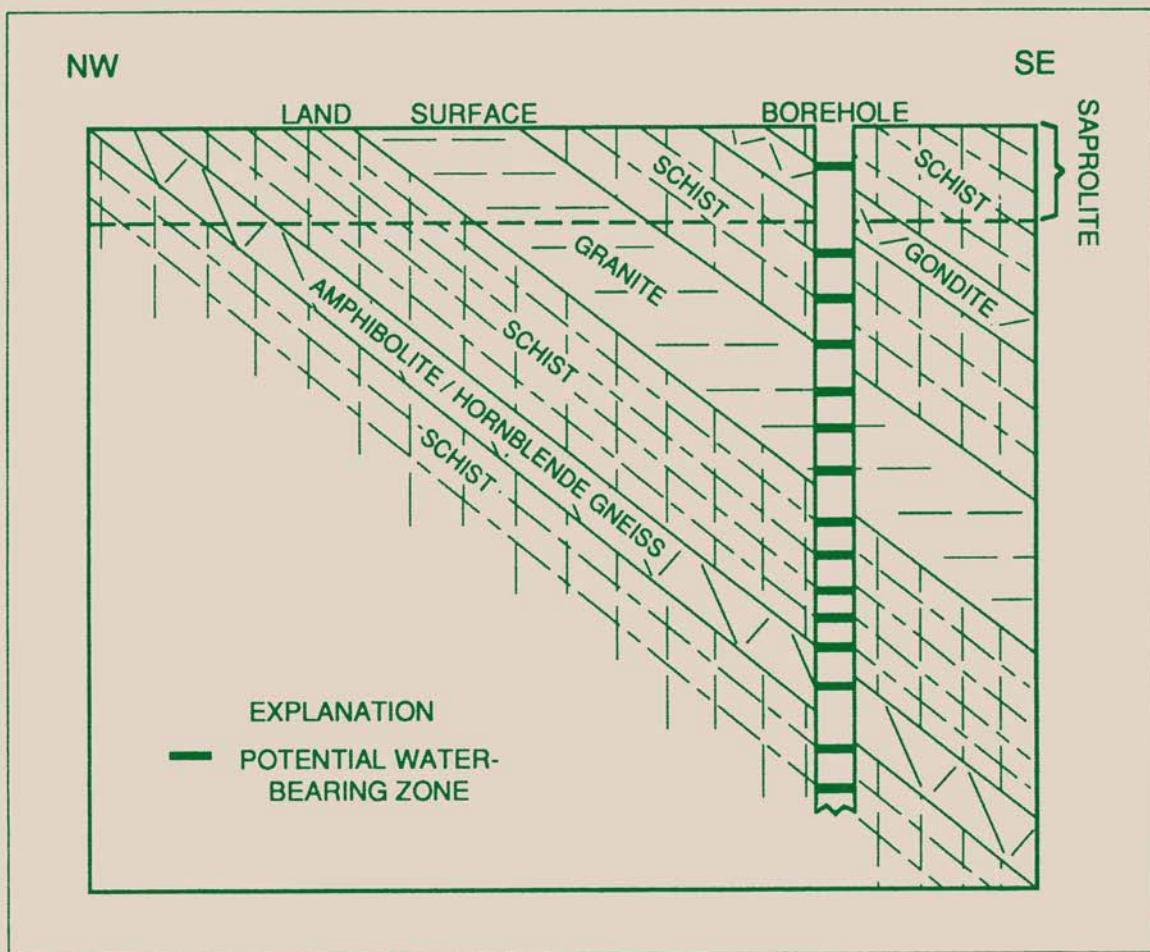


GEOLOGY AND GROUND-WATER RESOURCES IN THE ZEBULON AREA, GEORGIA

U.S. GEOLOGICAL SURVEY



Prepared in cooperation with
CITY OF ZEBULON, GEORGIA



WATER-RESOURCES INVESTIGATIONS REPORT 93-4161

Cover: Diagrammatic section through crystalline rocks in the Zebulon area.
Dark horizontal bars show potential water-bearing zones in a conceptual borehole.

