GROUND-WATER RECHARGE TO THE REGOLITH-FRACTURED CRYSTALLINE ROCK AQUIFER SYSTEM, ORANGE COUNTY, NORTH CAROLINA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 96-4220

Prepared in cooperation with

ORANGE COUNTY, NORTH CAROLINA

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Cover photograph:

Observation well NC-126. The well is hand-dug, has an approximate diameter of 3 feet, and is lined with rock. The measured depth of the well in August 1986 was 46.2 feet. The well, which is owned by the Chi Psi Fraternity, is located in Chapel Hill, west of the University of North Carolina campus, and southeast of the intersection of Cameron Avenue and Ransom Street. Water levels in this well have been measured by the U.S. Geological Survey since August 1938. (Photograph by Charles C. Daniel, III, U.S. Geological Survey, Raleigh, N.C.)

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Raleigh, North Carolina
1996

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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	4047	square meter
square mile (mi^2)	640	acre
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
gallon (gal)	0.003785	cubic meter
	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)	0.003785	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	SR	State Road
HYSEP	Hydrograph Separation Program	USGS	United States Geological Survey

Ground-Water Recharge to the Regolith-Fractured Crystalline Rock Aquifer System, Orange County, North Carolina

By Charles C. Daniel, III

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 Orange 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 12 selected drainage basins and subbasins using streamflow data and an analytical technique known as hydrograph separation. Methods for determining the quality of ground water in storage also are described.

Orange County covers approximately 401 square miles in the eastern part of the Piedmont Province. The population of the county in 1990 was about 93,850; approximately 41 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 most of the county. Ground water also is obtained from Triassic age sedimentary rocks that occur in a small area in southeastern Orange County.

Under natural conditions, recharge to the county's ground-water system is derived from the 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 17 gaging stations that measure streamflow within or from Orange County were analyzed to produce daily estimates of ground-water recharge in 12 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 12 basins and subbasins ranges from 4.15 to 6.40 inches per year, with a mean value of 4.90 inches per year for all basins. In general, recharge rates are highest for basins along a north-south zone extending down the center of the county, and lowest in the western and southeastern parts of the county. Median recharge rates in the 12 basins range from 1.08 inches per year (80.7 gallons per day per acre) to 4.97 inches per year (370 gallons per day per acre), with a median value of 3.06 inches per year (228 gallons per day per acre) for all basins.

Recharge estimates for the Morgan Creek Basin upstream from White Cross and upstream from Chapel Hill are higher than any other basin or subbasin in Orange County. Ground water also constitutes a higher percentage of total streamflow in Morgan Creek (44.4 percent upstream from White Cross; 47.9 percent upstream from Chapel Hill) than in any other stream in the county. Greater topographic relief and depth of channel incision may explain the high recharge estimates (base-flow rates) in the Morgan Creek Basin. The

presence of large areas of regolith derived from the metaigneous, felsic hydrogeologic unit may magnify the effects of topographic relief and channel incision. Base flow in the New Hope River subbasin, as a percentage of total streamflow, at 32.2 percent, is the lowest of the 12 basins and subbasins. Much of the New Hope River subbasin is underlain by the Triassic sedimentary rock hydrogeologic unit that occurs within a rift basin of Triassic age. These data suggest that in areas underlain by Triassic sedimentary rock, 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.

Recharge duration statistics also were determined for the same 12 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.

One example illustrates the use of estimates of mean 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 wastewater treatment will be handled by on-site septic systems. 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. The wells that supply water to the development are to be located in an area 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 has 100-percent backup against pump or well failure by having two wells.

INTRODUCTION

Growth of population and light industry in Orange 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 uncertainly of obtaining adequate yields from wells tapping the county's bedrock aquifers. Furthermore, the amount of ground water available in Orange County for potable supplies is currently unknown. According to the U.S. Bureau of the Census (1992), ground water is used by about 41 percent of the population in Orange County. This is lower than 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 Orange 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 Orange County, began a study in 1995 to assess recharge to 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.

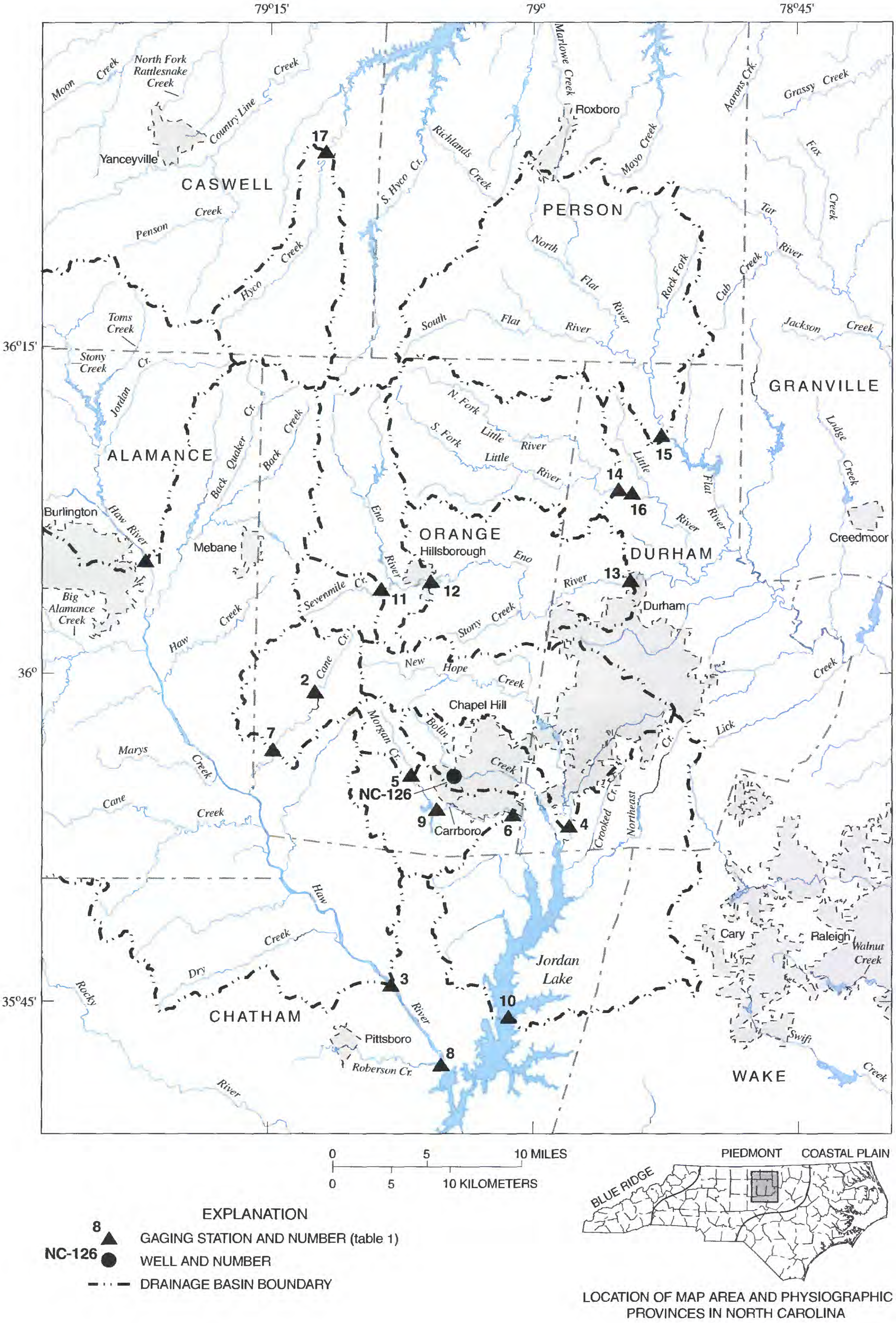


Figure 1. Regional setting of the Orange County study area in the Piedmont physiographic province of North Carolina, selected drainage basins, and locations of gaging stations used in the ground-water recharge analysis.

Location and Background

The area of this investigation includes Orange County, North Carolina, and areas in adjacent counties extending to the basin boundaries of streams that receive streamflow from Orange County (fig. 1). The area of investigation in and around Orange County can be considered fairly typical of the eastern 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.

The amount of ground water available in Orange 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 Orange 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 Orange County Water Resources Committee, during meetings held in 1994 and early 1995, proposed that recharge rates to the regolith-bedrock aquifer system in Orange County be determined. 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 included: (1) an evaluation of long-term ground-water recharge rates throughout Orange 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 recharge rates in different drainage basins throughout the county--in addition to electronic data bases of non-map products, such as recharge-duration tables and hydrographs of monthly recharge estimates, 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 Orange 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 17 streamflow gaging stations located within and outside of Orange County (fig. 1; table 1). Estimates of recharge on a regional scale are based on assumptions 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.

Table 1. Gaging stations that record streamflow within and from Orange 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]
		Cape Fear River Basin				
1	02096500	Haw River at Haw River	36°05'13"	79°22'02"	606	1929-95
2	02096846	Cane Creek near Orange Grove	35°59'13"	79°12'23"	7.54	1990-95
3	02096960	Haw River near Bynum	35°45'48"	79°08'02"	1,275	1974-95
4	[b]02097314	New Hope Creek near Blands	35°53'05"	78°57'58"	75.9	1983-95
5	02097464	Morgan Creek near White Cross	35°55'25"	79°06'56"	8.35	1990-95
6	02097517	Morgan Creek near Chapel Hill	35°53'36"	79°01'10"	41.0	1984-95
7	[c]02096850	Cane Creek near Teer	35°56'34"	79°14'46"	33.7	1960-73
8	[c]02097000	Haw River near Pittsboro	35°42'07"	79°05'12"	1,310	1929-73
9	[c]02097500	Morgan Creek near Chapel Hill	35°53'51"	79°05'28"	30.1	1924-31
10	[c]02098000	New Hope River near Pittsboro	35°44'12"	79°01'36"	285	1950-73
		Neuse River Basin				
11	02084909	Sevenmile Creek near Efland	36°03'56"	79°08'39"	14.1	1988-95
12	02085000	Eno River at Hillsborough	36°04'18"	79°06'14"	66.0	1928-71, 1986-95
13	02085070	Eno River near Durham	36°04'20"	78°54'30"	141	1964-95
14	0208521324	Little River at SR 1461 near Orange Factory	36°08'30"	78°55'10"	78.2	1988-95
15	02085500	Flat River at Bahama	36°10'57"	78°52'44"	149	1926-95
16	[c]02085220	Little River near Orange Factory	36°08'20"	78°54'24"	80.4	1962-87
		Roanoke River Basin				
17	02077200	Hyco Creek near Leasburg	36°23'57"	79°11'50"	45.9	1965-95

[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] Approximately 11 ft^3/s from Neuse River discharged into New Hope Creek.

[c] Discontinued.

Statistical summaries of annual recharge, monthly recharge, and recharge duration estimates are presented for 12 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 Orange County, North Carolina. The yields to wells tapping the various hydrogeologic units in the county have been investigated in several studies. Orange County was included in a multi-county study by Bain (1966); as part of this study 79 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 the area west of the Haw River Basin drainage divide in western Orange 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 Orange 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 Orange County.

Ground-water resources in the western part of the 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 Study Area

The Orange County study area in North Carolina includes Orange County and surrounding areas in Alamance, Caswell, Chatham, Durham, Person, and Wake Counties which contain parts of drainage basins receiving runoff from Orange County (fig. 1). Orange County covers approximately 401 square miles (mi^2) in the eastern part of the Piedmont Province. The major population centers in Orange County are Carrboro, Chapel Hill, and Hillsborough. The county population in 1990 was about 93,850 people; of the total population, about 55,440 people obtained water from public water systems which were dependent upon surface water as the raw water source. The remaining 38,410 residents (40.9 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 northern part of Orange County are generally greater than 700 ft above sea level, but altitudes decrease to less than 230 ft in the southeastern corner of the county in the Triassic basin and to less than 400 ft in the southwestern part of the county along the Haw River. A few mountains that rise above the general Piedmont surface reach altitudes of almost 800 ft.

The climate of the Orange 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 32 to 36 degrees Fahrenheit (°F), whereas mean maximum July temperatures range from 88 to 90 °F. Average annual precipitation in the area is 44 to 48 inches (in.). 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

The author gratefully acknowledges the assistance of Paul K. Thames, Orange County Engineer; P. David Stancil, Orange County Planning Department; Don N. Cox, Chairman of the Orange County Water Resources Committee; members of the Water Resources Committee; and Alice M. Gordon, County Commissioner, for their considerable input into the planning and execution of this project. The support and guidance provided by these people has helped the author and project staff better understand the needs of the county for ground-water resources information, thus ensuring that this study helps to satisfy these needs.

HYDROGEOLOGIC SETTING OF ORANGE COUNTY

The hydrogeologic setting of Orange 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 Orange 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.

River, Streams, and Drainage Basins

Rivers and streams draining Orange 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 Orange County belong to two major river systems--the Haw River Basin in the west and the Neuse River Basin in the east (fig. 1). Hyco Creek, which has its headwaters in northwestern Orange County, flows to the north-northeast into Caswell County where it joins other streams to become the Hyco River. The Hyco River continues in a northeasterly direction out of Caswell County, across Person County, and 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.

Tributaries of the Haw River that drain western Orange County include Back Creek, Haw Creek, Cane Creek, and Collins Creek (fig. 1). Other streams, including Morgan Creek, Bolin Creek, and New Hope Creek, that drain the southcentral and southeastern part of the county are part of the New Hope River drainage system that flows into the Haw River in Chatham County southeast of Pittsboro. The B. Everett Jordan Dam on the Haw River impounds water in the Haw River and New Hope River valleys to form Jordan Lake. The New Hope River no longer exists as a free-flowing stream.

The Eno River, Little River, and Flat River drain north central, central, and northeastern Orange County (fig. 1). These rivers flow generally to the east and southeast out of Orange County into Durham County. They are headwater streams of the Neuse River Basin.

Average annual runoff from the unregulated streams draining Orange County ranges between 12.38 and 13.90 inches per year (in/yr) and averages about 12.83 in/yr. Data from gaging stations 02097314 (site 4, fig. 1) and 02097517 (site 6, fig. 1) are not included in this evaluation because of regulation and return flows from wastewater-treatment plants.

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. The western margin of one of these rift basins, the Durham subbasin of the Deep River Triassic basin, crosses southeastern Orange County. Metamorphic and igneous crystalline rocks underlie the remainder of Orange County.

In Orange 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).

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 within the 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 Orange County is thought to be similar to that of the Piedmont as a whole.

Careful augering of three wells 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.

