Investigation of Ground-Water Availability and Quality in Orange County, North Carolina

By William L. Cunningham and Charles C. Daniel, III

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 00–4286

Prepared in cooperation with Orange County, North Carolina

Raleigh, North Carolina
2001

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

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CONVERSION FACTORS, RELATION OF RECHARGE RATES, VERTICAL DATUM, SPECIFIC CONDUCTANCE, TEMPERATURE, and DEFINITIONS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.0929	square meter
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.0283	cubic meter
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	3.785	liter per minute
	Flow per Length	
gallon per minute per foot ([gal/min]/ft)	12.418	liter per minute per meter
	0.1242	cubic meter per minute per meter
	Radioactivity	
picocurie per liter (pCi/L)	3.785	becquerel per liter

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]

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Temperature: Temperature conversions between degrees Celsius (°C) and degrees Fahrenheit (°F) can be made by using the following equations:

$$^{\circ}\mathrm{F} = 1.8\ (^{\circ}\mathrm{C} + 32)$$

$$^{\circ}\mathrm{C} = 5/9\ (^{\circ}\mathrm{F} - 32)$$

Definitions:

BTEX	benzene, toluene, ethylbenzene, and xylene
CERCLIS	USEPA Comprehensive Environmental Response, Compensation, and Liability Act Information System
CGIA	North Carolina Center for Geographic Information and Analysis
DENR	North Carolina Department of Environment and Natural Resources
ELISA	enzyme-linked immunosorbent assay
GIS	geographic information system
GWSI	USGS Ground-Water Site Inventory data base
HMP	harmonic mean permeability
HSD	honestly significant difference (a statistical analysis procedure)
MCL	Maximum Contaminant Level, established by the U.S. Environmental Protection Agency
NAD27	North American Datum 1927
NAD83	North American Datum 1983
NPDES	National Pollutant Discharge Elimination System
OWASA	Orange Water and Sewer Authority
PLGR	precise lightweight global positioning system receiver
TSDF	treatment, storage, and disposal facility
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UST	underground storage tank

µg/L	microgram per liter
mg/L	milligram per liter
mL	milliliter
<	less than
+/–	plus or minus

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ABSTRACT

A countywide inventory was conducted of 649 wells in nine hydrogeologic units in Orange County, North Carolina. As a result of this inventory, estimates of ground-water availability and use were calculated, and water-quality results were obtained from 51 wells sampled throughout the County from December 1998 through January 1999. The typical well in Orange County has an average depth of 208 feet, an average casing length of 53.6 feet, a static water level of 26.6 feet, a yield of 17.6 gallons per minute, and a well casing diameter of 6.25 inches. The saturated thickness of the regolith averages 27.0 feet and the yield per foot of total well depth averages 0.119 gallon per minute per foot. Two areas of the County are more favorable for high-yield wells—a west-southwest to east-northeast trending area in the northwestern part of the County, and a southwest to northeast trending area in the southwestern part of the County. Well yields in Orange County show little correlation with topographic or hydrogeologic setting.

Fifty-one sampling locations were selected based on (a) countywide areal distribution, (b) weighted distribution among hydrogeologic units, and (c) permission from homeowners. The list of analytes for the sampling program consisted of common anions and cations, metals and trace elements, nutrients, organic compounds, and radon. Samples were screened for the presence of fuel compounds and pesticides by using immunoassay techniques. Dissolved oxygen, pH, temperature, specific conductance, and alkalinity were measured in the field. The median pH was 6.9, which is nearly neutral, and the median hardness was 75 milligrams per liter calcium carbonate. The median dissolved solids concentration was 125 milligrams per liter, and the median specific conductance was 175 microsiemens per centimeter at 25 degrees Celsius. Orange County ground water is classified as a calcium-bicarbonate type.

High nutrient concentrations were not found in samples collected for this study. Nitrate was detected in 82 percent of the samples at concentrations ranging up to 7.2 milligrams per liter, although the median concentration was 0.49 milligram per liter; all other samples had a concentration of 2.9 milligrams per liter or less. In general, trace elements were detected infrequently or at concentrations less than State drinking-water standards. However, exceedances of North Carolina drinking-water standards were observed for iron (3 exceedances of 51 analyses, detection up to 1,100 micrograms per liter), manganese (12 exceedances of 51 analyses, detection up to 890 micrograms per liter), and zinc (4 exceedances of 31 analyses, detection up to 4,900 micrograms per liter). Lead was detected in 8 of 31 samples with a concentration up to 3.5 micrograms per liter. Zinc, manganese, iron, and copper were the most frequently detected trace metals at 100, 94, 80, and 61 percent, respectively. Lead, arsenic, bromide, aluminum, and selenium were detected in 13 to 26 percent of the analyses. No benzene, toluene, ethylbenzene, and xylene (BTEX) or atrazine compounds were detected in any of the samples.

Radon activities in ground water can be high because of the rock units present in Orange County. Radon activity ranged from 38 to 4,462 picocuries per liter countywide, with a median activity of 405 picocuries per liter. Median radon activities in Orange County were highest in felsic rocks (487 picocuries per liter) and lowest in mafic rocks (357 picocuries per liter). When evaluated by individual hydrogeologic units, the median radon activity was highest in the phyllite unit (1,080 picocuries per liter in 2 samples) and the felsic metaigneous unit (571 picocuries per liter in 13 samples).

Overall, water-quality data in Orange County indicate few drinking-water concerns. No organic contaminants analyzed (total BTEX and atrazine) or excessive nutrient concentrations were detected, and few exceedances of North Carolina drinking-water standards were detected.

INTRODUCTION

Orange County, North Carolina, has experienced regular population growth over the past 20 years. The population increased nearly 22 percent from 1980 to 1990, and an additional 20 percent growth is projected from 1990 to 2000. The rural population of Orange County, which is about 40 percent of the total population, relies exclusively on ground water as a water-supply source. Further development of the rural areas of the County will require a reliable, high-quality source of ground water. Most of the previous investigations that describe ground-water resources in Orange County were regional in scope, and the results tended to be general in nature.

The Orange County Water Resources Committee, during meetings held in 1994 and early 1995, recognized the importance of the County's ground-water resources and the general lack of ground-water resource information. A pilot investigation was conducted by the U.S. Geological Survey (USGS) to evaluate ground-water recharge rates to the regolith-fractured crystalline rock aquifer system in Orange County (Daniel, 1996). As a result of this pilot investigation, recharge rates in 12 drainage basins and subbasins of the County were defined. A second phase of the investigation was proposed to quantify ground-water availability, determine the quality of the ground water, and estimate the susceptibility of ground water to contamination from the surface and shallow subsurface.

The results of these investigations provide County managers and planners with critical information on the availability and quality of the ground-water resource. This information can be used to develop policies in the County to protect and manage ground water used by rural residents and to begin plans to integrate surface-water and ground-water protection measures. This information will become even more important as the County's rural population increases and surface-water resources used by incorporated areas become fully allocated. Results of this investigation, when combined with other investigations in the Piedmont region of North Carolina and the Eastern United States, will help in the management of the Nation's water resources by defining the quantity and quality of these resources.

Purpose and Scope

The purpose of this report is to present the results of this investigation and describe the methods used to estimate ground-water availability and characterize ground-water quality throughout Orange County, North Carolina. This report is based on a countywide inventory of 649 wells in nine hydrogeologic units, estimates of ground-water availability and use, and water-quality results from 51 wells sampled throughout the County. Additional well data from adjacent Chatham and Durham Counties were evaluated in support of the ground-water availability discussion later in this report.

Description of Study Area

Orange County covers approximately 401 square miles (mi^2) in the eastern part of the Piedmont physiographic province in North Carolina (fig. 1). The major population areas in Orange County are Carrboro, Chapel Hill, and Hillsborough. The estimated County population in 1998 was 109,288 people; an increase of 16.4 percent since 1990 (North Carolina Office of State Budget and Planning Management, 1999). Of the total population, about 65,000 people obtain water from public water systems that are dependent upon surface water as the raw water source. The remaining residents, about 40 percent of the total population, obtain water

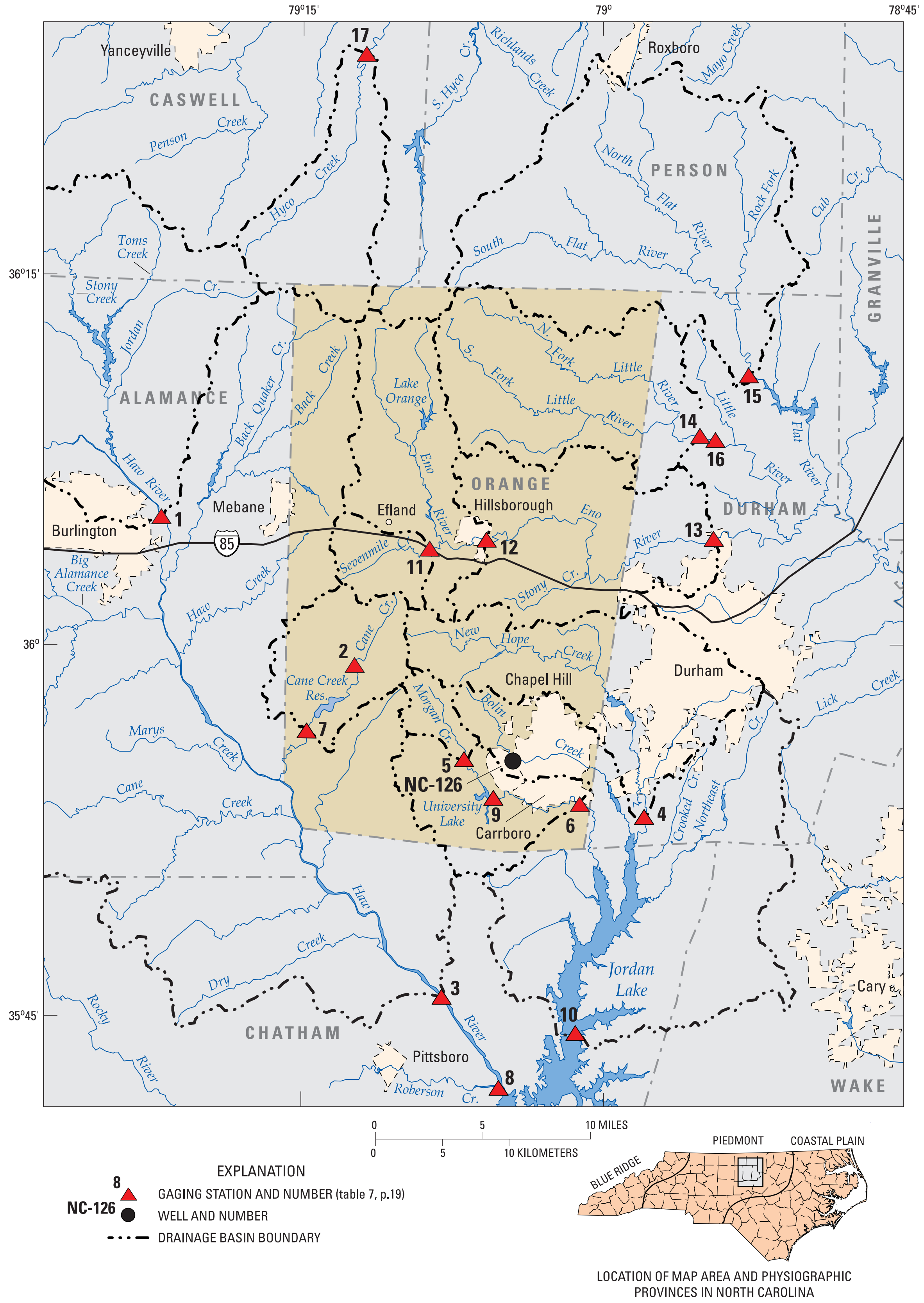

Figure 1. Regional setting of the Orange County study area in the Piedmont physiographic province of North Carolina, selected drainage basins, and locations of gaging stations used in the ground-water recharge analysis.

from individual wells and ground-water-based community systems (North Carolina Office of State Budget and Planning Management, 1999). Residents who rely on ground water as their source of potable water live almost exclusively in rural areas of the County.

The geological characteristics of Orange County can be considered fairly typical of those of the eastern Piedmont of North Carolina. The Piedmont of North Carolina is part of the Piedmont physiographic province, as described by Fenneman (1938), which 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. 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 ft (feet) 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, 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 more than 800 ft.

Orange County has a moderate, humid, subtropical climate. The area is characterized by short, mild winters and long, hot, humid summers. Mean January temperatures range from 32 to 36 degrees °F (Fahrenheit), whereas mean July temperatures range from 88 to 90 °F. Average annual precipitation in the area is 44 to 48 in. (inches). Prevailing winds are from the southwest with a mean annual wind speed 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).

Previous Investigations

Terziotti and Eimers (1999) evaluated the relative susceptibility of Orange County ground water to contamination from surface and shallow sources. A geographic information system (GIS) was used to evaluate susceptibility by use of soil permeability, land use/land cover, and land-surface slope. Results from the Terziotti and Eimers (1999) report are summarized in further detail in a subsequent section of this report.

Ali (1998) and Kwitnicki (1999) investigated the relations among well yield, topographic setting, drainage patterns, and geologic structures in and around Orange County. Some high-yield wells in the County may be associated with fracture-controlled drainage patterns; lower yielding wells are found in topographic highs as well as in topographic lows where the drainage pattern is not fracture controlled (Ali, 1998; Kwitnicki, 1999).

Briel (1997) summarized the inorganic chemical quality of ground water in the Appalachian Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces of the Eastern United States. Loomis (1987) summarized the results of radon activities in ground water from 133 public water-supply systems in the Piedmont and Blue Ridge Provinces of North Carolina. Spruill and others (1997) presented radon activities in water from 70 wells sampled in Guilford County. Results from these investigations provide a useful comparison for Orange County water-quality results. Orange County was included in a multicounty study by Bain and Thomas (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. Water-quality analyses were presented for 11 wells.

Daniel (1996) defined recharge rates to the regolith-fractured crystalline rock aquifer system during the first phase of the Orange County investigation. Daily, seasonal, and long-term recharge rates to the regolith-fractured crystalline rock aquifer were calculated by using hydrograph separation of streamflow data from 17 gaging stations in 12 drainage basins and subbasins in the County. Mean annual basin recharge ranged from 4.15 to 6.4 inches per year, with a mean value of 4.90 inches per year for all basins.

The hydrogeologic units in Orange County were defined 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 these regional studies are considered applicable to Orange County. Investigations by Floyd and Peace (1974), Daniel and Sharpless (1983), Harned and Daniel (1987), McKelvey (1994), and Daniel (1996) provided background material for this report.

Acknowledgments

The authors would like to thank the homeowners who graciously permitted access to their wells for this study. The authors also would like to thank the Orange County Water Resources Committee members for their support of the Orange County–USGS cooperative program. These committee members include P. David Stancil, Director of the Orange County Department of Environment and Resource Conservation; Paul K. Thames, Orange County Engineer; Don N. Cox, Chairman of the Orange County Water Resources Committee; and Alice M. Gordon, Orange County Commissioner.

HYDROGEOLOGIC SETTING

The hydrogeologic setting of Orange County is complex. This section describes the delineation of hydrogeologic units used in this report and the conceptual ground-water flow system within the regolith-fractured crystalline rock aquifer system beneath the County.

Hydrogeologic Units

The geologic framework of Orange County is complex; the bedrock beneath much of the County consists of folded, fractured, and metaigneous 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 and ground-water-quality characteristics of the ground-water system in the County.

Within the Piedmont and Blue Ridge physiographic provinces, hundreds of rock units 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). This classification of rocks in the Piedmont and Blue Ridge Provinces of North Carolina has resulted in 21 distinct hydrogeologic units. Of these 21 units, 9 occur in Orange County (fig. 2; table 1).

The rationale behind the hydrogeologic units shown in table 1 is 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 also determine, in part, the rate and depth of weathering of these units and the water-bearing properties of the resulting regolith.

Using the classification scheme from Daniel (1989) 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 computer data base for analysis of the hydrologic characteristics of each unit. Summaries of these characteristics are presented by Daniel (1989).

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 Basin, crosses

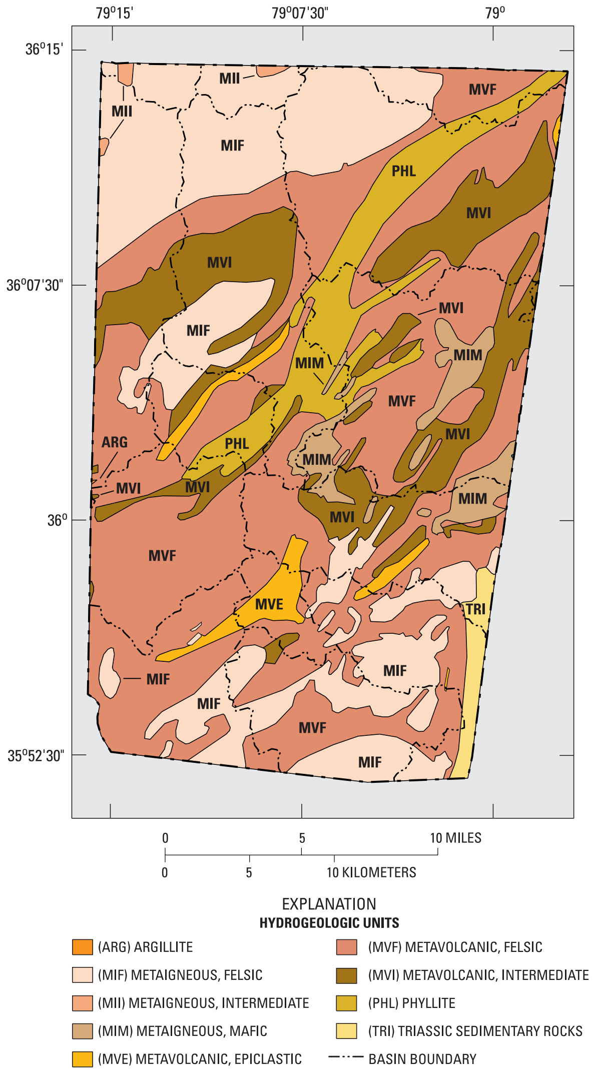

Figure 2. Hydrogeologic units in Orange County, N.C.

southeastern Orange County. Metamorphic and igneous crystalline rocks underlie the remainder of Orange County (fig. 2).

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. 3) shows the following components of the system: (1) the unsaturated zone above the water table in the regolith, which generally contains the organic layers of the surface soil; (2) the saturated zone in the regolith beneath the water table; (3) the lower part of the regolith, which contains the transition zone between saprolite and bedrock; and (4) the fractured crystalline bedrock.

Collectively, the uppermost layer is regolith, which can be 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 fragmented material ranging in grain size from silt to boulders. Because of its high porosity, the regolith provides the bulk of the water storage in the Piedmont ground-water system (Heath, 1980).

Saprolite is the clay-rich, residual material derived from inplace weathering of bedrock. Saprolite commonly is 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 inplace 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 riverbeds; soil generally is restricted to a thin mantle on top of both the saprolite and alluvial deposits. Weathering processes in the saprolite contribute to the water-quality characteristics of Piedmont ground water.

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 usually are 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. 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 (Harned and Daniel, 1992).

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

Table 1. Classification, lithologic description, and area of hydrogeologic units in Orange County, N.C. (from Daniel, 1996, table 2)

[mi^2, square miles]

Map symbol (fig. 2)	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 typically 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. Commonly 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

(1989) to be 52 ft. The thickness of regolith in Orange County is similar to that of the Piedmont as a whole.

Harned and Daniel (1992) found that the transition zone over a highly foliated mafic gneiss was approximately 15 ft thick. 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 in reports by well drillers of so-called “first water” in drillers' logs (Nutter and Otton, 1969).

The high permeability of the transition zone probably is 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

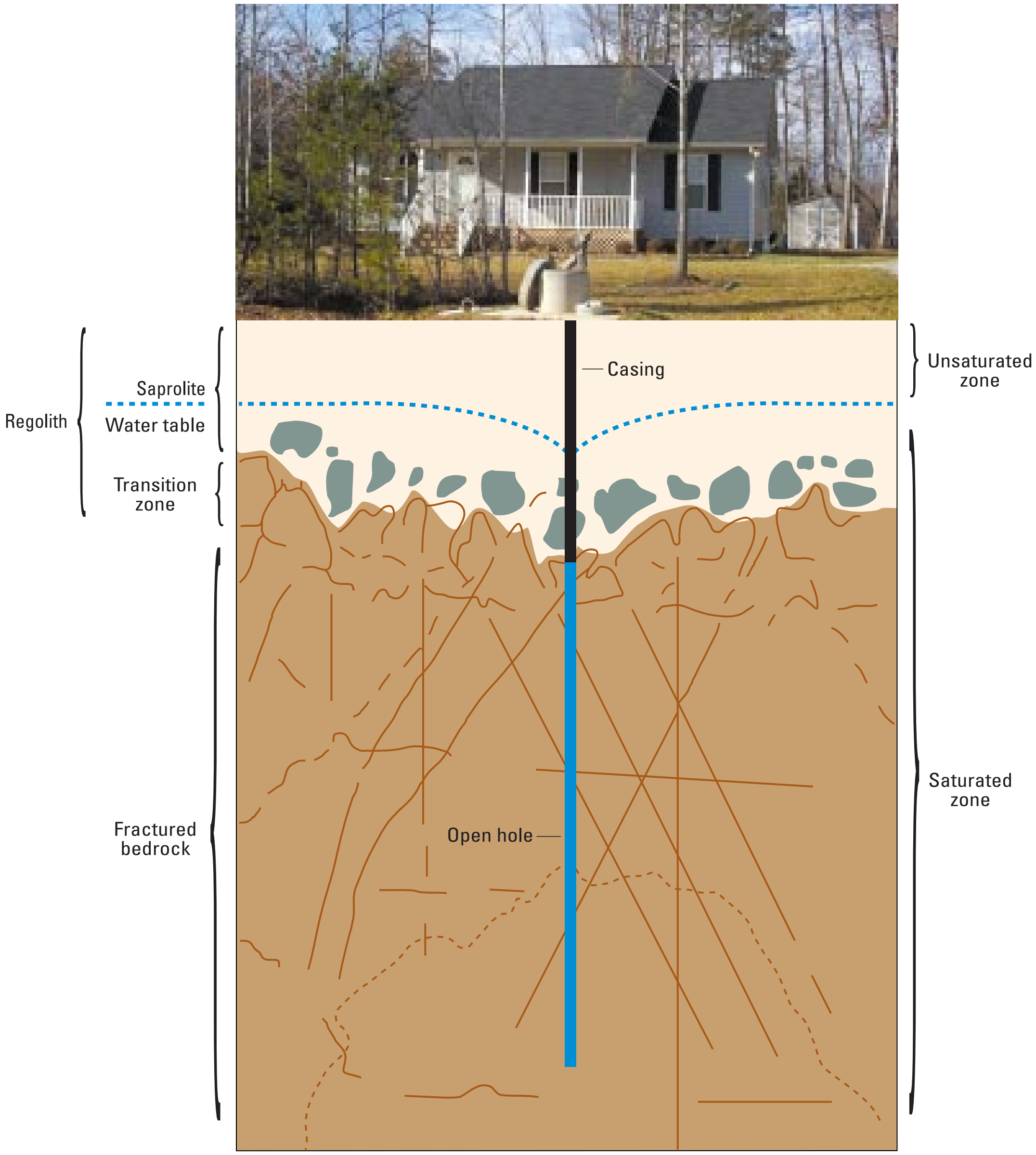

Figure 3. Principal components of the ground-water system in the Piedmont physiographic province of North Carolina.

the regolith reservoir, the bedrock fracture system, and the well.

The regolith contains water in pore spaces between rock particles. The bedrock, on the other hand, does not have any significant intergranular porosity. It contains water in sheet-like 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. 4), and these differences result in different water-quality characteristics between the units. The porosity of regolith typically is 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 (Heath, 1980).

