remaining 38 percent of the year, or 139 days, will total about 110,400 (gal/yr)/acre, or 794 (gal/d)/acre. For 38 percent of the year, recharge will exceed the pumping rate by an average 382 (gal/d)/acre. The recharge in excess of that removed by pumping will replenish long-term storage and replace water removed during low-recharge times of the year.

During the 226 days of below-average recharge, long-term storage will supply about 235 (gal/d)/acre of the total 412 (gal/d)/acre to be pumped. The total for the 37 acres will be 8,695 gal/d from long-term storage. This is well below the 14,489 gal/d (for 226 days) estimated to be available under equilibrium pumping conditions. In this example, pumping at 35 gal/min for 7.26 hours per day will not exceed availability.

The results of this analysis illustrate how data from two wells can be analyzed to arrive at a pumping schedule that is in balance with recharge by using ground water from long-term storage to meet demand during dry periods. The pumping rate for each well will be 35 gal/min. The pumping period will be 6.26 hours per day. Pumping is to be alternated between the two wells. The total recharge area will be about 74 acres. In reality, the cones of depression will cover slightly less than 74 acres if the wells are pumped for 7.26 hours rather than 12 hours as during the aquifer tests, but the total area might be considered during site planning in case the pumping period needs to be increased for emergencies. At a pumping rate of 35 gal/min and a pumping period of 7.26 hours per day, total production will be 15,246 gal/d. In this example, this will supply 38 housing units. If the housing units are clustered on 0.5-acre lots, the housing area will require 19 acres, and the entire development will cover 93 acres. The average area per housing unit (for the entire development) is 2.45 acres. The placement and the impervious area of streets in the development is not considered in this example, but could increase the area required for the development.

POTENTIAL EFFECTS OF GROUND-WATER WITHDRAWALS ON STREAMFLOW

Withdrawal of ground water from wells has the potential to reduce streamflow and produce adverse effects on aquatic systems under certain conditions. The base-flow component of streamflow is the most likely part of streamflow to be affected because too many wells could capture much of the recharge and also deplete ground-water storage. The base-flow component of streamflow in Guilford County ranges from 33.6 to 60.7 percent of total streamflow. The number of wells in a basin will have little effect on surface runoff to streams except in those areas where pumping has lowered the water table so that recharge is induced rather than rejected during recharge events. This situation is most likely to occur when the cone of depression that develops around a pumping well extends beneath a natural discharge area.

The most pronounced effects on streamflow are likely to occur when wastewater is removed by a municipal sewer system and routed to a treatment plant beyond the boundaries of the basin. None of this water will be returned to the ground-water system or streams within the basin. The least effect is likely to occur in developed areas where on-site treatment (septic system) is used. Intermediate to these two extremes will be developed areas that rely on small treatment plants that discharge to the same stream that drains the developed area.

With on-site systems, there may be some seasonal effect on recharge to the ground-water system. Most septic systems, especially the newer conventional and low-pressure systems, are installed with the drain field shallow enough that soil-moisture evaporation and transpiration by plants will remove part of the wastewater. This is the intended effect of shallow drain-field installation. Because of the pronounced seasonality of climatic conditions that drive soil-moisture evaporation and transpiration, recharge to the ground-water system will be most effective during the winter and early spring. If soil conditions permitted, drain fields could be installed deeper than is currently permitted, and more of the wastewater would return to the ground-water system.

An estimate of the effect of on-site septic systems on streamflow can be derived from the potential evapotranspiration excess (the difference between potential evapotranspiration and actual evapotranspiration) and assumptions about the infiltration area in the drain field. Using the Penman method (Criddle, 1958; Schulz, 1973) and climatic data from the National Weather Service, the annual potential evapotranspiration in the central Piedmont of North Carolina is estimated to be approximately 40 in/yr. Water budgets from seven watersheds in central and eastern North Carolina, totaling 40 years of record, indicate actual evapotranspiration in each watershed ranges from 21 to 30 in/yr (Winner and Simmons, 1977; Daniel, 1981; Daniel and Sharpless, 1983) and averages 27 in/yr. Thus, the long-term average potential evapotranspiration excess is estimated to be about 13 in/yr. If shallow drain fields introduce water into the root zone and shallow soil moisture remains high all year, evapotranspiration over the drain field will likely occur at or near potential.