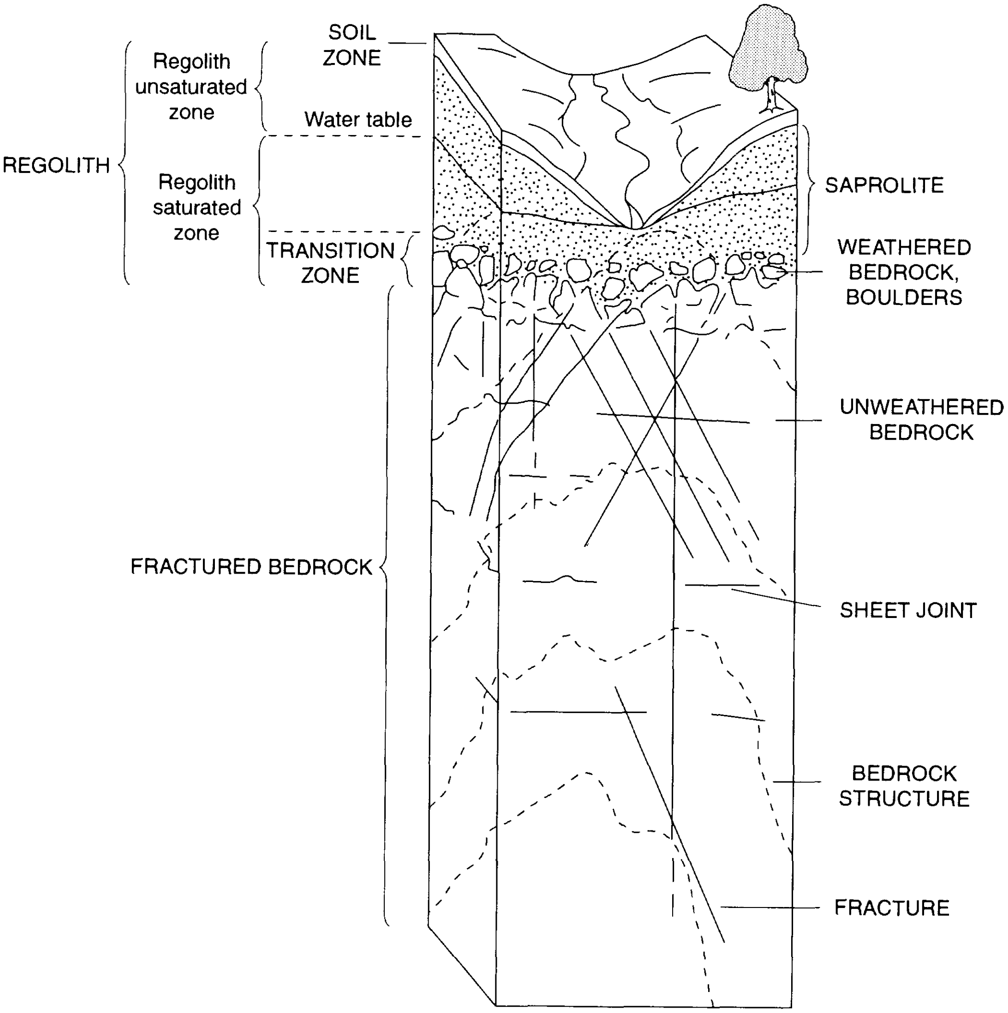


Figure 2. Principal components of the ground-water system in the Piedmont physiographic province of North Carolina (from Harned and Daniel, 1992).

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 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 either 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 Orange County is very complex; beneath much of the county the bedrock consists of folded, fractured, and metamorphosed sedimentary and igneous basement rocks. Intruded into these metamorphic rocks are lesser bodies of slightly metamorphosed or unmetamorphosed igneous rocks. Typical bedrock lithologies include granite, diorite, slate, tuff, and schist. In the southeastern corner of the county, sedimentary rocks of Triassic age occur along the western margin of a large basin (graben) down-faulted into the basement rocks. 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 Orange 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 Orange County area of the hydrogeologic unit map is shown in figure 4.

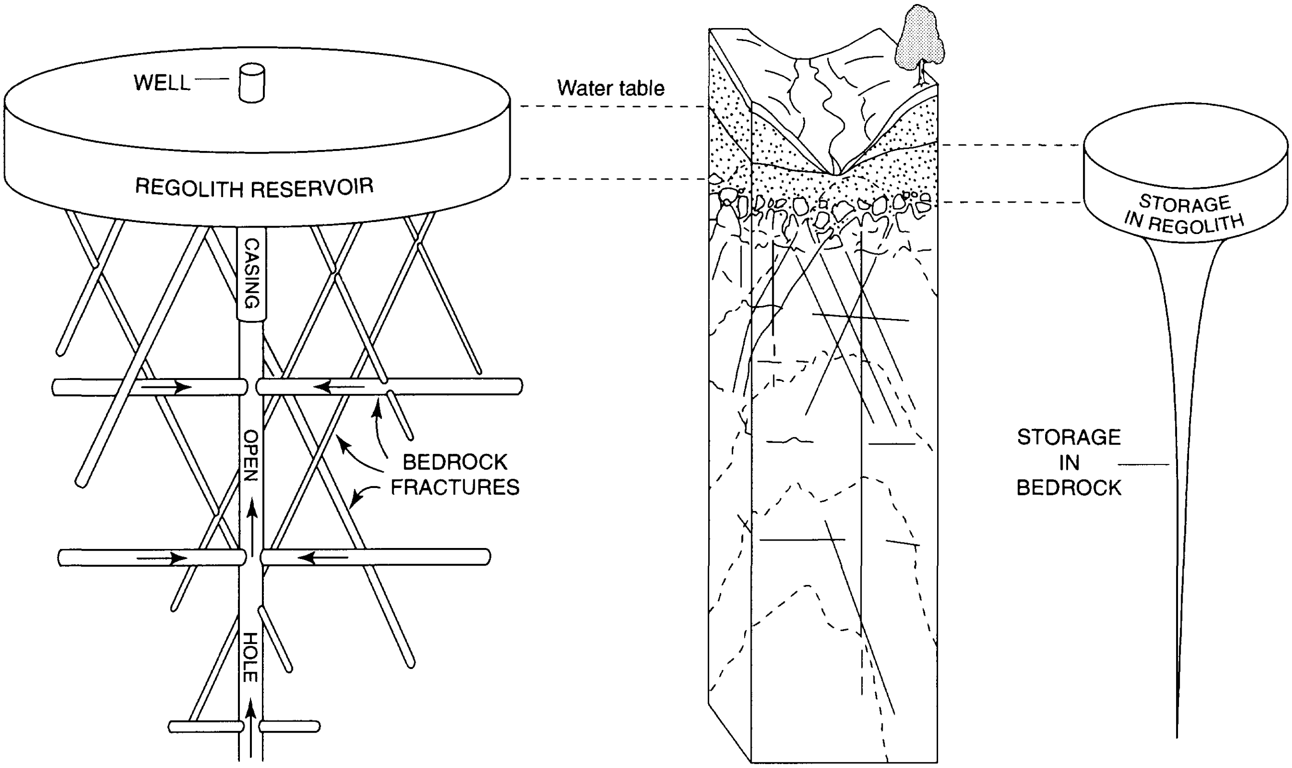


Figure 3. The reservoir-pipeline conceptual model of the Piedmont ground-water system and the relative volume of ground-water storage within the system (modified from Heath, 1984).

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

[mi^2, square miles]

Map symbol (fig. 4)	Hydrogeologic unit	Lithologic description	Area (mi^2)
		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.	104
MII	Metaigneous, intermediate	Gray to greenish-gray, medium- to coarse-grained, massive to foliated, well-jointed, metamorphosed bodies of dioritic composition.	1
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.	14
		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.	182
MVI	Metavolcanic, intermediate	Gray to dark-grayish-green tuffs and crystal tuffs generally of andesitic composition; most with well-developed cleavage; also includes interbedded lithic tuffs and flows of probable andesitic and basaltic composition and minor felsic volcanic rocks.	58
MVE	Metavolcanic, epiclastic	Primarily coarse sediments including interbedded graywackes and arkoses and minor conglomerates, interbedded argillites and felsic volcanic rocks; much of the sequence is probably subaqueous in origin and most of the rocks were derived from volcanic terranes.	9
		Metasedimentary Rocks	
ARG	Argillite	Fine-grained, thinly laminated rock having prominent bedding plane and axial plane cleavage; locally includes beds of mudstone, shale, thinly laminated siltstone, conglomerate, and felsic volcanic rock.	.01
PHL	Phyllite	Light-gray to greenish-gray to white, fine-grained rock having well-developed cleavage; composed primarily of sericite but may contain chlorite; phyllitic zones are common throughout the Carolina slate belt and probably represent zones of shearing although displacement of units is usually not recognizable.	29
		SEDIMENTARY ROCKS	
TRI	Triassic sedimentary rocks	Mainly red beds, composed of shale, sandstone, arkose, and conglomerate (fanglomerate near rift basin margins).	5

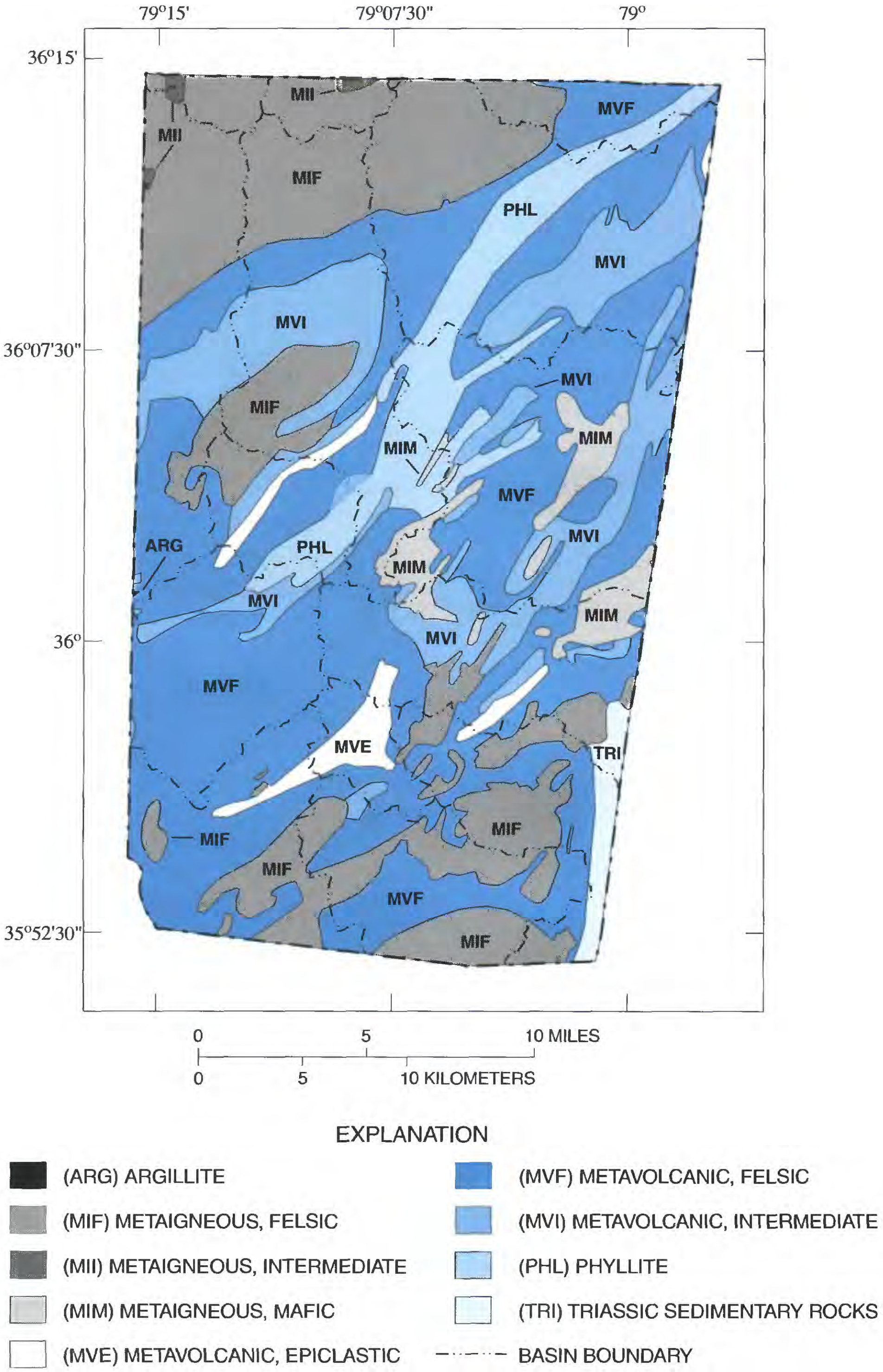


Figure 4. Hydrogeologic unit map of Orange County, N.C. (from Daniel and Payne, 1990).

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 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 Orange 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.

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 (1996) 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 Orange County can be estimated from the following general relation:

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

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.

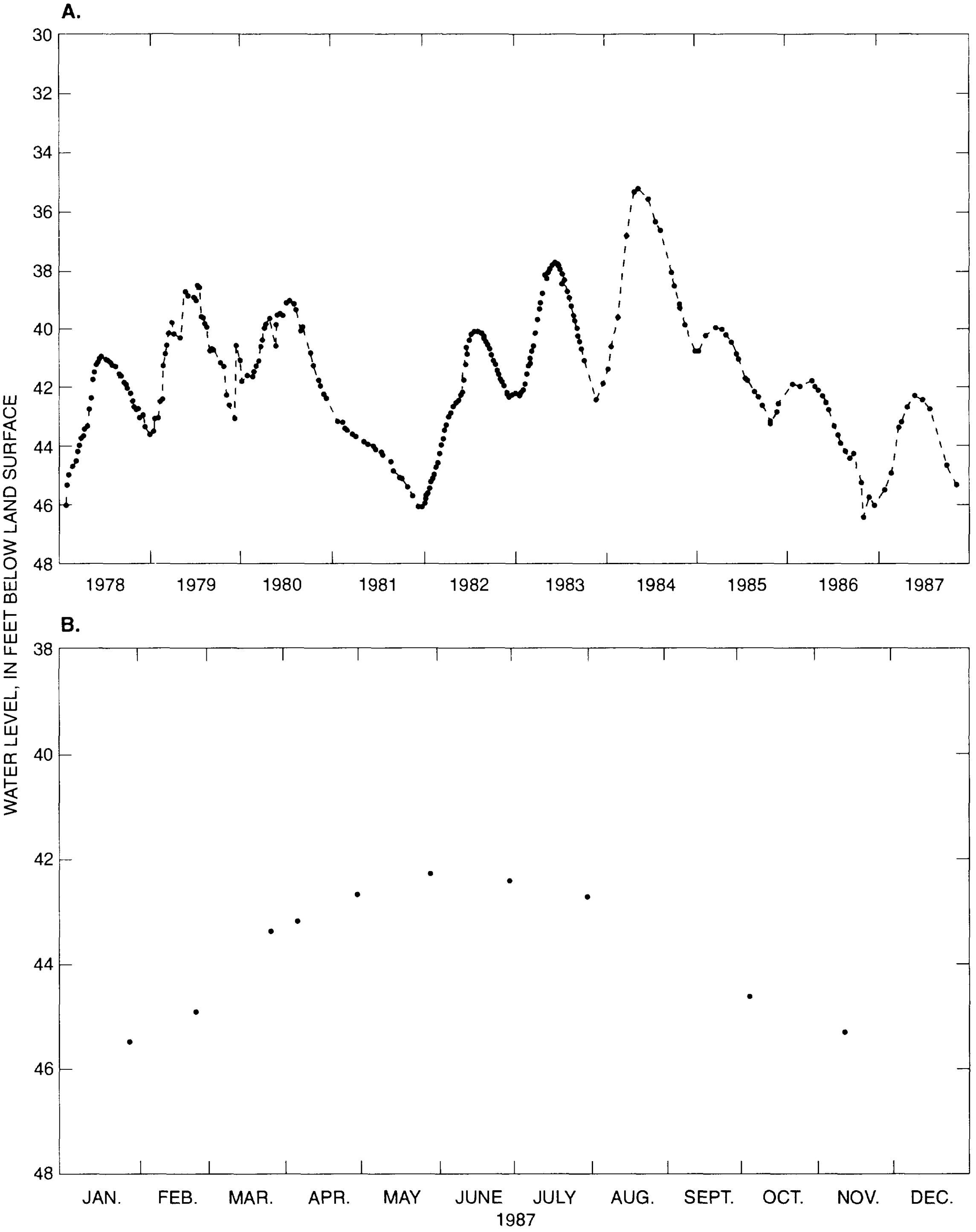


Figure 5. Water level in observation well NC-126, Orange County, N.C. (from Coble and others, 1989)--(A) decade hydrograph for the period 1978-87, and (B) annual hydrograph for the year 1987.