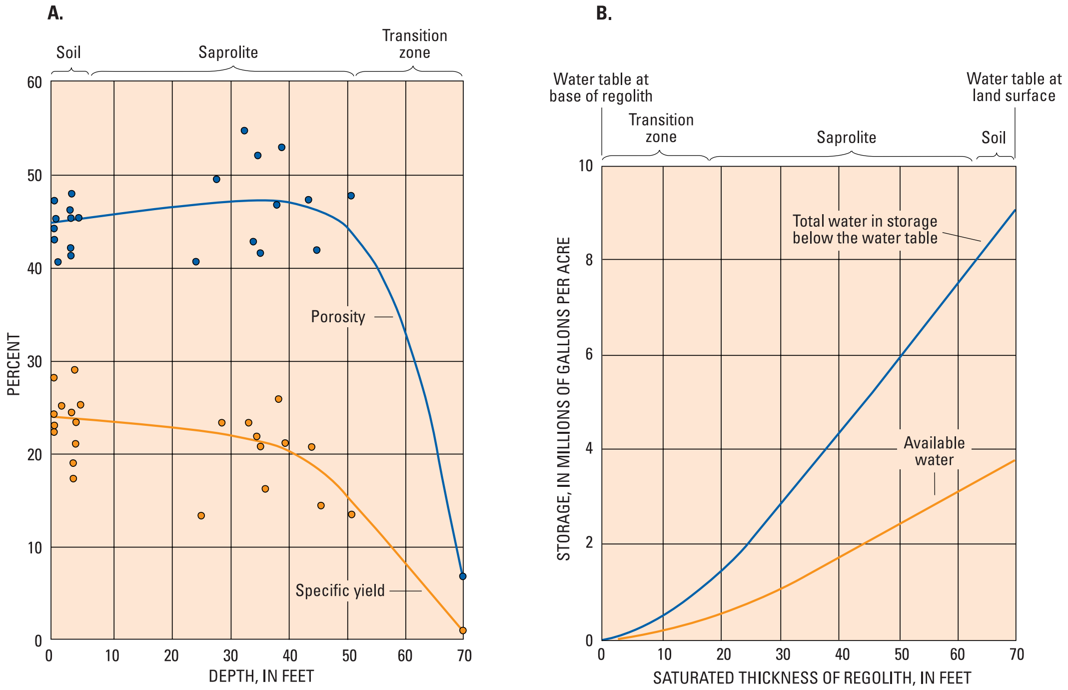

Figure 4. Relation of (A) porosity and specific yield with depth in the regolith, and (B) total water in storage below the water table and water available by gravity drainage, Orange County, N.C. (from Daniel and others, 1997).

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.

GROUND-WATER AVAILABILITY

Data from a number of wells in Orange County, North Carolina, were used to characterize wells in the County, identify factors that are associated with above-average yields, and determine the areal distribution and characteristics of high-yield wells. A major part of this analysis includes a statistical analysis of hydrologic, geologic, topographic, and well-construction data that were obtained from records of more than 600 wells.

The records of water wells, obtained from published and unpublished sources, were used to compile information on well yields and water levels; water use; well-construction variables, such as total depth, diameter, and casing depth; and the siting of wells in relation to topography and geology. Well construction records were obtained from files of the USGS, Orange County, and the North Carolina Department of Environment and Natural Resources. Well siting information was determined during field visits by USGS staff and students under USGS supervision. A total of nine major rock types of metaigneous, metasedimentary, metavolcanic, and sedimentary origin occur in the study area and are considered to have quantifiable hydrogeologic properties. Because of their hydrogeologic properties, these major rock types are designated herein as hydrogeologic units.

Also presented are estimates of available ground water based on estimates of recharge to the regolith-bedrock aquifer system and quantities of ground water in storage. Estimates of rates of ground-water recharge were made by using long-term streamflow data from 17 gaging stations (see table 7, p. 19) and an analytical technique for determining the ground-water component of total streamflow known as hydrograph separation. By assuming that there are no long-term changes in ground-water storage, the ground-water component of streamflow is considered to be equal to ground-water recharge. The quantity of available ground water in storage was estimated for selected topographic settings by using data from well records and assumptions about the specific yield of the regolith.

Finally, the distribution of wells and prevalence of ground-water use in the County were determined from census tract data that were analyzed and mapped to show the spatial distribution of wells in the County, as well as the relative use of ground water and surface water as sources of supply. These topics will be discussed more fully in the following sections, beginning with results from the statistical analysis of well data.

Relation of Well Yield to Construction Practices and Siting of Wells

Information on 649 wells was compiled and statistically analyzed to characterize wells in the County and to identify relations between well yield and various geologic, topographic, and construction factors. This compilation contained well records from throughout the County. A conscious effort was made to select wells distributed throughout the County, as well as among the different hydrogeologic units and topographic settings. Well data used for this evaluation were compiled in the USGS Ground-Water Site Inventory (GWSI) data base.

Specific information categories (variables) in the data base include (1) the County where the well is located, (2) the latitude and longitude of the well location, (3) the well number, (4) well yield, (5) the total depth of the well, (6) the well diameter, (7) the casing depth, (8) the static water level below land surface, (9) the intended well use, (10) the topographic setting of the well site, and (11) the hydrogeologic unit in which the well is drilled. The total number of entries for each variable is shown in table 2.

Table 2. Total number of entries for Orange County for selected well variables in the U.S. Geological Survey Ground-Water Site Inventory (GWSI) data base

Variable	Total number of data entries
County	649
Latitude and longitude	649
Well number	649
Yield	630
Total depth	632
Well diameter	635
Casing depth	604
Static water level	536
Use	634
Topographic setting	634
Hydrogeologic unit	644

For inclusion in the data base, a well must meet certain requirements. The well must be drilled into bedrock, and the location must be known. As a general rule, it is desirable to know the yield of the well; only 19 wells in the data set do not have this information. All wells in the resulting compilation are cased to the top of bedrock and have no screened or slotted intervals in the regolith, and nearly all are finished as open holes drilled into bedrock. A small number of wells have casings extending into bedrock to prevent fragmented rock debris from entering the well bore. One well has 148 ft of casing, and 37 wells, or 6.1 percent, have more than 100 ft of casing. Only two wells, however, are cased to within the bottom 5 ft of the boreholes.

The wells range in diameter from 5 to 6.625 in., and most (65.7 percent) have a diameter of 6.25 in. Large-diameter bored or dug wells were not included in the compilation because these wells are not typical of modern well construction. Nearly all new wells in the Piedmont are drilled by air rotary methods. Further, large-diameter wells are rarely dug below the top of bedrock and are not characteristic of wells used for domestic supplies.

A GIS coverage was made of the well locations and overlaid on a map of the hydrogeologic units (Daniel and Payne, 1990) to assign the wells to the units in which they occur. The geologic units reported on the well-completion forms and in published sources were not entered into the data file because of the conflicting variety of names and naming conventions that were used by the various authors and persons filling out the well-completion forms. The reported geologic units were not ignored, however. If a well was located on or near a contact between units on the hydrogeologic unit map, the reported geologic descriptions helped guide the assignment of the hydrogeologic unit. By using a combination of the hydrogeologic unit map and the reported geologic descriptions, each well in the data base subsequently was assigned to one of the nine hydrogeologic units in the County.

All data related to well construction, yield, topographic setting, and static water level were entered as reported. If a topographic setting was not reported, well locations were plotted on topographic maps, and the topographic setting was determined from the plotted location. The intended use of each well was inferred from the listed owner or the use reported for the wells, and from other information in the remarks column of the well records. Wells were placed in one of three use categories—domestic, commercial/industrial, or public supply. Domestic wells serve single-family residences or, at most, a small number of homes. The commercial/industrial category includes wells that serve businesses that range in size from large farms and factories to service stations and small shops. Public-supply wells serve subdivisions, trailer parks, churches, campgrounds, and other facilities having 25 or more users.

Analysis of variance was used to evaluate the data in the topographic, hydrogeologic unit, and well-use classifications to determine if any of the apparent differences among classifications were statistically significant. The data also were checked by using the Kruskal-Wallis nonparametric test with nearly the same results. Because the classification groups have unequal numbers of observations, Tukey's studentized range test honestly significant difference (HSD) procedure (Steel and Torrie, 1960, p. 109–110) was used to make the multiple-comparison tests for significant differences at the 0.95-confidence level. Tukey's HSD procedure is a conservative test that controls for the experiment-wise error rate rather than on a per-comparison basis. For some comparisons, confidence levels were changed systematically to test for significant differences at levels less than 0.95.

The first group of statistics, presented in table 3, characterizes the wells in the study area with regard to their physical and hydrologic characteristics. The average value of each characteristic can be compared to the quartile data, which define the frequency at which a given value of a well characteristic can be expected to occur. At the 5th percentile, 5 percent of the wells in the sample have values below the given value; at the first decile, 10 percent of the wells have values below the given value; at the first quartile, 25 percent of the wells have values below the given value; at the median, half of the wells have values below the given value; at the third quartile, 75 percent of the wells have values below the given value; at the ninth dectile 90 percent of the wells have values below the given value; and at the 95th percentile, 95 percent of the wells have values below the given value.

The yield per foot of well depth and saturated thickness of regolith are computed characteristics. The yield per foot is the yield divided by the total depth of

Table 3. Statistical summary of selected well characteristics for inventoried wells in Orange County, N.C.

Well characteristic	Average	Quartiles for all wells									Number of wells
		Minimum	5th percentile	First decile	First quartile	Median	Third quartile	Ninth dectile	95th percentile	Maximum	
Yield[a] (gallons per minute)	17.6	0.1	1.5	2	5	10	20	40	60	240	630
Yield per foot (gallons per minute per foot of total well depth)	.119	.0001	.0049	.0094	.024	.062	.143	.311	.417	1.297	625
Depth (feet)	208.0	24	73	85	125	180	250	365	420	805	625
Casing (feet)	53.6	4	21	24	37	49.5	64	86	103.5	148	600
Water level (feet below land surface)	26.6	0	10	15	20	25	30	40	40	88	534
Saturated thickness of regolith (feet)	27.0	0	0	0	7	22	41	61	74	126	512

[a] Unadjusted for differences in depth and diameter.

the well. The saturated thickness of regolith is the difference between the depth of casing and the depth of the static water level. If the water level in a well was below the bottom of the casing, the saturated regolith thickness of that well was considered to be zero.

In the computation of the saturated thickness of regolith, casing depth was used to estimate regolith thickness. The depth of surface casing in a drilled well is a good approximation of regolith thickness in the Piedmont (Daniel and Sharpless, 1983; Snipes and others, 1983; Daniel, 1989). Surface casing is usually set no more than 1 or 2 ft into fresh bedrock, just below the interface and between the interface and the overlying regolith. Wells drilled in North Carolina since the passage of the North Carolina Well Construction Act of 1967 (Heath and Coffield, 1970) are required to have a minimum of 20 ft of casing, regardless of how shallow the bedrock may be. Changes to this Act, as well as local ordinances enacted since 1967, require deeper minimum well casing. Thus, casing data from wells drilled since 1967 can lead to overestimated regolith thickness. Most of the wells in the Orange County data set have been drilled in the last three decades. The statistics for casing depth in table 3 indicate that only 5 percent of the wells in the sample have casing depths less than 21 ft.

The typical well in Orange County has an average depth of 208 ft, an average casing of 53.6 ft, a static water level of 26.6 ft below land surface, a yield of 17.6 gal/min (gallons per minute), and a casing diameter of 6.25 in. The saturated thickness of regolith averages 27.0 ft, and the yield per foot of total well depth averages 0.119 [gal/min]/ft (gallon per minute per foot). Previous studies of wells in the North Carolina Piedmont (Mundorff, 1948; Daniel, 1989; Daniel and others, 1997), however, have shown that well characteristics can vary, sometimes systematically, depending on the topographic setting of the well site, the intended use of the well, and the hydrogeologic unit that the well taps.

Distribution of Well Yields

Well yield and yield-per-foot values were placed on GIS coverages so that maps could be prepared showing the distribution of well yields in the County. Maximum well yields were contoured into zones of similar yield to identify areas of the County favorable for ground-water development based on available data (fig. 5). Drilling new wells in any of the indicated areas does not guarantee that the maximum yield will be obtained; rather, yields of new wells can be expected to fall within the range between zero and the maximum value for the indicated area. The significance of figure 5 is the clear indication that two areas of the County are obviously more favorable for high-yield wells—a west-southwest to east-northeast trending area in the northwestern part of the County, and a southwest to northeast trending area in the southwestern part of the County. Within these two areas, maximum reported yields range from 25 gal/min to more than 100 gal/min. Nearly everywhere else, with the exception of a few small isolated areas, the maximum reported yields are less than 25 gal/min.

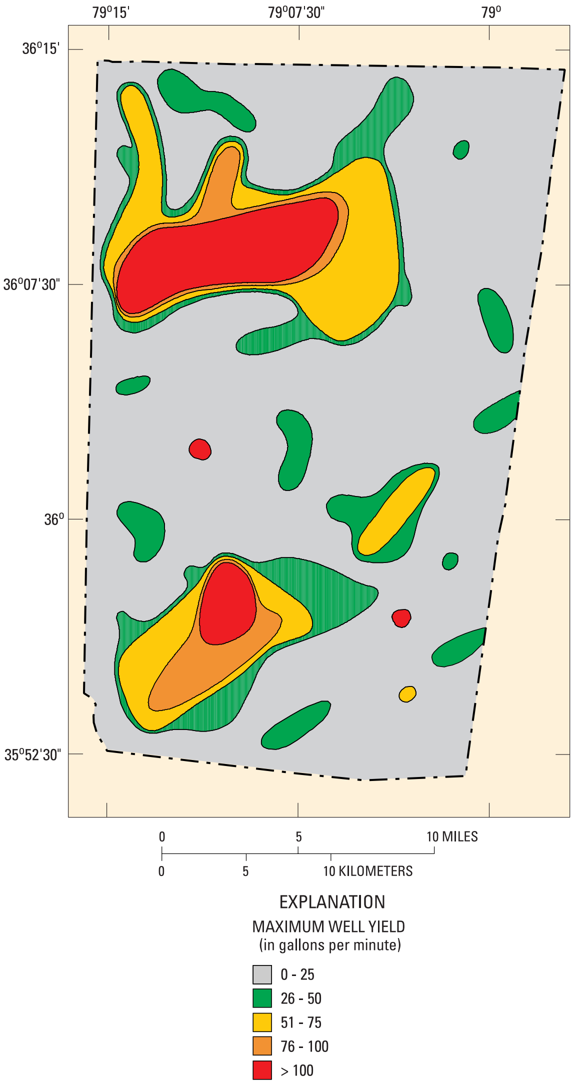

Figure 5. Distribution of maximum well yields in Orange County, N.C.

Previous work has shown that yields of wells tapping fractured crystalline rock can be positively correlated with well depth and well diameter (Daniel, 1989, 1992; Daniel and others, 1997). As a consequence, it is often useful for purposes of comparison to adjust well yields for differences in construction. The casing diameter of wells in the Orange County data base ranges from 5 to 6.625 in.; more than 65 percent of the wells have diameters that are 6.25 in. On the other hand, the depth of wells in the data base ranges from 24 to 805 ft (table 3). Because of the narrow range of well diameters and the predominance of 6.25-in.-diameter wells, the effect of differences in diameter on yield is relatively insignificant and adjustments are not needed. The sufficiently large range in well depths, however, warrants adjustments for differences in depth. The most straightforward adjustment is to divide the well yield by the total well depth (Daniel and others, 1997). The resulting yield-per-foot values were plotted, and maximum values were contoured in the same manner as the yield values (fig. 6).

Like the yield data in figure 5, two areas of the County stand out with respect to high maximum values of yield per foot of total well depth (fig. 6). The centers of these two areas generally coincide with the two areas of high maximum yields; but overall, the higher values of yield per foot extend over larger areas. This suggests that, in some areas, low well yields are the result of shallow wells that do not tap the full potential of the aquifer and the influence of shallow wells only becomes apparent when differences in depth are taken into consideration. In Orange County, maximum values of yield per foot exceed 0.4 (gal/min)/ft of total well depth.

It is apparent that yield per foot of total well depth varies areally (fig. 6). It also is important to recognize that yield per foot varies vertically as well (fig. 7). The well data were subset by 100-ft intervals of well depth, and the average depth, yield, and yield per foot of total well depth were calculated for each interval. The plot showing the variation of yield with depth (fig. 7) indicates that, on average, shallow wells tend to have higher yields than deep wells and that there may be an increase in yield in the interval between 100 and 200 ft. This would be in general agreement with Daniel (1989, fig. 11); however, the increase in yield with depth does not extend nearly as deep in Orange County as in the Piedmont and Blue Ridge as a whole. Daniel (1989) determined that the maximum average yield occurs in the interval between 500 and 550 ft, and only at greater depths does it decline. The rapid, non-linear decrease in yield per foot of total well depth with depth (fig. 7) is consistent with other work in North Carolina (Freeze and Cherry, 1979, fig. 4.10; Daniel, 1989, figs. 11, 12; Daniel and others, 1997, fig. 36A). It also is consistent with analyses of well yields and hydraulic conductivity in fractured-rock terrains in other parts of the world; for example, Gustafson and Krásný (1994, fig. 4) show similar non-linear declines in fractured rock in Sweden.

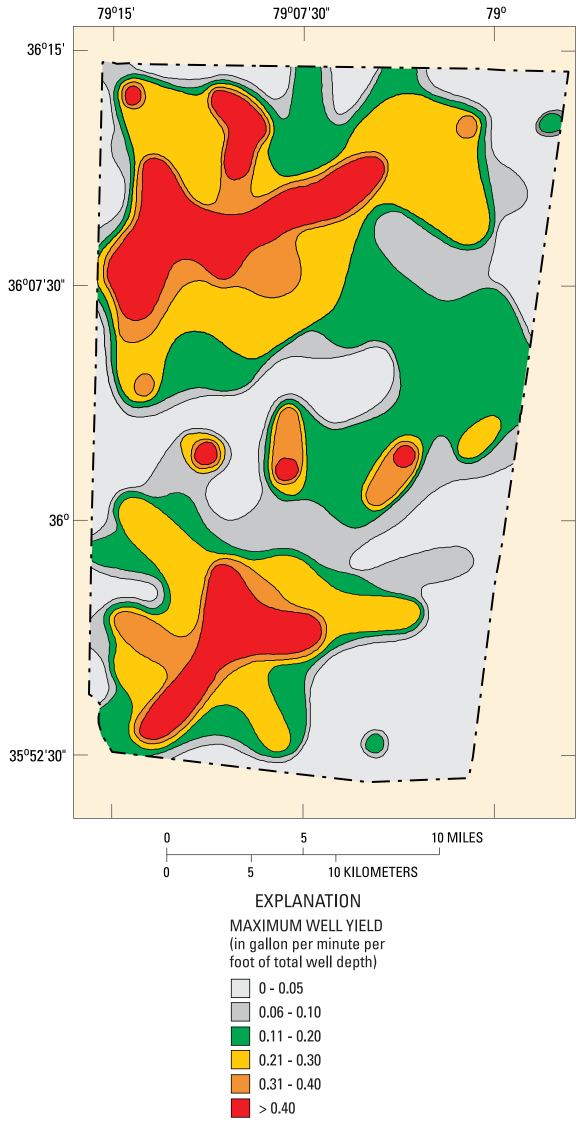

Figure 6. Distribution of maximum values of yield per foot of total well depth in Orange County, N.C.

The yield per foot of total well depth is inversely proportional to the depth of the well, indicating that the amount of additional water obtained by drilling deeper continuously decreases. This is consistent with the observation that in a regolith-crystalline bedrock

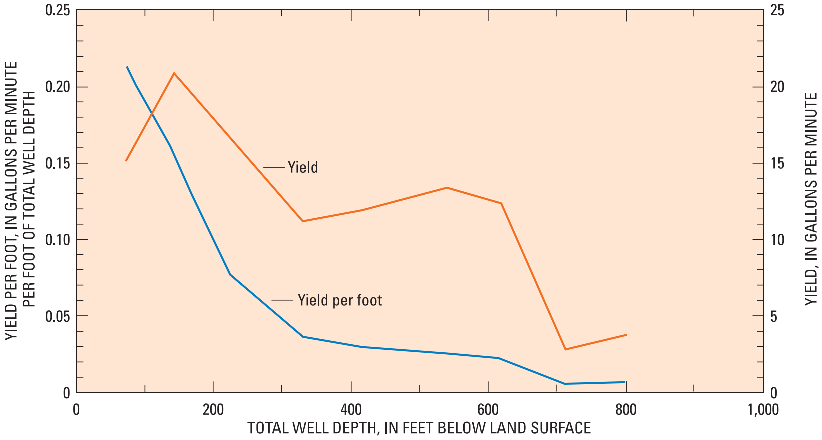

Figure 7. Relation of yield and yield per foot of total well depth in Orange County to total well depth.

aquifer system, fractures are most numerous and have the largest openings near the top of the bedrock. As depth increases, the pressure of the overlying material, or lithostatic pressure, holds these fractures closed, and the total porosity of the bedrock can be less than 1 percent. The base of the ground-water system is indistinct because the fractures tend to decrease in size and number with increasing depth.

Well Characteristics by Topographic Setting

In previous statistical analyses of well data from the Piedmont and Blue Ridge Provinces of North Carolina, Daniel (1989) and Daniel and others (1997) found that when well data were subset by topographic settings, analysis of variance indicated that the data fell into three general categories—wells in valleys and draws, wells in slopes and flats, and wells in hills and ridges. Inspection of available well records (Daniel and others, 1997) revealed that it was impractical, if not impossible, to distinguish between wells in flat interstream uplands, in flat valley bottoms, or in any other flat area. Consequently, wells located in flats were left out of analyses in which the data were subset by topographic setting, and the three principal topographic subsets became wells in valleys and draws, wells in slopes, and wells in hills and ridges. For this study, subsets of well data were created based on the three principal topographic groups identified by Daniel and others (1997). Results of the analyses of grouped data are presented in table 4.

In general, average yield, average yield per foot, casing depth, depth to the water table, and saturated thickness of regolith increase at higher topographic settings (table 4). The well depth follows the opposite pattern. However, analysis of variance (Tukey's HSD procedure) found no difference in yield, yield per foot, and water level among the three topographic groups at the 0.95-confidence level. Well depth was lower, but casing depth and saturated thickness of regolith were higher for wells in hills and ridges than for wells in valleys and draws and in slopes at the 0.95-confidence level. With regard to depth, casing depth, and saturated thickness of the regolith, the wells in hills and ridges fall into one group, and wells in valleys and draws and in slopes fall into a second group.

In Orange County, wells in hills and ridges have the highest average yields, and wells in valleys and draws have the lowest; however, differences among settings were not statistically significant. In contrast, previous studies of ground water in the Piedmont and Blue Ridge Provinces of North Carolina have identified a significant relation between well yield and topographic setting. In a study of more than 6,200 water wells from all 65 counties in these two provinces, Daniel (1989) concluded that the average yield of wells in valleys and draws was nearly three times greater than the average yield of wells in hills and ridges. The average yield of wells in slopes and flats was intermediate to the other two groups.

One possible explanation for why well yields in Orange County show little, if any, correlation with topographic setting is local variation in the regional relation between drainage patterns and structures in the underlying bedrock. Recent studies have shown that some high-yield wells in the County apparently are associated with fracture-controlled drainage patterns

Table 4. Average and median values of selected well characteristics according to topographic setting and statistics for all wells, Orange County, N.C.

Well characteristic	Statistical value by topographic setting			All wells	Number of wells
	Valleys and draws	Slopes	Hills and ridges		
Average yield[a] (gallons per minute)	15.6	16.6	18.1	16.8	553
Median yield (gallons per minute)	10	10	10	10	553
Average yield per foot (gallons per minute per foot of total well depth)	.092	.109	.136	.113	549
Median yield per foot (gallons per minute per foot of total well depth)	.062	.057	.061	.061	549
Average depth (feet)	223.1	219.2	183.8	211.5	549
Median depth (feet)	200	185	167.5	185	549
Average casing (feet)	49.6	52.9	61.1	53.9	526
Median casing (feet)	42	47	60	50	526
Average water level (feet below land surface)	25.7	26.6	28.0	26.6	466
Median water level (feet below land surface)	25	25	30	25	466
Average saturated thickness of regolith (feet)	22.8	26.5	33.4	27.2	446
Median saturated thickness of regolith (feet)	19	20	28	22	446

[a] Unadjusted for differences in depth and diameter.

and that lower yielding wells are located not only in topographic highs but also in topographic lows where the drainage pattern is not fracture controlled (McKelvey, 1994; Ali, 1998; Kwitnicki, 1999). When drainage patterns are fracture controlled, the fractures tend to be steeply dipping, and wells tapping these fractures have higher yields than wells in upland sites where the bedrock is less fractured. However, if most of the streams in the County are not incised into zones of weakness associated with fractured bedrock, then most of the wells drilled in valleys and draws are not likely to tap highly fractured bedrock. When streams are incised into massive bedrock or along elongated bodies or layers of rock that, because of composition or texture, are more susceptible to weathering and erosion than adjacent rock, the topographic lows usually have little relation to fracture abundance. In fact, the abundance of fractures may not be much different beneath any topographic setting, and well yields may tend to be more uniform among settings. More importantly, when the bedrock is massive, the principal form of fracturing may be subhorizontal stress-relief fracturing, which will not be evident in patterns of surface topography (Cressler and others, 1983). In addition, Cressler and others (1983) identified a number of high-yield wells tapping stress-relief fractures beneath topographic highs. An analysis of the relation between well yields and topographic settings in a terrain like that studied by Cressler and others (1983) may reveal higher average yields associated with topographic highs rather than topographic lows.

A paucity of high-angle fracture zones beneath valleys and draws in the County would help explain more than the general lack of high-yield wells in topographic lows. It also would explain the shallow depth at which the maximum average yield is reached, as shown in figure 7. Wells drilled into or intersecting steeply dipping fracture zones could be expected to yield greater quantities of water at greater depths than wells that tap ground water in subhorizontal stress-relief fractures that are most abundant near the top of bedrock. This could explain the fact that the maximum average well yield in Orange County occurs in the interval between 100 and 200 ft, whereas the maximum average well yield in the North Carolina Piedmont and Blue Ridge is reached between 500 and 550 ft (Daniel, 1989).