If the potential exists to return an additional 13 in/yr to the atmosphere over the area of the drain field, then the wetted area needs to be considered. If the drain field for the average house is 300 ft long and the soil 3 ft on either side of the drain line is wetted, then an 1,800 ft^2 area will support evapotranspiration at or near potential. If the daily average household demand is 268 gal/d and an additional 13 in/yr is returned to the atmosphere, then only 85 percent of the wastewater will be returned to the ground-water system. If an additional 10 percent is returned to the atmosphere through consumptive losses such as watering lawns and gardens, and other outdoor uses, then only 75 percent of the wastewater will be returned to the ground-water system.

Although a 6-foot width for the wetted zone in a drain field is fairly typical, in some cases it may be wider. At the extreme, it is probably no more than 12 ft wide (6 ft on either side of the line). Assuming a 12-foot width and a line length of 300 ft, the wetted area will be 3,600 ft^2. Using the same average household demand of 268 gal/d and potential evapotranspiration excess of 13 in/yr, only 70 percent of wastewater discharge will be returned to the ground-water system beneath the larger wetted area. If an additional 10 percent is returned to the atmosphere through consumptive losses, this amount is reduced to 60 percent.

The effect of reduced wastewater return to the ground-water system will be most pronounced in a watershed that has been completely developed. If, as in the first example illustrating the use of recharge rates to determine recharge areas for individual homes (p. 55–57), homes served by wells and septic systems are built on the minimum lot size that balances recharge with household demand, base flow to streams will be reduced by the amount of wastewater that is returned to the atmosphere. If drain fields have wetted areas of 1,800 ft^2, base flow will be reduced 15–25 percent; if the wetted areas are 3,600 ft^2, base flow will be reduced 30–40 percent. Thus, in a Guilford County watershed where base flow is 33.6 percent of total streamflow, development of the entire watershed could result in reduction of total streamflow by as little as 5 percent (15-percent base-flow reduction) to as much as 13 percent (40-percent base-flow reduction). On the other hand, in a watershed where base flow is 60.7 percent of total streamflow, a 15-percent base-flow reduction would reduce total streamflow 9 percent, and a 40-percent base-flow reduction would reduce total streamflow 24 percent. These estimated reductions are calculated on the average annual flow. However, as discussed previously, it is unlikely that the effect will be uniform throughout the year; nearly all the potential evapotranspiration excess occurs in the 6-month period from April through September. Most of the reduction in base flow is likely to occur during these months.

In a completely developed watershed where homes are served by wells, lot sizes are based on recharge rates, and the wastewater is piped to a treatment plant outside the watershed, streamflow could be reduced by an amount equivalent to base flow. In Guilford County, the average annual reduction of streamflow could be as much as 34 to 61 percent, depending on the area of the county where the developed watershed is located.

The preceding discussion illustrates the importance of recognizing that withdrawal of ground water on a large scale will cause a reduction in streamflow in the area of the pumping well(s) and downstream from the well site(s). The amount of streamflow reduction will depend, of course, on the amount of pumpage and the return flow from wastewater discharges. In order not to totally deplete ground-water storage during the summer, pumping rates may need to be lower than the average yearly recharge rate; the pumping rates could be increased in winter. Thus, it is not desirable and, perhaps, impossible to attempt to withdraw all of the available ground water. On the other hand, the thickness and seasonal variations in the thickness of the saturated zone will place practical limits on the amount of water that can be withdrawn.

One can conclude, however, that with prudent planning and seasonal pumping schedules designed to account for the seasonal variation in recharge, both natural and from on-site wastewater systems, significant quantities of water can be obtained by withdrawing ground water that would otherwise eventually be discharged to streams, and by tapping, for short periods, the water in drainable storage.

SUMMARY AND CONCLUSIONS

The amount of ground water available from the regolith-fractured crystalline rock aquifer system in Guilford County, North Carolina, is largely unknown. Ground water has commonly been ignored as a water-supply source because of the uncertainty of obtaining adequate yields from wells tapping the county's bedrock aquifers. Growth of population and industry in Guilford County has resulted in increased demand for water from all sources. If historical patterns seen throughout the Piedmont continue into the future, the number of ground-water users in the county can be expected to increase. Planners and managers of suburban development can benefit from additional knowledge of ground-water resources in the county. In order to determine the maximum population that can be supplied by ground water, planners and managers must know the amount of ground water that can be withdrawn without exceeding recharge and(or) overdrafting water in long-term storage. As part of this study, ground-water recharge in Guilford County was estimated for selected drainage basins using streamflow data and an analytical technique known as hydrograph separation. Methods for determining the quantity of ground-water in storage also are described.