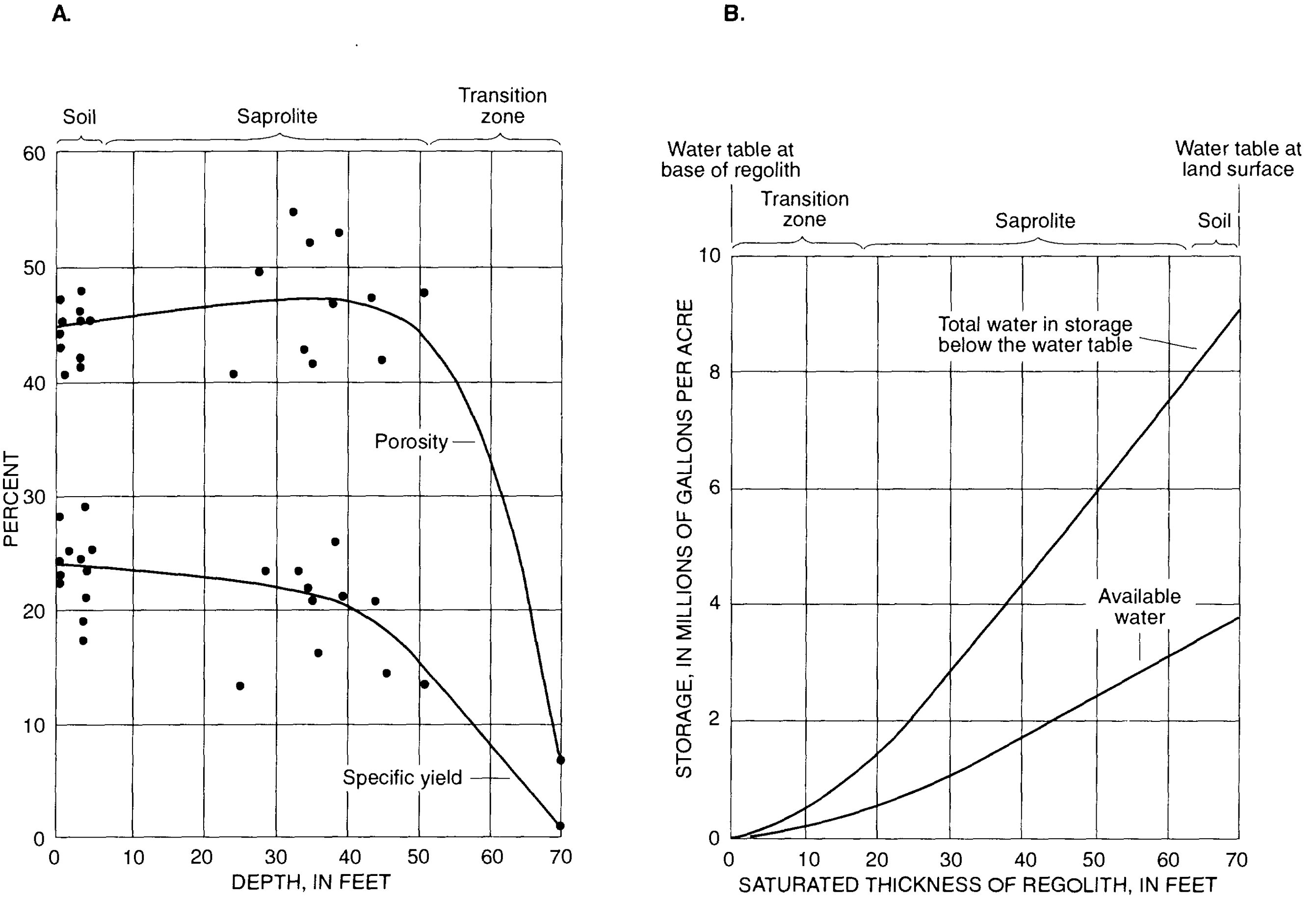


Figure 6. Relation of porosity and specific yield to total ground-water storage and available water in the regolith--(A) variation of porosity and specific yield with depth in the regolith (from Stewart, 1962), and (B) total ground water in storage below the water table and water available by gravity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

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 a 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 eastern Piedmont of North Carolina appears to be in the saprolite, as determined from water levels in bored and hand-dug wells (Mundorff, 1948; Bain, 1966; May and Thomas, 1968). 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 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:

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

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 eastern 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 de-watering of saprolite during a pumping test in a similar hydrogeologic setting in the central Piedmont of North Carolina 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 runoff 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 440 years of available streamflow record from gaging stations that measure streamflow within and from Orange 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 (base flow) and the percentages of time that specified estimates of recharge were equaled or exceeded. In a strict sense, the recharge-duration data apply only to the period for which data were used to develop the frequency distribution. If base flow during the period on which the duration table is based represents the long-term base flow of the stream, the curve may be considered a probability curve and used to estimate the percentage of time that a specified recharge will be equaled or exceeded in the future.

The duration data provide a convenient means for studying base-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

Seventeen gaging stations were selected to provide nearly complete coverage of streamflow conditions in Orange 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 17 stations represent all the continuous-record gaging stations that have been used to measure streamflow within or from Orange County. Twelve of the stations were active in 1995; data collection at five 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.

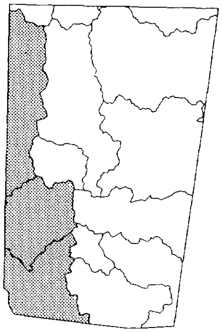
When multiple gaging stations occur along the same stream or within the same drainage system, the drainage basins defined by the gaging stations overlap. When periods of data collection at stations also overlap, it is possible to estimate the ground-water contribution to streamflow from the intervening 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. Using data from the 17 gaging stations, it was possible to analyze 12 basin and subbasin areas in Orange County. Drainage areas for the parts of the 12 basins and subbasins that lie within the boundaries of Orange 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 and hydrographs of monthly recharge estimates are presented to illustrate the seasonal variation in recharge during a water year. 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 12 basins and subbasins within the boundaries of Orange County, N.C.

[mi^2, square miles; --, unnumbered]

Site number (fig. 1)	River or stream name and extent of basin within Orange County	Drainage area (mi^2)
3	Haw River subbasin between station 02096500 at Haw River, N.C. (site 1, fig. 1), and station 02096960 near Bynum, N.C., excluding area of Cane Creek Basin upstream from station 02096850 near Teer, N.C., (site 7, fig. 1)	67.6
4	New Hope Creek Basin upstream from station 02097314 near Blands, N.C.	34.6
5	Morgan Creek Basin upstream from station 02097464 near White Cross, N.C.	8.35
6	Morgan Creek Basin upstream from station 02097517 near Chapel Hill, N.C., excluding area of Morgan Creek Basin upstream from station 02097464 near White Cross, N.C. (site 5, fig. 1)	29.3
7	Cane Creek Basin upstream from station 02096850 near Teer, N.C.	30.8
10	New Hope River subbasin between station 02097314 near Blands, N.C. (site 4, fig. 1), station 02097517 near Chapel Hill, N.C. (site 6, fig. 1), and station 02098000 near Pittsboro, N.C.	24.5
11	Sevenmile Creek Basin upstream from station 02084909 near Efland, N.C.	14.1
12	Eno River Basin upstream from station 02085000 at Hillsborough, N.C., excluding area of Sevenmile Creek Basin upstream from station 02084909 near Efland, N.C. (site 11, fig. 1)	51.9
13	Eno River subbasin between station 02085000 at Hillsborough, N.C. (site 12, fig. 1), and station 02085070 near Durham, N.C.	56.3
14	Little River Basin upstream from station 0208521324 at State Road 1461 near Orange Factory, N.C.	63.6
15	Flat River Basin upstream from station 02085500 at Bahama, N.C	10.5
17	Hyco Creek Basin upstream from station 02077200 near Leasburg, N.C.	4.09
--	Ungaged area on South Hyco Creek	5.52
	Total area in county	401.16



Haw River Subbasin

The Haw River subbasin is the 669-mi^2 part of the Haw River Basin that lies between gaging station 02096500 (site 1, fig. 1) at Haw River, N.C., and gaging station 02096960 (site 3, fig. 1) near Bynum, N.C. Tributaries to the Haw River, such as Back Creek, Haw Creek, Cane Creek, and Collins Creek, extend eastward from the Haw River and receive runoff from the western part of Orange County. The area of the Haw River subbasin within Orange County is 98.4 mi^2, or 25 percent of the land area of the county. Discharge records are available for Cane Creek; however, the recharge analysis for the Haw River subbasin includes the Cane Creek Basin area because the Haw River subbasin has a longer period of record, 67 years compared to 20 years for Cane Creek, and a larger drainage area, 669 mi^2 compared to 33.7 mi^2. An analysis of the Cane Creek Basin is presented separately.

Discharge records for gaging station 02097000 (site 8, fig. 1) near Pittsboro, N.C., and gaging station 02096960 (site 3, 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 0209700 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). Estimates of recharge at 02096500 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 4 and 5 and figure 7. Annually, estimated mean recharge in the Haw River subbasin is 4.15 in., or 311 (gal/d)/acre. The median recharge is 194 (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 Haw River subbasin between station 02096500 at Haw River, 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	4.15	1.63	1.39	9.45	37.0

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	67	97.2	0.00	767
Nov.	67	170	0.00	892
Dec.	67	303	2.43	1,050
Jan.	67	534	32.1	1,540
Feb.	67	675	69.9	1,800
Mar.	67	689	179	1,920
Apr.	67	522	16.3	1,280
May	67	284	37.5	1,090
June	67	159	6.18	748
July	67	135	0.00	482
Aug.	67	97.1	0.00	383
Sept.	67	65.4	0.00	395
All months	804	311	0.00	1,920

Table 5. Ground-water recharge duration statistics for the Haw River subbasin between station 02096500 at Haw River, 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	2,810						
1	1,530	26	439	51	187	76	49.1
2	1,260	27	426	52	177	77	44.3
3	1,140	28	414	53	170	78	40.1
4	1,050	29	401	54	164	79	35.7
5	983	30	387	55	156	80	31.6
6	932	31	376	56	150	81	27.8
7	888	32	365	57	143	82	23.9
8	844	33	355	58	137	83	18.9
9	805	34	345	59	132	84	14.8
10	775	35	334	60	126	85	10.1
11	748	36	322	61	121	86	6.20
12	724	37	311	62	116	87	1.76
13	695	38	300	63	112	88	0.00
14	669	39	289	64	107	89	0.00
15	641	40	280	65	102	90	0.00
16	617	41	270	66	97.0	91	0.00
17	594	42	261	67	92.3	92	0.00
18	573	43	251	68	87.6	93	0.00
19	553	44	243	69	82.4	94	0.00
20	535	45	235	70	77.1	95	0.00
21	518	46	227	71	71.9	96	0.00
22	503	47	219	72	67.1	97	0.00
23	487	48	211	73	62.0	98	0.00
24	471	49	203	74	57.5	99	0.00
25	455	50	194	75	53.2	100	0.00

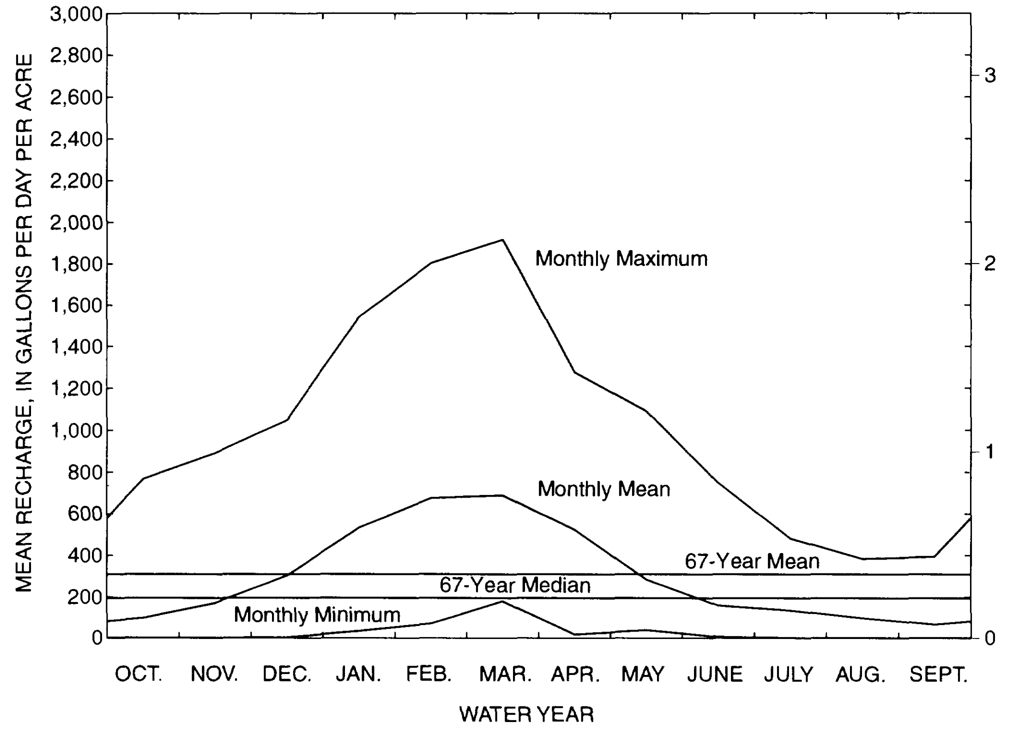
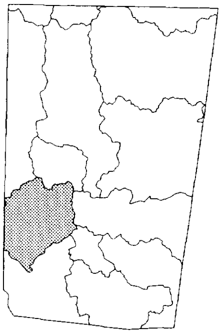


Figure 7. Variation of monthly mean ground-water recharge in the Haw River subbasin between station 02096500 at Haw River, N.C., and station 02096960 near Bynum, N.C.



Cane Creek Basin

The Cane Creek Basin is the 33.7-mi^2 area that lies upstream of gaging station 02096850 (site 7, fig. 1) near Teer, N.C. Cane Creek originates in the southwestern part of Orange County and flows in a southwesterly direction out of the county. Cane Creek is a tributary to the Haw River and lies within the Haw River subbasin. The area of the Cane Creek Basin within Orange County is 30.8 mi^2, or 8 percent of the land area of the county.

Discharge records for gaging station 02096850 (site 7, fig. 1) near Teer, N.C., and gaging station 02096846 (site 2, fig. 1) near Orange Grove, N.C., were analyzed by hydrograph separation and the daily estimates of recharge were combined to make a composite record for 20 water years of the period between 1960 and 1995. Station 02096850 was in operation for 14 water years from 1960 through 1973. Station 02096846 has been in operation since the 1990 water year (table 1). Estimates of recharge were determined for the basin area upstream from the station near Teer because the station at Teer has a longer period of record, 14 years compared to 6 years for the station near Orange Grove, and a larger drainage area, 33.7 mi^2 compared to 7.54 mi^2. The daily recharge estimates were further analyzed to produce the results presented in tables 6 and 7 and figure 8. Annually, estimated mean recharge in the Cane Creek Basin is 4.83 in., or 361 (gal/d)/acre. The median recharge is 235 (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 Cane Creek Basin upstream from station 02096850 near Teer, N.C.

[Analysis based on combined data from stations 02096846 and 02096850]

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
20	4.83	2.02	2.35	10.85	39.9

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	20	114	1.30	481
Nov.	20	202	12.6	716
Dec.	20	333	47.3	959
Jan.	20	585	168	1,220
Feb.	20	684	283	1,510
Mar.	20	879	444	2,580
Apr.	20	654	156	1,330
May	20	357	60.2	860
June	20	214	66.6	504
July	20	163	4.80	847
Aug.	20	91.8	12.4	338
Sept.	20	58.8	1.88	189
All months	240	361	1.30	2,580

Table 7. Ground-water recharge duration statistics for the Cane Creek Basin upstream from station 02096850 near Teer, N.C.