The results of the statistical analysis of Orange County well data indicate that wells drilled in topographic lows, such as valleys and draws, may not consistently result in high-yield wells. Drilling wells in topographic lows may have other benefits, such as higher long-term sustained yields and more complete recovery of drawdown in pumped wells (Daniel and Sharpless, 1983; Daniel, 1990) because ground-water flow occurs naturally toward well sites in topographic lows and away from well sites in topographic highs. The goal of drilling high-yield wells with long-term sustained yields, however, requires careful site selection that distinguishes between valleys and draws that are associated with underlying fracture zones and those that are not (McKelvey, 1994). The site-selection process may even need to be further refined by the use of innovative technology, such as surface geophysical methods, to locate water-bearing fracture zones in the underlying bedrock (Kwitnicki, 1999).

Well Characteristics by Use

Nearly 95 percent of the wells in the Orange County sample were domestic-supply wells (table 5). The average yield of domestic-supply wells is about half that of commercial/industrial and public-supply wells. This difference, however, is not statistically significant, probably because of the limited number of commercial/industrial wells in the comparison. Depths of domestic-supply wells average about 206 ft and are 52 ft and 36 ft less than the depths of commercial/industrial and public-supply wells, respectively. There is little difference, however, in the average casing depth and average water level among the three use categories. The average yield per foot of total well depth, a statistic that tends to compensate for differences in well depth, is highest for the public-supply and commercial/industrial wells. The data in table 5 indicate that public-supply and commercial/industrial wells more likely are sited and constructed in an effort to obtain as much water as possible, whereas many domestic wells are sited for convenience or aesthetics and drilled only deep enough to obtain the yield necessary to satisfy domestic demand.

Well Yields by Hydrogeologic Unit

Well yields were matched to rock types to determine the relative yields of the different hydrogeologic units. Because yield is strongly influenced by well depth and diameter, which can lead to cultural bias favoring one hydrogeologic unit over another (Daniel, 1989), a series of calculations were performed to remove the variation in well yield attributed to differences in depth and diameter. By using methods outlined by Daniel (1989) and Daniel and others (1997), the well yields were adjusted to an average 208-ft depth and 6.25-in. diameter—the average of all wells in the data set. The results of computations to compare yield and hydrogeologic unit are presented in table 6. The hydrogeologic unit TRI (sedimentary rocks of Triassic age) had fewer than 15 observations having the necessary data (depth, diameter, yield, topography) to adjust the yields. Statistics from Orange County wells (in hydrogeologic unit TRI) are not given. Because the sedimentary rocks of Triassic age found in southeastern Orange County extend to the east and south over large areas of Durham

Table 5. Relation of selected well characteristics to well use in Orange County, N.C.

[gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot; ft, feet]

Use of well	Statistical summary of well characteristics according to use: Average yield (gal/min)	Average yield per foot ([gal/min]/ft)	Average depth (ft)	Average casing (ft)	Average water level (ft)	Number of wells
Domestic	16.4	0.1153	206.2	53.5	26.4	590
Public	30.0	.1614	242.1	55.5	30.0	14
Commercial/industrial	34.4	.1441	258.0	47.9	28.2	20

Table 6. Relation of well yields to hydrogeologic units in Orange County, N.C.

[Yield data are adjusted to account for differences in yield due to differences in well depth and diameter. The average well is 6.25 inches in diameter and 208 feet deep. The hydrogeologic units are described in table 1. gal/min, gallons per minute]

Hydrogeologic unit	Average	Yield of all wells (gal/min)							Number of wells
		Minimum	First decile	First quartile	Median	Third quartile	Ninth decile	Maximum	
MI (grouped)[a]	16.5	0.5	2	5	10	20	40	75	127
MV (grouped)[b]	17.8	.1	2	5	10	20	40	240	455
PHL	15.2	1	2	4	11	20	25	100	26
TRI (Orange County)	[c]	[c]	[c]	[c]	[c]	[c]	[c]	c	3
TRI (Chatham and Durham Counties)[d]	13.1	0	4	7	11	17	24	49	101

[a] The metaigneous units, MIF, MII, and MIM, are grouped into a single category, MI.

[b] The metavolcanic units, MVE, MVF, and MVI, are grouped into a single category, MV.

[c] Statistics for units having less than 15 observations are not given.

[d] Data for wells tapping Triassic sedimentary rocks in Chatham and Durham Counties are given for comparison because they tap rocks that are continuous with Triassic sedimentary rocks in southeastern Orange County.

and Chatham Counties, data from wells in these counties were used to characterize the TRI unit.

Nine of the 21 hydrogeologic units identified in the North Carolina Piedmont and Blue Ridge by Daniel (1989) and mapped by Daniel and Payne (1990) are found in Orange County (table 1). The hydrogeologic units ARG (argillite), MII (metaigneous intrusive rocks of intermediate composition), MIM (metaigneous intrusive rocks of mafic composition), and TRI (sedimentary rocks of Triassic age) each had fewer than 15 observations having the necessary data (depth, diameter, yield, topography) to adjust the yields. Rather than omit these units from the analysis of yield by hydrogeologic unit, the data were grouped according to their primary lithologic category (metaigneous, metavolcanic, metasedimentary, and sedimentary) so that the units represented by low numbers of wells could be included in the comparison. Daniel (1989, fig. 13) ranked average yields from hydrogeologic units in the Piedmont and Blue Ridge and found that igneous and metaigneous rocks clustered in the rankings. The hydrogeologic unit TRI had the lowest average yield and was alone at the bottom of the ranking.

In table 6, the metaigneous and metavolcanic units are grouped into two categories—MI and MV. The metasedimentary rocks are represented by the unit PHL (phyllite), because no wells in the data base tapped the unit ARG (argillite); the unit TRI forms a fourth category. Although the unit PHL is considered to be metasedimentary rock because of its fine grain size and abundant sericite, it may include alteration products of other units that have been highly sheared.

Analysis of variance was used to determine whether hydrogeologic units differed in terms of yield. Analysis of variance tests first were run on the ungrouped data. Because the average yields of all hydrogeologic units are not very different and the range of yields within units is very large, no units were found to be statistically different (at the 0.95-confidence level). Additional tests were run using lower confidence levels; the probability that the average yields of any units are significantly different is less than 30 percent. Analysis of variance tests then were run to compare the four categories of grouped data presented in table 6. Again, no units were found to be statistically different at the 0.95-confidence level. When additional tests were run, the probability that the average yields of the grouped data were significantly different was found to be less than 10 percent.

It is important to note that the unadjusted yields and construction characteristics of wells tapping the unit TRI are quite different from the unadjusted yields and construction characteristics of wells tapping metamorphic rocks in Orange County. The average depth of wells tapping metamorphic rocks is 208 ft, and the average well diameter is 6.25 in. The average unadjusted yield (from raw data) is 17.6 gal/min, which is not much different from the adjusted yields shown in table 6. On the other hand, the average depth of wells tapping the unit TRI, including wells in adjacent Durham and Chatham Counties, is 117 ft and the average well diameter is 5.93 in. The average unadjusted yield is only 7.4 gal/min. The low yield of wells tapping the unit TRI may, in part, be attributed to their shallow depth. It is more likely, however, that the low yield and shallow depth are characteristic of sedimentary rocks in the Triassic rift basins of the eastern Piedmont, which have the lowest yields of any hydrogeologic unit in the Piedmont of North Carolina (Daniel, 1989, 1990). Drilling deeper wells is no guarantee for obtaining higher yields. The TRI unit, however, is found only in a relatively small area of southeastern Orange County where municipal water supply generally is available.

Estimate of Available Ground Water

Conservationists, planners, and potential developers 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, planners must know the amount of water that can be withdrawn without overdrafting water in long-term storage—the yield 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 in Orange County, the USGS began a study in 1995 in cooperation with Orange County to assess recharge to the regolith-bedrock aquifer system in the County. The results of this study were published in 1996 (Daniel, 1996). As part of the 1995 study, ground-water recharge was estimated for selected drainage basins by using streamflow data and an analytical technique known as hydrograph separation. The computer program developed by Sloto (1991) to perform the Pettyjohn and Henning (1979) local minimum method was used to make the estimates. The recharge estimates were analyzed, and 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 (Searcy, 1959). The selected drainage basins for which recharge characteristics were determined are shown in figure 1. Also described in the Daniel (1996) report are methods for evaluating quantities of ground water in storage beneath tracts of land. Examples are presented for illustrating use of the recharge estimates, in conjunction with ground-water storage data, for ground-water management and planning.

Statistical summaries of annual recharge, monthly recharge, and recharge duration estimates are presented by Daniel (1996) for 12 selected drainage basins and subbasins that include all of the land area of Orange County. Presentation and discussion of the estimates are organized by drainage basin to better define the areal distribution of these characteristics within the County.

Recharge

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 ultimately is limited by the availability of this resource. In Orange County, ground water is available from wells tapping the regolith-crystalline rock 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-crystalline rock 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 is released from storage in the aquifer to springs, streams, lakes, and pumped 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—must be evaluated. Understanding the sustained yield of the ground-water system depends upon knowledge of recharge areas and recharge rates.

Nearly all of the data used in this evaluation were derived from base-flow analyses of streamflow records collected at 17 streamflow gaging stations located in and around Orange County (fig. 1; table 7). 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, all of which affect infiltration. Because conditions in drainage basins are rarely uniform throughout the entire basin, regional estimates may not precisely quantify recharge in all areas.

Ground-water recharge rates in 12 Orange County drainage basins and subbasins are compared in figure 8. The box plots summarize the recharge duration characteristics of the 12 basins and subbasins. Recharge rates that will be equaled or exceeded 90-,

Table 7. Gaging stations that record streamflow within and from Orange County, N.C. (from Daniel, 1996, table 1)

[The period of record shown in the table is the period used for the ground-water recharge analysis. mi^2, square miles]

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	02097314[b]	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	02096850[c]	Cane Creek near Teer	35°56'34"	79°14'46"	33.7	1960–73
8	02097000[c]	Haw River near Pittsboro	35°42'07"	79°05'12"	1,310	1929–73
9	02097500[c]	Morgan Creek near Chapel Hill	35°53'51"	79°05'28"	30.1	1924–31
10	02098000[c]	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 Secondary Road 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	02085220[c]	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 is defined by the USGS as the period from October 1 through September 30 and is identified by the calendar year in which it ends.

[b] Approximately 11 cubic feet per second of water from the Neuse River discharged into New Hope Creek.

[c] Discontinued.

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 (inches per year) or 311 [gal/d]/acre (gallons per day per 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 (upstream from sites 5 and 6, fig. 1) 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 is 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 or 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 that 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 also on land use and land cover. In general, the highest recharge rates and infiltration capacities are in forested areas; the lowest are in urban areas. Agricultural land

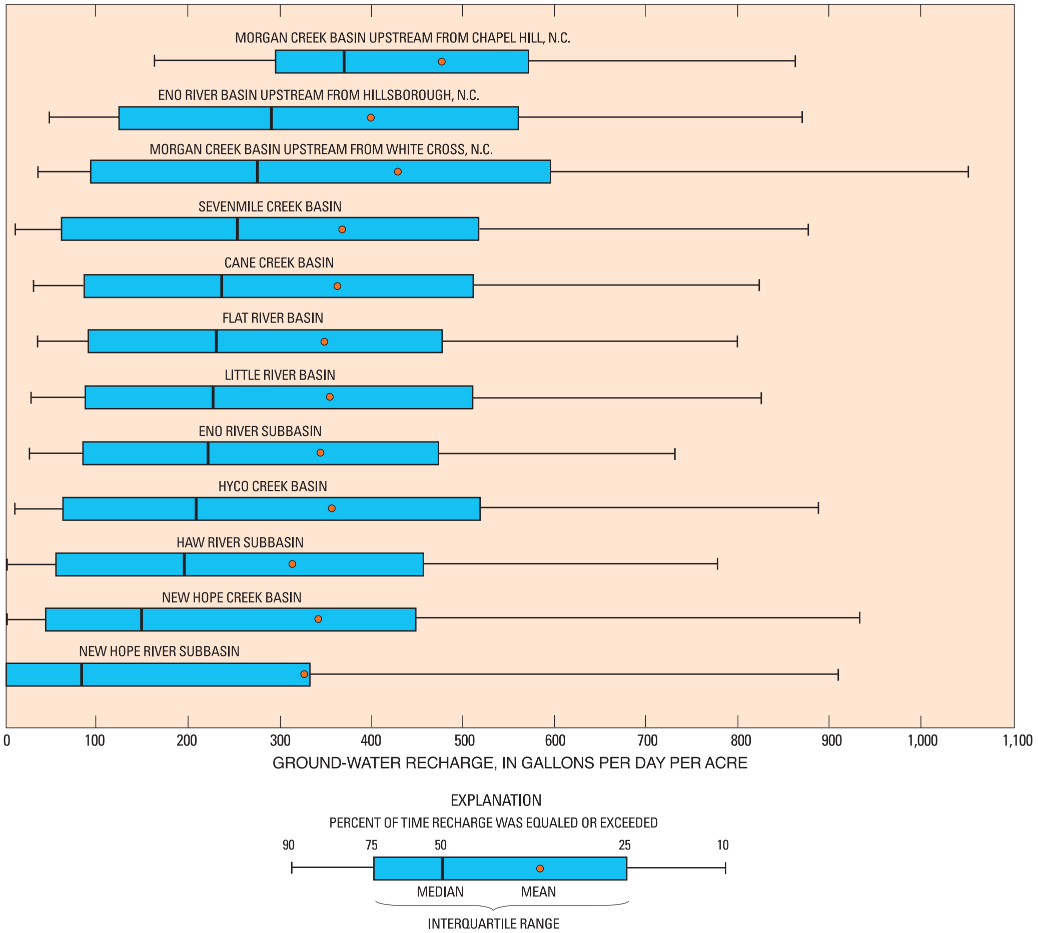

Figure 8. Selected ground-water recharge duration characteristics and mean recharge in 12 basins and subbasins in Orange County, N.C. (from Daniel, 1996, fig. 19).

uses typically are intermediate. Topography also is 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) units predominate (fig. 2; table 1). The fact that more than half (62 percent) of the County is underlain by metavolcanic rocks that 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. Farther downstream, however, where a stream channel is 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 is 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, Morgan Creek 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.

The relation between hydrogeologic units and ground-water recharge perhaps is 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 or 324 [gal/d]/acre) and the lowest median recharge (1.08 in/yr or 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 indicate 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. These results are consistent with the work of Daniel (1989, 1990) and Daniel and Payne (1990), which 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.

Ground-Water Storage

Nearly all ground-water storage in the Piedmont ground-water system is in the regolith. The quantity of water stored in the bedrock is small by comparison. Ground-water levels vary seasonally; levels decline during summer and early fall when atmospheric conditions enhance evaporation and plants transpire substantial quantities of water, and rise during winter and early spring when plants are dormant. The decadal hydrograph from observation well NC-126 in Orange County indicates a seasonal range of water-level change of about 4–6 ft (fig. 9A), with the upper and lower whiskers (fig. 9B) indicating a 12-ft range in water levels over the past 62 years; thus, the average saturated thickness of the regolith can vary by 4 to 12 ft. Year-to-year variations, however, usually are small; on an annual basis, ground-water storage in the study area probably is 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 April, May, or June (fig. 9B). This 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 was reported by Daniel and others (1997) for 36 wells tapping regolith and bedrock in the southwestern Piedmont of North Carolina. However, peak recharge in that region usually occurs during the months of February through April, and the highest ground-water levels typically 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.

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. The climate throughout Orange County, however, is relatively uniform, and the water-bearing properties of the hydrogeologic units 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.

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

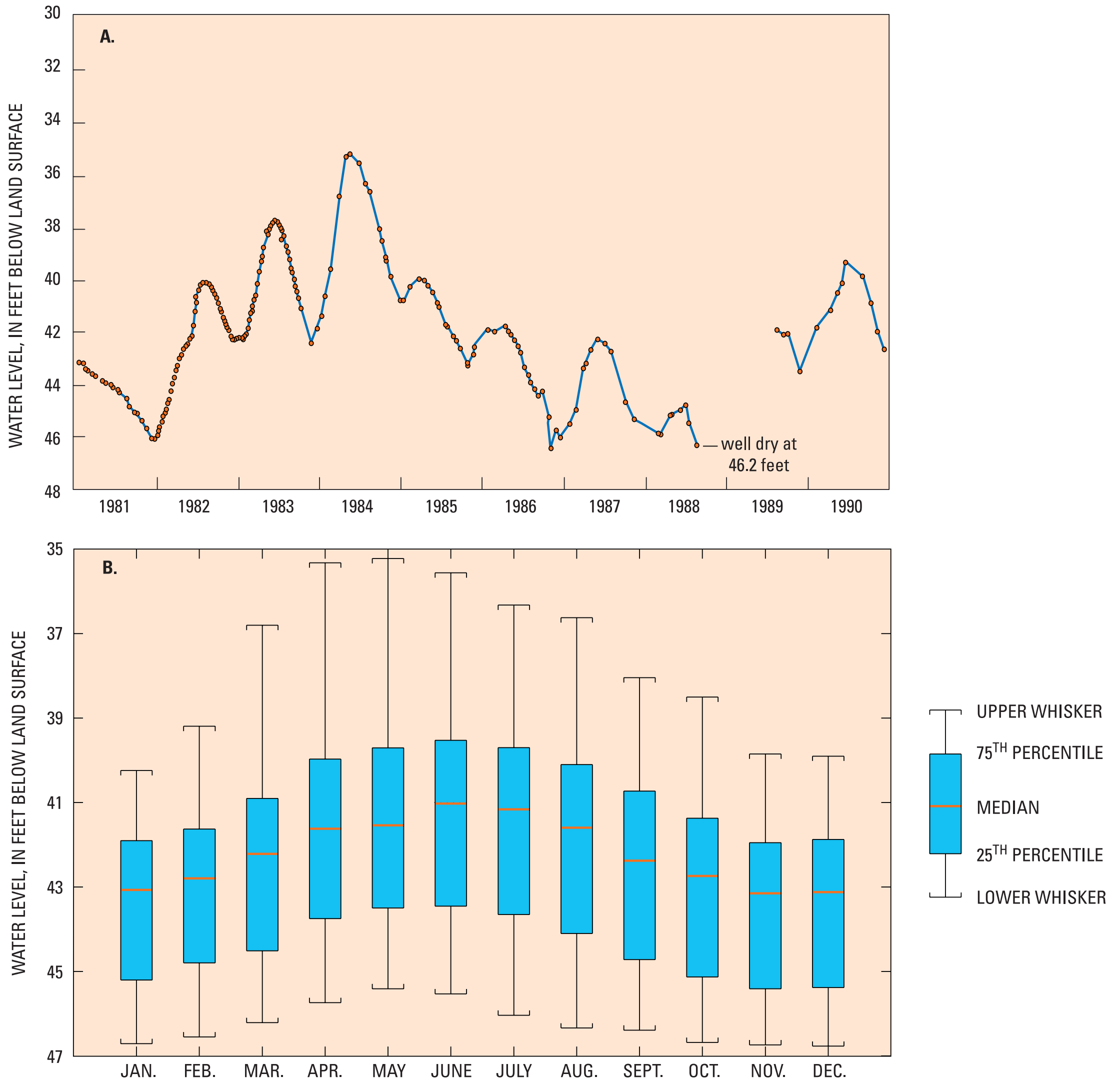

Figure 9. Water-level data from Orange County observation well NC-126 showing (A) decadal hydrograph for the period 1981–90, and (B) box plots of monthly water-level data for the period 1938–99.

bottom of the casing, the saturated thickness of regolith is set equal to zero. Table 4 presents a statistical summary of data for wells in different topographic settings in Orange County. The saturated thickness of regolith is greatest beneath hills and ridges (average 33.4 ft) and least beneath valleys and draws (average 22.8 ft). The saturated thickness of regolith beneath slopes (average 26.5 ft) is intermediate to these extremes. The average saturated thickness of regolith for all wells is 27.2 ft.

The quantity of ground water available from regolith storage in Orange County can be estimated from the following general relation:

$$\text{ground water available in storage} = \text{saturated thickness of regolith} \times \text{specific yield} \qquad (1)$$

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 film on rock surfaces. Based on average thicknesses of saturated regolith (table 4) and the relations in figure 4B, the average quantity of available water in storage in Orange County is approximately 1.3 Mgal/acre (million gallons per acre) beneath hills and ridges, 0.9 Mgal/acre beneath slopes, and 0.7 Mgal/acre beneath valleys and draws. The average quantity of water available beneath all sites is 0.9 Mgal/acre.

The specific yield to be used in the above storage computation can be derived from the relation shown in figure 4A. 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.

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, most noticeably at the base of the saprolite and across the transition zone. Consequently, equation 1 will be nonlinear, and a plot of this relation will be nonlinear as shown in figure 4B. The quantity of water available from storage can be estimated from figure 4B. It is worth noting, however, 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 and Thomas, 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 4B, water available from storage in the saprolite follows a more or less linear part of the relation with a specific yield of about 20 percent (fig. 4A). Therefore, both the annual and period of record change in potential yield in the saprolite can be estimated by the linear equation:

$$\begin{aligned}&\text{ground water available in storage}\\&\quad= 0.20 \times \text{change in water table}\end{aligned} \qquad (2)$$

Based on this equation and a 4- to 12-ft variation in the water table, the quantity of water in storage can increase or decrease by 0.8 to 2.4 ft^3/ft^2 (cubic feet per square foot) of aquifer area (0.3 to 0.8 Mgal/acre).

Sufficient similarities exist between the Piedmont of northeastern Georgia and the eastern Piedmont of North Carolina that this information can be used with reasonable confidence. The depth of weathering, lithology of the underlying bedrock, and geologic structures are similar in both areas. Additional discussion of techniques for determination of the quantity of ground water available from storage and, in particular, storage in the regolith can be found in Daniel (1996).

Distribution of Ground-Water Use

Data regarding sources of household water supply by census block were compiled from the 1990 census and analyzed to evaluate the use of ground water within the County. According to the U.S. Bureau of the Census (1992), ground water is used by approximately 41 percent of the population of Orange County. This is less than the approximately 47 percent of the population in the North Carolina Piedmont that relies on ground water for potable supplies; however, when the data are analyzed at the scale of census blocks, it is apparent that ground-water use by the rural population approaches 100 percent over a large area of the County.

The relative percentages of the County’s population served by ground-water and surface-water sources were determined based on census-block population, the number of housing units, and the number of housing units that have wells. Most of the 59 percent of the Orange County population that use surface-water-based public supplies live in Chapel Hill, Carrboro, Hillsborough, and outlying areas of these towns. In the southeastern part of the County, residents of Chapel Hill, Carrboro, and some contiguous residential areas are supplied water by Orange Water and Sewer Authority (OWASA). OWASA draws raw water from University Lake and the Cane Creek Reservoir (fig. 1). In the center of the County, residents of Hillsborough and contiguous residential areas are supplied water by the town of Hillsborough, which draws water from the Eno River and indirectly from Lake Orange, which provides storage upstream from the treatment plant intake. In the western part of the County, a number of residents living in an area generally north of Interstate 85 between the city of Mebane and the village of Efland (fig. 1) are supplied water by the Orange-Alamance Water System. Nearly everywhere else in the County, residents use ground water as a source of supply.

The distribution of ground-water-based supplies can be shown in several ways, but perhaps two of the most informative ways are maps showing the number of wells per square mile by census block (fig. 10) and the percentage of housing units served by wells by census block (fig. 11). In figure 10, the estimated number of wells per square mile was computed by dividing the number of housing units served by wells (assuming one well per household) by the area of the census block in square miles. This computation adjusts for differences in the areas of the census blocks. In figure 11, the percentage of housing units that are served by wells in a census block is simply the ratio of the number of housing units served by wells to the total number of housing units, expressed as a percentage.

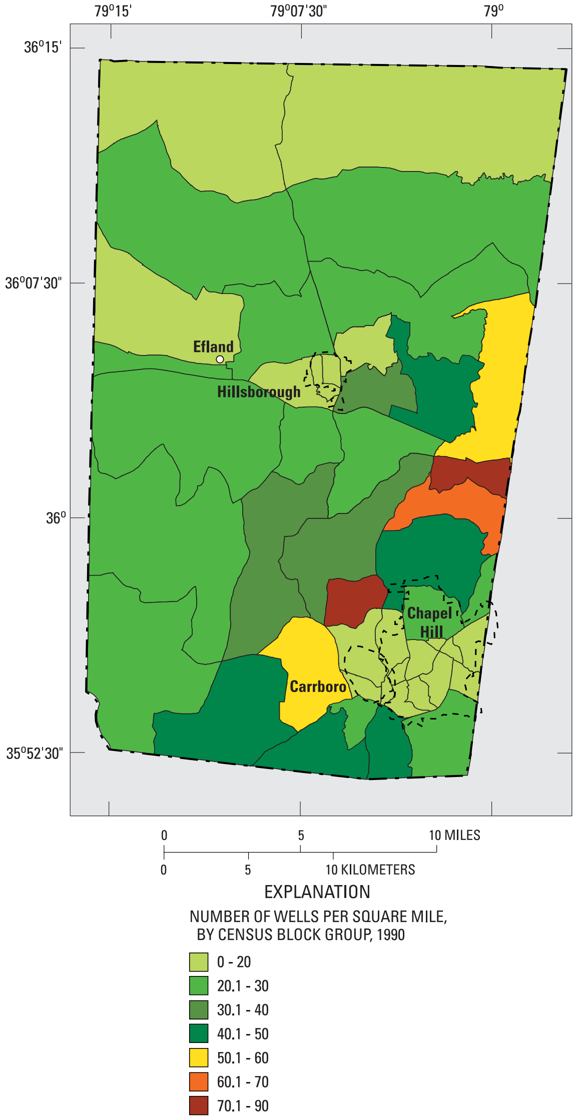

Figure 10. Number of wells per square mile in Orange County, N.C., 1990.