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By Melinda J. Chapman, Barbara J. Milby, and Michael F. Peck

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Water-Resources Investigations Report 93-4161



**Prepared in cooperation with the
CITY OF ZEBULON, GEORGIA**

Atlanta, Georgia

1993

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

Conversion Factors

Multiply by to obtain

Length

| | | |
|------------|--------|------------|
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |

Flow

| | | |
|----------------------------------|---------|------------------------|
| gallons per minute (gal/min) | 3.785 | liter per minute |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second |

Temperature

Temperature in degrees Fahrenheit ($^{\circ}\text{F}$) can be converted to degrees Celsius ($^{\circ}\text{C}$) as follows:

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

Vertical Datum

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum 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.”

Acronyms

| | |
|------|--------------------------------------|
| EPA | U.S. Environmental Protection Agency |
| MCL | Maximum Contaminant Level |
| SMCL | Secondary Maximum Contaminant Level |
| USGS | U.S. Geological Survey |

GEOLOGY AND GROUND-WATER RESOURCES IN THE ZEBULON AREA, GEORGIA

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ABSTRACT

The current (1991) surface-water source of drinking-water supply for the city of Zebulon, Pike County, Georgia, no longer provides an adequate water supply and periodically does not meet water-quality standards. The hydrogeology of crystalline rocks in the Zebulon area was evaluated to assess the potential of ground-water resources as a supplement or alternative source of water to present surface-water supplies. As part of the ground-water resource evaluation, well location and construction data were compiled, a geologic map was constructed, and ground water was sampled and analyzed.

Three mappable geologic units delineated during this study provide a basic understanding of hydrogeologic settings in the Zebulon area. Rock types include a variety of aluminosilicate schists, granitic rocks, amphibolites/hornblende gneisses, and gondites. Several geologic features that may enhance ground-water availability were identified in the study area. These features include contacts between contrasting rock types, where a high degree of differential weathering has occurred, and well-developed structural features, such as foliation and jointing, are present. High-yielding wells (greater than 25 gallons per minute) and low-yielding wells (less than one gallon per minute) were located in all three geologic units in a variety of topographic settings. Well yields range from less than one gallon per minute to 250 gallons per minute. The variable total depths and wide ranges of casing depths of the high-yielding wells are indicative of variations in depths to water-bearing zones and regolith thicknesses, respectively. The depth of water-bearing zones is highly variable, even on a local scale.

Analyses of ground-water samples indicate that the distribution of iron concentration is as variable as well yield in the study area and does not seem to be related to a particular rock type. Iron concentrations in ground-water samples range from 0.02 to 5.3 milligrams per liter. Both iron concentration and well yield varies substantially over a relatively small area.

INTRODUCTION

Widespread and rapid population growth in much of the Piedmont physiographic province of northern Georgia has increased demands for water supply. Virtually untapped ground-water resources could provide a supplemental source of water to meet the ever-increasing demands of municipal, industrial, commercial, and domestic users. Ground-water availability in the Piedmont Province (fig. 1) generally is considered limited, requiring difficult exploration methods because of the high variability of well yields in the crystalline rock aquifers in this region. However, recent investigators (Cressler and others, 1983; Clarke and Peck, 1991) have identified numerous high-yield wells in the area. A better understanding of the relation between geology and occurrence of ground water is needed to effectively develop this water-supply resource. The need for useful and practical guidelines to evaluate and develop ground water in the area is becoming more apparent as a result of recent droughts (1980–1982, 1986, and 1988) that severely reduced the quantity of surface water available (U.S. Geological Survey, 1991) to meet supply needs.