[Analysis based on combined data from stations 02096846 (site 2, fig. 1) and 02096850 (site 7, 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	4,730						
1	1,840	26	496	51	229	76	80.4
2	1,470	27	483	52	219	77	76.3
3	1,300	28	474	53	214	78	73.7
4	1,200	29	460	54	207	79	69.2
5	1,110	30	450	55	199	80	65.6
6	1,020	31	438	56	194	81	61.6
7	954	32	423	57	186	82	58.1
8	899	33	414	58	177	83	53.9
9	861	34	399	59	172	84	50.9
10	821	35	387	60	165	85	46.9
11	785	36	372	61	156	86	41.7
12	754	37	360	62	150	87	39.0
13	722	38	354	63	145	88	36.2
14	702	39	340	64	138	89	33.6
15	689	40	330	65	132	90	30.0
16	667	41	318	66	126	91	26.8
17	650	42	303	67	122	92	23.1
18	630	43	296	68	116	93	18.8
19	610	44	283	69	111	94	15.6
20	596	45	272	70	107	95	12.3
21	575	46	265	71	102	96	9.59
22	562	47	256	72	98.0	97	6.89
23	542	48	248	73	93.8	98	4.19
24	526	49	241	74	87.1	99	2.68
25	509	50	235	75	84.4	100	0.00

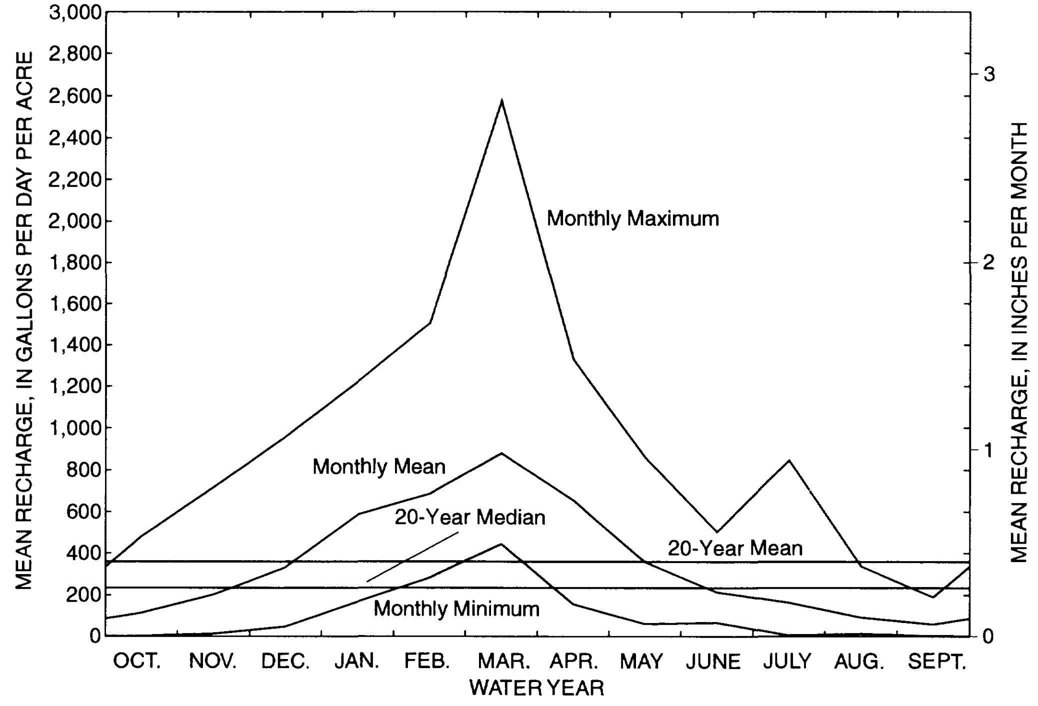
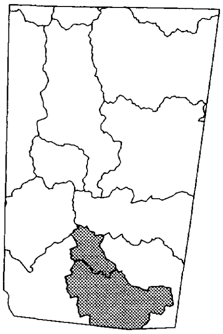


Figure 8. Variation of monthly mean ground-water recharge in the Cane Creek Basin upstream from station 02096850 near Teer, N.C.



Morgan Creek Basin Upstream from Chapel Hill, N.C.

The Morgan Creek Basin upstream from Chapel Hill, N.C., is the 41.0-mi^2 area that lies upstream from gaging station 02097517 (site 6, fig. 1) near Chapel Hill, N.C. Morgan Creek originates in the southern part of Orange County and flows in a southeasterly direction out of the county into Durham County. Morgan Creek eventually flows into Jordan Lake in northern Chatham County. The area of the Morgan Creek Basin within Orange County is 37.6 mi^2 or 9 percent of the land area of the county.

Discharge records for gaging station 02097517 (site 6, fig. 1) near Chapel Hill, N.C., and gaging station 02097500 (site 9, fig. 1), also near Chapel Hill, were analyzed by hydrograph separation, and the daily estimates of recharge were combined to make a composite record for 20 water years of the period between 1924 and 1995. Station 02097500 was in operation for 8 water years from 1924 through 1931. Station 02097517 has been in operation since the 1984 water year (table 1). Flow in Morgan Creek also is measured at gaging station 02097464 (site 5, fig. 1) near White Cross, N.C. No attempt was made to analyze recharge in the subbasin area between stations 02097464 and 02097517 because the area upstream from station 02097464 is small and, more importantly, the 6 years of record available from station 02097464 would have eliminated 14 additional years of data at stations 02097517 and 02097500 from the subbasin analysis. An analysis of the Morgan Creek Basin upstream from station 02097464 near White Cross is presented separately.

The recharge analysis for the Morgan Creek Basin upstream from Chapel Hill represents all of the drainage area upstream from station 02097517. The daily recharge estimates were further analyzed to produce the results presented in tables 8 and 9 and figure 9. The estimated mean annual recharge in the Morgan Creek Basin is 6.40 in., or 477 (gal/d)/acre. The estimated median recharge is 370 (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 Morgan Creek Basin upstream from station 02097517 near Chapel Hill, N.C.

[Analysis based on combined data from stations 02097517 and 02097500]

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
20	6.40	1.70	3.62	9.79	47.9

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	20	341	50.2	953
Nov.	20	383	99.4	847
Dec.	20	455	156	987
Jan.	20	643	320	1,380
Feb.	20	702	322	1,140
Mar.	20	844	350	2,000
Apr.	20	638	316	1,340
May	20	426	211	846
June	20	331	107	716
July	20	328	52.6	954
Aug.	20	314	45.0	740
Sept.	20	321	33.5	1,030
All months	240	477	33.5	2,000

Table 9. Ground-water recharge duration statistics for the Morgan Creek Basin upstream from station 02097517 near Chapel Hill, N.C.

[Analysis based on combined data from stations 02097517 (site 6, fig. 1) and 02097500 (site 9, 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	6,170						
1	1,930	26	567	51	369	76	288
2	1,580	27	555	52	369	77	282
3	1,390	28	542	53	361	78	275
4	1,240	29	537	54	353	79	271
5	1,120	30	521	55	345	80	271
6	1,030	31	509	56	345	81	263
7	965	32	498	57	345	82	254
8	925	33	492	58	345	83	246
9	883	34	480	59	337	84	241
10	862	35	470	60	334	85	225
11	828	36	468	61	328	86	209
12	805	37	453	62	322	87	197
13	773	38	443	63	320	88	187
14	745	39	436	64	320	89	176
15	731	40	426	65	320	90	164
16	709	41	419	66	320	91	148
17	689	42	407	67	315	92	135
18	670	43	403	68	311	93	127
19	651	44	395	69	305	94	118
20	637	45	395	70	301	95	105
21	616	46	394	71	296	96	83.9
22	610	47	390	72	296	97	67.4
23	595	48	382	73	296	98	53.7
24	585	49	374	74	296	99	40.3
25	571	50	370	75	295	100	0.0

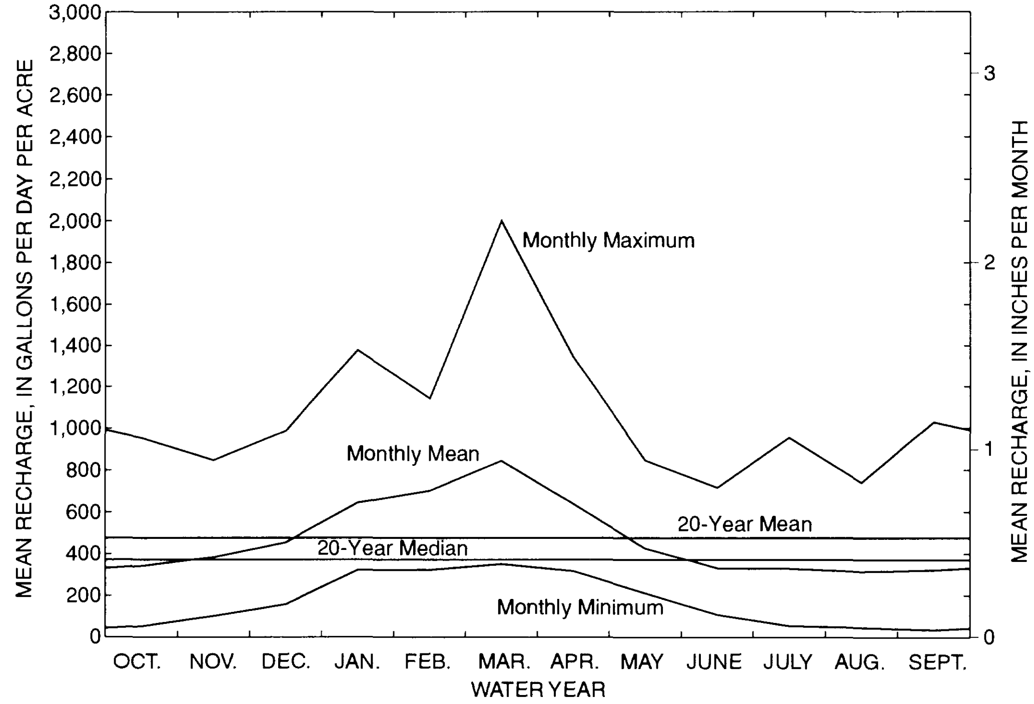
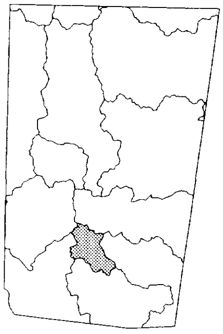


Figure 9. Variation of monthly mean ground-water recharge in the Morgan Creek Basin upstream from station 02097517 near Chapel Hill, N.C.



Morgan Creek Basin Upstream from White Cross, N.C.

The part of the Morgan Creek Basin that lies upstream from gaging station 02097464 (site 5, fig. 1) near White Cross, N.C., has a drainage area of 8.35 mi^2, or 2 percent of the land area of Orange County. Gaging station 02097464 is the most upstream station on Morgan Creek and measures flow from the rural headwaters of Morgan Creek. Station 02097464 has been in operation since the 1990 water year (table 1).

Discharge records for station 02097464 were analyzed by hydrograph separation to give estimates of recharge for the 6-year period between 1990 and 1995. The daily recharge estimates were further analyzed to produce the results presented in tables 10 and 11 and figure 10. Annually, estimated mean recharge in the Morgan Creek Basin upstream from station 02097464 near White Cross, N.C., is 5.72 in., or 427 (gal/d)/acre. The median recharge is 275 (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 Morgan Creek Basin upstream from station 02097464 near White Cross, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
6	5.72	2.48	3.58	10.48	44.4

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	6	164	48.6	559
Nov.	6	235	79.9	567
Dec.	6	373	84.3	889
Jan.	6	696	234	1,040
Feb.	6	735	403	1,580
Mar.	6	1,010	659	1,470
Apr.	6	778	256	1,520
May	6	448	100	1,140
June	6	286	94.3	489
July	6	193	32.1	504
Aug.	6	111	29.7	229
Sept.	6	95.2	7.70	248
All months	72	427	7.70	1,580

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Table 11. Ground-water recharge duration statistics for the Morgan Creek Basin upstream from station 02097464 near White Cross, 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	3,990						
1	1,920	26	577	51	265	76	88.3
2	1,690	27	566	52	250	77	84.7
3	1,560	28	555	53	241	78	82.2
4	1,460	29	544	54	230	79	78.6
5	1,350	30	527	55	218	80	76.2
6	1,320	31	509	56	210	81	75.0
7	1,210	32	493	57	206	82	72.6
8	1,170	33	484	58	197	83	68.9
9	1,100	34	472	59	194	84	64.1
10	1,050	35	461	60	184	85	59.3
11	994	36	448	61	179	86	53.2
12	943	37	431	62	171	87	48.4
13	883	38	420	63	169	88	43.5
14	841	39	404	64	160	89	39.9
15	822	40	393	65	157	90	36.3
16	801	41	381	66	148	91	33.9
17	786	42	369	67	140	92	31.4
18	764	43	356	68	134	93	29.0
19	738	44	345	69	127	94	27.8
20	704	45	337	70	121	95	25.4
21	677	46	327	71	115	96	20.6
22	652	47	312	72	109	97	18.1
23	631	48	299	73	104	98	10.9
24	617	49	285	74	98.0	99	7.26
25	594	50	275	75	93.1	100	2.42

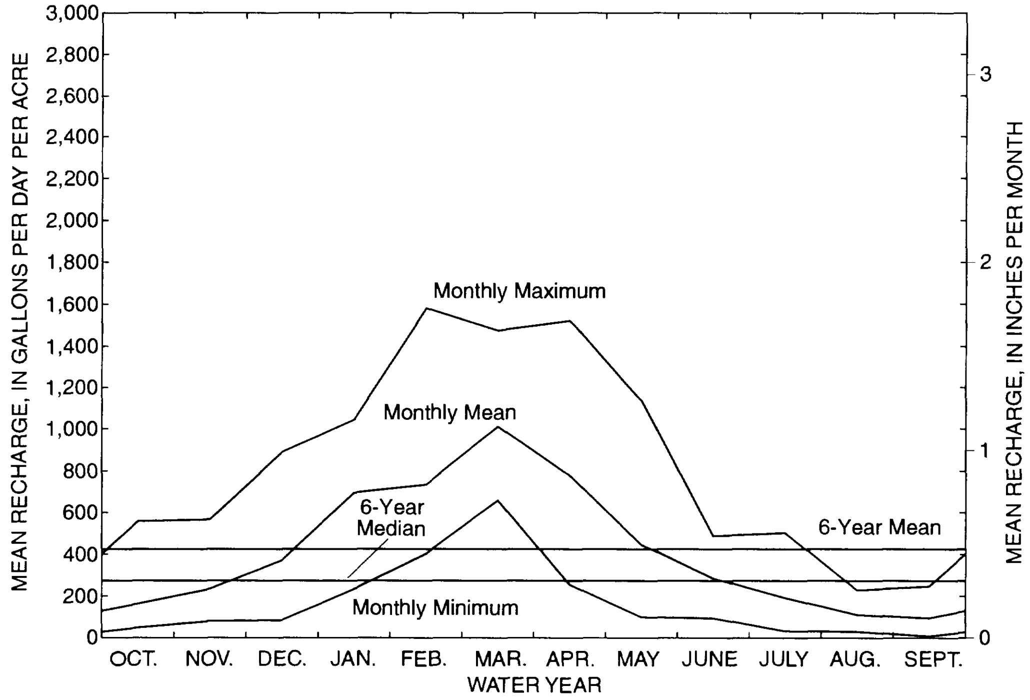
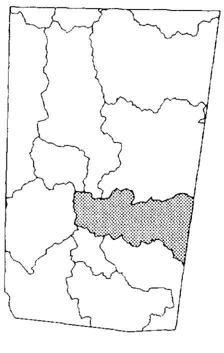


Figure 10. Variation of monthly mean ground-water recharge in the Morgan Creek Basin upstream from station 02097464 near White Cross, N.C.



New Hope Creek Basin

The New Hope Creek Basin is the 75.9-mi^2 area that lies upstream from gaging station 02097314 (site 4, fig. 1) near Blands, N.C. New Hope Creek originates in central Orange County between Hillsborough and Chapel Hill and flows in an east-southeasterly direction into southern Durham County where it turns and flows to the south. New Hope Creek flows into Jordan Lake near the Durham-Chatham County line. The area of the New Hope Creek Basin within Orange County is 34.6 mi^2, or 9 percent of the land area of the county. Station 02097314 has been in operation since the 1983 water year (table 1).