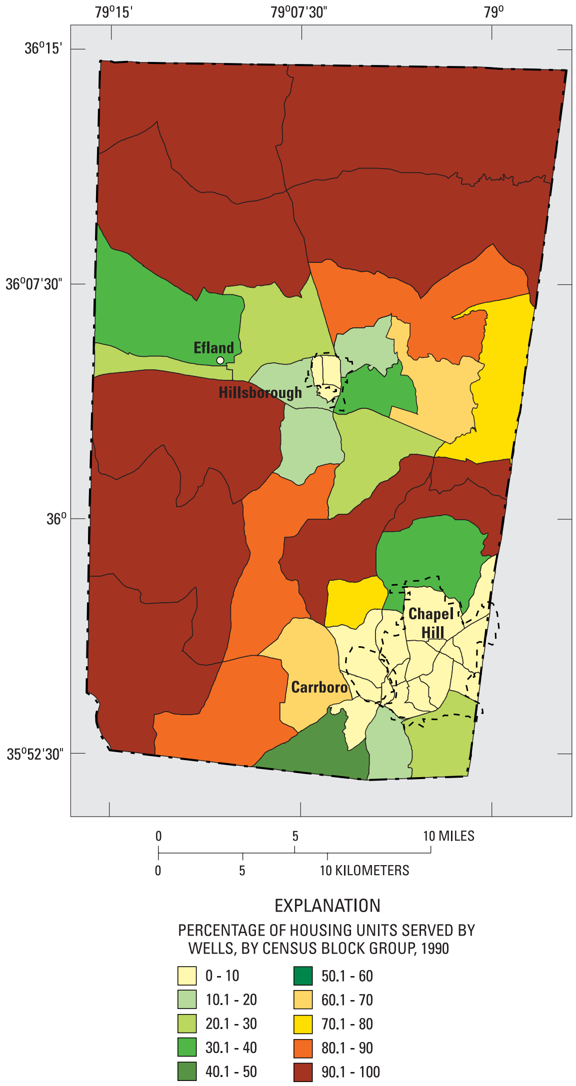

Figure 11. Percentage of housing units served by wells in Orange County, N.C., 1990.

The number of wells per square mile by census block ranges from fewer than 10 to more than 80. The lowest number of wells per square mile (fig. 10) occurs in four general areas—(1) in and near Chapel Hill and Carrboro in the southeastern part of the County, (2) in and near Hillsborough in the center of the County, and (3) around and west of Efland in the west-central part of the County, and (4) in the rural farming area in the northern part of the County. The highest numbers of wells per square mile occur in areas north, northwest, west, and southwest of Chapel Hill and Carrboro, and east of Hillsborough. The remainder of the County, for the most part, extending in a broad band from the northeast corner to the southwest corner has a moderate density of wells ranging from 20 to 30 wells per square mile (fig. 10).

The percentage of housing units served by wells by census block is a measure of the relative number of housing units that obtains water from ground-water or surface-water sources and accounts for differences in housing density within census blocks. As shown in figure 11, the lowest percentage of housing units served by wells (0–10 percent) occurs within and adjacent to Chapel Hill and Carrboro in the southeastern part of the County, and in Hillsborough in the center of the County. Intermediate to the urban centers and the more rural parts of the County are census blocks supplied by a mixture of wells and surface-water sources. In census blocks nearly surrounding Chapel Hill and Carrboro, and in a band extending across central Orange County from the Durham County line east of Hillsborough to the Alamance County line west of Hillsborough, the number of housing units supplied by wells ranges from 10 to 80 percent. Throughout the remainder of the County, more than 90 percent of the housing units are supplied by wells.

GROUND-WATER QUALITY

This section of the report summarizes the susceptibility of ground water to contamination and uses historical data and data from 51 wells sampled during this investigation to describe the chemical quality of the County's ground water. An inventory of potential contaminant sources is presented for use as a management tool by Orange County planners and resource managers. The relative susceptibility of ground water to contamination from the surface and shallow sources has been investigated by Terziotti and Eimers (1999).

Contaminant-Source Inventory

For any planning exercise with the purpose of using or protecting the ground-water resource, it is important to document the type and location of potential contaminant sources. Potential contamination sources primarily were identified from existing data bases. Only underground storage tank (UST) locations were field verified by the USGS.

Sites of National Pollutant Discharge Elimination System (NPDES)-permitted and other point discharges on June 28, 1994, were obtained from the North Carolina Department of Environment and Natural Resources (DENR) at a scale of 1:24,000 (North Carolina Department of Environment and Natural Resources, 1994a). Locations of active municipal solid-waste landfills in March 1994 were obtained from the North Carolina Division of Waste Management, DENR, at a scale of 1:24,000 (North Carolina Department of Environment and Natural Resources, 1994b). The locations of treatment, storage, and disposal facilities (TSDF’s), regulated under the requirements of the Resource Conservation and Recovery Act, were determined from a data base from the North Carolina Center for Geographic Information and Analysis (CGIA). These locations are not field verified and were current only through 1990. Locations of uncontrolled and unregulated, hazardous-waste sites (formerly called superfund sites) were determined from the U.S. Environmental Protection Agency (USEPA) Comprehensive Environmental Response, Compensation, and Liability Act Information System (CERCLIS), the National Priorities List, the State Inactive Hazardous Sites List (from DENR), and the Sites Priority List (from DENR). These data are current through 1996 and also were not field verified. UST locations were obtained from DENR. UST's were field located by using a Rockwell precise lightweight global positioning system receiver (PLGR) in North American Datum 1927 (NAD27) units with an estimated accuracy of no more than plus or minus (+/–) 10 meters in the horizontal. Locations then were converted to North American Datum 1983 (NAD83) units and projected to state plane coordinates. Potential contamination sources in Orange County are presented in figure 12.

Susceptibility to Contamination

The susceptibility of ground water to contamination from surface and shallow sources was determined countywide by using a layered GIS evaluation approach. A detailed description of this technique is described in Terziotti and Eimers (1999) and summarized herein. Three contributing factors were used to compute the relative susceptibility index—soil permeability, land use/land cover, and land-surface slope. Each contributing factor was derived from individual GIS spatial data layers, or from the analytical combination of more than one GIS layer. Harmonic mean permeability (HMP) is determined for each soil zone from data obtained in the U.S. Department of Agriculture Natural Resources

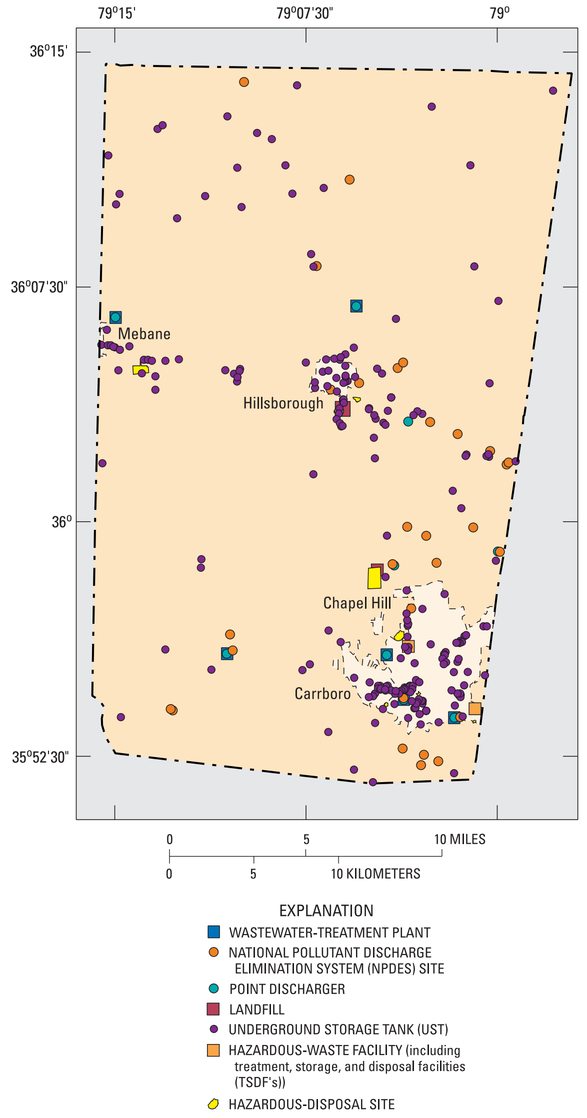

Figure 12. Surface or shallow sources of potential contamination to the ground-water system, Orange County, N.C.

Conservation Service Soil Survey Geographic data base. HMP was defined as the harmonic mean of the log mean permeabilities calculated for each of the four soil layers in any given location. Land use/land cover was determined from the Multi-Resolution Land Characterization data base. The primary source for this data base is Landsat imagery collected between 1990 and 1993 and stored at a 30-meter resolution. Land-surface slope was determined from analysis of a digital elevation model generated by the USGS.

This process results in map layers representing soil permeability, land use/land cover, and land-surface slope. The ranges of permeability, land-use/land-cover characteristics, and ranges of land-surface slope are assigned a contamination potential rating that contributes to an overall relative susceptibility value. These ratings were used by Terziotti and Eimers (1999) to generate a countywide map of relative susceptibility to ground-water contamination from surface and shallow subsurface sources (fig. 13). In general, areas of high relief, low permeability, and forested land use have the lowest susceptibility to ground-water contamination. Areas of low relief, high permeability, and a high-risk land use, such as landfills or UST's, have the highest potential for ground-water contamination. The relative susceptibility index for about

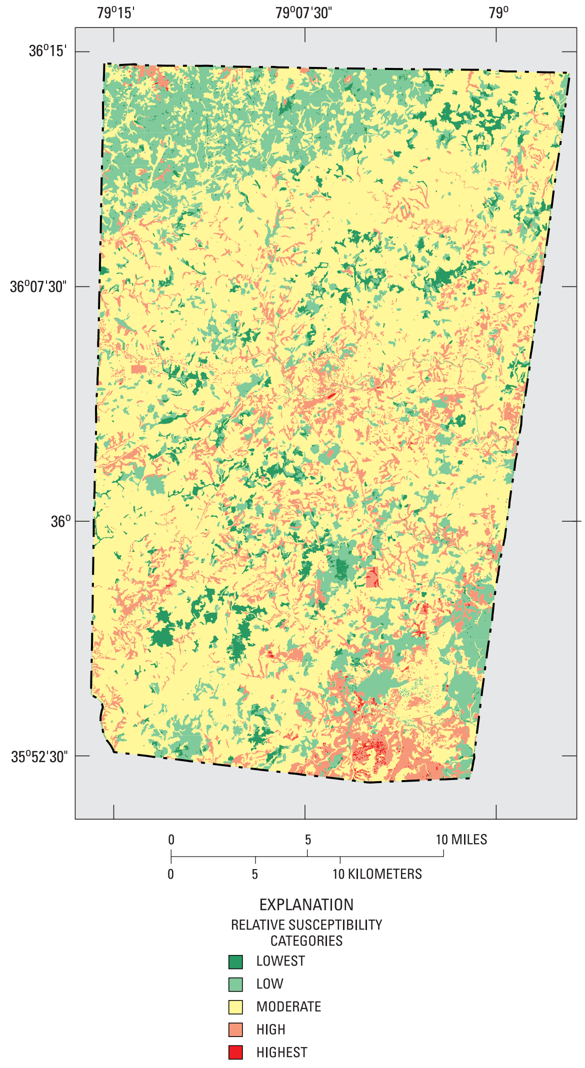

Figure 13. Relative susceptibility to ground-water contamination from surface or shallow subsurface sources, Orange County, N.C. (from Terziotti and Eimers, 1999).

12 percent of the area in Orange County was categorized as high or highest. About 21 percent of the County was ranked as low or lowest potential for ground-water contamination (Terziotti and Eimers, 1999).

Previous water-quality investigations in Orange County are sparse. Bain and Thomas (1966) presented results from 11 wells with a limited suite of analytes. Briel (1997) used these data, along with thousands of analyses from throughout the Appalachian Piedmont and Mountains region of the Eastern United States to characterize the regional ground-water quality. Additional ground-water-quality data were obtained from the North Carolina Division of Water Quality, Groundwater Section, DENR.

The historic water-quality data for Orange County generally are limited to standard anion and cation analyses. Historic data are available from 1950 to 1978 (table 8). The comparability of historic water-quality data can be problematic because methods for sample collection and analytical techniques typically are poorly documented or unknown. These data, however, can be useful in making general comparisons to more recent analyses. If an analysis is complete (concentrations of all major ionic species measured) and analytical error is small, the sum of the milliequivalents per liter of cations should be approximately equal to the sum of the milliequivalents per liter of anions. The nearness to this standard is a good means of testing the acceptability of an analysis. Historic chemical analyses with cation/anion sums within 5 percent were used in this report.

Historic ground-water-quality data for Orange County indicate a mixed cation bicarbonate water type (fig. 14). The median water-quality sample has a pH of 6.7, and is soft, with a hardness of 75 mg/L (milligrams per liter) calcium carbonate ($CaCO_3$). The median sample contains 84 mg/L dissolved solids and has a specific conductance of 119 µS/cm @ 25 °C (microsiemens per centimeter at 25 degrees Celsius). Although water from well OR-072 had high specific conductance (552 µS/cm) and very high nitrate (75 mg/L) concentrations (table 8), ground water in Orange County was found overall to be of good quality (Bain and Thomas, 1966).

Water-Quality Methods

Fifty-one sampling locations were selected among new wells inspected by Orange County

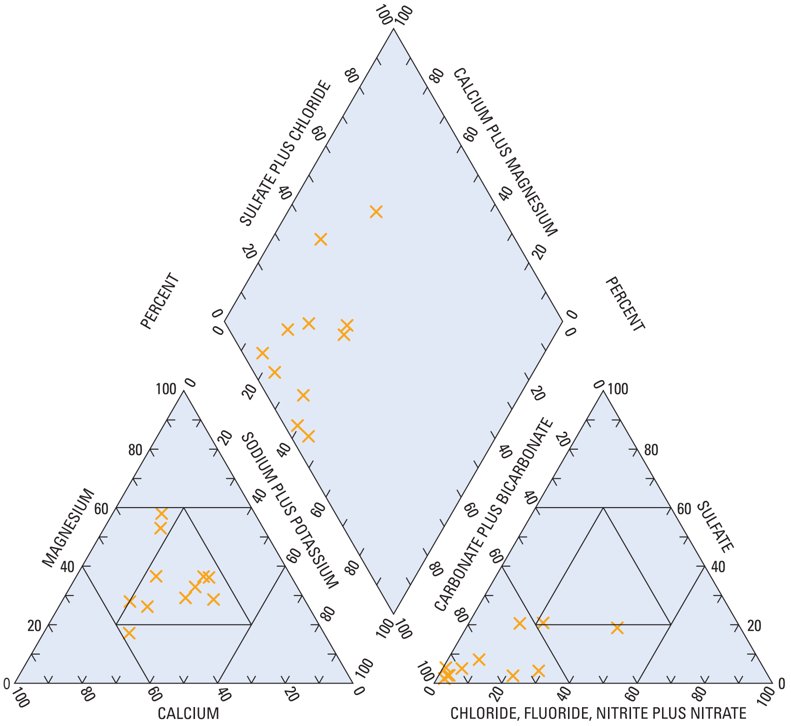

Figure 14. Selected historic ground-water-quality data, Orange County, N.C.

Table 8. Selected historic ground-water-quality data, Orange County, N.C.

[—, not reported; µS/cm, microsiemens per centimeter at 25 degrees Celsius; ANC, acid neutralizing capacity; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Data	OR-004	OR-011	OR-019	OR-029	OR-031	OR-039	OR-047	OR-053	OR-059	OR-072	OR-076	OR-683	OR-684	OR-685
Date	12/18/62	12/18/62	12/18/63	12/18/62	12/18/62	12/18/62	6/6/50	12/18/62	12/18/62	12/18/62	12/18/62	8/29/78	6/6/74	9/14/76
Depth of well, total (feet)	76	86	62	87	72	200	40	45	76	70	140	320	—	—
Specific conductance (µS/cm)	107	73	132	90	131	67	136	76	83	552	262	—	—	130
pH water, whole field (standard units)	6.6	6.5	7.1	6.8	6.6	6.7	6.4	6.3	6.4	6.5	7.2	7.8	8.1	6.9
ANC water, unfiltered fixed endpoint titration field (mg/L as HCO_3)	54	30	46	52	44	36	66	28	40	83	127	—	—	80
Nitrogen, nitrate dissolved (mg/L as NO_3)	.8	1.1	.4	.1	5.2	1.1	1.6	.7	.4	75	.0	—	—	—
Phosphate, total (mg/L as PO_4)	.1	.1	.0	.0	.4	.2	—	.0	.1	.1	.2	—	—	—
Hardness, total (mg/L as $CaCO_3$)	32	18	54	34	41	18	58	20	26	198	101	156	156	50
Calcium, dissolved (mg/L as Ca)	6.9	2.9	6.9	5	7.7	3.4	15	3.4	5.4	51	31	54	53.2	—
Magnesium, dissolved (mg/L as Mg)	3.5	2.6	8.8	5.3	5.1	2.2	4.9	2.9	3	17	5.6	5.2	5.6	—
Sodium, dissolved (mg/L as Na)	8.1	5.3	4.1	3.1	10	6.4	4.2	5.6	3.6	32	15	—	10	7
Potassium, dissolved (mg/L as K)	.1	.1	.1	.1	1.4	.1	4.2	.1	.1	.2	1.1	—	.4	.24
Chloride, dissolved (mg/L as Cl)	2	.4	10	1	6	.2	4.1	7	.2	59	21	5	4	2.0
Sulfate, dissolved (mg/L as SO_4)	2.4	.4	13	1.2	11	.8	5.1	1.4	1.8	34	3.4	—	—	—
Fluoride, dissolved (mg/L as F)	.0	.0	.1	.0	.0	.2	.1	.0	.0	.1	.3	.14	.19	.2
Silica, dissolved (mg/L as SiO_2)	40	23	15	29	16	33	27	19	22	42	39	—	—	15
Arsenic, dissolved (µg/L as As)	—	—	—	—	—	—	—	—	—	—	<10	<10	—	—
Cadmium, dissolved (µg/L as Cd)	—	—	—	—	—	—	—	—	—	—	<10	<10	—	—
Chromium, dissolved (µg/L as Cr)	—	—	—	—	—	—	—	—	—	—	—	<50	<50	<40
Copper, dissolved (µg/L as Cu)	—	—	—	—	—	—	—	—	—	—	—	<50	<50	—
Iron, total recoverable (µg/L as Fe)	40	620	360	2,000	80	200	990	1,300	100	40	140	150	<50	<50
Lead, dissolved (µg/L as Pb)	—	—	—	—	—	—	—	—	—	—	<50	<50	<40	—
Manganese, total recoverable (µg/L as Mn)	.0	10	40	.0	30	.0	.0	10	20	10	40	210	130	<50
Lithium, suspended recoverable (µg/L as Li)	.0	.0	.0	.0	.1	.0	—	.0	.0	.1	.1	—	—	50
Zinc, dissolved (µg/L as Zn)	—	—	—	—	—	—	—	—	—	—	—	180	10	—
Aluminum, total recoverable (µg/L as Al)	.0	.0	100	100	200	.0	—	.0	.1	.1	.0	—	—	<100
Solids, sum of constituents, dissolved (mg/L)	91	51	82	71	85	66	99	54	57	353	180	—	—	94
ANC unfiltered titration 4.5 lab (mg/L as $CaCO_3$)	—	—	—	—	—	—	—	—	—	—	—	152	158	66

Health Department staff during 1996–98 based on (a) countywide areal distribution, (b) weighted distribution among hydrogeologic units, and (c) permission from homeowners. Wells were located by using a global positioning system and were plotted on a hydrogeologic unit map (fig. 15). Hydrogeologic units were grouped into felsic and mafic categories in order to have populations sufficient for statistical comparison. The sampling distribution and the distribution of hydrogeologic units by land area are presented in table 9. Samples were collected from December 1998 through January 1999. At all 51 wells, physical properties were measured in the field, and samples were collected for analysis of major ions, nutrients, organic compounds (total benzene, toluene, ethylbenzene, and xylene [BTEX] and atrazine), and radon. Samples for metals and trace elements were collected at 31 of the 51 wells (fig. 15).

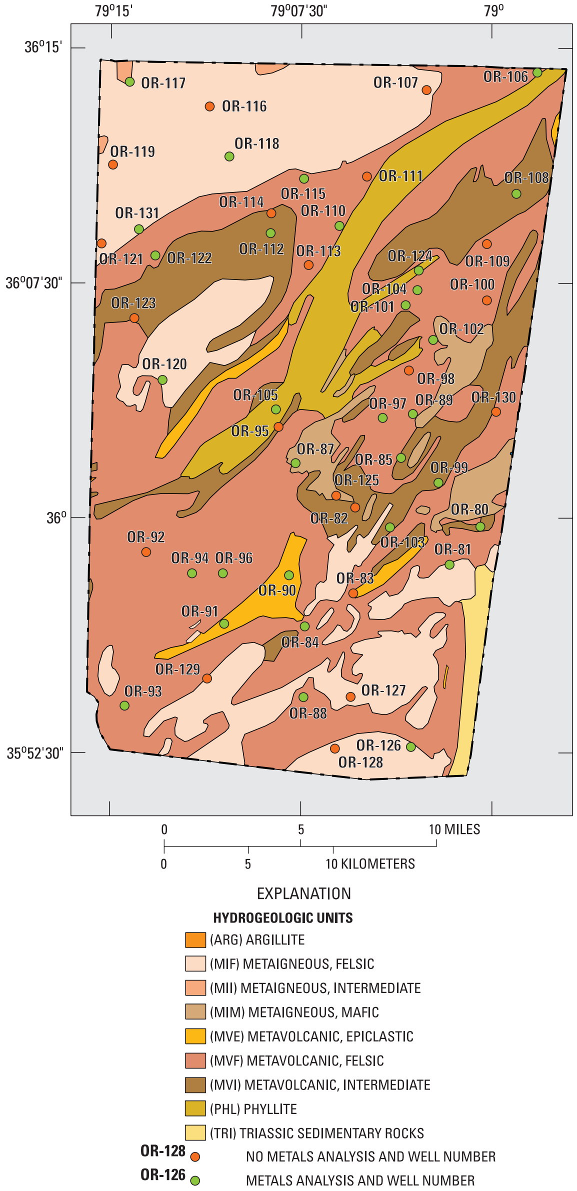

Figure 15. Hydrogeologic units and locations of wells sampled from December 1998 through January 1999, Orange County, N.C.

The water level in each well was measured by using a graduated steel tape. Well depth and casing length were obtained from well-construction logs in Orange County files. Wells were purged until measured physical properties stabilized. Field-measured physical properties were considered to be stable when five consecutive measurements, each separated by 5 minutes, had pH values within +/– 0.2 unit, temperature within +/– 0.5 °C, and specific conductance within +/– 5 percent for values less than 100 µS/cm and +/– 3 percent for values greater than 100 µS/cm. Physical properties were measured with a Hydrolab minisonde instrument recording dissolved oxygen, percent dissolved oxygen saturation, pH, oxidation-reduction potential, temperature, and specific conductance. Measurements of physical properties were recorded automatically at 30-second intervals on a laptop computer connected to the minisonde instrument. Dissolved oxygen, pH, and specific conductance probes were calibrated daily before the site visit. An Orion pH meter was used for incremental alkalinity titrations. Final measurements of physical properties were recorded on field sampling forms at the time of sample collection and are on file at the USGS District office in Raleigh, N.C.

All domestic wells were sampled from hose bibs at the wellhead before the water entered the home distribution system. Hoses and fittings used to obtain samples were washed in soap and water, rinsed, soaked in 5-percent hydrochloric acid for 30 minutes, rinsed in deionized water, and stored in plastic containers at the District laboratory. Samples for analysis of dissolved constituents were filtered through a 0.45-micron disposable capsule filter by using a peristaltic pump. Capsule filters were conditioned in the field with 1 liter of deionized water prior to sample collection.