The availability of ground water in crystalline rock aquifer settings is related directly to complex geologic terranes (Cressler and others, 1983; Radtke and others, 1986). The occurrence of water in crystalline rock aquifers does not conform to hydrogeologic factors governing ground-water flow in poorly lithified sedimentary rock aquifers in the Coastal Plain Province of Georgia, or to the highly lithified, folded sedimentary rock aquifers in the Valley and Ridge Province (fig. 1). In other hydrogeologic settings of Georgia, aquifers are more areally extensive and have reported transmissivities that are several orders of magnitude higher than aquifers in the Piedmont Province. Therefore, conventional methods used to evaluate the ground-water resource potential of sedimentary-rock aquifers are not applicable in these crystalline rock settings. Ground water in crystalline-rock settings is present in irregularly distributed, highly localized, and discontinuous water-bearing zones. Crystalline rock water-bearing zones are present along foliation, fractures, joints, contacts, veins, pegmatites, and other geologic features that have been enhanced by differential weathering. Field investigations are useful in evaluating the ground-water-resource potential of these regions and can contribute substantially to delineating the hydrogeologic and hydrochemical settings of an area.

Elkins Creek is the current (1991) drinking-water source for the city of Zebulon and surrounding areas (plate 1); however, the creek might not provide an adequate water supply to meet future demands (S.K. Stover, city of Zebulon, oral commun., 1991). Recent droughts and increases in water-supply demands have reduced the quantity of available surface water from the creek. Elkins Creek also periodically contains high concentrations of iron and manganese (Neil Monroe, city of Zebulon, oral commun., 1991). Moreover, the pump intake station on Elkins Creek is about 1-1/2 mi downstream of the county landfill, which could a potential source of contamination (S.K. Stover, city of Zebulon, oral commun., 1991). In July 1991, the U.S. Geological Survey (USGS), in cooperation with the city of Zebulon, began a study to evaluate ground-water resources in the Zebulon area. The investigation included a well inventory, geologic mapping, and ground-water-quality sampling.

In 1986, five wells (wells 11Y001–11Y005, table 1 and plate 1) were drilled for the city of Zebulon near the water-treatment plant on Elkins Creek, as supplemental water-supply sources to be used during periods of low flow in the creek. Occasionally, the city mixes ground water from the wells with the water from Elkins Creek to reduce the degree of treatment necessary to obtain a potable supply (Neil Monroe, city of Zebulon, oral commun., 1991). These five wells do not yield an adequate water supply (25 gallons per minute (gal/min)) and cannot be pumped simultaneously because of their proximity to one another. The initial yield of a sixth well (well 11Y028), drilled for the city of Zebulon in 1990, was reported to be about 15 gal/min; however, subsequent to the use of explosives to increase fracturing in the open borehole, the yield increased to about 50 gal/min. This well probably will be used as a supplement water-supply source for the city of Zebulon (S.K. Stover, city of Zebulon, oral commun., 1991).

Purpose and Scope

This report describes results of a study of the geology of the Zebulon, Ga., area, and its relation to ground-water availability and quality. The objectives of this report are to (1) describe geologic settings, (2) evaluate hydrogeologic factors that may affect well yield and ground-water quality, and (3) formulate a conceptual framework that aids in the explanation of the availability of ground water in crystalline rock settings. The relation among geologic factors, well yield, and ground-water quality is discussed in this report. The report also provides information that enhances the understanding of the potential for ground-water development in the study area and in similar hydrogeologic settings. Results of this study can be used by water-resource managers to guide ground-water development and management in the Zebulon study area and similar crystalline rock settings elsewhere in Georgia.

This ground-water resource investigation included geologic mapping, the compilation of well-inventory information, and the collection of selected ground-water quality samples. Maps were constructed showing rock types, geologic structures, well yield, and ground-water quality data. Well-inventory data include yield, construction characteristics, and field verification of 54 wells and one spring within an approximate 3-mi radius of Zebulon (plate 1, table 1). Most of the wells were drilled; however, some wells were bored and included in the study because of their close proximity to the drilled wells. Ground water was sampled from selected wells and analyzed to evaluate water-quality conditions.