Discharge records for gaging station 02097314 (site 4, fig. 1) were analyzed by hydrograph separation to produce daily estimates of recharge for the 13-year period between 1983 and 1995. A wastewater-treatment plant (operated by the City of Durham) discharges treated wastewater into New Hope Creek upstream from the gaging station. This water was diverted from the Neuse River Basin for Durham's municipal water supply; therefore, the wastewater discharges were subtracted from total streamflow before conducting the hydrograph separation. During the water years from 1983 through 1995, annual average wastewater discharges ranged from 5.2 ft^3/s to 15.2 ft^3/s. The average wastewater discharge for the 13-year period was 11.4 ft^3/s.

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 New Hope Creek Basin is 4.51 in., or 339 (gal/d)/acre. The median recharge is 147 (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 New Hope Creek Basin upstream from station 02097314 near Blands, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
13	4.51	1.53	1.82	7.16	37.8

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	13	52.6	0.00	175
Nov.	13	174	0.00	751
Dec.	13	267	0.00	638
Jan.	13	706	118	1,950
Feb.	13	849	433	1,530
Mar.	13	895	182	1,990
Apr.	13	513	20.4	1,190
May	13	232	54.2	761
June	13	136	7.51	465
July	13	101	0.00	297
Aug.	13	74.7	0.00	191
Sept.	13	63.5	0.00	202
All months	156	339	0.00	1,990

Table 13. Ground-water recharge duration statistics for the New Hope Creek Basin upstream from station 02097314 near Blands, N.C.

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
Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time							
0	7,680						
1	2,090	26	425	51	140	76	37.4
2	1,630	27	402	52	135	77	34.6
3	1,480	28	383	53	130	78	31.9
4	1,360	29	361	54	125	79	28.1
5	1,250	30	344	55	118	80	26.6
6	1,160	31	332	56	111	81	23.2
7	1,100	32	317	57	107	82	18.8
8	1,030	33	306	58	101	83	16.1
9	978	34	295	59	98.1	84	13.4
10	930	35	285	60	93.5	85	11.6
11	885	36	276	61	88.9	86	6.79
12	837	37	264	62	85.0	87	4.12
13	783	38	253	63	81.2	88	0.00
14	731	39	242	64	77.2	89	0.00
15	698	40	232	65	72.3	90	0.00
16	666	41	223	66	68.0	91	0.00
17	634	42	214	67	64.3	92	0.00
18	601	43	202	68	61.9	93	0.00
19	573	44	193	69	58.7	94	0.00
20	554	45	183	70	55.9	95	0.00
21	532	46	173	71	53.0	96	0.00
22	512	47	166	72	50.6	97	0.00
23	495	48	161	73	46.7	98	0.00
24	468	49	153	74	44.4	99	0.00
25	446	50	147	75	41.5	100	0.00

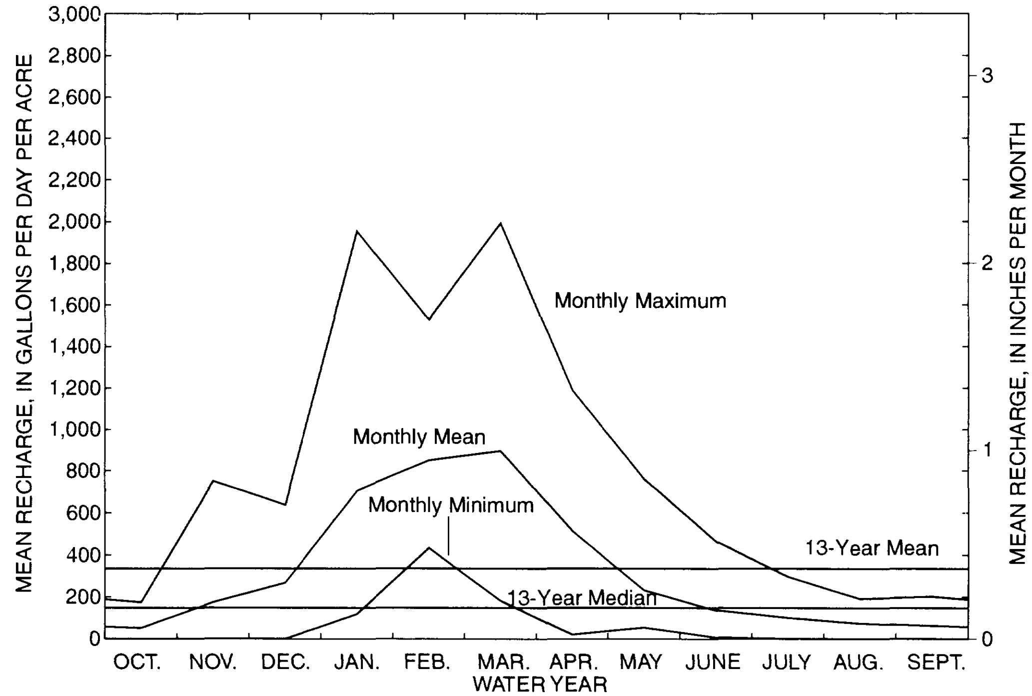
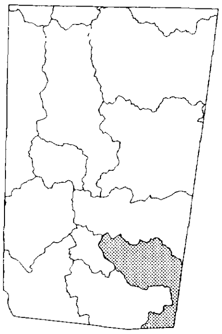


Figure 11. Variation of monthly mean ground-water recharge in the New Hope Creek Basin upstream from station 02097314 near Blands, N.C.



New Hope River Subbasin

The New Hope River subbasin is the 168-mi^2 part of the New Hope River Basin that lies between gaging station 02097517 (site 6, fig. 1) near Chapel Hill, N.C., gaging station 02097314 (site 4, fig. 1) near Blands, N.C., and the former site of gaging station 02098000 (site 10, fig. 1) near Pittsboro, N.C. The area of the New Hope River subbasin in Orange County is 24.5 mi^2, or 6 percent of the land area of the county. Station 02098000 was in operation for 24 water years from 1950 through 1973 (table 1). The station was discontinued in 1973 because of flooding caused by backwater from the partially closed B. Everett Jordan Dam which was under construction. The site of the station, which is now beneath Jordan Lake, is immediately north of the new U.S. Highway 64 causeway.

The recharge analysis for the New Hope River subbasin required a different approach from other subbasin analyses because discharge data from gaging stations 02097517 and 02097314 do not overlap the 24-year period from 1950 through 1973 when station 02098000 was in operation (table 1). Overlapping data are available only for stations 02097517 and 02097314 during the 12 water years from 1984 through 1995. By ranking annual discharges at the three stations, wet, average, and dry years could be identified and matched. Some data for stations 02097517 and 02097314 were duplicated in order to compile 24 years of record. Discharge records from the three stations were analyzed by hydrograph separation to obtain daily estimates of recharge. Estimates of recharge for stations 02097517 and 02097314 were subtracted, on a daily basis, from estimates of recharge for station 02098000 to produce 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 14 and 15 and figure 12. Annually, estimated mean recharge in the New Hope River subbasin is 4.32 in., or 324 (gal/d)/acre. The median recharge is 80.7 (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 New Hope River subbasin between station 02097314 near Blands, N.C., station 02097517 near Chapel Hill, N.C., and station 02098000 near Pittsboro, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
24	4.32	3.26	1.55	16.50	32.2

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	24	125	0.00	1,680
Nov.	24	164	0.00	1,770
Dec.	24	349	0.00	2,110
Jan.	24	471	0.00	2,270
Feb.	24	871	110	2,940
Mar.	24	687	0.00	2,580
Apr.	24	562	0.86	2,130
May	24	305	0.00	1,690
June	24	89.3	0.00	389
July	24	131	0.00	1,140
Aug.	24	81.6	0.00	365
Sept.	24	57.7	0.00	348
All months	288	324	0.00	2,940

Table 15. Ground-water recharge duration statistics for the New Hope River subbasin between station 02097314 near Blands, N.C., station 02097517 near Chapel Hill, N.C., and station 02098000 near Pittsboro, 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	6,590						
1	3,230	26	305	51	77.0	76	0.00
2	2,450	27	285	52	73.6	77	0.00
3	2,050	28	271	53	70.0	78	0.00
4	1,780	29	255	54	66.2	79	0.00
5	1,490	30	240	55	62.6	80	0.00
6	1,330	31	225	56	57.4	81	0.00
7	1,200	32	212	57	52.7	82	0.00
8	1,070	33	198	58	48.9	83	0.00
9	979	34	188	59	45.1	84	0.00
10	908	35	179	60	41.5	85	0.00
11	852	36	166	61	37.7	86	0.00
12	787	37	156	62	33.9	87	0.00
13	720	38	148	63	28.9	88	0.00
14	676	39	139	64	25.1	89	0.00
15	642	40	130	65	21.3	90	0.00
16	606	41	125	66	18.3	91	0.00
17	570	42	120	67	15.7	92	0.00
18	531	43	113	68	12.9	93	0.00
19	501	44	106	69	10.4	94	0.00
20	473	45	100	70	7.05	95	0.00
21	437	46	96.5	71	3.95	96	0.00
22	405	47	93.8	72	1.41	97	0.00
23	372	48	89.2	73	0.00	98	0.00
24	347	49	84.9	74	0.00	99	0.00
25	328	50	80.7	75	0.00	100	0.00

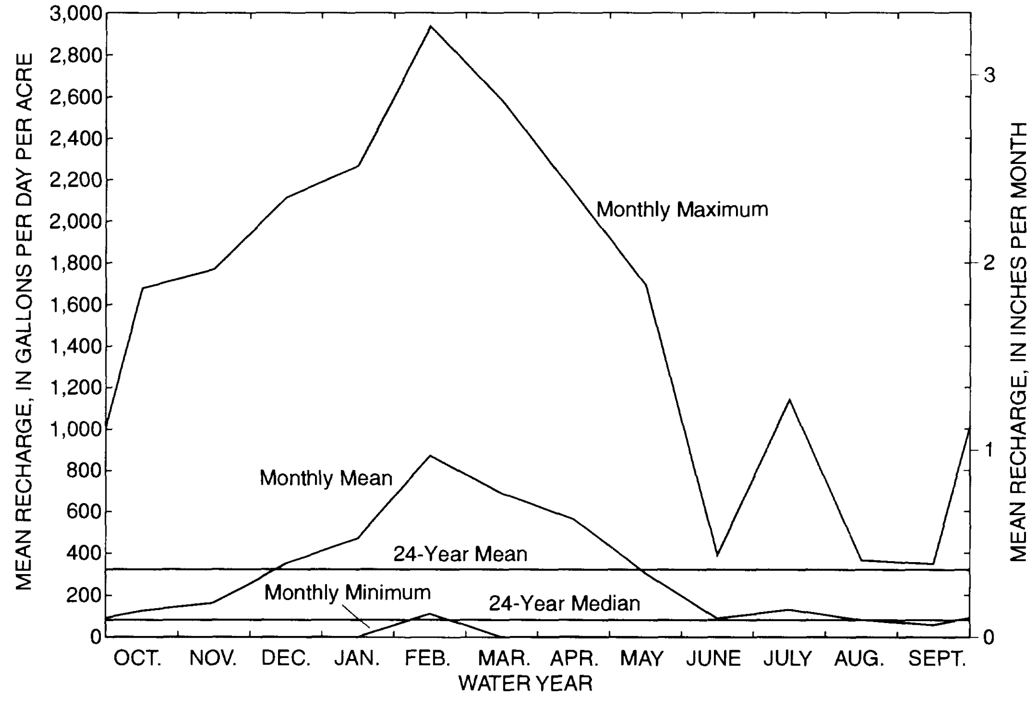
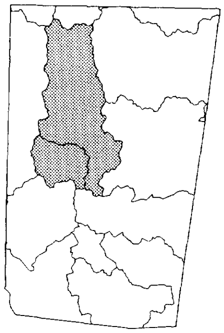


Figure 12. Variation of monthly mean ground-water recharge in the New Hope River subbasin between station 02097314 near Blands, N.C., station 02097517 near Chapel Hill, N.C., and station 02098000 near Pittsboro, N.C.



Eno River Basin Upstream from Hillsborough, N.C.

The part of the Eno River Basin that lies upstream from gaging station 02085000 (site 12, fig. 1) at Hillsborough, N.C., has a drainage area of 66.0 mi^2 or 16 percent of the land area of Orange County. The Eno River originates in northwestern Orange County and flows in a southerly direction to a point just west of Hillsborough where it turns to the east. The Eno River then flows through the southern part of Hillsborough as it continues on its way eastward toward the Durham County line. Discharge records are available for Sevenmile Creek, a tributary of the Eno River that joins the Eno west of Hillsborough; however, the recharge analysis for the Eno River Basin includes the area of the Sevenmile Creek Basin because the Eno River Basin has a longer period of record, 54 years compared to 8 years for Sevenmile Creek, and a larger drainage area, 66.0 mi^2 compared to 14.1 mi^2. An analysis of the Sevenmile Creek Basin is presented separately.

Discharge records for gaging station 02085000 were analyzed by hydrograph separation and daily estimates of recharge were generated for 54 water years in the period between 1928 and 1995. Station 02085000 was in operation for 44 water years from 1928 through 1971 (table 1). Measurements at the gage were discontinued in 1971. The station was reactivated at the beginning of the 1986 water year and has been in operation since that time.

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 Eno River Basin is 5.32 in., or 399 (gal/d)/acre. The median recharge is 291 (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 Eno River Basin upstream from station 02085000 at Hillsborough, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
54	5.32	1.87	2.06	8.98	42.6

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	54	152	2.54	582
Nov.	54	236	11.2	769
Dec.	54	395	32.8	1,250
Jan.	54	608	58.0	1,690
Feb.	54	782	109	1,630
Mar.	53	785	365	1,510
Apr.	54	696	179	1,640
May	54	408	75.1	1,110
June	54	263	11.2	1,430
July	54	181	2.38	679
Aug.	54	159	4.20	593
Sept.	54	130	2.25	853
All months	647	399	2.25	1,690

Table 17. Ground-water recharge duration statistics for the Eno River Basin upstream from station 02085000 at Hillsborough, 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	6,920						
1	1,710	26	547	51	281	76	117
2	1,460	27	533	52	275	77	110
3	1,320	28	520	53	268	78	104
4	1,210	29	505	54	260	79	98.5
5	1,130	30	492	55	253	80	93.6
6	1,070	31	478	56	245	81	88.9
7	1,010	32	466	57	241	82	83.9
8	958	33	457	58	231	83	78.2
9	907	34	444	59	230	84	72.5
10	869	35	429	60	221	85	68.2
11	839	36	415	61	214	86	64.4
12	809	37	403	62	209	87	61.2
13	780	38	393	63	199	88	56.6
14	756	39	383	64	194	89	52.2
15	732	40	371	65	185	90	48.5
16	707	41	362	66	182	91	43.8
17	687	42	352	67	174	92	38.3
18	668	43	346	68	168	93	33.7
19	652	44	337	69	164	94	29.4
20	634	45	329	70	155	95	24.5
21	619	46	321	71	152	96	18.4
22	602	47	311	72	145	97	10.7
23	589	48	306	73	138	98	6.43
24	574	49	297	74	131	99	3.21
25	559	50	291	75	124	100	0.31

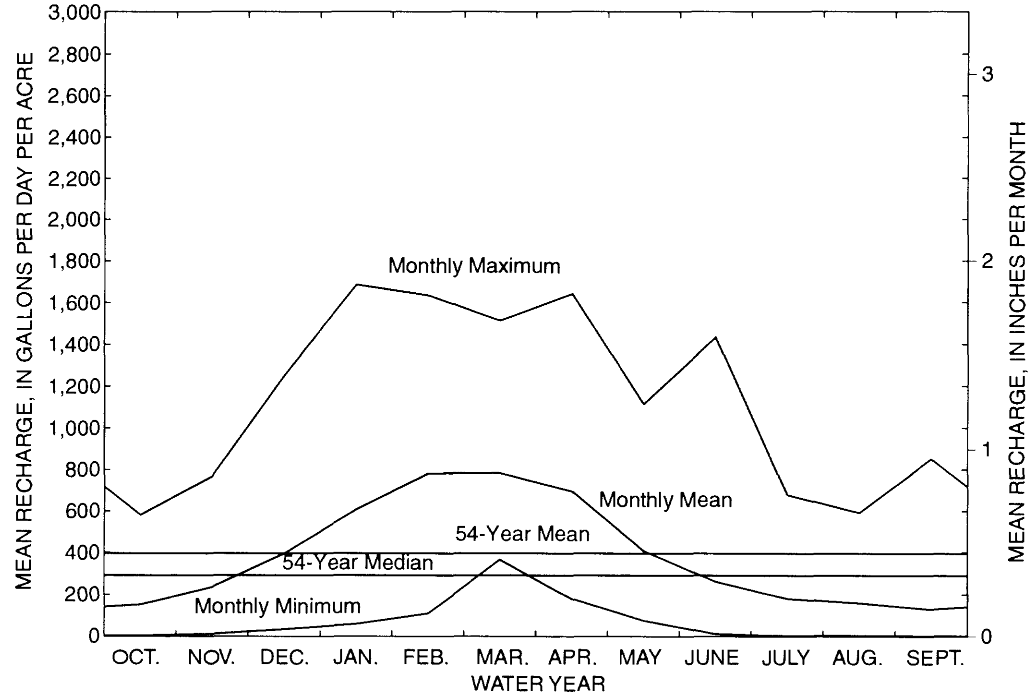
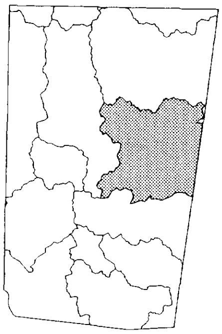


Figure 13. Variation of monthly mean ground-water recharge in the Eno River Basin upstream from station 02085000 at Hillsborough, N.C.