Guilford County covers approximately 658 mi^2 in the central part of the Piedmont Province. The population of the county in 1990 was about 347,420; approximately 21 percent of the population depends on ground water as a source of potable supplies (U.S. Bureau of the Census, 1992). Ground water is obtained from wells tapping the regolith-fractured crystalline rock aquifer system that underlies all of the county. Typical bedrock lithologies include granite, diorite, slate, tuff, and schist.

The ground-water system serves two functions: (1) it stores water to the extent of its porosity, and (2) it transmits water from recharge areas to discharge areas. Under natural conditions, ground water in the intergranular pore spaces of the regolith and bedrock fractures is derived from infiltration of precipitation. Ground-water recharge from precipitation cannot be measured directly; however, an estimate of the amount of precipitation that infiltrates into the ground and ultimately reaches the streams of the region can be determined by the technique of hydrograph separation. The hydrograph separation method employed in this study is the local-minimum method of Pettyjohn and Henning (1979).

Hydrograph separation entails dividing the streamflow graph (hydrograph) into two components—ground-water discharge (base flow) and overland runoff. By assuming that there has been no long-term change in ground-water storage, ground-water discharge is equal to the ground-water recharge. Data from 19 gaging stations that measure streamflow within or from Guilford County were analyzed to produce daily estimates of ground-water recharge in 15 drainage basins and subbasins in the county. The recharge estimates were further analyzed to determine seasonal and long-term recharge rates, as well as recharge duration statistics.

Mean annual recharge in the 15 basins and subbasins ranges from 4.03 to 9.69 in/yr, with a mean value of 6.28 in/yr for all basins. In general, recharge rates are highest for basins in the northern and northwestern parts of the county and lowest in the southern and southeastern parts of the county. Median recharge rates in the 15 basins range from 2.47 inches per year (184 (gal/d)/acre) to 9.15 inches per year (681 (gal/d)/acre), with a median value of 4.65 inches per year (346 (gal/d)/acre) for all basins.

Recharge estimates for the North Buffalo Creek Basin, Reedy Fork basin upstream from Oak Ridge, and the Dan River subbasin are higher than any other basin or subbasin in Guilford County. Ground water also constitutes a higher percentage of total streamflow in Reedy Fork upstream from Oak Ridge (60.7 percent) and the Dan River subbasin (59.7 percent) than in any other streams in the county. Four other basins, Haw River upstream from Benaja, East Fork Deep River, Reedy Fork subbasin, and Horsepen Creek, have similarly high recharge estimates. Six of these seven basins and subbasins occur generally to the north and northwest of an imaginary line that extends from the northeast corner of Guilford County to the southeast corner of Forsyth County. The presence of large areas of regolith derived from the IFI (igneous, felsic intrusive) hydrogeologic unit may explain the high recharge estimates (base-flow rates) in the six basins and subbasins northwest of this line. The seventh basin, North Buffalo Creek, generally lies southeast of this imaginary line and is underlain by MIF (metaigneous, felsic) and MII (metaigneous, intermediate). Known, but unaccounted for, wastewater discharges may contribute to the high recharge estimate for this basin. However, the high recharge estimate for the North Buffalo Creek Basin has little practical effect on ground-water development in Guilford County because most of the basin lies within the city limits of Greensboro, N.C.

South and southeast of the imaginary line described in the preceding paragraph are eight basins and subbasins that have the lowest base flows in the county. Six of these, West Fork Deep River, South Buffalo Creek, upper Haw River subbasin, Big Alamance Creek, Abbotts Creek, and upper Deep River subbasin, are underlain primarily by the MIF (metaigneous, felsic) hydrogeologic unit. Base flows in these six basins are slightly higher than base flows in the lower Haw River subbasin and lower Deep River subbasin.

Base flows in the lower Haw River subbasin, at 4.03 in/yr, and the lower Deep River subbasin, at 4.15 in/yr, are the lowest of the 15 basins and subbasins. Base flow in the lower Deep River subbasin, as a percentage of total streamflow, at 33.6 percent, is the lowest of the 15 basins and subbasins. Base flow in the lower Haw River subbasin, as a percentage of total streamflow, at 37.0 percent, is the third lowest. Much of the area drained by the lower Haw River subbasin and lower Deep River subbasin lies, respectively, to the east-southeast and south of Guilford County. Large areas of both subbasins are underlain by hydrogeologic units of metavolcanic origin; the MVF (metavolcanic, felsic) hydrogeologic unit predominates. These data suggest that in areas underlain by MVF there is less recharge to the ground-water system, and that the quantity of ground water retained in storage is lower than in other hydrogeologic units in the county.