Description of Study Area

The study area lies in the Piedmont physiographic province of northern Georgia in the vicinity of the city of Zebulon, Pike County. Zebulon is approximately 50 mi south of Atlanta and 12 mi south of Griffin (fig. 1, plate 1). Pike County is located on the western side of a drainage divide that separates the Flint and Ocmulgee River watersheds. Topography consists of low hills and moderately entrenched stream valleys that range in altitude from 740 to 940 ft above sea level.

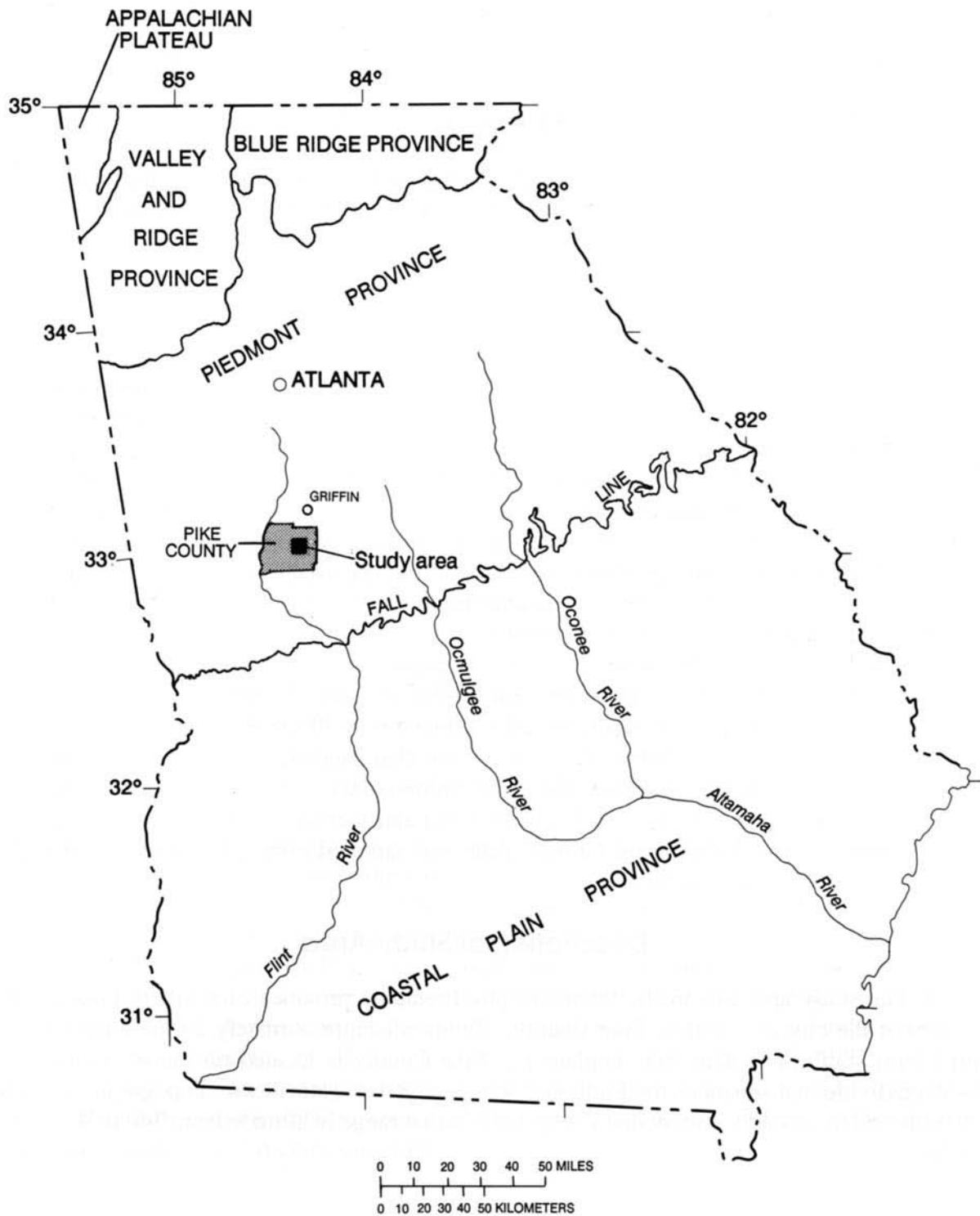


Figure 1.—Study area and physiographic provinces of Georgia. (Modified from Clark and Zisa, 1976.)