Eno River Subbasin

The Eno River subbasin is the 75.0-mi^2 part of the Eno River Basin that lies between gaging station 02085000 (site 12, fig. 1) at Hillsborough, N.C., and gaging station 02085070 (site 13, fig. 1) near Durham, N.C. The Eno River originates in northwestern Orange County and flows in a southerly direction to a point just west of Hillsborough where it turns to the east. The Eno River then flows through the southern part of Hillsborough as it flows on an eastward course toward Durham County. The Eno River continues its eastward course across central Durham County until it joins the Neuse River northeast of Durham near the Durham-Granville County line. The area of the Eno River subbasin within Orange County is about 56.3 mi^2, or 14 percent of the land area of the county.

Discharge records for gaging station 02085000 (site 12, fig. 1) at Hillsborough, N.C., and gaging station 02085070 (site 13, fig. 1) near Durham, N.C., were analyzed by hydrograph separation, and daily estimates of recharge were generated for 18 water years of the period between 1964 and 1995. Station 02085000 was in operation for 44 water years from 1928 through 1971 (table 1). Measurements at the station were discontinued in 1971. The station was reactivated at the beginning of the 1986 water year and has been in operation since that time. Gaging station 02085070 has operated continuously since the 1964 water year. Estimates of recharge at 02085000 were subtracted, on a daily basis, from the record for the Eno River at Durham for the period between 1964 and 1971 and the period between 1986 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 18 and 19 and figure 14. Annually, estimated mean recharge in the Eno River subbasin is 4.55 in., or 341 (gal/d)/acre. The estimated median recharge is 220 (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 Eno River subbasin between station 02085000 at Hillsborough, N.C., and station 02085070 near Durham, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
18	4.55	1.68	2.28	8.11	41.7

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	18	72.0	6.97	229
Nov.	18	141	33.4	397
Dec.	18	270	101	582
Jan.	18	538	198	1,370
Feb.	18	679	272	1,470
Mar.	18	766	355	2,170
Apr.	18	628	240	1,340
May	18	407	115	1,260
June	18	215	42.7	582
July	18	159	20.4	981
Aug.	18	114	0.55	524
Sept.	18	99.8	1.32	221
All months	216	341	0.55	2,170

Table 19. Ground-water recharge duration statistics for the Eno River subbasin between station 02085000 at Hillsborough, N.C., and station 02085070 near Durham, 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	4,160						
1	2,140	26	458	51	213	76	77.6
2	1,610	27	444	52	206	77	71.4
3	1,280	28	431	53	199	78	67.2
4	1,120	29	415	54	191	79	62.7
5	993	30	402	55	185	80	59.2
6	911	31	390	56	177	81	55.1
7	862	32	377	57	171	82	51.4
8	809	33	365	58	164	83	48.5
9	768	34	355	59	161	84	45.9
10	730	35	345	60	154	85	42.6
11	697	36	336	61	148	86	39.7
12	671	37	326	62	143	87	36.1
13	648	38	317	63	138	88	32.3
14	633	39	310	64	132	89	29.5
15	619	40	299	65	127	90	26.3
16	604	41	290	66	121	91	24.2
17	583	42	283	67	118	92	20.6
18	566	43	274	68	113	93	16.7
19	546	44	269	69	109	94	14.0
20	531	45	261	70	106	95	12.1
21	518	46	253	71	103	96	8.35
22	505	47	244	72	97.9	97	6.46
23	492	48	234	73	93.9	98	0.00
24	479	49	228	74	87.8	99	0.00
25	471	50	220	75	82.8	100	0.00

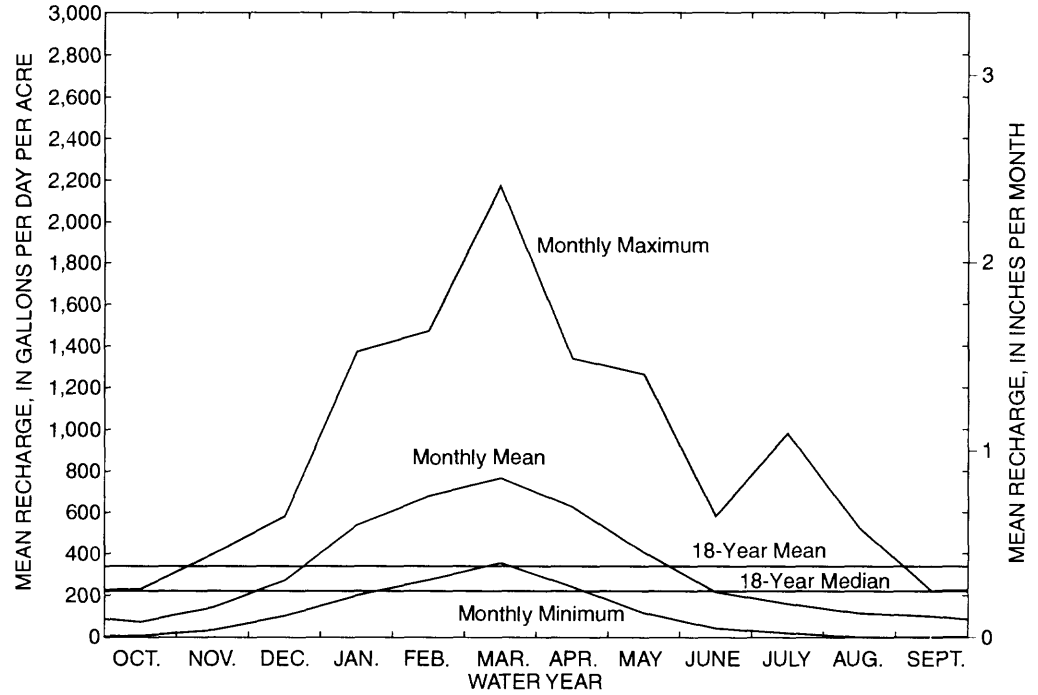
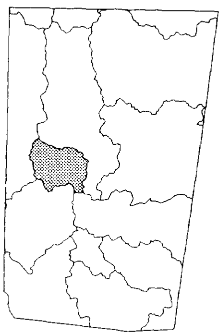


Figure 14. Variation of monthly mean ground-water recharge in the Eno River subbasin between station 02085000 at Hillsborough, N.C., and station 02085070 near Durham, N.C.



Sevenmile Creek Basin

The Sevenmile Creek Basin is the 14.1-mi^2 area that lies upstream from gaging station 02084909 (site 11, fig. 1) near Efland, N.C. Sevenmile Creek originates on the eastern flank of the Haw River-Eno River drainage divide in west-central Orange County; it flows in an easterly direction until it joins the Eno River just west of Hillsborough, N.C. Sevenmile Creek lies within the part of the Eno River Basin upstream from gaging station 02085000 (site 12, fig. 1) at Hillsborough that was described in a previous section. The area within the Sevenmile Creek Basin upstream from station 02084909 is 4 percent of the land area of the county. Station 02084909 has been in operation since the 1988 water year (table 1).

Discharge records for gaging station 02084909 were analyzed by hydrograph separation to give daily estimates of recharge for the 8-year period between 1988 and 1995. The daily recharge estimates were further analyzed to produce the results presented in tables 20 and 21 and figure 15. Annually, estimated mean recharge in the Sevenmile Creek Basin is 4.92 in., or 367 (gal/d)/acre. The median recharge is 253 (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 Sevenmile Creek Basin upstream from station 02084909 near Efland, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
8	4.92	2.16	2.14	7.83	40.6

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	8	137	4.97	419
Nov.	8	228	69.8	644
Dec.	8	337	33.2	775
Jan.	8	728	112	1,700
Feb.	8	599	228	1,150
Mar.	8	817	275	1,400
Apr.	8	597	25.7	1,230
May	8	391	4.02	987
June	8	230	18.2	482
July	8	161	11.0	464
Aug.	8	116	0.65	418
Sept.	8	63.6	1.48	200
All months	96	367	0.65	1,700

Table 21. Ground-water recharge duration statistics for the Sevenmile Creek Basin upstream from station 02084909 near Efland, N.C.

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
Recharge, in gallons per day per acre, that was equaled or exceeded for indicated percentage of time							
0	3,580						
1	1,810	26	501	51	245	76	55.9
2	1,560	27	488	52	233	77	51.6
3	1,380	28	476	53	226	78	48.0
4	1,290	29	461	54	216	79	43.7
5	1,180	30	452	55	203	80	41.5
6	1,070	31	444	56	196	81	37.2
7	1,000	32	429	57	188	82	33.7
8	940	33	417	58	179	83	30.8
9	911	34	406	59	171	84	27.9
10	875	35	397	60	160	85	25.8
11	860	36	387	61	156	86	22.2
12	823	37	375	62	145	87	17.9
13	789	38	366	63	133	88	15.8
14	761	39	355	64	125	89	13.6
15	718	40	345	65	118	90	11.5
16	696	41	333	66	113	91	10.0
17	673	42	322	67	107	92	8.60
18	653	43	311	68	98.8	93	7.16
19	630	44	301	69	93.1	94	5.73
20	608	45	284	70	86.7	95	5.01
21	589	46	277	71	80.9	96	4.30
22	570	47	271	72	77.4	97	3.58
23	551	48	263	73	70.9	98	1.43
24	536	49	258	74	65.9	99	0.00
25	516	50	253	75	60.2	100	0.00

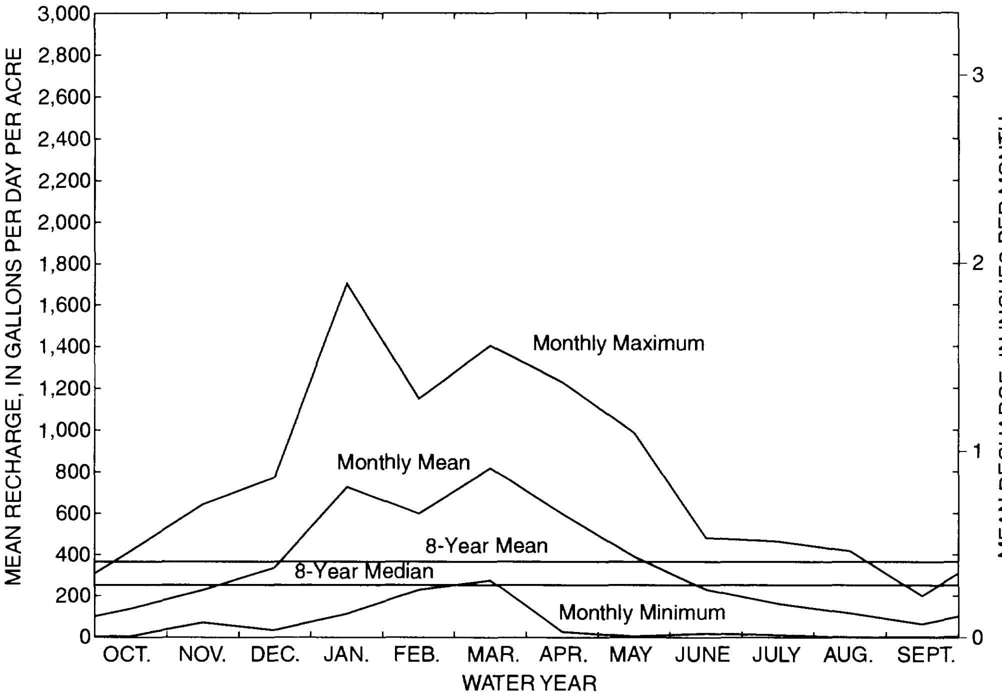
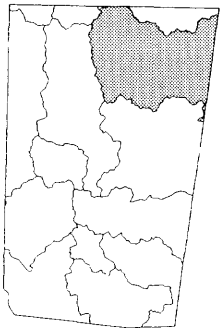


Figure 15. Variation of monthly mean ground-water recharge in the Sevenmile Creek Basin upstream from station 02084909 near Efland, N.C.



Little River Basin

The Little River Basin is the 78.2-mi^2 area that lies upstream from gaging station 0208521324 (site 14, fig. 1) at State Road 1461 near Orange Factory, N.C. Little River originates in the north-central part of Orange County and flows in an east-southeasterly direction into northern Durham County where it joins the Eno River north of Durham, N.C. The area of the Little River Basin within Orange County is 63.6 mi^2, or 16 percent of the land area of the county.

Discharge records for gaging station 0208521324 (site 14, fig. 1) at State Road 1461 near Orange Factory, N.C., and gaging station 02085220 (site 16, fig. 1) near Orange Factory, N.C., were analyzed by hydrograph separation, and the daily estimates of recharge were combined to make a composite record spanning 34 water years from 1962 to 1995. Station 02085220 was discontinued in 1987 and replaced by 0208521324 the same year. 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 Little River Basin is 4.70 in., or 352 (gal/d)/acre. The median recharge is 226 (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 Little River Basin upstream from station 0208521324 at State Road 1461 near Orange Factory, N.C.

[Analysis based on combined data from stations 0208521324 and 02085220]

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
34	4.70	1.82	1.73	9.04	39.2

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	34	100	1.32	647
Nov.	34	176	7.26	758
Dec.	34	329	75.3	948
Jan.	34	609	116	1,310
Feb.	34	701	197	1,310
March	34	786	222	1,540
April	34	593	208	1,280
May	34	367	68.7	782
June	34	222	51.8	599
July	34	140	9.01	481
Aug.	34	119	1.34	398
Sept.	34	77.1	1.71	331
All months	408	352	1.32	1,540

Table 23. Ground-water recharge duration statistics for the Little River Basin upstream from station 0208521324 at State Road 1461 near Orange Factory, N.C.