Because radon is highly volatile, these samples were collected by using special procedures to prevent radon degassing. A radon-specific sampling hose was attached at the wellhead, and air was removed from the hose. A 40-mL (milliliter) syringe was filled in excess of 15 mL and evacuated twice. The syringe was filled a

Table 9. Relative areas of hydrogeologic units in Orange County, N.C. (from Daniel and Payne, 1990), and wells sampled from December 1998 through January 1999

[NA, not applicable]

Hydrogeologic unit map symbol (fig. 2)	Geologic description	Percent area	Wells sampled	Percentage of samples	Grouped hydrogeologic units
MVF	Metavolcanic, felsic	45.2	21	41	Felsic
MIF	Metaigneous, felsic	25.9	13	26	Felsic
MVI	Metavolcanic, intermediate	14.5	9	17	Mafic
MVE	Metavolcanic, epiclastic	2.2	3	6	Mafic
PHL	Phyllite	7.2	2	4	Felsic
MIM	Metaigneous, mafic	3.5	2	4	Mafic
MII	Metaigneous, intermediate	.2	1	2	Mafic
TRI	Triassic sedimentary	1.2	0	0	NA
ARG	Argillite	.1	0	0	NA

third time, and discharged to 12 mL. The syringe then was inserted into mineral oil contained in a 20-mL vial, and 10 mL was discharged into the mineral oil, leaving 2 mL in the syringe. The vial then was sealed and agitated to emulsify the oil and water mixture. The radon samples were shipped unchilled to the USGS National Water Quality Laboratory in Denver, Colo. Samples for major ions, trace metals, and nutrients were stored on ice and shipped overnight to the USGS analytical laboratory in Ocala, Fla. Immunoassay samples were stored on ice and analyzed at the District laboratory. Alkalinity titrations were done in the field.

Samples were analyzed by using standard laboratory analysis techniques. The list of chemical constituents, reporting units and levels, analytical methods, and regulatory limits used for this report are presented in table 10.

In addition to the collection of environmental samples, quality-assurance samples also were collected. Nine blank samples were collected, including six equipment blanks and three ambient blanks. Blank samples were analyzed for common ions, nutrients, and trace elements. Most constituents were not detected in the blank samples. Among the major ions, chloride concentrations were detected in three blank samples in a range from 0.1 to 1.1 mg/L, and silica concentrations were present in six blank samples in a range from 0.01 to 0.08 mg/L. Among the nutrients, phosphorus was detected in two blank samples in concentrations of 0.02 and 0.03 mg/L. Ammonia and orthophosphate were detected in one blank sample at concentrations of 0.016 and 0.01 mg/L, respectively. Among the trace elements, iron was detected in two blank samples at 1.1 and 2.1 µg/L, and zinc was present in one sample at a concentration of 4.4 µg/L. The quality-assurance data do not indicate problems with any of the constituents except ammonia. The one detection of ammonia in a blank sample exceeded 8 of the 21 ammonia detections countywide.

Water-Quality Results

Laboratory and field analyses of water samples from 51 wells are summarized in the following sections. Complete laboratory results are available in the appendix. Analyses were evaluated by the total sample set, which includes seven of the nine hydrogeologic units in the County, by individual hydrogeologic units, and by hydrogeologic units grouped into felsic (containing light-colored quartz, feldspars, muscovite) rocks and mafic (containing dark-colored iron and magnesium-rich minerals) rocks.

Many variables may have an effect on the water-quality characteristics of an individual sample. For instance, hydrogeologic unit, well depth, residence time of the ground water, anthropogenic effects, casing and pump materials, and the mineralogy of the producing fractures can affect water quality. The hydrogeologic mapping available in Orange County is two dimensional, meaning that the hydrogeologic map presents the inferred geology at the bedrock surface. The hydrogeologic unit present at depth is assumed to be that which is mapped as the bedrock surface, but this

Table 10. List of chemical constituents, reporting units and levels, analytical methods, and regulatory limits, Orange County, N.C.

[USEPA, U.S. Environmental Protection Agency; MCL, Maximum Contaminant Level; NC, North Carolina; SMCL, secondary maximum contaminant level; NA, not applicable; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; ICP, inductively coupled plasma; AA, atomic absorption; IC, ion chromatography; ISE, ion selective electrode; GFAA, graphite furnace atomic absorption; µg/L, micrograms per liter, pCi/L, picocuries per liter]

Parameter code	Chemical constituent	Analytical method	Reporting unit	Reporting level	USEPA MCL[a] (if applicable)	NC MCL[b] or SMCL (if applicable)
		PHYSICAL AND CHEMICAL PROPERTIES				
00010	Water temperature, field	Thermistor	degrees Celsius	0.5	NA	NA
00095	Specific conductance, field	Electrometric	µS/cm at 25 °C	1	NA	NA
00300	Dissolved oxygen, field	Electrometric	mg/L	0.1	NA	NA
00400	pH, field	Electrometric	standard units	0.1	NA	NA
00453	Bicarbonate, dissolved, field	Incremental titration	mg/L as HCO_3	1	NA	NA
00915	Calcium, dissolved	ICP	mg/L	0.02	NA	NA
00925	Magnesium, dissolved	ICP	mg/L	0.01	NA	NA
00930	Sodium, dissolved	AA, direct	mg/L	0.1	NA	NA
00935	Potassium, dissolved	AA, direct	mg/L	0.1	NA	NA
00940	Chloride, dissolved	IC	mg/L	0.10	NA	250 mg/L
00945	Sulfate, dissolved	IC	mg/L	0.20	NA	250 mg/L
00950	Fluoride, dissolved	ISE, automatic	mg/L	0.10	4.0 mg/L	20 mg/L
00955	Silica, dissolved	ICP	mg/L	0.01	NA	NA
		DISSOLVED NUTRIENTS				
00608	Nitrogen, ammonia, dissolved	Colorimetry	mg/L	0.01	NA	NA
00613	Nitrogen, nitrite, dissolved	Colorimetry	mg/L	0.01	1 mg/L	1 mg/L
00623	Nitrogen ammonia + organic, dissolved	Colorimetry	mg/L	0.20	NA	NA
00631	Nitrogen, nitrate + nitrite, dissolved	Colorimetry	mg/L	0.02	10 mg/L	10 mg/L
00666	Phosphorus, dissolved	Colorimetry	mg/L	0.02	NA	NA
00671	Phosphorus, orthophosphate, dissolved	Colorimetry	mg/L	0.01	NA	NA
		METALS AND TRACE ELEMENTS				
01000	Arsenic, dissolved	GFAA	µg/L	1.0	50.0 µg/L	50.0 µg/L
01005	Barium, dissolved	ICP	µg/L	0.20	2,000 µg/L	2,000 µg/L
01010	Beryllium, dissolved	ICP	µg/L	0.50	4.0 µg/L	NA
01025	Cadmium, dissolved	ICP	µg/L	0.50	5.0 µg/L	5.0 µg/L
01030	Chromium, dissolved	ICP	µg/L	1.0	100 µg/L	50.0 µg/L
01035	Cobalt, dissolved	ICP	µg/L	1.0	NA	NA
01040	Copper, dissolved	ICP	µg/L	1.0	1,300 µg/L	1,000 µg/L
01046	Iron, dissolved	ICP	µg/L	1.0	NA	300 µg/L

Table 10. List of chemical constituents, reporting units and levels, analytical methods, and regulatory limits, Orange County, N.C.—Continued

[USEPA, U.S. Environmental Protection Agency; MCL, Maximum Contaminant Level; NC, North Carolina; SMCL, secondary maximum contaminant level; NA, not applicable; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; ICP, inductively coupled plasma; AA, atomic absorption; IC, ion chromatography; ISE, ion selective electrode; GFAA, graphite furnace atomic absorption; µg/L, micrograms per liter, pCi/L, picocuries per liter]

Parameter code	Chemical constituent	Analytical method	Reporting unit	Reporting level	USEPA MCL[a] (if applicable)	NC MCL[b] or SMCL (if applicable)
			METALS AND TRACE ELEMENTS (Continued)			
01049	Lead, dissolved	ICP	µg/L	1.0	0 µg/L	15.0 µg/L
01056	Manganese, dissolved	ICP	µg/L	0.20	NA	50 µg/L
01060	Molybdenum, dissolved	ICP	µg/L	2.0	NA	NA
01065	Nickel, dissolved	ICP	µg/L	1.0	100 µg/L	100 µg/L
01075	Silver, dissolved	ICP	µg/L	1.0	NA	18 µg/L
01090	Zinc, dissolved	ICP	µg/L	1.0	NA	2,100 µg/L
01106	Aluminum, dissolved	ICP	µg/L	3.0	NA	NA
01145	Selenium, dissolved	GFAA	µg/L	1.0	50 µg/L	50 µg/L
39086	Alkalinity, dissolved, field	Incremental titration	mg/L as $CaCO_3$	1	NA	NA
70300	Dissolved solids, residue upon evaporation, 180 °C	Gravimetric	mg/L	1.0	NA	500 mg/L
71870	Bromide, dissolved	IC	mg/L	0.05	NA	NA
			RADIOACTIVE COMPOUNDS			
82303	Radon-222, total	Liquid scintillation	pCi/L	26	NA	NA
			ORGANIC COMPOUNDS			
NA	Total benzene, toluene, ethylbenzene, and xylene	Immunoassay	µg/L	1	NA	NA
NA	Atrazine	Immunoassay	µg/L	1	3 µg/L	3 µg/L

[a] U.S. Environmental Protection Agency (2000).

[b] North Carolina Department of Environment and Natural Resources (1994a).

assumption may not always be valid. Hydrogeologic mapping at depth requires a detailed geologic log from each borehole, which was not available for the domestic wells sampled during this investigation.

For the purposes of data presentation, the water-quality data are grouped as physical properties, major ions, trace elements, organic compounds, and radon. Statistical data are summarized in tables. Concentrations in ground water are discussed in the following sections by using the median concentration, the mean concentration, and the minimum and maximum concentrations, which represent the data extremes. Data distribution also is presented graphically in box plots, which illustrate the median concentration as well as the range of data. Felsic and mafic sample groups were compared by using the Wilcoxon rank sum statistical test. No significant difference was found between felsic and mafic sample groups for any constituent collected during this investigation. Although the median values are not significantly different, the box plots illustrate the distribution of the data sets. Statistics and box plots are presented for all samples (51 analyses), for felsic rocks (36 analyses), and for mafic rocks (15 analyses). Data also were compared to relevant State and Federal standards. Exceedances of these standards are noted in this section.

The hypothetical median well sampled in Orange County for this investigation is 205 ft deep with a depth to water of 28 ft just prior to sampling. The well is about 3 years old. The median sample is nearly neutral, with a pH of 6.9, and moderately hard, with a hardness of 75 mg/L $CaCO_3$. The median sample has a dissolved solids concentration of 125 mg/L and a specific conductance of 175 µS/cm. Variations in ground-water quality in Orange County may result from water–rock interactions in the regolith and crystalline bedrock, recharge water characteristics (ambient and affected by man), and effects of microorganisms. Variations in trace-metal concentrations at low concentrations may be a function of well casing and pump materials. In general, ground water in Orange County was found to be of good quality.

Field Measurements

Measurements of physical properties and water-quality constituents in the field can provide a broad indication of water-quality conditions. Field measurements collected during this study include pH, specific conductance, temperature, dissolved oxygen, and alkalinity (table 11; figure 16).

The pH is a measure of the activity of hydrogen ions in water, expressed in negative logarithmic units.

Table 11. Summary of water-quality field measurements, Orange County, N.C.

[µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

Chemical constituent	Reporting units	Sample group	Number of analyses	Minimum	Mean	Median	Maximum	Standard deviation
pH, field	standard units	All samples	51	4.72	6.77	6.93	8.31	0.77
		Felsic rocks	36	4.72	6.65	6.66	8.31	.82
		Mafic rocks	15	5.92	7.06	7.10	8.08	.60
Specific conductance, field	µS/cm at 25 °C	All samples	51	26	210	175	523	121
		Felsic rocks	36	26	195	162	523	122
		Mafic rocks	15	63	244	268	427	116
Temperature	°C	All samples	51	11.0	14.76	15.0	18.4	1.27
		Felsic rocks	36	11.0	14.7	15.1	16.7	1.27
		Mafic rocks	15	12.7	15.0	15.0	18.4	1.30
Dissolved oxygen, field	mg/L	All samples	51	0.03	2.98	2.50	9.4	2.58
		Felsic rocks	36	.05	3.10	2.65	9.4	2.69
		Mafic rocks	15	.03	2.69	2.40	6.60	2.34
Alkalinity	mg/L as $CaCO_3$	All samples	51	24	103	103	194	51.4
		Felsic rocks	36	24	96	85	185	49.3
		Mafic rocks	15	24.3	120	140	194	53.8

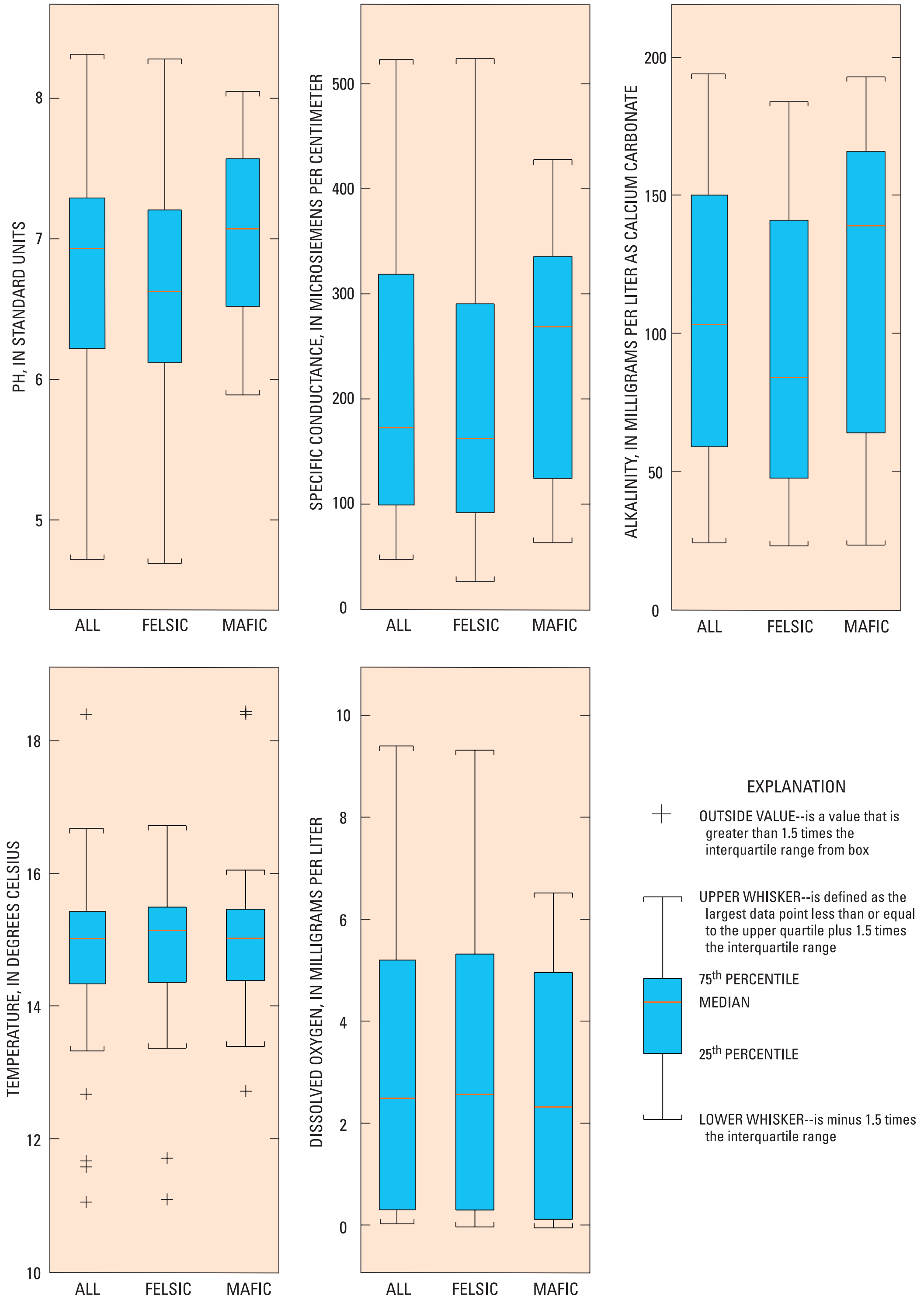

Figure 16. Box plots of pH, specific conductance, alkalinity, temperature, and dissolved oxygen in ground water, Orange County, N.C.

A pH of 7 is considered neutral. Water with a pH less than 7 is considered acidic, and water with a pH greater than 7 is considered basic. Generally, the corrosiveness of water increases with decreasing pH. The median pH in Orange County ground water was 6.93. The median pH of samples from felsic rocks was 6.66, and the median pH of samples from mafic rocks was 7.10. The highest pH was in a sample from phyllite rock (8.31), and the lowest pH was in a sample from felsic metavolcanic rock (4.72). The pH measured in water from Orange County is within the interquartile range of 6.1 to 7.4 as determined by Briel (1997). Specific conductance is a measure of the ability of water to conduct an electrical current. It is expressed in units of microsiemens per centimeter at 25 degrees Celsius and is directly related to the concentration of total dissolved solids in water, usually by a factor ranging between 0.55 and 0.75 (Hem, 1985, p. 67). The median specific conductance of Orange County ground water was 175 µS/cm. The median specific conductance was 162 µS/cm for samples from felsic rocks and 268 µS/cm for samples from mafic rocks. The highest and lowest specific conductance measurements were in water from felsic metavolcanic rock (523 and 26 µS/cm, respectively). The specific conductance measured in water from Orange County is within the interquartile range of 115 to 554 µS/cm as reported by Briel (1997) for Piedmont rocks.

Dissolved oxygen occurs in ground water through recharge by precipitation and air within the unsaturated zone. Dissolved oxygen remains in ground water until oxidation occurs by bacteria, organic material, or reduced minerals such as pyrite. Low dissolved oxygen usually is not an indicator of contamination, although low dissolved-oxygen concentrations may be associated with high concentrations of dissolved iron, manganese, and sulfate. High dissolved-oxygen concentrations may indicate relatively rapid ground-water recharge.

The median dissolved oxygen from samples collected in Orange County was 2.50 mg/L, and measurements were within the expected range for Piedmont rocks (Briel, 1997). The median dissolved-oxygen concentration for samples from felsic rocks was 2.65 mg/L, and the median dissolved-oxygen concentration for samples from mafic rocks was 2.40 mg/L. The highest dissolved-oxygen concentration was detected in a sample from felsic metavolcanic rock (9.4 mg/L), and the lowest concentration was detected in epiclastic metavolcanic rock (0.03 mg/L).

Alkalinity is a measure of the capacity for solutes in water to neutralize acid (Hem, 1985, p. 106). In most cases, alkalinity is produced by dissolved carbon dioxide, bicarbonate, and carbonate. In this report, alkalinity is expressed in terms of an equivalent concentration of calcium carbonate ($CaCO_3$). The median alkalinity in Orange County ground water was 103 mg/L $CaCO_3$ (table 11). The median alkalinity in samples from felsic rocks was 85 mg/L $CaCO_3$, and the median concentration in samples from mafic rocks was 140 mg/L. The highest alkalinity concentration was in a sample from intermediate metavolcanic rock (194 mg/L $CaCO_3$), and the lowest concentration was in a sample from felsic metaigneous rock (24 mg/L $CaCO_3$).

Major Ions

The chemical composition of ground water develops over time from atmospheric and anthropogenic sources and dissolution of soil and bedrock. Major ions dissolved in ground water can be used to describe the general chemical composition of ground water. These major ions include cations (ions with a positive electrical charge) and anions (ions with a negative electrical charge). The most common cations in ground water are calcium, magnesium, sodium, and potassium. The most common anions are bicarbonate, sulfate, chloride, fluoride, and nitrate. In general, Orange County ground water can be classified, based on the predominant cations and anions, as a calcium-bicarbonate type. When grouped by mafic or felsic rock type, a subtle pattern emerges, as shown in the trilinear diagrams in figure 17. When all samples are considered, calcium-bicarbonate is the dominant water type. Waters from the mafic rocks are almost uniformly a calcium-bicarbonate type. Water samples from the felsic rocks range from calcium-bicarbonate to calcium-sodium-bicarbonate type. Summary statistics for the major ions are presented in table 12.

Calcium and magnesium in ground water are dissolved from nearly all rock and soil types. These constituents create most of the hardness in ground water. Hardness in water generally is considered undesirable because hard water consumes soap before it lathers. Hard water also contributes scale formation in pipes. The median concentrations of calcium and

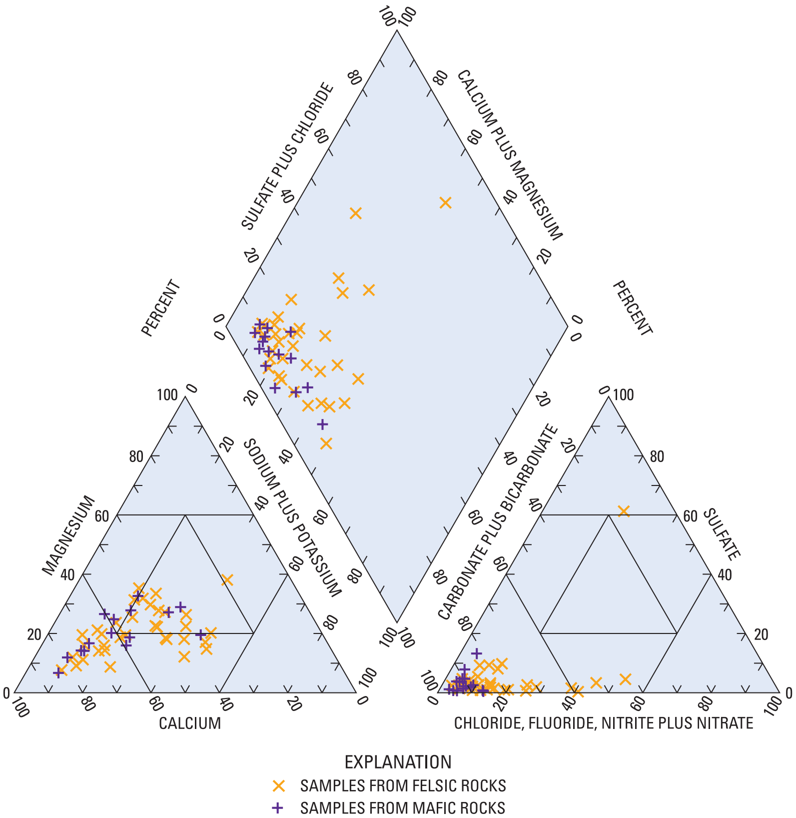

Figure 17. Trilinear diagram of data for mafic and felsic hydrogeologic units, Orange County, N.C.

magnesium in Orange County ground water were 23 mg/L and 4.4 mg/L, respectively. The median concentrations for water samples from felsic rocks were 18 mg/L and 3.9 mg/L, respectively, and the median concentrations for water samples from mafic rocks were 34 mg/L and 5.6 mg/L, respectively. The highest concentrations of calcium and magnesium (64 mg/L and 21 mg/L, respectively) and the lowest concentrations of calcium and magnesium (0.80 mg/L and 1.0 mg/L, respectively) were in a water sample from felsic metavolcanic rocks. The distribution of calcium and magnesium concentrations in Orange County ground water is shown in figure 18. Concentrations of calcium and magnesium in water samples from felsic rocks are not significantly different from concentrations of these elements in water samples from mafic rocks.

Sodium and potassium in ground water are dissolved from nearly all rock and soil types. The median concentrations of sodium and potassium in Orange County ground water were 8.30 mg/L and 0.5 mg/L, respectively (fig. 19). The median concentrations of sodium and potassium in water samples from felsic rocks were 8.45 mg/L and 0.5 mg/L, respectively, and the median concentrations of sodium and potassium in samples from mafic rocks were 8.1 mg/L and 0.4 mg/L, respectively. The highest sodium concentration was in a water sample from phyllite rock (33 mg/L), and the lowest concentration of sodium was in a water sample from felsic metavolcanic rock (2.1 mg/L). The highest (5.6 mg/L) and lowest (0.1 mg/L) concentrations of potassium were detected in water samples from felsic metavolcanic rock. Concentrations of sodium and potassium in water samples from felsic rocks are not significantly different from concentrations of these elements in water samples from mafic rocks.

The median concentrations of bicarbonate and sulfate in Orange County ground-water samples were

Table 12. Summary of water-quality statistics for major ions, Orange County, N.C.