The distribution of recharge rates in the study area is almost the reverse of the distribution of precipitation across the study area. Average annual precipitation varies across the study area from 43 to 48 inches. The lowest rainfall occurs in the northern and northwestern parts of the study area; the highest rainfall occurs in the southern and southeastern parts of the study area. Within the county, annual rainfall varies from less than 44 inches in the northwest to about 46 inches in the southeast. The fact that the highest recharge rates occur in the areas of lowest rainfall and the lowest recharge rates occur in the areas of highest rainfall, further supports the conclusion that recharge rates are highly dependent on hydrogeologic conditions. Although there is less precipitation in the northwestern part of the county, much of this area is underlain by IFI, which, when it weathers, produces a sandy regolith into which precipitation readily infiltrates.

Recharge duration statistics also were determined for the same 15 basins and subbasins. Recharge duration statistics provide information needed by planners wanting to evaluate the availability of ground water at different levels of demand so that overuse, or overdrafting, can be prevented, or other sources of water can be made available during periods of low recharge. Use of water from ground-water storage is one option during periods of low recharge. Methods for determining the amount of ground water available from storage are described and two examples describing the use of recharge and storage data for planning and ground-water management are presented.

One example illustrates the use of estimates of average annual recharge and the area of impervious cover to arrive at minimum lot sizes for single-family dwellings that will be supplied by individual wells and serviced by on-site septic systems for wastewater treatment. A second example illustrates the use of recharge duration statistics, test data from wells, and knowledge of the quantity of ground water in long-term storage to develop a community water system for a planned cluster development containing multiple homes with on-site wastewater treatment. In the second example, the ground-water based community system is to have 100 percent backup against pump or well failure by having at least two wells. In order to have the highest possible recharge rates in the capture area, the wells that supply water to the development are to be located in an area of forest and old pasture that is to be set aside as a recreational area; the houses with their septic systems will be clustered on another part of the tract. The problem is to determine how many homes the community system will support and how large the capture area will be around the wells. Both examples are set in the Big Alamance Creek Basin and mean annual recharge is 412 (gal/d)/acre.

In the first example, the minimum lot size for a 2,400-ft^2 house and garage and 1,000 ft^2 of driveway is 1.05 acres. In the second example, the community water system requires 74 acres for the capture area and will supply 38 housing units. If the housing units are clustered on 0.5-acre lots, the housing area will require 19 acres, and the entire development will cover 93 acres. In the second example, the average area per housing unit (for the entire development) is 2.45 acres. This may be reduced by putting some houses, with restrictions, inside the capture area. However, regulations and other safeguards pertaining to community water systems almost certainly will require more area per housing unit than individual systems. Community systems also have a hydrogeologic limitation in that individual public-supply wells in a Piedmont hydrogeologic environment can only extract ground water from a limited area of the aquifer because of the discontinuous nature of bedrock fractures and the fact that the regolith reservoir is dissected by streams. The more wells that are drilled, the more ground water that can be extracted from the system. Many low-yield wells can more effectively extract ground water from the Piedmont ground-water system than a few high-yield wells which can be developed only in locations that have abundant and intensive bedrock fracturing and where the bedrock is overlain by thick saturated regolith.

Consideration also must be given to the number of wells drilled in a basin and the type of wastewater treatment that is used. Too many wells may reduce base flow in streams, especially in basins where the wastewater is treated at a plant outside of the basin and there is no return flow into the basin where the wells are located. Wells used in conjunction with on-site septic systems will have the least effect on the quantity of ground water in long-term storage. Based on several assumptions regarding annual average excess potential evapotranspiration, housing density, household water demand, the wetted area associated with septic system drain fields, and the base-flow contribution to total streamflow, it is estimated that the use of on-site septic systems and wells could reduce streamflow in a Guilford County drainage basin from as little as 5 percent to as much as 24 percent. By comparison, in a completely developed basin where the wastewater is piped to a treatment plant outside the basin, annual average streamflow could be reduced as much as 34 to 61 percent, depending on the area of the county where the drainage basin is located.

There is considerable ground water available in Guilford County. The ground-water system is recharged continually from precipitation. Through careful planning and application of sound hydrogeologic principles supported by good data, these resources can be relied upon to supply potable water to a significant part of the growing population.

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