[Analysis based on combined data from stations 0208521324 (site 14, fig. 1) and 02085220 (site 16, 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	3,820						
1	1,610	26	496	51	221	76	82.5
2	1,340	27	482	52	214	77	78.5
3	1,220	28	467	53	207	78	75.5
4	1,130	29	455	54	201	79	71.2
5	1,070	30	441	55	194	80	66.8
6	1,010	31	427	56	188	81	64.9
7	956	32	411	57	181	82	60.3
8	915	33	394	58	175	83	56.6
9	867	34	380	59	167	84	52.5
10	824	35	365	60	162	85	48.6
11	788	36	353	61	155	86	44.0
12	762	37	342	62	151	87	40.1
13	742	38	335	63	144	88	35.8
14	720	39	327	64	138	89	31.0
15	694	40	317	65	133	90	27.4
16	669	41	305	66	126	91	24.6
17	648	42	294	67	122	92	21.6
18	624	43	284	68	117	93	17.7
19	607	44	276	69	112	94	15.1
20	588	45	264	70	106	95	12.4
21	571	46	255	71	102	96	9.04
22	553	47	248	72	98.0	97	6.53
23	540	48	240	73	95.3	98	3.89
24	525	49	234	74	90.8	99	1.81
25	509	50	226	75	86.0	100	0.00

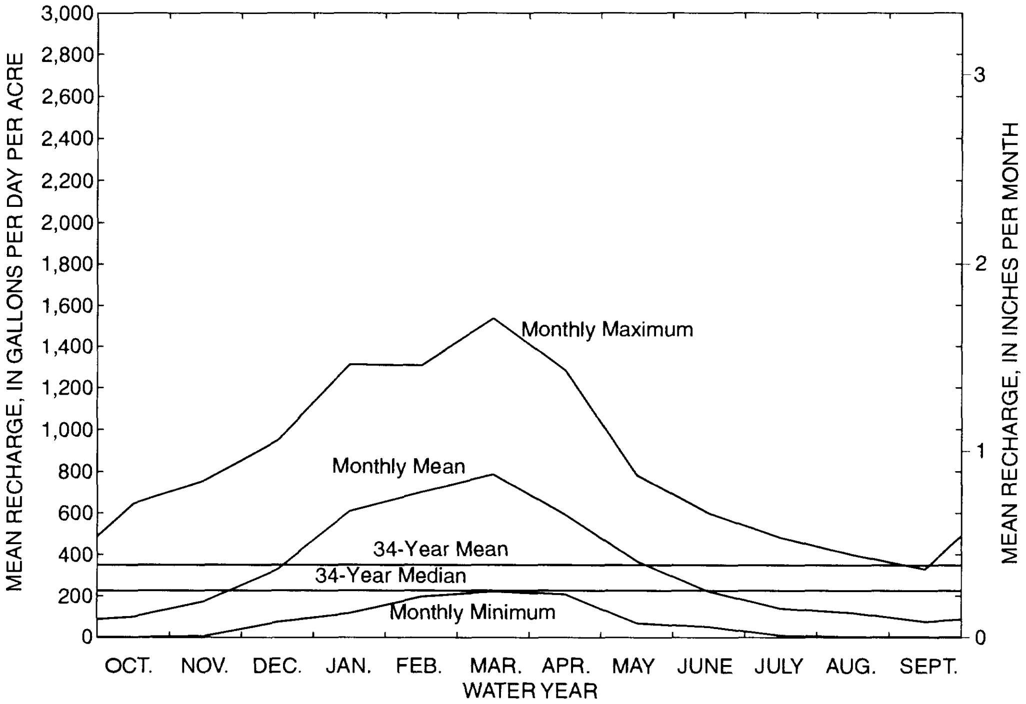
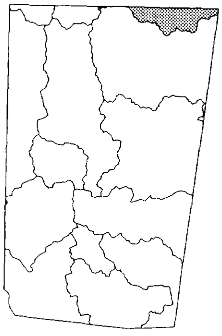


Figure 16. Variation of monthly mean ground-water recharge in the Little River Basin upstream from station 0208521324 near Orange Factory, N.C.



Flat River Basin

The Flat River Basin is the 149-mi^2 area that lies upstream from gaging station 02085500 (site 15, fig. 1) at Bahama, N.C. Most of the Flat River Basin lies within Person County. Tributaries to the South Flat River that originate in the northeast corner of Orange County flow north and northeast into Person County where they join the South Flat River. The South Flat River flows in an easterly direction across southern Person County; it joins the North Flat River in southeastern Person County to form the Flat River, which flows in a southeasterly direction into Durham County. The area of the Flat River Basin within Orange County is 10.5 mi^2, or 3 percent of the land area of the county. Station 02085500 has been in operation since the 1926 water year (table 1).

Discharge records for station 02085500 were analyzed by hydrograph separation to give estimates of daily recharge for the 70-year period between 1926 and 1995. The daily recharge estimates were further analyzed to produce the results presented in tables 24 and 25 and figure 17. Annually, estimated mean recharge in the Little River Basin upstream of station 02085500 at Bahama, N.C., is 4.63 in., or 347 (gal/d)/acre. The median recharge is 230 (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 Flat River Basin upstream from station 02085500 at Bahama, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
70	4.63	1.67	1.64	9.65	36.7

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	70	107	6.52	567
Nov.	70	189	4.43	990
Dec.	70	324	9.48	1,060
Jan.	70	557	24.1	1,430
Feb.	70	718	76.6	1,580
Mar.	70	760	251	1,800
Apr.	70	610	153	1,540
May	70	334	101	1,080
June	70	194	49.4	451
July	70	147	11.2	573
Aug.	70	129	7.63	490
Sept.	70	91.2	4.44	333
All months	840	347	4.43	1,800

Table 25. Ground-water recharge duration statistics for the Flat River Basin upstream from station 02085500 at Bahama, 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	3,860						
1	1,690	26	461	51	224	76	85.3
2	1,410	27	447	52	217	77	81.3
3	1,260	28	434	53	210	78	77.1
4	1,160	29	421	54	203	79	74.6
5	1,070	30	412	55	197	80	69.4
6	994	31	399	56	190	81	66.5
7	941	32	386	57	183	82	63.6
8	889	33	376	58	177	83	59.4
9	840	34	365	59	172	84	55.4
10	797	35	355	60	164	85	52.2
11	767	36	345	61	160	86	49.5
12	735	37	336	62	154	87	45.9
13	707	38	325	63	148	88	42.7
14	683	39	315	64	142	89	39.1
15	656	40	306	65	136	90	35.9
16	630	41	298	66	131	91	31.4
17	609	42	289	67	127	92	27.5
18	590	43	281	68	122	93	24.0
19	568	44	272	69	116	94	21.0
20	550	45	264	70	112	95	17.8
21	533	46	258	71	108	96	14.8
22	517	47	251	72	102	97	11.5
23	503	48	244	73	98.3	98	8.13
24	488	49	237	74	94.7	99	5.49
25	475	50	230	75	88.9	100	1.83

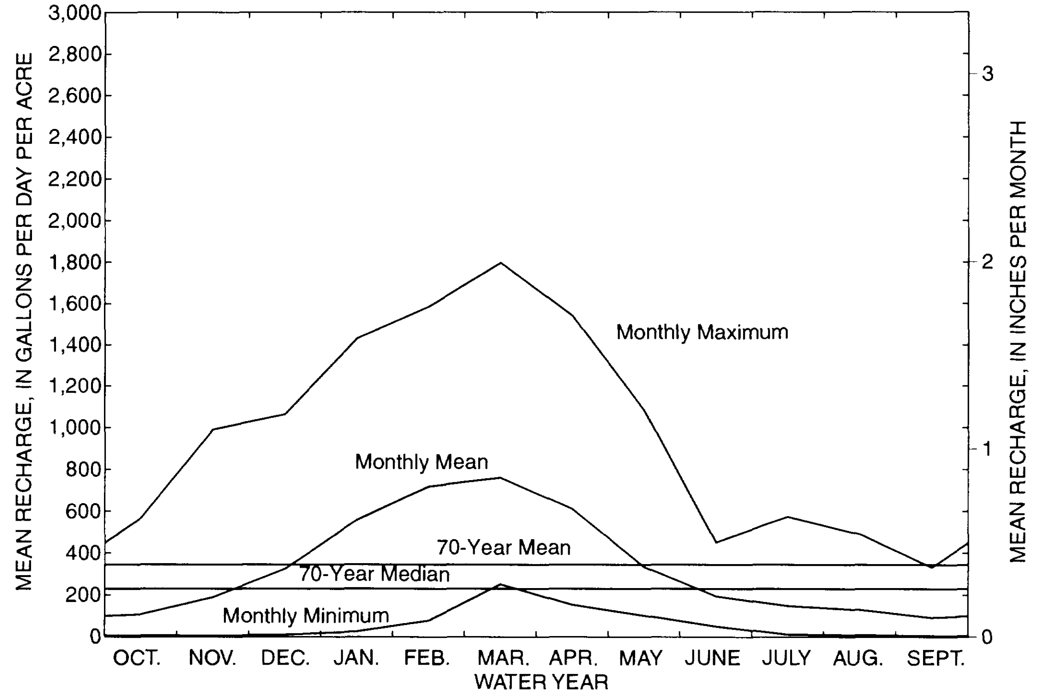
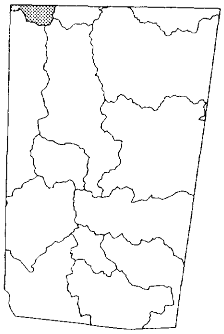


Figure 17. Variation of monthly mean ground-water recharge in the Flat River Basin upstream from station 02085500 at Bahama, N.C.



Hyco Creek Basin

The Hyco Creek Basin is the 45.9-mi^2 area that lies upstream from gaging station 02077200 (site 17, fig. 1) near Leasburg, N.C. Tributaries to Hyco Creek that originate in the northwest corner of Orange County flow northwest into Caswell County where they join Hyco Creek. The area of the Hyco Creek Basin within Orange County is 4.09 mi^2, or 1 percent of the land area of the county. Station 02077200 has been in operation since the 1965 water year (table 1).

Discharge records for station 02077200 were analyzed by hydrograph separation to give estimates of daily recharge for the 31-year period between 1965 and 1995. The daily recharge estimates were further analyzed to produce the results presented in tables 26 and 27 and figure 18. Annually, estimated mean recharge in the Hyco Creek Basin upstream of station 02077200 near Leasburg, N.C., is 4.71 in., or 353 (gal/d)/acre. The median recharge is 207 (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 Hyco Creek Basin upstream from station 02077200 near Leasburg, N.C.

A. Annual recharge, in inches per year

Number of years	Mean	Standard deviation	Minimum	Maximum	Percent of total runoff
31	4.71	1.63	1.64	8.60	36.7

B. Monthly recharge, in gallons per day per acre

Month	Number of months	Mean	Minimum	Maximum
Oct.	31	103	0.00	498
Nov.	31	204	36.2	940
Dec.	31	415	87.5	1,110
Jan.	31	700	102	1,550
Feb.	31	780	343	1,530
Mar.	31	808	337	1,650
Apr.	31	539	166	1,210
May	31	307	47.8	987
June	31	154	23.4	460
July	31	101	1.17	497
Aug.	31	70.5	0.21	435
Sept.	31	50.4	0.00	206
All months	372	353	0.00	1,650

Table 27. Ground-water recharge duration statistics for the Hyco Creek Basin upstream from station 02077200 near Leasburg, 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	4,620						
1	1,830	26	504	51	196	76	55.7
2	1,420	27	488	52	186	77	52.4
3	1,280	28	476	53	176	78	48.6
4	1,190	29	462	54	167	79	46.0
5	1,130	30	445	55	159	80	41.8
6	1,070	31	430	56	151	81	37.4
7	1,010	32	417	57	145	82	33.7
8	968	33	397	58	138	83	29.7
9	924	34	391	59	132	84	26.4
10	885	35	374	60	127	85	23.1
11	837	36	364	61	121	86	19.8
12	795	37	352	62	114	87	17.2
13	763	38	340	63	109	88	14.1
14	733	39	330	64	103	89	11.2
15	706	40	318	65	98.6	90	8.14
16	683	41	308	66	93.9	91	5.50
17	660	42	295	67	89.8	92	3.74
18	642	43	286	68	85.4	93	2.42
19	625	44	272	69	81.2	94	1.32
20	604	45	264	70	77.0	95	0.44
21	585	46	250	71	73.7	96	0.00
22	569	47	242	72	70.4	97	0.00
23	549	48	225	73	67.1	98	0.00
24	529	49	216	74	63.6	99	0.00
25	516	50	207	75	60.1	100	0.00

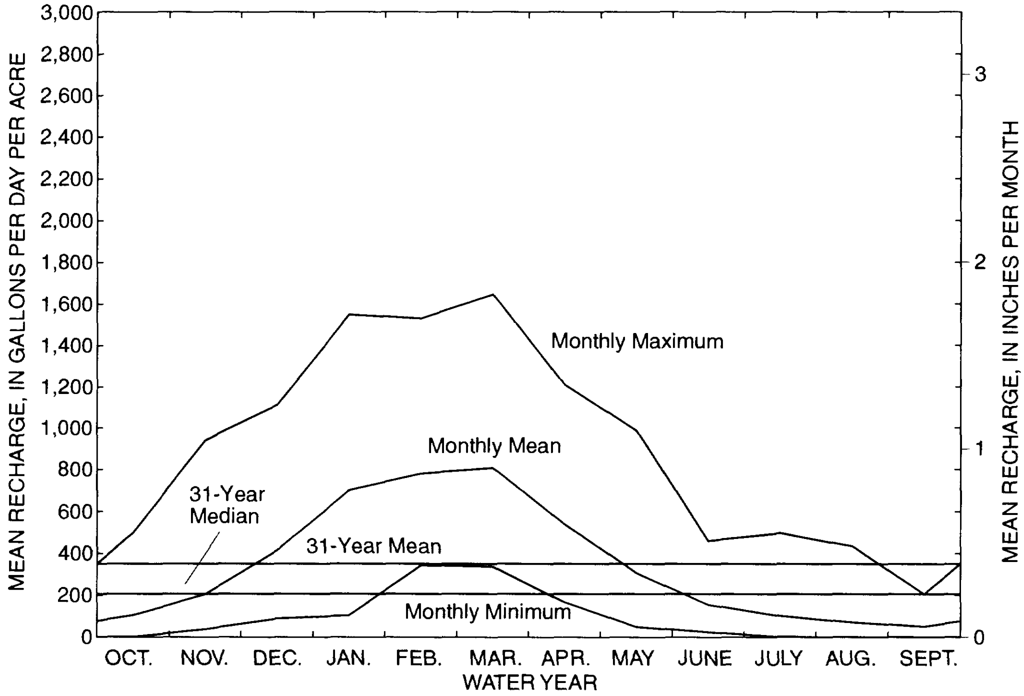


Figure 18. Variation of monthly mean ground-water recharge in the Hyco Creek Basin upstream from station 02077200 near Leasburg, N.C.

Comparison of Basins

Ground-water recharge in 12 Orange County drainage basins and subbasins is compared in figure 19. The box plots summarize the recharge duration characteristics of the 12 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 12 drainage basins and subbasins ranges from 4.15 in/yr (311 (gal/d)/acre) in the Haw River subbasin to 6.40 in/yr (477 (gal/d)/acre) in the Morgan Creek Basin upstream from Chapel Hill. The mean recharge for the 12 basins is 4.90 in/yr (365 (gal/d)/acre). If the two Morgan Creek Basins (basins upstream from sites 5 and 6) are not considered in the comparison, the range of recharges is reduced almost by half from 2.25 in/yr to 1.17 in/yr. The highest mean recharge in the 10 remaining basins is 5.32 in/yr (399 (gal/d)/acre) in the Eno River Basin upstream from Hillsborough.

Median ground-water recharge (recharge that will be equaled or exceeded 50-percent of the time) in the 12 drainage basins and subbasins ranges from 1.08 in/yr (80.7 (gal/d)/acre) in the New Hope River subbasin to 4.97 in/yr (370 (gal/d)/acre) in the Morgan Creek Basin upstream from Chapel Hill. The median recharge for the 12 basins is 3.06 in/yr (228 (gal/d)/acre).