[mg/L, milligrams per liter; <, less than]

Chemical constituent	Reporting units	Sample group	Number of analyses	Minimum	Mean	Median	Maximum	Standard deviation
Calcium, dissolved	mg/L	All samples	51	0.80	27.07	23	64	18.81
		Felsic rocks	36	.80	24.28	18	64	18.57
		Mafic rocks	15	4.80	32.21	34	63	19.16
Magnesium, dissolved	mg/L	All samples	51	1	5.47	4.4	21	4.13
		Felsic rocks	36	1.00	4.92	3.9	21	4.01
		Mafic rocks	15	1.60	6.51	5.6	18	4.33
Sodium, dissolved	mg/L	All samples	51	2.1	9.54	8.30	33	5.28
		Felsic rocks	36	2.1	9.60	8.45	33	5.83
		Mafic rocks	15	5.1	9.40	8.1	20	3.82
Potassium, dissolved	mg/L	All samples	51	0.1	0.86	0.5	5.6	1.04
		Felsic rocks	36	.1	.85	.5	5.6	1.02
		Mafic rocks	15	.1	.88	.4	3.5	1.10
Bicarbonate	mg/L as HCO_3	All samples	51	<1	120	110	237	64
		Felsic rocks	36	<1	112	100	226	61.5
		Mafic rocks	15	29.6	140	161	237	68.7
Sulfate, dissolved	mg/L	All samples	51	0.2	4.19	2.0	27	5.26
		Felsic rocks	36	.2	3.54	1.7	20	4.31
		Mafic rocks	15	.3	5.74	3.1	27	6.98
Chloride, dissolved	mg/L	All samples	51	1.5	7.56	3.9	81	13.48
		Felsic rocks	36	1.6	8.93	3.95	81	15.85
		Mafic rocks	15	1.5	4.29	3.8	9.5	2.09
Fluoride, dissolved	mg/L	All samples	51	0.1	0.17	0.12	0.6	0.11
		Felsic rocks	36	.1	.19	.16	.6	.12
		Mafic rocks	15	.1	.11	.11	.14	.02
Silica, dissolved	mg/L	All samples	51	10	31.1	30	56	8.7
		Felsic rocks	36	10.0	31.9	30	56	9.7
		Mafic rocks	15	21	29	29	40	5.53
Total solids, dissolved	mg/L	All samples	51	28	147	125	324	66.3
		Felsic rocks	36	28	141	122	324	68.5
		Mafic rocks	15	71	160	176	256	60.9

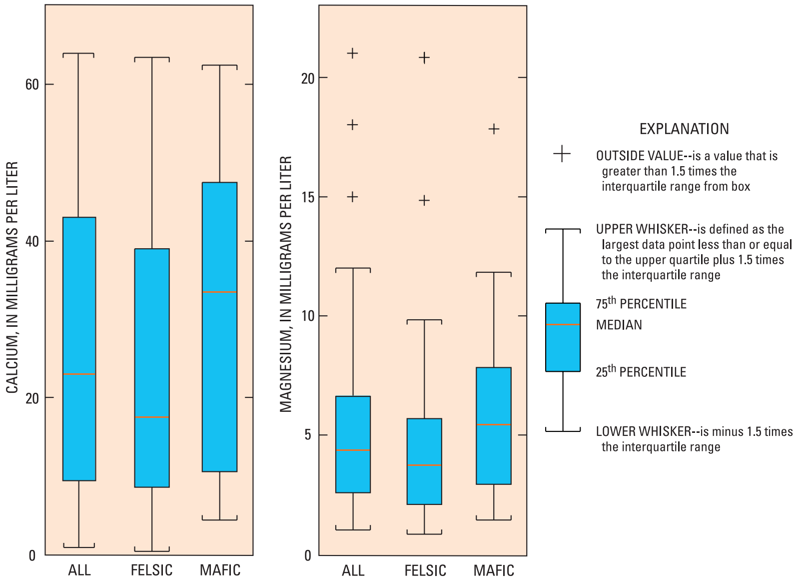

Figure 18. Calcium and magnesium concentrations in ground water, Orange County, N.C.

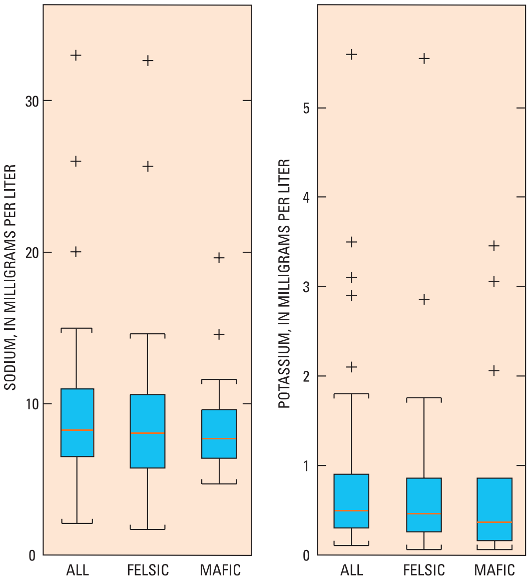

Figure 19. Sodium and potassium concentrations in ground water, Orange County, N.C.

110 mg/L and 2.0 mg/L, respectively (fig. 20). The median concentrations of bicarbonate and sulfate in water samples from felsic rocks were 100 mg/L and 1.7 mg/L, respectively, and the median bicarbonate and sulfate concentrations in water samples from mafic rocks were 161 mg/L and 3.1 mg/L, respectively. The highest concentrations of bicarbonate and sulfate were detected in intermediate metavolcanic rocks (237 mg/L and 27 mg/L, respectively), and the lowest concentrations of bicarbonate and sulfate were in samples from felsic metavolcanic rocks (less than 1 mg/L and 0.2 mg/L, respectively). Concentrations of bicarbonate and sulfate in water samples from felsic rocks are not significantly different from concentrations of these elements in water samples from mafic rocks.

The median concentrations of chloride and fluoride in Orange County ground-water samples were 3.9 mg/L and 0.12 mg/L, respectively (fig. 21). The median concentrations of chloride and fluoride in water samples from felsic rocks were 3.95 mg/L and 0.16 mg/L, respectively, and the median concentrations of chloride and fluoride in water samples from mafic rocks were 3.8 mg/L and 0.11 mg/L, respectively. The highest chloride concentration was in a water sample from felsic metavolcanic rock (81 mg/L), and the lowest chloride concentration was in a water sample from intermediate metavolcanic rock (1.5 mg/L). The highest fluoride concentration was in a water sample from felsic rock (0.6 mg/L). Several ground-water samples had no detected fluoride concentrations. Concentrations of chloride and fluoride in ground-water samples from felsic rocks are not significantly different from concentrations of these elements in ground-water samples from mafic rocks.

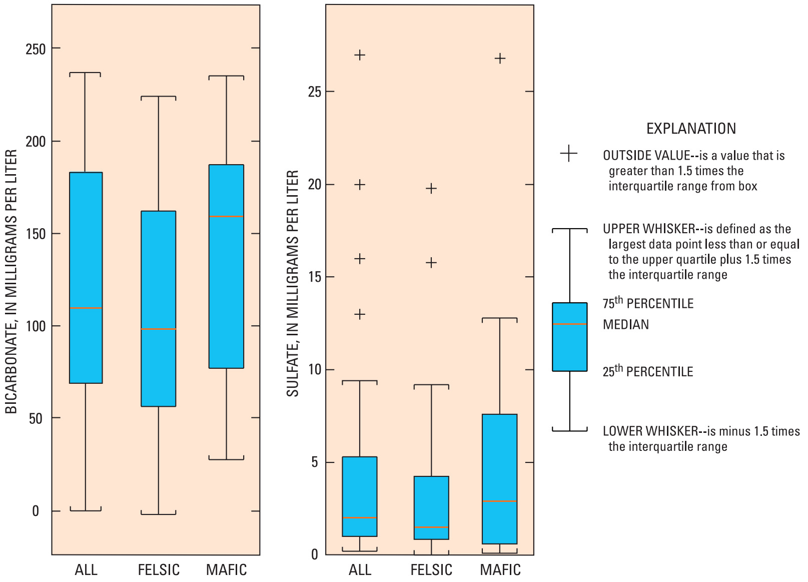

Figure 20. Bicarbonate and sulfate concentrations in ground water, Orange County, N.C.

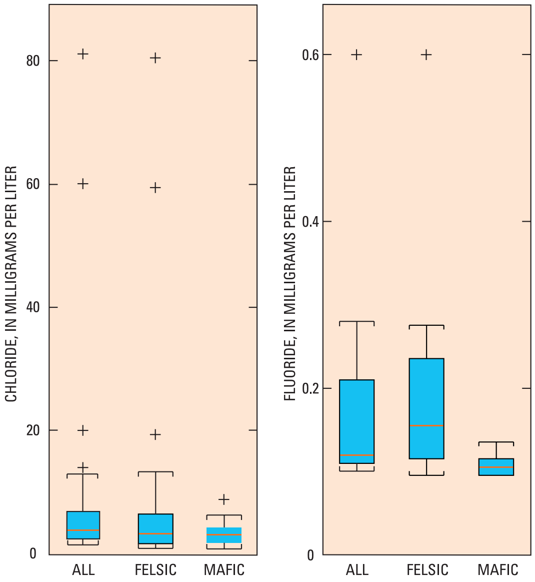

Figure 21. Chloride and fluoride concentrations in ground water, Orange County, N.C.

Nutrients

Nutrients, such as the chemical species of nitrogen and phosphorous, are essential to plant and animal growth. Human activities, such as agricultural and urban uses of fertilizers, agricultural uses of manure, septic systems, and combustion of fossil fuels, have increased nutrient concentrations in some shallow ground-water systems (U.S. Geological Survey, 1999). Nitrogen is present in ground water principally as nitrate (NO_3), nitrite (NO_2), and ammonia (NH_4), with nitrate being the most common nitrogen species. The U.S. Environmental Protection Agency (2000) has established a nitrate Maximum Contaminant Level (MCL) for drinking water of 10 mg/L, because this concentration is considered harmful to infants. Orthophosphate is the most common phosphate species in ground water.

Given proper well siting and well construction, nutrient concentrations in ground-water samples from domestic wells in Orange County should be low because these wells are sealed from the surface and completed deep within the crystalline rock. High concentrations of nutrients may indicate direct connection with the surface by a poor well seal or other means. In this study of 51 wells in Orange County, nitrate was detected in 82 percent of the water samples at concentrations ranging up to 7.2 mg/L (table 13), although the median concentration was 0.49 mg/L; all other water samples had concentrations of 2.9 mg/L or less. Nitrate concentrations greater than 3 mg/L usually are the result of human activity (Bachman, 1984). Ammonia and orthophosphate were detected at low concentrations. Ammonia was detected in 41 percent of the water samples at concentrations ranging up to 0.15 mg/L. Orthophosphate was detected in 88 percent of the water samples at concentrations ranging up to 0.14 mg/L. Although the nitrate concentration in one sample indicates anthropogenic effects, none of the ground-water samples collected exceeded the Federal MCL for nitrate of 10 mg/L.

Table 13. Percentage and range of nutrient concentrations detected in ground-water samples, Orange County, N.C.

[mg/L, milligrams per liter]

Chemical constituent	Reporting level	Number of analyses	Number of detections	Percent detections	Range of detections
Nitrogen, ammonia, dissolved	0.01 mg/L	51	21[a]	41	0.01–0.15 mg/L
Nitrogen, nitrite, dissolved	0.01 mg/L	51	4	8	0.01–0.016 mg/L
Nitrogen, ammonia + organic, dissolved	0.20 mg/L	51	2	4	0.23–0.31 mg/L
Nitrogen, nitrite + nitrate, dissolved	0.02 mg/L	51	42	82	0.02–7.2 mg/L
Phosphorus, dissolved	0.02 mg/L	51	39	76	0.02–0.15 mg/L
Phosphorus, orthophosphate, dissolved	0.01 mg/L	51	45	88	0.01–0.14 mg/L

[a] Eight of these detections were less than the concentration detected in one of nine blank quality-assurance samples.

Total Dissolved Solids

Total dissolved solids is a measure of the mass of solutes in a water sample after the water has been evaporated. Dissolved solids generally are lower in water from wells completed in crystalline rocks, such as in the Piedmont, relative to wells completed in the regolith, or in the Coastal Plain, for instance. The median dissolved solids concentration in Orange County ground water was 125 mg/L (fig. 22; table 12). The median dissolved solids concentration in water samples from felsic rocks was 122 mg/L, and the median dissolved solids concentration in water samples from mafic rocks was 176 mg/L. Both the highest and lowest dissolved solids concentrations were detected in water samples from felsic metavolcanic rock (324 mg/L and 28 mg/L, respectively).

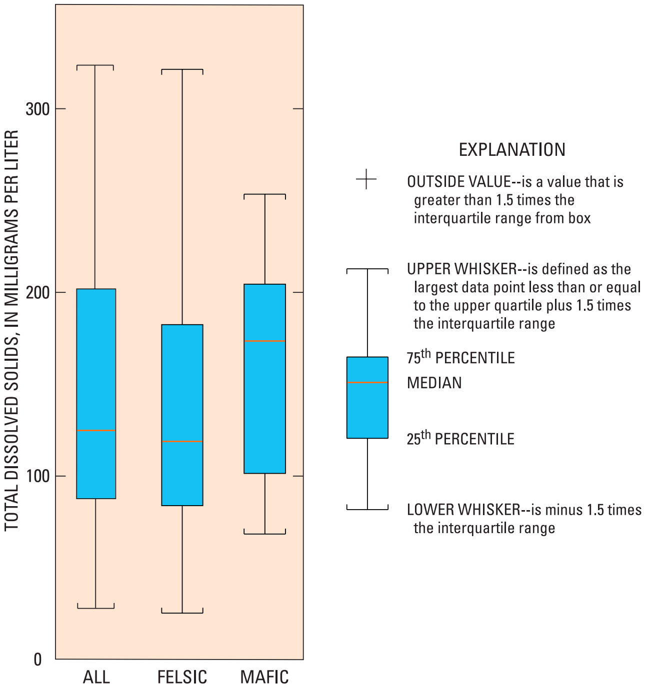

Figure 22. Total dissolved solids concentrations in ground water, Orange County, N.C.

Metals and Trace Elements

In general, trace elements were detected infrequently, or at concentrations less than State drinking-water standards (tables 10, 14). No trace elements were detected at concentrations exceeding Federal MCL's (U.S. Environmental Protection Agency, 2000), although some concentrations exceeded Federal secondary standards. Zinc, manganese, iron, and copper were the most frequently detected metals at 100, 94, 80, and 61 percent of the analyses, respectively. Detections of lead, arsenic, bromide, aluminum, and selenium were made in 13 to 26 percent of the ground-water samples analyzed.

Exceedances of North Carolina drinking-water standards were observed for iron (3 exceedances in 51 analyses, in concentrations up to 1,100 µg/L), manganese (12 exceedances in 51 analyses, in concentrations up to 890 µg/L), and zinc (4 exceedances in 31 analyses, in concentrations up to 4,900 µg/L). Both iron and manganese exceeded State standards in water samples from three wells. Lead was detected in 8 of 31 samples in concentrations up to 3.5 µg/L. The highest lead concentration (3.5 µg/L) is less than the State MCL of 15 µg/L but greater than the USEPA Maximum Contaminant Level Goal (MCLG) of zero. Exceedances of North Carolina drinking-water standards are summarized in table 15.

Elevated lead exposure is known to cause delayed physical and mental development in babies and

Table 14. Percentage and range of concentrations of trace elements and organic compounds in ground-water samples, Orange County, N.C.

[mg/L, milligrams per liter; µg/L, micrograms per liter; NA, not applicable]

Chemical constituent	Reporting level	Number of analyses	Number of detections	Percent detections	Range of detections
Trace elements					
Arsenic, dissolved	1.00 µg/L	31	5	16	1.3–4.3 µg/L
Beryllium, dissolved	0.50 µg/L	31	0	0	NA
Cadmium, dissolved	0.50 µg/L	31	1	3	3.5 µg/L
Chromium, dissolved	1.00 µg/L	31	2	7	1.2–2.1 µg/L
Cobalt, dissolved	1.00 µg/L	31	1	3	3.0 µg/L
Copper, dissolved	1.00 µg/L	31	19	61	1.1–24 µg/L
Iron, dissolved	1.00 µg/L	51	41	80	1.00–1,100 µg/L
Lead, dissolved	1.00 µg/L	31	8	26	1.1–3.7 µg/L
Manganese, dissolved	0.20 µg/L	51	48	94	0.4–890 µg/L
Molybdenum, dissolved	2.00 µg/L	31	2	6	2.9–6.4 µg/L
Nickel, dissolved	1.00 µg/L	31	3	10	1.1–3.5 µg/L
Silver, dissolved	1.00 µg/L	31	0	0	NA
Zinc, dissolved	1.00 µg/L	31	31	100	4.5–4,900 µg/L
Aluminum, dissolved	3.00 µg/L	31	4	13	3.1–199 µg/L
Selenium, dissolved	1.00 µg/L	31	4	13	1.1–7.0 µg/L
Bromide, dissolved	0.05 mg/L	51	8	16	0.05–0.5 mg/L
Organic compounds					
Total benzene, toluene, ethylbenzene, and xylene, immunoassay	0.1 µg/L	50	0	0	NA
Atrazine, immunoassay	0.1 µg/L	50	0	0	NA

Table 15. Summary of trace elements exceeding North Carolina drinking-water standards in ground-water samples from Orange County, N.C.

[µg/L, micrograms per liter; USEPA MCLG, U.S. Environmental Protection Agency Maximum Contaminant Level Goal; <, less than; NA, not applicable]

Chemical constituent	Reporting units	Number of analyses	Number of detections	Number of exceedances	Range of detections (µg/L)	USEPA MCLG (µg/L)	North Carolina MCL (µg/L)
Iron, dissolved	µg/L	51	41	3	1–1,100	NA	300
Lead, dissolved	µg/L	31	8	8	1.2–3.5	0	15.0
Manganese, dissolved	µg/L	51	48	12	0.4–890	NA	50
Zinc, dissolved	µg/L	31	31	4	4.5–4,900	NA	2,100

young children, and lifetime exposure may cause kidney disease (U.S. Environmental Protection Agency, 1998). Most lead found in household drinking water occurs from corrosion of lead pipes, solder, and alloys used in pumps and faucets. Iron, manganese, and zinc are essential elements for metabolism in plants and animals. However, in excessive amounts, these elements can cause cosmetic effects, such as stained teeth or skin, or aesthetic effects, such as taste or odor. The locations of wells in Orange County in which iron, manganese, zinc, and lead detections exceeded the State standard or Federal MCLG are shown in figure 23.

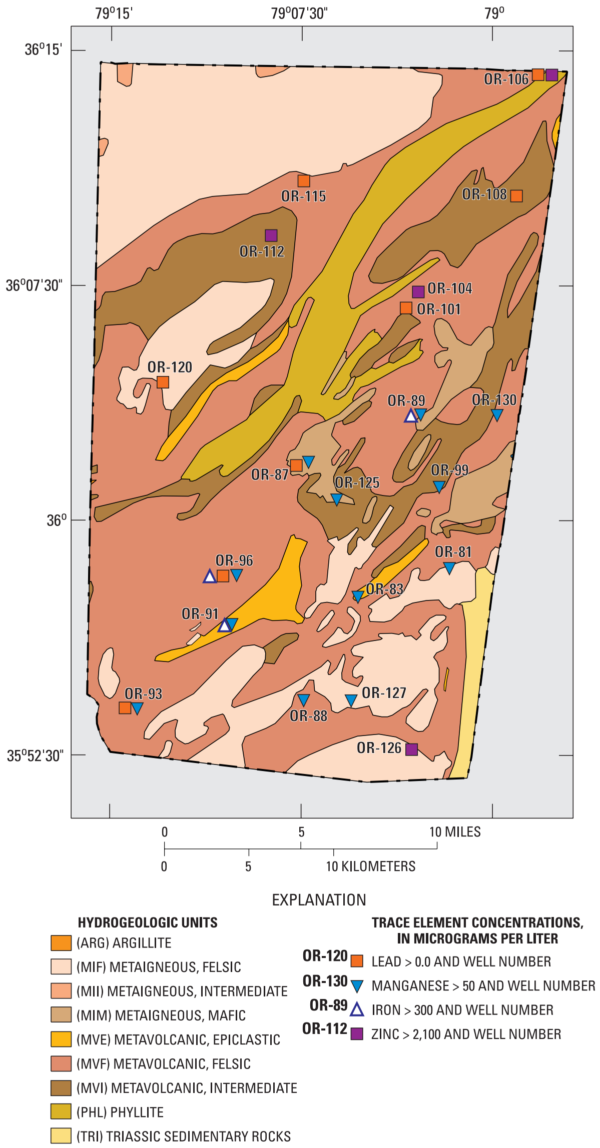

Figure 23. Hydrogeologic units, and locations and concentrations of trace elements exceeding North Carolina drinking-water standards in ground water, Orange County, N.C.

Organic Compounds

Ground-water samples were collected and analyzed for atrazine compounds and total petroleum-hydrocarbon compounds, including benzene, toluene, ethylbenzene, and xylene (BTEX). Atrazine is one of the most commonly used herbicides; in this study, atrazine detection was used as an indicator of herbicide contamination. BTEX compounds are in gasoline and other fuels, and the presence of BTEX compounds in Orange County ground-water samples is an indication of fuel contamination. Immunoassay techniques that were used to screen for these organic compounds were performed by using kits developed specifically for atrazine and BTEX. These immunoassay techniques use the enzyme-linked immunosorbent assay (ELISA) method whereby antibodies and enzyme conjugates are used to detect and to quantify the target compounds in field samples. The compound of interest competes with an enzyme conjugate to bind to the antibodies. The ELISA method is considered qualitative but is relatively fast and has a low reporting level— less than 1 µg/L (Ohmicron Corporation, 1999). Results are quantified by use of a spectrophotometer. The sample kits that were used were designed to detect atrazine and BTEX compounds, but they also can indicate the presence of other triazine and total petroleum-hydrocarbon compounds.

No BTEX or atrazine compounds were detected in any of the Orange County ground-water samples. Results from this screening of potential organic contaminants indicate that contamination by organic compounds is not a widespread problem in the County. However, wells sampled during this investigation were no more than 3 years old and were located in housing developments away from known sources of contamination. A more complete suite of organic analyses is needed to determine the presence of contamination. These results, however, serve as a useful screening tool to identify two likely contaminants. The results from the organic analyses presented in this report are not comprehensive and should not be interpreted as such.

Radon

In this report, radon refers to the specific isotope radon-222. Radon is a naturally occurring, radioactive gas formed as an intermediate product of the decay of uranium-238. Radon is highly mobile and nearly ubiquitous in the environment. Uranium-bearing rocks are common in the Earth's crust and usually more abundant in felsic rocks (containing light-colored minerals—quartz, feldspars, muscovite) than in mafic rocks (containing dark-colored iron and magnesium-rich minerals). As uranium slowly decays, the decay products migrate through rock fractures and soil. Radon dissolves in ground water and, thus, can be present in well water. When ground water is exposed to air, radon diffuses rapidly into the air. Thus, exposure from radon in ground water primarily occurs after radon has diffused into the air rather than from ingestion (Code of Federal Register, 1999). Radon has a half-life of about 3.8 days.

Loomis (1987) summarized the results of radon analyses from 133 public water systems in the North Carolina Piedmont and Blue Ridge regions. Samples were broadly classified by lithology and presented by geometric mean (table 16). Because Loomis' classification was very general, his lithologic characterization does not correlate easily with the more detailed hydrogeologic units presented in this report. The data, however, are useful for comparison to radon data presented in this report. Loomis also cited several factors that contribute to the variability of radon activities in ground water, including the physical properties of source rocks, the properties of the aquifer, well design, sampling and analysis errors, and meteorological factors (Loomis, 1987).

Table 16. Radon analyses of 133 public water systems in the North Carolina Piedmont and Blue Ridge regions (modified from Loomis, 1987)

[pCi/L, picocuries per liter]

Lithology	Number of samples	Geometric mean radon activity (pCi/L)
Granite	24	5,910
Precambrian sedimentary	2	5,260
Gneiss/schist	71	1,502
Metavolcanic	21	1,184
Metasedimentary	4	645
Triassic	6	499
Mafic	5	264

Because dissolved radon gas can be present in ground water and air, two exposure pathways exist for humans—ingestion (drinking) and inhalation (breathing). This somewhat unique characteristic of radon has made it difficult for the USEPA to develop appropriate regulations. The USEPA has proposed a multimedia approach to the drinking-water standard for radon (Code of Federal Register, 1999). If no statewide or local USEPA-approved multimedia mitigation program exists, the Federal MCL is proposed as 300 pCi/L (picocuries per liter). If a State or local multimedia mitigation program is in place, then an alternative MCL of 4,000 pCi/L is proposed as the standard. This approach was taken because of the rather unique nature of radon exposure from drinking water. Radon results in this report are compared to the two proposed standards, and evaluated and grouped by hydrogeologic units. Because strict sampling protocols were followed during sample collection, handling, and analysis, and well construction was similar for all wells selected for this study, some of the potential variability discussed by Loomis (1987) was eliminated. Variability resulting from source rocks, aquifer properties, and meteorological factors remains.

Radon activity measured in Orange County ground water ranged from 38 to 4,462 pCi/L countywide, with a median activity of 405 pCi/L (table 17). The median radon activity in ground-water samples from Orange County (fig. 24) was highest in felsic rocks (487 pCi/L) and lowest in mafic rocks (357 pCi/L). The highest radon activity was detected in a sample from phyllitic rock (4,462 pCi/L), and the lowest radon activity was detected in a sample from mafic metaigneous rock (38 pCi/L; table 17). Both samples collected from wells completed in the felsic metaigneous unit in the southeastern part of Orange

Table 17. Summary of water-quality statistics for radon, Orange County, N.C.