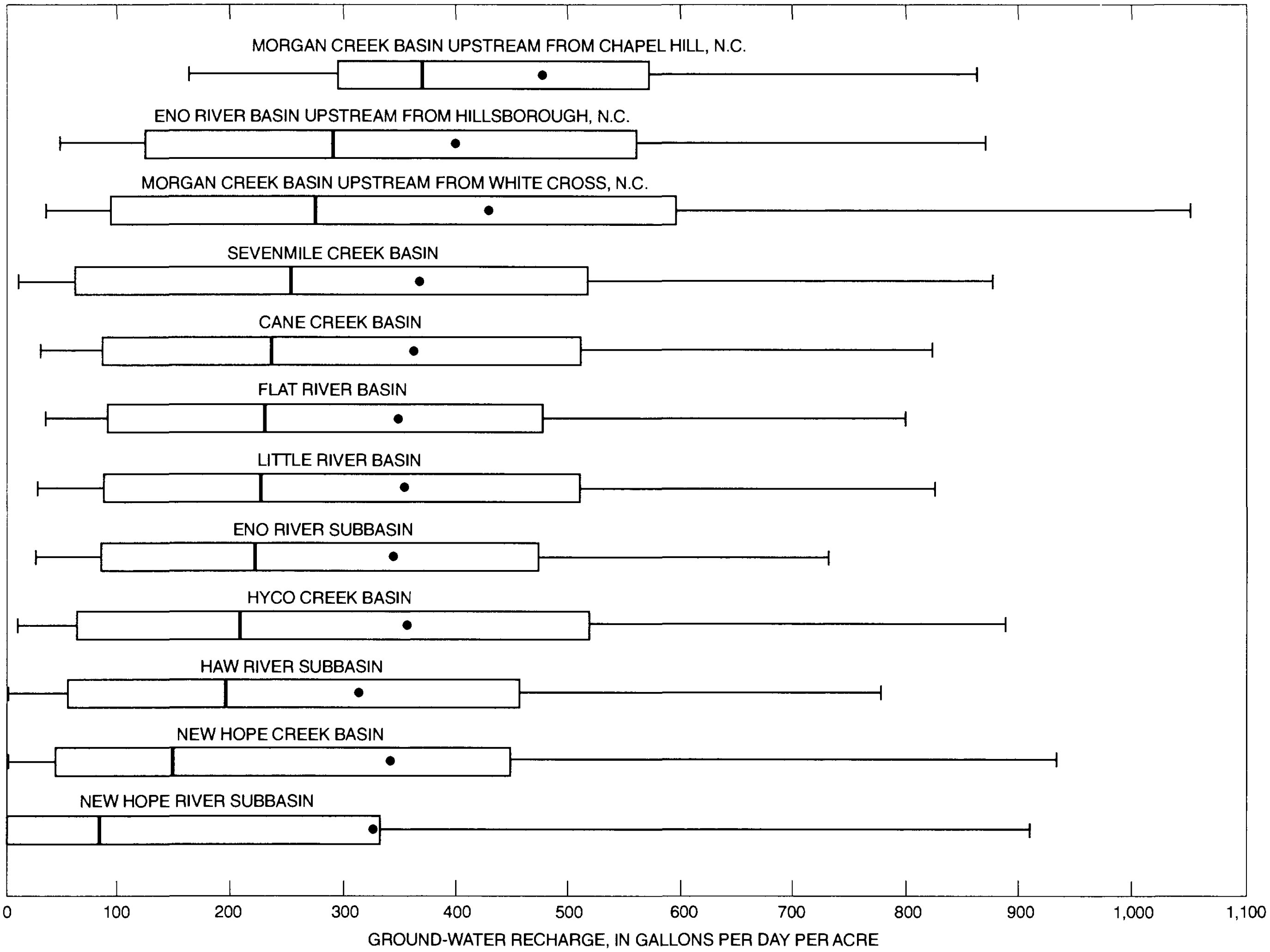
Correlations between recharge rates and hydrogeologic units (and derived regolith) are not immediately apparent. None of the basins that were studied are sufficiently small to characterize recharge rates according to individual hydrogeologic units. All 12 basins and subbasins contain multiple hydrogeologic units in varying proportions. 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 Orange County is underlain by hydrogeologic units consisting of metamorphic rocks of several types, although MVF (metavolcanic, felsic), MIF (metaigneous, felsic) and MVI (metavolcanic, intermediate) predominate (table 2; fig. 4). The fact that more than half (62 percent) of the county is underlain by metavolcanic rocks which have similar weathering properties may explain the narrow range in recharge rates among most basins and subbasins.

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.

Topography and depth of channel incision may explain the high recharge estimates (base-flow rates) in the Morgan Creek Basin. Some of the highest relief in the county occurs east and southeast of Chapel Hill where streams cross the margin of the Triassic basin. The more resistant metavolcanic and metaigneous rocks west and northwest of the basin margin stand as much as 100 to 300 ft higher than the more easily eroded sedimentary rocks in the Triassic basin. Thus, the stream is more deeply incised into the aquifer system as it approaches the Triassic basin downstream. Several of the larger areas of the MIF (metaigneous, felsic) hydrogeologic unit also occur in the southeastern part of the county, including the Morgan Creek Basin. This unit tends to weather deeply and produce a deep, sandy, porous regolith with high infiltration capacity. The presence of large areas of regolith derived from the MIF unit may magnify the effects of topographic relief and channel incision.

Data from several sites in the Morgan Creek, Cane Creek, and Eno River Basins will help illustrate the effect of topography on recharge estimates. Each of these basins is entirely underlain by hydrogeologic units of metavolcanic and metaigneous origin. In table 28, sites within each basin are presented in order of



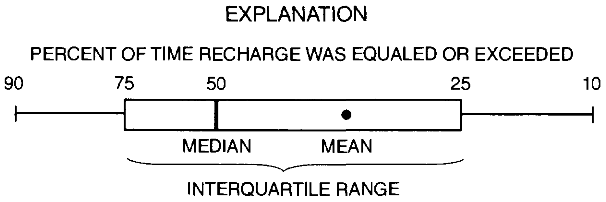


Figure 19. Box plots showing selected ground-water recharge duration characteristics and mean recharge in 12 basins and subbasins in Orange County, N.C.

topographic setting beginning with the most upstream site, or in the case of the Eno River Basin, the site with the shortest stream distance from the drainage divide. The estimates of recharge are for the entire drainage basin upstream from each site without combination with, or subtraction of, the record of any upstream site. For example, data for sites 6 and 9 were combined for the analysis of recharge in the Morgan Creek Basin upstream from Chapel Hill (tables 8 and 9). However, in this discussion, results for sites 6 and 9 are considered separately.

Table 28. Estimates of mean annual recharge at selected sites in three basins that illustrate the relation between recharge and topographic setting

[See figure 1 for basin and site locations]

Basin	Upstream sites		Downstream sites
	Increasing stream incision--------->		
A. Morgan Creek Basin	Site 5	Site 9	Site 6
Mean recharge, in/yr:	5.72	6.21	6.52
B. Cane Creek Basin	Site 2	Site 7	
Mean recharge, in/yr:	4.28	5.07	
C. Eno River Basin	Site 11	Site 12	Site 13
Mean recharge, in/yr:	4.92	5.32	5.03

In the Morgan Creek Basin, mean annual recharge increases in the downstream direction. At site 5 near White Cross, the basin is almost entirely rural and the stream is not deeply incised. At site 9 the stream is deeply incised, and at site 6 it is still deeply incised. A short distance east of site 6, which is very near the margin of the Triassic basin, Morgan Creek flows into a region of gentle topography and low-gradient streams typical of much of the Triassic basin. The same pattern of increasing recharge estimates (base flow) can be seen in the Cane Creek Basin and Eno River Basin downstream to site 12 at Hillsborough. The recharge estimate at site 13 near Durham is slightly lower than the estimate at site 12, but it is higher than the most upstream site (site 11, Sevenmile Creek near Efland). The presence of the Chapel Hill wastewater-treatment plant upstream from site 6 on Morgan Creek might be cause for questions about the accuracy of the recharge estimate at site 6; however, streamflow was measured at site 9 during the 1924 through 1931 water years, prior to the construction of University Lake and to the construction of a wastewater-treatment plant on Morgan Creek. Recharge estimates for site 9 are higher than for other sites in Orange County and fall between estimates for sites 5 and 6; thus, the three sites on Morgan Creek fit a consistent pattern. Ground water also constitutes a higher percentage of total streamflow in Morgan Creek than in any other stream in the county.

The relation between hydrogeologic units and ground-water recharge is perhaps most apparent in the New Hope River subbasin. The New Hope River subbasin between sites 4, 6, and 10 (fig. 1) lies almost entirely within the Triassic basin. Sedimentary rocks of Triassic age (hydrogeologic unit TRI) underlie a narrow strip of land in the southeastern corner of Orange County (fig. 4), but Triassic sediments occur beneath much of southern Durham County, eastern Chatham County, and western Wake County as far east as Cary, N.C. (fig. 1). The New Hope River subbasin has the second lowest estimate of mean annual recharge (4.32 in/yr, 324 (gal/d)/acre) and the lowest median recharge (1.08 in/yr, 80.7 (gal/d)/acre). Base flow, as a percentage of total streamflow, at 32.2 percent, is the lowest of the 12 basins and subbasins. These data suggest that in the Triassic basin 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 low estimates of ground-water recharge in the New Hope River subbasin may be due to the analytical technique used for this one basin (see the discussion of the "New Hope River Subbasin," page 32); however, recharge estimates for the New Hope Creek Basin, which is underlain by TRI in the eastern half of the basin, are similarly low. These results also are consistent with the work of Daniel (1989; 1990a) and Daniel and Payne (1990) that concluded that well yields in the Triassic basins of the eastern Piedmont of North Carolina were the lowest yields of all hydrogeologic units in the Piedmont and Blue Ridge Provinces of North Carolina.

Because so much of the New Hope River subbasin is underlain by hydrogeologic unit TRI, it is possible that recharge estimates for the Bolin Creek part of the subbasin are low. It is likely that recharge in the Bolin Creek area, which is underlain by hydrogeologic units of metaigneous and metavolcanic origin, is closer to estimates for the Morgan Creek Basin.

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 by-products 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 north-central Piedmont, including Orange County (Mundorff, 1948; 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 limit of availability, or is actually projected to reach the limit based on estimated 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 at 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 Orange 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 Orange 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 vary 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 mean 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 Cane Creek Basin upstream from gaging station 02096850 near Teer, N.C. (site 7, fig. 1). The mean annual recharge for 20 years of record is 4.83 in/yr, or 361 (gal/d)/acre (table 6). 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 Orange 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:

$$\text{demand} / \text{recharge} = \text{recharge area, or} \tag{4}$$

$$(400 \text{ gal/d}) / (361 \text{ (gal/d)/acre}) = 1.108 \text{ acres}$$

One acre is 43,560 ft^2, and 1.108 acres is 48,266 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 51,666 ft^2, or about 1.19 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 pre-development rate of recharge per homesite, the recharge area in the example would have to be increased from 1.108 acres to 2.577 acres. Including the impervious area of the house, garage, and driveway, the minimum land area for the example housing unit would be about 2.66 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 Cane 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 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. 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, Cane Creek Basin upstream from gaging station 02096850 near Teer, 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 Cane Creek Basin (table 7) indicates that recharge will satisfy this level of demand only about 15 percent of the time. For 85 percent of the time, or about 10.2 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 361 (gal/d)/acre indicates that average recharge on 37 acres (the surface area of one cone of depression) is 13,357 gal/d. To produce 25,200 gal/d, the well will have to extract, on average, 11,843 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 is available from 37 acres under equilibrium pumping conditions. On average, an additional 2,872 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, mean annual recharge of 361 (gal/d)/acre on the surface of the cone of depression is 13,357 gal/d. At a pumping rate of 35 gal/min, this amount of water can be extracted in 6.4 hours. Inspection of table 7 indicates that recharge will satisfy a demand of 361 gallons per minute 37 percent of the time. Water in long-term storage will have to satisfy part of the demand 63 percent of the time, or about 230 days a year (7.4 months). Inspection of figure 8 indicates that these months will most likely be October, November December, June, July, August, and September. Integration of the duration data (table 7) for the lower 63 percent of recharge indicates that recharge during this period will total about 39,000 gallons per year per acre [(gal/yr)/acre] or 170 (gal/d)/acre. Recharge during the remaining 37 percent of the year, or 135 days, will total about 93,000 (gal/yr)/acre, or 688 (gal/d)/acre. For 37 percent of the year, recharge will exceed the pumping rate by an average 327 (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 230 days of below-average recharge, long-term storage will supply about 191 (gal/d)/acre of the total 361 (gal/d)/acre to be pumped. The total for the 37 acres will be 7,067 gal/d from long-term storage. This is well below the 14,237 gal/d (for 230 days) estimated to be available under equilibrium pumping conditions. In this example, pumping at 35 gal/min for 6.4 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 6.4 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 6.4 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 6.4 hours per day, total production will be 13,440 gal/d. In this example, this will supply 34 housing units. If the housing units are clustered on 0.5-acre lots, the housing area will require 17 acres, and the entire development will cover 91 acres. The average area per housing unit (for the entire development) is 2.68 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 Orange County ranges from 32.2 to 47.9 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.

It is important to note that withdrawal of ground-water on a large scale will cause a reduction in streamflows 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, 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 Orange 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 light industry in Orange 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 Orange 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.

Orange County covers approximately 401 mi^2 in the eastern part of the Piedmont Province. The population of the county in 1990 was about 93,850; approximately 41 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 most of the county. Typical bedrock lithologies include granite, diorite, slate, tuff, and schist. Ground water also is obtained from sedimentary rocks of Triassic age that occur in a small area in southeastern Orange County.

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 17 gaging stations that measure streamflow within or from Orange County were analyzed to produce daily estimates of ground-water recharge in 12 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 12 basins and subbasins ranges from 4.15 to 6.40 in/yr, with a mean value of 4.90 in/yr for all basins. In general, recharge rates are highest for basins along a north-south zone extending down the center of the county and lowest in the western and southeastern parts of the county. Median recharge rates in the 12 basins range from 1.08 in/yr (80.7 (gal/d)/acre) to 4.97 in/yr (370 (gal/d)/acre), with a median value of 3.06 in/yr (228 (gal/d)/acre) for all basins.

Recharge estimates for the Morgan Creek Basin upstream from White Cross and upstream from Chapel Hill are higher than any other basin or subbasin in Orange County. Ground water also constitutes a higher percentage of total streamflow in Morgan Creek (44.4 percent upstream from White Cross; 47.9 percent upstream from Chapel Hill) than in any other stream in the county. Greater topographic relief and depth of channel incision may explain the high recharge estimates (base-flow rates) in the Morgan Creek Basin. The presence of large areas of regolith derived from the MIF (metaigneous, felsic) hydrogeologic unit may magnify the effects of topographic relief and channel incision. Base flow in the New Hope River subbasin, as a percentage of total streamflow, at 32.2 percent, is the lowest of the 12 basins and subbasins.

Much of the New Hope River subbasin is underlain by the TRI (Triassic sedimentary rocks) hydrogeologic unit that occurs within a rift basin of Triassic age. These data suggest that in areas underlain by TRI 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.

Recharge duration statistics also were determined for the same 12 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 mean 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 Cane Creek Basin and mean annual recharge is 361 (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 1.19 acres. In the second example, the community water system requires 74 acres for the capture area and will supply 34 housing units. If the housing units are clustered on 0.5-acre lots, the housing area will require 17 acres, and the entire development will cover 91 acres. In the second example, the average area per housing unit (for the entire development) is 2.68 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.

There is considerable ground water available in Orange 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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