[pCi/L, picocuries per liter]

Chemical constituent	Reporting units	Sample group	Number of analyses	Minimum	Mean	Median	Maximum	Standard deviation
Radon-222, total	pCi/L	All samples	51	38	875	405	4,462	1,044
		Felsic rocks	36	62	980	487	4,462	1,094
		Mafic rocks	15	38	622	357	3,785	898

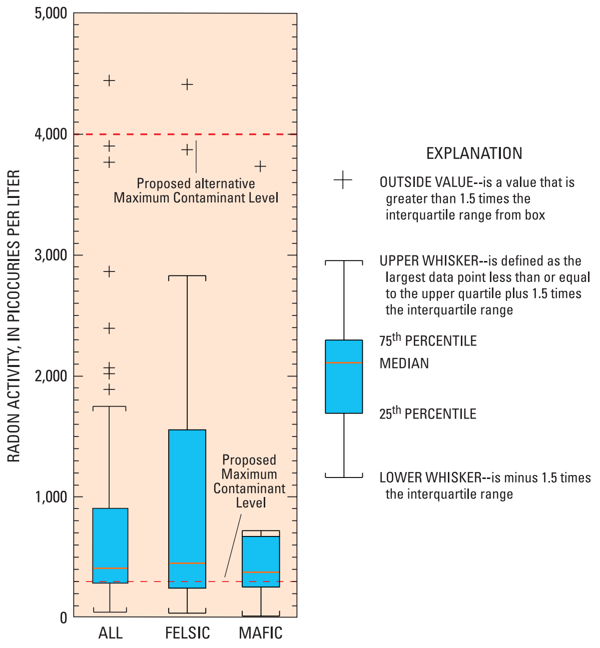

Figure 24. Box plots of radon activity in ground water, Orange County, N.C.

County had activities greater than 2,500 pCi/L (fig. 25). The hydrogeologic unit in this area is composed of a granitic pluton containing a high percentage of light-colored felsic minerals, such as feldspars and micas. The elevated radon activities measured in samples from these wells likely are the result of uranium decay in these rocks. Activities likely would be high in samples from other wells completed in this geologic unit. The relative distribution of radon activities among hydrogeologic units agrees with general findings reported by Loomis (1987).

Sixty-seven percent of the radon samples exceeded the USEPA proposed MCL of 300 pCi/L, and one sample exceeded the proposed alternative MCL of 4,000 pCi/L. Radon activities in Orange County were lower than those measured during similar work in nearby Guilford County, where the median activity was 735 pCi/L (Spruill and others, 1997), and lower than most of the results cited by Loomis (1987). Median radon activities measured in five of the seven hydrogeologic units, however, exceeded the USEPA's proposed MCL of 300 pCi/L (fig. 26). When evaluated by individual hydrogeologic units, the median radon activity was highest in the phyllite unit (1,080 pCi/L in 2 samples) and the felsic metaigneous unit (571 pCi/L in 13 samples).

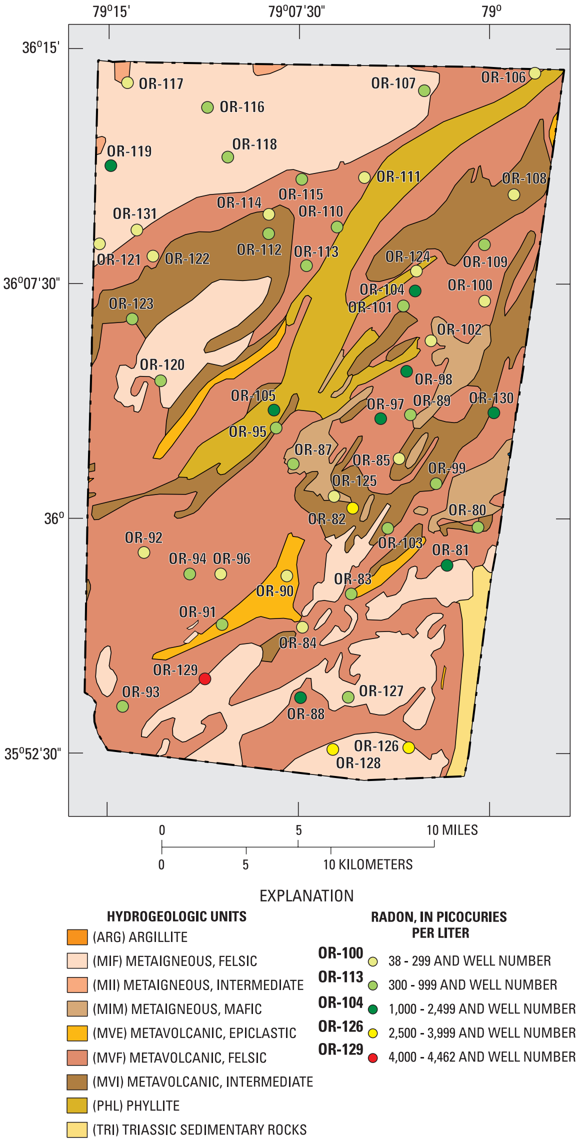

Figure 25. Hydrogeologic units, and locations and activity of radon in ground water, Orange County, N.C.

Overall water-quality data in Orange County indicate few drinking-water concerns. No organic contaminants or excessive nutrient concentrations were observed, and few exceedances of North Carolina drinking-water standards were found. This is attributed to generally good ambient ground-water quality in Orange County and to good well-siting and well-construction practices among relatively new wells in the County. Orange County Environmental Health Department well siting and construction requirements exceed North Carolina standards.

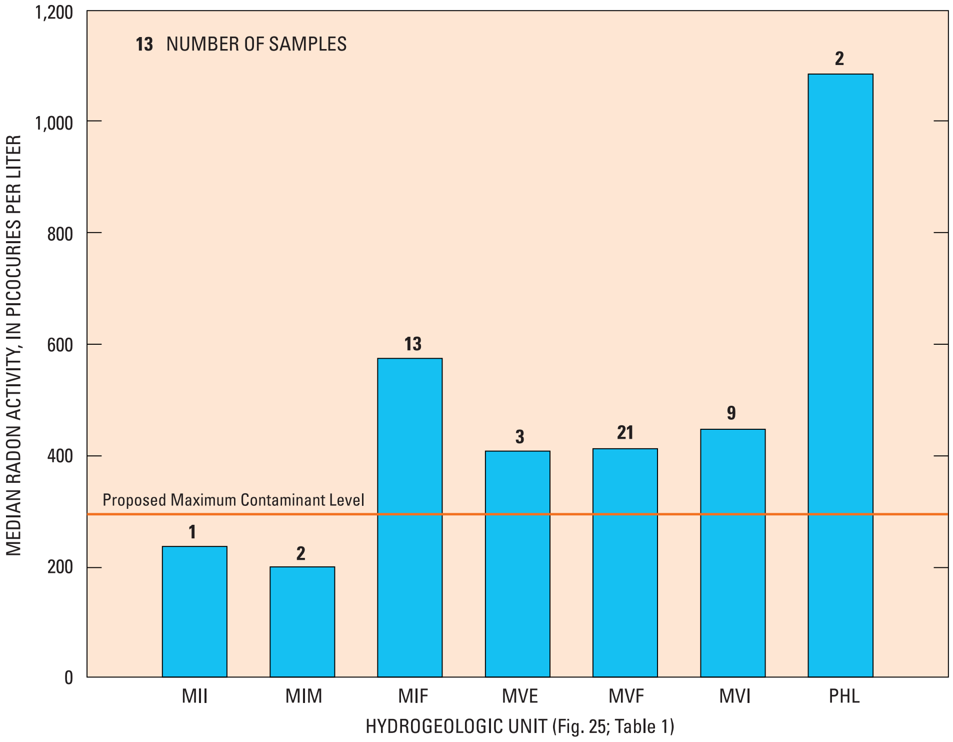

Figure 26. Median activity of radon in ground water among hydrogeologic units in Orange County, N.C.

SUMMARY

Orange County covers approximately 401 mi^2 in the eastern part of the Piedmont physiographic province of North Carolina. The County population in 1998 was estimated to be 109,288. About 65,000 people who live in the municipalities of Chapel Hill, Carrboro, Hillsborough, and surrounding areas are served by a surface-water-derived public supply. Most of the remaining population (about 40 percent) is served by community wells or individual domestic wells. This report is based on a countywide inventory of 649 wells in nine hydrogeologic units, estimates of ground-water availability and use, and water-quality results from 51 wells sampled throughout Orange County.

Orange County can be considered fairly typical of the eastern Piedmont of North Carolina. The topography of this area consists of low, rounded hills and long, rolling ridges. Recharge to the ground-water system originates as precipitation that infiltrates the soil zone, and recharges the water table in the regolith. Recharge rates differ areally based on precipitation, topography, soil, and land use.

Metamorphic and igneous crystalline rocks underlie all of Orange County except for a small area in the southeast that is underlain by sedimentary rocks of Triassic age. These crystalline and sedimentary rocks are covered by regolith ranging in thickness from zero to 150 ft. The average thickness of regolith in Orange County is 54 ft, based on the depth of casings in open-hole wells. The regolith is composed of soil, alluvium, saprolite, and a transition zone between the saprolite and unweathered crystalline bedrock. The regolith has a high porosity (up to 55 percent) compared to the crystalline bedrock (usually 1 to 3 percent) and acts as the primary storage reservoir for ground water. Water in the crystalline bedrock occurs only within fractures, and these fractures decrease in abundance with depth. Most wells are cased through the regolith and finished as open holes in the bedrock.

Location and construction details from 649 wells were compiled into a data base and analyzed statistically. The typical well in Orange County has an average depth of 208 ft, an average casing of 53.6 ft, a static water level of 26.6 ft below land surface, a yield of 17.6 gal/min, and a diameter of 6.25 in. The saturated thickness of regolith averages 27.0 ft, and the yield per foot of total well depth averages 0.119 (gal/min)/ft. The yield per foot of total well depth is inversely proportional to the depth of the well, indicating that the amount of additional water obtained by drilling deeper decreases with depth.

Yield and yield-per-foot values were analyzed spatially. Two areas of the County were found to be more favorable for high-yield wells—a west-southwest to east-northeast trending area in the northwestern part of the County, and a southwest to northeast trending area in the southwestern part of the County. Within these two areas, maximum reported yields range from 25 gal/min to more than 100 gal/min. Nearly everywhere else, with the exception of a few small isolated areas, the maximum reported yields are less than 25 gal/min.

Well yields in Orange County showed little correlation with topographic setting. This likely is because some high-yield wells in the County are associated with fracture-controlled drainage patterns, and lower-yielding wells are found not only on topographic highs but also in topographic lows where the drainage pattern is not fracture controlled. Drilling wells in topographic lows, such as valleys and draws, will not consistently result in a high percentage of high-yield wells. Site selection with the goal of drilling high-yield wells with long-term sustained yields requires careful site selection that distinguishes between valleys and draws that are associated with underlying fracture zones and those that are not. Well yields were matched to rock types to determine the relative yields of the different hydrogeologic units. No units were found to be statistically different at the 0.95-confidence level.

Ground-water recharge rates were estimated from base-flow analyses of streamflow records. Mean ground-water recharge in the 12 drainage basins and subbasins in Orange County 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).

The saturated thickness of regolith is greatest beneath hills and ridges (average 33.4 ft) and least beneath valley and draws (average 22.8 ft). The saturated thickness of regolith beneath slopes (average 26.5 ft) is intermediate to these extremes. The average saturated thickness of regolith for all wells in this study is 27.2 ft. Using a specific yield of 0.20, the average quantity of available water in storage in Orange County is 1.28 Mgal/acre beneath hills and ridges, 0.87 Mgal/acre beneath slopes, and 0.68 Mgal/acre beneath valleys and draws. Given a seasonal range of water-level change in Orange County of about 4 ft, and a 12-ft range in water levels over the past 45 years, the quantity of water in storage can increase or decrease by 0.8 to 2.4 ft^3/ft^2 of aquifer area (0.31 to 0.89 Mgal/acre).

The lowest percentage of housing units served by wells occurs in and adjacent to Chapel Hill and Carrboro in the southeastern part of the County and Hillsborough in the center of the County. In areas surrounding Chapel Hill and Carrboro, and extending across central Orange County from the Durham County line east of Hillsborough to the Alamance County line west of Hillsborough, the number of homes supplied by wells ranges from 20 to 80 percent. Throughout the remainder of the County, more than 80 percent of the homes are supplied by wells.

In general, areas of high relief, low permeability, and forested land use have the lowest susceptibility to ground-water contamination. Areas of low relief, high permeability, and a high-risk land use, such as landfills or underground storage tanks, have the highest potential for ground-water contamination. The relative susceptibility index for about 12 percent of the area in Orange County was categorized as high or highest. About 21 percent of the County was ranked as low or lowest potential for ground-water contamination.

Fifty-one sampling locations were selected among new wells inspected by Orange County Health Department staff during 1996–98 based on (a) countywide areal distribution, (b) weighted distribution among hydrogeologic units, and (c) permission from homeowners. Wells were sampled from December 1998 through January 1999.

The list of analytes for the sampling program consisted of common anions and cations, metals and trace elements, nutrients, and radon. Samples also were screened for the presence of fuel compounds and atrazine herbicides by using immunoassay techniques. Dissolved oxygen, pH, temperature, specific conductance, and alkalinity were measured in the field. Thirty-one of the 51 samples collected were analyzed for trace elements. All domestic wells were sampled from hose bibs at the wellhead, before the water entered the home distribution system. Analyses were evaluated by the total sample set, which includes seven of the nine hydrogeologic units in the County, and by hydrogeologic units grouped into felsic rocks and mafic rocks in order to have populations sufficient for statistical comparison. No water-quality constituents differed significantly between the groups.

The hypothetical median well sampled in Orange County is 205 ft deep, with a depth to water of 28 ft just prior to sampling. The median sample is nearly neutral, with a pH of 6.9, and is moderately hard, with a hardness of 75 mg/L calcium carbonate. The median sample contains 125 mg/L dissolved solids and has a specific conductance of 175 µS/cm @ 25 °C. Variations in ground-water quality in Orange County may result from water–rock interactions in the regolith and crystalline bedrock, recharge water characteristics (ambient and affected by man), and the effects of microorganisms. Variations in trace metal concentrations at low concentrations may be a function of well casing and pump materials. Ground water in Orange County was found to be of good quality.

Bicarbonate was the dominant anion in nearly all samples collected. Calcium was the dominant cation in most samples, although sodium and(or) magnesium concentrations exceeded calcium concentrations in some samples. In general, Orange County ground water can be classified as a calcium-bicarbonate type. Concentrations of major cations and anions were found to be within normal ranges for the Piedmont region of North Carolina. In general, high nutrient concentrations were not found in Orange County. Nitrate was detected in 82 percent of the samples at concentrations ranging up to 7.2 mg/L, although the median concentration was only 0.49 mg/L; all other samples had a concentration of 2.9 mg/L or less. Ammonia was detected in 41 percent of the samples at concentrations ranging up to 0.15 mg/L. Orthophosphate was detected in 88 percent of the samples at concentrations ranging up to 0.14 mg/L.

In general, trace elements were detected infrequently, or at concentrations less than State drinking-water standards. No trace elements were detected at concentrations exceeding Federal Maximum Contaminant Levels, although some concentrations exceeded secondary standards. Zinc, manganese, iron, and copper were the most frequently detected trace metals at 100, 94, 80, and 61 percent, respectively. Lead, arsenic, bromide, aluminum, and selenium were detected in 13 to 26 percent of the analyses.

Exceedances of North Carolina drinking-water standards were observed for iron (3 exceedances of 51 analyses, detection up to 1,100 µg/L), manganese (12 exceedances of 51 analyses, detection up to 890 µg/L), and zinc (4 exceedances of 31 analyses, detection up to 4,900 µg/L). Both iron and manganese exceeded North Carolina standards at three wells. Lead was detected in 8 of 31 samples with a concentration up to 3.5 µg/L. This concentration is less than the State and Federal Action Level of 15 µg/L, but greater than the U.S. Environmental Protection Agency's Maximum Contaminant Level Goal of zero.

Immunoassay techniques were used to screen for selected organic compounds. Samples were collected and analyzed for atrazine compounds and the petroleum-hydrocarbon compounds—benzene, toluene, ethylbenzene, and xylene (BTEX). No BTEX or atrazine compounds were detected in any of the samples at a reporting level of 1 µg/L.

Radon activities in ground water can be naturally high due to the rock units present in Orange County. Radon activity ranged from 38 to 4,462 pCi/L countywide, with a median activity of 405 pCi/L. Median radon activities in Orange County were highest in felsic rocks (487 pCi/L), and lowest in mafic rocks (357 pCi/L). When evaluated by individual hydrogeologic units, the median radon activity was highest in the phyllite unit (1,080 pCi/L in 2 samples) and the felsic metaigneous unit (571 pCi/L in 13 samples).

The U.S. Environmental Protection Agency has proposed a radon Maximum Contaminant Level of 300 pCi/L, and an alternative Maximum Contaminant Level of 4,000 pCi/L based on a multimedia mitigation approach. Sixty-seven percent of the samples exceeded the proposed Maximum Contaminant Level, and one sample exceeded the proposed alternative Maximum Contaminant Level. Radon activities in Orange County were lower than those measured during similar work in nearby Guilford County, where the median activity was 735 pCi/L, and lower than most of the results cited from other areas of the Piedmont. However, the median activities measured in five of the seven hydrogeologic units exceeded the proposed Maximum Contaminant Level of 300 pCi/L.

Overall water-quality data in Orange County indicated few drinking-water concerns. No organic contaminants or excessive nutrient concentrations were found, and few exceedances of North Carolina drinking-water standards were found. This is attributed to generally good ambient ground-water quality in Orange County and to good well-siting and well-construction practices used in relatively new well construction in the County.

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APPENDIX

Table 1A. Water-quality analyses, Orange County, N.C.

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; —, no data; <, less than; µg/L, micrograms per liter; pCi/L, picocuries per liter. Numbers in parentheses are U.S. Geological parameter codes]

Site identification	Local well number	Latitude	Longitude	Depth of well (ft)	Aquifer code (fig. 2; table 1)	Sample date	Temperature water (°C) (00010)	Specific conductance (µS/cm) (00095)	Oxygen, dissolved (mg/L) (00300)	pH water whole field (standard units) (00400)	pH water whole lab (standard units) (00403)	Bicarbonate incremental titration field (mg/L as HCO3) (00453)	Nitrogen, ammonia dissolved (mg/L as N) (00608)
OR-80	360003079002101	36°00'02.0"	79°00'24.0"	405	MVI	11-02-98	18.4	427	4.09	7.6	7.85	—	0.012
OR-81	355831079014001	35°58'34.0"	79°01'39.0"	345	MIF	11-04-98	15.64	369	.05	7.2	7.76	183	.026
OR-85	360157079033501	36°01'56.0"	79°03'30.5"	385	MVI	11-04-98	15.42	318	5.45	7.6	7.94	183	.028
OR-82	360020079052101	36°00'21.0"	79°05'20.0"	200	MVI	11-05-98	14.34	100	3.07	6.55	6.54	110	.02
OR-83	355735079052601	35°57'36.5"	79°05'25.0"	125	MVE	11-05-98	14.95	352	.03	7.72	7.74	—	.02
OR-84	355632079072101	35°56'33.0"	79°07'20.0"	185	MVF	11-09-98	16.68	329	1.5	7.14	7.37	183	.01
OR-90	355811079075601	35°58'11.0"	79°07'55.0"	385	MVE	11-09-98	15.8	166	6.06	7.37	7.61	110	.031
OR-88	355418079072301	35°54'18.0"	79°07'19.0"	305	MVF	11-12-98	15.12	409	.06	7.77	7.35	226	<.01
OR-91	355638079102501	35°56'38.5"	79°10'25.5"	125	MVE	11-12-98	14.58	320	.03	7.04	7.57	183	<.01
OR-92	355854079133301	35°58'57.0"	79°13'38.0"	205	MVF	11-18-98	15.49	133	5.18	6.47	7.04	80.2	.011
OR-93	355401079142201	35°54'01.5"	79°14'17.5"	215	MVF	11-18-98	14.98	523	.07	6.96	7.31	204	.012
OR-94	355815079114401	35°58'15.0"	79°11'45.0"	120	MVF	11-18-98	15.1	64	7.11	6.16	6.46	37	.011
OR-87	360146079074201	36°01'48.5"	79°07'47.0"	305	MIM	11-19-98	14.98	249	.08	6.98	7.47	161	<.01
OR-95	360254079082301	36°02'53.0"	79°08'26.0"	320	MVI	11-19-98	16.01	82	5.04	6.36	6.76	49.4	.014
OR-96	355815079103401	35°58'16.0"	79°10'33.0"	120	MVF	11-30-98	15.35	26	.46	4.72	4.89	<1	<.01
OR-97	360312079041701	36°03'13"	79°04'17"	300	MVF	11-30-98	15.22	228	.69	7.57	8.07	198	<.01
OR-89	360320079030601	36°03'20.5"	79°03'06.0"	105	MVF	12-01-98	14.59	290	.15	7.29	7.88	173	.15
OR-98	360444079031601	36°04'44.0"	79°03'15.0"	165	MVF	12-01-98	14.38	200	1.58	6.85	7.46	130	<.01
OR-99	360107079020601	36°01'09.0"	79°02'04.5"	265	MVI	12-02-98	15.09	335	.33	7.5	8.1	204	.013
OR-100	360658079001101	36°06'58.5"	79°00'10.5"	405	MVF	12-03-98	16.06	235	1.08	6.95	7.58	124	<.01
OR-101	360647079032401	36°06'48.0"	79°03'21.5"	245	MVF	12-03-98	15.2	260	.29	7.51	7.9	164	<.01
OR-102	360540079021801	36°05'41.0"	79°02'18.0"	185	MVF	12-07-98	14.92	149	6.7	6.48	7.29	80	<.01
OR-103	355943079035901	35°59'43.0"	79°03'58.0"	565	MVI	12-07-98	15.35	364	3.15	7.1	7.83	237	<.01
OR-104	360719079025601	36°07'19.5"	79°02'56.0"	365	MVF	12-10-98	15.48	161	2.5	6.93	7.5	91.4	<.01
OR-105	360328079082701	36°03'28.0"	79°08'27.0"	245	PHL	12-10-98	14.25	86	5.2	6.05	6.7	46.9	<.01
OR-106	361413078581201	36°14'13.5"	78°58'12.5"	225	MVF	12-14-98	15.09	175	2.9	6.71	7.2	104	<.01
OR-107	361341079023201	36°13'41.5"	79°02'32.0"	140	MIF	12-14-98	14.64	374	4	6.21	6.49	91.4	<.01
OR-108	361022078590201	36°10'21.5"	78°59'02.5"	665	MVI	12-15-98	15.11	305	1.2	7.28	7.82	185	<.01

Table 1A. Water-quality analyses, Orange County, N.C.—Continued

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; —, no data; <, less than; µg/L, micrograms per liter; pCi/L, picocuries per liter. Numbers in parentheses are U.S. Geological parameter codes]

Site identification	Local well number	Latitude	Longitude	Depth of well (ft)	Aquifer code (fig. 2; table 1)	Sample date	Temperature water (°C) (00010)	Specific conductance (µS/cm) (00095)	Oxygen, dissolved (mg/L) (00300)	pH water whole field (standard units) (00400)	pH water whole lab (standard units) (00403)	Bicarbonate incremental titration field (mg/L as HCO3) (00453)	Nitrogen, ammonia dissolved (mg/L as N) (00608)
OR-109	360845079001001	36°08'45.5"	79°00'10.5"	505	MVF	12-15-98	14.44	162.3	2	6.41	6.91	96.3	<0.01
OR-110	360922079055901	36°09'22.0"	79°05'59.0"	80	MVF	12-16-98	15.14	64	6	5.83	6.38	31.1	.028
OR-111	361055079045501	36°10'54.5"	79°04'55.0"	165	MVF	12-22-98	16.37	87	4.7	6.22	7.01	48.1	.028
OR-112	360907079083901	36°09'07.0"	79°08'39.5"	185	MVI	01-04-99	13.85	124	2.4	5.92	6.68	79	.024
OR-113	360804079071201	36°08'06.0"	79°07'10.5"	165	MVF	01-04-99	13.67	119	3.3	6.48	6.44	46.4	.04
OR-114	360943079084001	36°09'44.0"	79°08'39.5"	185	MVI	01-05-99	12.67	185	2.2	7.25	6.99	72	.012
OR-115	361051079072201	36°10'51.0"	79°07'22.0"	185	MVF	01-05-99	11.04	96	5.2	7.27	6.93	80.5	<.01
OR-116	361307079110401	36°13'07.5"	79°11'04.0"	205	MIF	01-06-99	11.66	138	2.8	6.58	6.85	57.3	<.01
OR-117	361354079141201	36°13'55.0"	79°14'12.0"	305	MII	01-06-99	13.35	268	.2	8.08	7.73	218	<.01
OR-118	361132079101801	36°11'32.5"	79°10'18.5"	125	MIF	01-07-99	13.49	75	5.9	6.14	6.69	128	<.01
OR-119	361105079145801	36°11'05.0"	79°14'59.0"	205	MIF	01-07-99	11.57	166	3.3	5.81	6.36	163	.014
OR-120	360424079125401	36°04'25.0"	79°12'54.5"	105	MIF	01-07-99	13.55	74	5.7	5.96	6.45	153	<.01
OR-121	360846079152001	36°08'46.5"	79°15'20.0"	140	MIF	01-12-99	13.32	262	.2	8.18	7.87	161	<.01
OR-122	360823079131301	36°08'23.5"	79°13'13.0"	200	MVF	01-12-99	14.84	100	9.4	6.6	7.41	75.3	<.01
OR-123	360619079135901	36°06'19.5"	79°13'59.5"	145	MVI	01-13-99	14.75	63	6.6	6.36	6.49	29.6	<.01
OR-124	360756079025201	36°07'56.0"	79°02'52.0"	265	PHL	01-13-99	13.43	290	.3	8.31	8.06	164	<.01
OR-125	360049079060601	36°00'49.5"	79°06'06.0"	520	MIM	01-13-99	15.01	304	1.6	6.87	7.21	189	<.01
OR-126	355244079030801	35°52'44.0"	79°03'08.5"	285	MIF	01-14-99	15.55	120	5.6	6.97	6.95	59.3	<.01
OR-127	355418079053101	35°54'18.5"	79°05'31.0"	225	MIF	01-14-99	15.79	324	.1	8.17	7.59	152	<.01
OR-128	355237079060201	35°52'37.0"	79°06'02.0"	305	MIF	01-20-99	15.42	118	5.8	5.45	6.44	69.2	.012
OR-129	355455079111501	35°54'55.5"	79°11'15.0"	90	MIF	01-20-99	14.59	84	2.2	5.32	6.44	38.3	<.01
OR-130	360321078595401	36°03'21.0"	78°59'54.5"	345	MVF	01-20-99	15.69	378	.2	7.2	6.92	198	.054
OR-131	360913079135301	36°09'14"	79°13'53"	120	MIF	04-08-99	15.26	54	8.17	5.96	6.48	29.6	<.01

Table 1A. Water-quality analyses, Orange County, N.C.—Continued

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; —, no data; <, less than; µg/L, micrograms per liter; pCi/L, picocuries per liter. Numbers in parentheses are U.S. Geological Survey parameter codes]

Site identification	Sample date	Nitrogen, nitrite dissolved (mg/L as N) (00613)	Nitrogen, ammonia + organic dissolved (mg/L as N) (00623)	Nitrogen, NO2+NO3 dissolved (mg/L as N) (00631)	Phosphorus dissolved (mg/L as P) (00666)	Phosphorus, ortho, dissolved (mg/L as P) (00671)	Calcium, dissolved (mg/L as Ca) (00915)	Magnesium, dissolved (mg/L as Mg) (00925)	Sodium, dissolved (mg/L as Na) (00930)	Potassium, dissolved (mg/L as K) (00935)	Chloride, dissolved (mg/L as Cl) (00940)	Sulfate, dissolved (mg/L as SO4) (00945)	Fluoride, dissolved (mg/L as F) (00950)
OR-80	11-02-98	<0.01	<0.2	<0.02	0.02	<0.01	43	18	20	0.9	6.7	27	0.14
OR-81	11-04-98	.016	<.2	.06	.02	.05	61	4.4	12	.4	8.6	16	.28
OR-85	11-04-98	<.01	<.2	.16	<.02	.03	41	11	10	.3	5	7.8	.1
OR-82	11-05-98	<.01	<.2	.33	.07	.09	11	2.2	5.1	.5	3.8	.3	<.1
OR-83	11-05-98	<.01	<.2	<.02	<.02	.02	63	3.1	8.1	.2	7	8.8	<.1
OR-84	11-09-98	<.01	<.2	1.1	.15	.06	58	3.3	7.5	.9	6.5	4.6	<.1
OR-90	11-09-98	<.01	<.2	.02	.08	.08	23	4.6	7.7	.2	2.5	.8	<.1
OR-88	11-12-98	<.01	<.2	.03	<.02	.02	64	6.1	9.5	1.7	9.9	8.4	<.1
OR-91	11-12-98	<.01	<.2	<.02	.08	.05	48	5.7	9.2	.1	4.4	13	.11
OR-92	11-18-98	<.01	<.2	.73	.09	.08	17	3.5	7.6	.2	5.8	1.4	.1
OR-93	11-18-98	<.01	<.2	<.02	.11	.08	43	21	26	5.6	81	.6	.25
OR-94	11-18-98	<.01	<.2	1	.06	.04	6.2	1.5	5.2	.3	2.3	.3	<.1
OR-87	11-19-98	<.01	<.2	<.02	.04	.03	31	8	10	.2	4.3	5.2	<.1
OR-95	11-19-98	<.01	<.2	.6	.08	.06	6.3	3	6.5	.3	2.5	.4	<.1
OR-96	11-30-98	<.01	<.2	.04	.04	<.01	.8	1	2.1	<.1	2.4	9.4	<.1
OR-97	11-30-98	<.01	<.2	.04	.05	.01	48	9	13	.6	13	4.8	.21
OR-89	12-01-98	<.01	<.2	<.02	.14	.02	41	5.6	8	.3	6.1	5.3	.2
OR-98	12-01-98	<.01	<.2	.21	.09	.06	27	4	8.3	.5	2.9	2.8	.16
OR-99	12-02-98	<.01	<.2	<.02	.04	<.01	55	5.1	7.4	.4	4.2	6.8	.11
OR-100	12-03-98	<.01	<.2	.96	.06	.03	28	6.9	9.7	.3	7	1	.11
OR-101	12-03-98	<.01	<.2	.4	.03	<.01	25	10	15	1.5	3.9	2.4	.16
OR-102	12-07-98	<.01	<.2	.03	.04	.02	23	3.9	3.6	.3	2.7	1.5	.1
OR-103	12-07-98	<.01	<.2	.11	.04	.02	58	6.9	12	.3	9.5	3.1	.12
OR-104	12-10-98	<.01	<.2	.5	.05	.02	23	1.8	8.9	.6	1.6	1.1	.1
OR-105	12-10-98	<.01	<.2	.35	.05	.04	11	2.1	4.3	.5	2.3	4.3	<.1
OR-106	12-14-98	<.01	<.2	.8	.08	.07	17	6.6	7.6	.2	7.3	1.3	.18
OR-107	12-14-98	<.01	<.2	1.8	.08	.06	32	15	15	.2	60	7.4	<.1
OR-108	12-15-98	<.01	<.2	.61	.03	.01	46	6.7	10	.3	4.2	1.2	<.1

Table 1A. Water-quality analyses, Orange County, N.C.—Continued

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; —, no data; <, less than; µg/L, micrograms per liter; pCi/L, picocuries per liter. Numbers in parentheses are U.S. Geological Survey parameter codes]

Site identification	Sample date	Nitrogen, nitrite dissolved (mg/L as N) (00613)	Nitrogen, ammonia + organic dissolved (mg/L as N) (00623)	Nitrogen, NO2+NO3 dissolved (mg/L as N) (00631)	Phosphorus dissolved (mg/L as P) (00666)	Phosphorus, ortho, dissolved (mg/L as P) (00671)	Calcium, dissolved (mg/L as Ca) (00915)	Magnesium, dissolved (mg/L as Mg) (00925)	Sodium, dissolved (mg/L as Na) (00930)	Potassium, dissolved (mg/L as K) (00935)	Chloride, dissolved (mg/L as Cl) (00940)	Sulfate, dissolved (mg/L as SO4) (00945)	Fluoride, dissolved (mg/L as F) (00950)
OR-109	12-15-98	<0.01	<0.2	0.49	0.03	0.01	17	5	7.8	0.5	4	1.8	0.12
OR-110	12-16-98	<.01	<.2	1	.06	.07	5.1	1.8	5.7	.4	3.4	.2	<.1
OR-111	12-22-98	<.01	.31	.8	.12	.14	9	2.6	6.3	.4	2.3	1.5	<.1
OR-112	01-04-99	<.01	<.2	.03	.05	.06	11	4.4	7.8	3.1	3.3	1.6	.1
OR-113	01-04-99	<.01	<.2	1.1	.04	.04	9.6	3.7	7.1	.1	14	.9	<.1
OR-114	01-05-99	<.01	<.2	.95	<.02	.01	20	6.5	6.8	3.5	3.5	2	<.1
OR-115	01-05-99	<.01	<.2	.03	<.02	.03	9.4	2.7	6	1.8	2	1.3	<.1
OR-116	01-06-99	<.01	<.2	2.9	.06	.07	11	4.3	8.6	.9	3.7	1.6	<.1
OR-117	01-06-99	<.01	<.2	.1	<.02	<.01	34	5.6	15	2.1	2.3	1.8	<.1
OR-118	01-07-99	<.01	<.2	.61	.05	.06	6.4	1.7	6.5	1.3	2.2	.4	<.1
OR-119	01-07-99	<.01	<.2	7.2	.07	.08	14	3.3	12	.6	8.1	2.6	<.1
OR-120	01-07-99	<.01	<.2	1.5	.03	.04	8.6	3.6	4.4	.4	3.1	.5	<.1
OR-121	01-12-99	<.01	<.2	<.02	<.02	.04	38	5	11	2.9	2.2	3.4	<.1
OR-122	01-12-99	<.01	<.2	.06	<.02	.02	19	2.4	5.1	.9	1.8	3.1	<.1
OR-123	01-13-99	<.01	<.2	.03	.06	.08	4.8	1.6	6.6	.5	1.5	.7	<.1
OR-124	01-13-99	<.01	.23	<.02	<.02	.02	22	5.4	33	1.7	5.8	3.5	.6
OR-125	01-13-99	<.01	<.2	.1	<.02	.02	34	12	8.8	.6	3.8	6.8	<.1
OR-126	01-14-99	<.01	<.2	.94	.26	.26	9	1.5	10	.4	2.8	1.5	.24
OR-127	01-14-99	<.01	<.2	.71	<.02	.03	47	9.3	11	.6	6.9	7.6	.12
OR-128	01-20-99	.01	<.2	.13	.05	.05	8.9	3.9	9.9	.9	3.4	.5	.26
OR-129	01-20-99	.012	<.2	.84	.06	.06	6.2	1.8	9.1	.7	6.4	.8	<.1
OR-130	01-20-99	.01	<.2	.05	<.02	<.01	59	5.4	13	.3	20	20	.12
OR-131	04-08-99	<.01	<.2	.32	E.12	.11	3.7	1.4	5.9	.6	1.9	2.4	<.1

E estimated.

Table 1A. Water-quality analyses, Orange County, N.C.—Continued

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; —, no data; <, less than; µg/L, micrograms per liter; pCi/L, picocuries per liter. Numbers in parentheses are U.S. Geological Survey parameter codes]

Site identification	Sample date	Silica, dissolved (mg/L as SiO2) (00955)	Arsenic, dissolved (µg/L as As) (01000)	Barium, dissolved (µg/L as Ba) (01005)	Beryllium, dissolved (µg/L as Be) (01010)	Cadmium, dissolved (µg/L as Cd) (01025)	Chromium, dissolved (µg/L as Cr) (01030)	Cobalt, dissolved (µg/L as Co) (01035)	Copper, dissolved (µg/L as Cu) (01040)	Iron, dissolved (µg/L as Fe) (01046)	Lead, dissolved (µg/L as Pb) (01049)	Manganese, dissolved (µg/L as Mn) (01056)	Molybdenum, dissolved (µg/L as Mo) (01060)
OR-80	11-02-98	24	<1	19	<0.5	<0.5	<1	<1	<1	3.8	<1	3.9	<2
OR-81	11-04-98	33	<1	77	<.5	<.5	<1	<1	<1	12	<1	190	2.9
OR-85	11-04-98	21	4.3	79	<.5	<.5	<1	<1	1.2	<1	<1	1.3	<2
OR-82	11-05-98	25	—	—	—	—	—	—	—	2.4	—	4	—
OR-83	11-05-98	22	—	—	—	—	—	—	—	1.5	—	110	—
OR-84	11-09-98	27	<1	1	<.5	<.5	<1	<1	3.8	2.3	<1	<.2	<2
OR-90	11-09-98	29	<1	4	<.5	<.5	<1	<1	3.1	<1	<1	.4	<2
OR-88	11-12-98	26	<1	14	<.5	<.5	<1	<1	<1	43	<1	410	<2
OR-91	11-12-98	25	4.3	.5	<.5	<.5	<1	<1	1.1	339	<1	330	<2
OR-92	11-18-98	30	—	—	—	—	—	—	—	<1	—	4.4	—
OR-93	11-18-98	35	<1	71	<.5	<.5	<1	<1	<1	61	1.2	890	<2
OR-94	11-18-98	28	—	—	—	—	—	—	—	1.4	—	.4	—
OR-87	11-19-98	40	<1	3	<.5	<.5	<1	<1	1.1	34	1.4	64	<2
OR-95	11-19-98	31	—	—	—	—	—	—	—	2.6	—	6.5	—
OR-96	11-30-98	10	<1	.7	<.5	3.5	<1	3	7.6	325	2.1	66	<2
OR-97	11-30-98	23	<1	54	<.5	<.5	<1	<1	6.7	2.1	<1	<.2	<2
OR-89	12-01-98	32	<1	120	<.5	<.5	<1	<1	<1	1,100	<1	490	<2
OR-98	12-01-98	25	—	—	—	—	—	—	—	<1	—	6.2	—
OR-99	12-02-98	26	<1	120	<.5	<.5	<1	<1	<1	254	<1	220	<2
OR-100	12-03-98	31	—	—	—	—	—	—	—	<1	—	7.8	—
OR-101	12-03-98	22	<1	83	<.5	<.5	<1	<1	<1	10	3.7	15	<2
OR-102	12-07-98	22	<1	8	<.5	<.5	<1	<1	7	<1	<1	.7	<2
OR-103	12-07-98	32	<1	8	<.5	<.5	<1	<1	1.1	<1	<1	5.1	<2
OR-104	12-10-98	30	<1	24	<.5	<.5	<1	<1	<1	2.3	<1	15	6.4
OR-105	12-10-98	26	<1	4	<.5	<.5	<1	<1	<1	2.5	<1	1.8	<2
OR-106	12-14-98	33	<1	18	<.5	<.5	<1	<1	24	2.2	2.6	6.1	<2
OR-107	12-14-98	40	—	—	—	—	—	—	—	9.6	—	4.7	—
OR-108	12-15-98	29	1.7	24	<.5	<.5	<1	<1	3.8	1.6	3.4	.4	<2

Table 1A. Water-quality analyses, Orange County, N.C.—Continued

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; —, no data; <, less than; µg/L, micrograms per liter; pCi/L, picocuries per liter. Numbers in parentheses are U.S. Geological Survey parameter codes]

Site identification	Sample date	Silica, dissolved (mg/L as SiO2) (00955)	Arsenic, dissolved (µg/L as As) (01000)	Barium, dissolved (µg/L as Ba) (01005)	Beryllium, dissolved (µg/L as Be) (01010)	Cadmium, dissolved (µg/L as Cd) (01025)	Chromium, dissolved (µg/L as Cr) (01030)	Cobalt, dissolved (µg/L as Co) (01035)	Copper, dissolved (µg/L as Cu) (01040)	Iron, dissolved (µg/L as Fe) (01046)	Lead, dissolved (µg/L as Pb) (01049)	Manganese, dissolved (µg/L as Mn) (01056)	Molybdenum, dissolved (µg/L as Mo) (01060)
OR-109	12-15-98	29	—	—	—	—	—	—	—	2.5	—	17	—
OR-110	12-16-98	30	<1	8	<0.5	<0.5	<1	<1	3.1	4.1	<1	.5	<2
OR-111	12-22-98	38	—	—	—	—	—	—	—	<1	—	3.8	—
OR-112	01-04-99	37	<1	35	<.5	<.5	<1	<1	2.7	1.6	<1	19	<2
OR-113	01-04-99	30	—	—	—	—	—	—	—	10	—	3.7	—
OR-114	01-05-99	28	—	—	—	—	—	—	—	7.6	—	5.1	—
OR-115	01-05-99	37	<1	9	<.5	<.5	<1	<1	4.3	1.3	3.5	9.9	<2
OR-116	01-06-99	52	—	—	—	—	—	—	—	1.4	—	7.2	—
OR-117	01-06-99	29	<1	6	<.5	<.5	<1	<1	1.9	6.3	<1	1.8	<2
OR-118	01-07-99	44	<1	30	<.5	<.5	2.1	<1	<1	1.9	<1	1.6	<2
OR-119	01-07-99	53	—	—	—	—	—	—	—	3.5	—	1.8	—
OR-120	01-07-99	31	<1	8	<.5	<.5	<1	<1	3.6	2.7	1.1	3.3	<2
OR-121	01-12-99	22	—	—	—	—	—	—	—	17	—	35	—
OR-122	01-12-99	23	<1	15	<.5	<.5	1.2	<1	8.4	8.7	<1	4	<2
OR-123	01-13-99	36	—	—	—	—	—	—	—	<1	—	<.2	—
OR-124	01-13-99	18	1.9	23	<.5	<.5	<1	<1	<1	2.9	<1	31	<2
OR-125	01-13-99	30	—	—	—	—	—	—	—	2.2	—	61	—
OR-126	01-14-99	56	<1	.9	<.5	<.5	<1	<1	<1	1.9	<1	31	<2
OR-127	01-14-99	36	—	—	—	—	—	—	—	<1	—	60	—
OR-128	01-20-99	33	—	—	—	—	—	—	—	1	—	2.8	—
OR-129	01-20-99	47	—	—	—	—	—	—	—	75	—	17	—
OR-130	01-20-99	34	1.3	100	<.5	<.5	<1	<1	2	37	<1	320	<2
OR-131	04-08-99	35	<1	9	<.5	<.5	<1	<1	4.1	5.1	<1	2	<2

Table 1A. Water-quality analyses, Orange County, N.C.—Continued

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; —, no data; <, less than; µg/L, micrograms per liter; pCi/L, picocuries per liter. Numbers in parentheses are U.S. Geological parameter codes]

Site identification	Sample date	Nickel, dissolved (µg/L as Ni) (01065)	Silver, dissolved (µg/L as Ag) (01075)	Zinc, dissolved (µg/L as Zn) (01090)	Aluminum, dissolved (µg/L as Al) (01106)	Selenium, dissolved (µg/L as Se) (01145)	Alkalinity water dissolved total incremental titration field (mg/L as CaCO3) (39086)	Solids, residue at 180 °C dissolved (mg/L) (70300)	Bromide, dissolved (mg/L as Br) (71870)	Radon-222 2 sigma precision estimate water, whole, total (pCi/L) (76002)	Radon-222 total (pCi/L) (82303)	Specific conductance lab (µS/cm) (90095)	Acid neutralizing capacity unfiltered titration 4.5 lab (mg/L as CaCO3) (90410)
OR-80	11-02-98	<1	<1	4.5	<3	<1	174	256	<0.05	22	444	421	192
OR-81	11-04-98	<1	<1	64	<3	4.6	150	242	<.05	42	2,021	382	171
OR-85	11-04-98	<1	<1	4.7	<3	7	150	196	<.05	18	158	331	162
OR-82	11-05-98	—	—	—	—	—	90	78	<.05	55	3,785	103	45
OR-83	11-05-98	—	—	—	—	—	170	218	<.05	23	443	359	172
OR-84	11-09-98	<1	<1	11	<3	4.3	150	210	<.05	20	279	338	161
OR-90	11-09-98	<1	<1	750	<3	<1	90	116	<.05	20	279	182	92
OR-88	11-12-98	<1	<1	250	<3	<1	185	250	.07	43	2,068	398	190
OR-91	11-12-98	<1	<1	130	<3	<1	150	202	<.05	23	405	318	149
OR-92	11-18-98	—	—	—	—	—	66	114	<.05	21	291	153	63
OR-93	11-18-98	<1	<1	65	<3	<1	167	324	.5	27	726	555	155
OR-94	11-18-98	—	—	—	—	—	30.4	70	<.05	27	752	72	29
OR-87	11-19-98	<1	<1	1,400	12	<1	130	176	<.05	23	357	258	127
OR-95	11-19-98	—	—	—	—	—	41	78	<.05	21	325	90	40
OR-96	11-30-98	1.1	<1	860	199	<1	—	28	<.05	19	166	37	2.4
OR-97	11-30-98	<1	<1	48	<3	<1	162	210	.06	44	2,400	328	167
OR-89	12-01-98	<1	<1	5.1	<3	<1	142	183	<.05	21	311	277	132
OR-98	12-01-98	—	—	—	—	—	106	125	<.05	38	1,747	182	95
OR-99	12-02-98	<1	<1	44	<3	<1	167	207	<.05	22	401	296	167
OR-100	12-03-98	—	—	—	—	—	101	154	<.05	21	259	232	108
OR-101	12-03-98	<1	<1	430	<3	<1	135	157	<.05	25	584	258	133
OR-102	12-07-98	<1	<1	190	<3	<1	66	102	<.05	18	172	158	77
OR-103	12-07-98	<1	<1	8.8	52	<1	194	233	<.05	27	748	376	183
OR-104	12-10-98	3.5	<1	4,400	<3	<1	75	118	<.05	40	1,430	168	87
OR-105	12-10-98	<1	<1	410	<3	<1	38.5	75	<.05	45	2,017	95	39
OR-106	12-14-98	<1	<1	4,500	<3	<1	85	124	<.05	19	216	178	77
OR-107	12-14-98	—	—	—	—	—	75	259	.4	21	313	377	75
OR-108	12-15-98	<1	<1	190	<3	1.1	152	187	<.05	17	106	304	156

Table 1A. Water-quality analyses, Orange County, N.C.—Continued

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; —, no data; <, less than; µg/L, micrograms per liter; pCi/L, picocuries per liter. Numbers in parentheses are U.S. Geological parameter codes]

Site identification	Sample date	Nickel, dissolved (µg/L as Ni) (01065)	Silver, dissolved (µg/L as Ag) (01075)	Zinc, dissolved (µg/L as Zn) (01090)	Aluminum, dissolved (µg/L as Al) (01106)	Selenium, dissolved (µg/L as Se) (01145)	Alkalinity water dissolved total incremental titration field (mg/L as CaCO3) (39086)	Solids, residue at 180 °C dissolved (mg/L) (70300)	Bromide, dissolved (mg/L as Br) (71870)	Radon-222 2 sigma precision estimate water, whole, total (pCi/L) (76002)	Radon-222 total (pCi/L) (82303)	Specific conductance lab (µS/cm) (90095)	Acid neutralizing capacity unfiltered titration 4.5 lab (mg/L as CaCO3) (90410)
OR-109	12-15-98	—	—	—	—	—	79	114	<0.05	26	647	170	79
OR-110	12-16-98	<1	<1	290	<3	<1	26	66	<.05	25	546	68	26
OR-111	12-22-98	—	—	—	—	—	39.4	85	<.05	42	275	96	42
OR-112	01-04-99	<1	<1	2,600	<3	<1	65	104	<.05	27	701	138	65
OR-113	01-04-99	—	—	—	—	—	38	100	<.05	21	317	136	40
OR-114	01-05-99	—	—	—	—	—	59	123	<.05	20	279	192	89
OR-115	01-05-99	<1	<1	1,500	<3	<1	66	85	<.05	22	409	103	49
OR-116	01-06-99	—	—	—	—	—	47	127	<.05	22	383	140	53
OR-117	01-06-99	<1	<1	550	<3	<1	140	164	<.05	20	234	266	139
OR-118	01-07-99	<1	<1	880	3.1	<1	105	83	<.05	25	571	82	35
OR-119	01-07-99	—	—	—	—	—	134	164	<.05	40	1,896	177	44
OR-120	01-07-99	<1	<1	2,100	<3	<1	126	82	<.05	21	380	102	40
OR-121	01-12-99	—	—	—	—	—	132	160	<.05	18	159	269	137
OR-122	01-12-99	2.1	<1	73	<3	<1	61	89	<.05	16	62	156	73
OR-123	01-13-99	—	—	—	—	—	24.3	71	<.05	27	726	68	32
OR-124	01-13-99	<1	<1	53	<3	<1	135	169	.05	18	143	279	139
OR-125	01-13-99	—	—	—	—	—	155	186	<.05	15	38	295	149
OR-126	01-14-99	<1	<1	4,900	<3	<1	48.6	119	<.05	48	2,870	116	51
OR-127	01-14-99	—	—	—	—	—	152	213	.07	29	900	338	159
OR-128	01-20-99	—	—	—	—	—	56.7	92	<.05	56	3,915	122	57
OR-129	01-20-99	—	—	—	—	—	31.4	88	.06	60	4,462	93	32
OR-130	01-20-99	<1	<1	97	<3	<1	162	255	.2	33	1,227	390	149
OR-131	04-08-99	<1	<1	980	<3	<1	24	65	<.05	19	264	63	24