Table 1.—Inventory of wells within a 3-mile radius of Zebulon, Georgia

[gal/min, gallons per minute. Topographic setting: V, valley; F, flat; S, hillside; H, hilltop; U, undulating; W, upland draw. Use of water: I, irrigation; H, domestic; P, public supply; U, unused; S, livestock; Z, other; —, information not available; Casing material; S, steel, P, polyvinylcarbon, C, Cement]

| Well number | Station name | Latitude | Longitude | Topographic setting | Depth of well (feet) | Casing material | Casing depth (feet) | Casing diameter (inches) | Yield (gal/min) | Date drilled | Water use | Geologic unit (plate 2) |
|-------------|-------------------------|-----------|-----------|---------------------|----------------------|-----------------|---------------------|--------------------------|-----------------|--------------|-----------|-------------------------|
| 10Y004 | The Cedar Golf Course | 33°06'14" | 84°23'13" | V | 165 | S | 74 | 6 | 125 | 07-21-81 | I | A |
| 10Y015 | Jamie Watts (305) | 33°06'36" | 84°23'19" | F | 305 | — | — | 6 | 12 | — | H | A |
| 10Y016 | Jamie Watts (605) | 33°06'37" | 84°23'20" | F | 605 | — | — | 6 | 6 | — | H | A |
| 10Z018 | Gene Dabbs | 33°07'32" | 84°23'08" | S | 305 | P | 130 | 6 | 80 | - -87 | H | A |
| 11Y001 | Zebulon, Georgia 1 | 33°06'06" | 84°21'37" | S | 505 | P | 34 | 6 | 20 | 09-19-86 | P | A |
| 11Y002 | Zebulon, Georgia 2 | 33°06'03" | 84°21'37" | S | 530 | P | 56 | 6 | 10 | 09-19-86 | P | A |
| 11Y003 | Zebulon, Georgia 3 | 33°06'05" | 84°21'36" | S | 510 | P | 109 | 6 | 25 | 09-19-86 | P | A |
| 11Y004 | Zebulon, Georgia 4 | 33°06'08" | 84°12'39" | S | 405 | P | 35 | 6 | 25 | 09- -86 | P | A |
| 11Y005 | Zebulon, Georgia 5 | 33°06'04" | 84°21'40" | S | 250 | P | 45 | 6 | 18 | 08-15-86 | P | A |
| 11Y010 | Frank Kirby | 33°04'58" | 84°18'37" | S | 555 | P | 72 | 6 | 6 | 08- -86 | H | C |
| 11Y019 | Howard Rawlands | 33°05'18" | 84°20'05" | F | 580 | P | 81 | 6 | 8 | 08-13-90 | H | C |
| 11Y020 | Jimmy Sandefur | 33°06'26" | 84°21'56" | F | 68 | C | 68 | 30 | — | 10-01-81 | U | A |
| 11Y021 | Harry Rawlins | 33°06'09" | 84°21'01" | F | 230 | P | 15 | 6 | 30 | 08-13-90 | H | B |
| 11Y022 | Pike County Shop Well | 33°07'02" | 84°21'39" | H | 42 | C | 42 | 30 | — | 11-25-80 | U | A |
| 11Y023 | Terrell Moody | 33°07'24" | 84°19'28" | F | — | C | — | 30 | — | — | H | B |
| 11Y024 | Danny Cox | 33°07'30" | 84°18'59" | F | 605 | P | 115 | 6 | 10 | 06-12-91 | H | B |
| 11Y025 | Moody Funeral Home | 33°07'25" | 84°19'41" | F | 225 | P | 65 | 6 | 12 | 05-08-81 | H | B |
| 11Y026 | Ed Edwards (1980 well) | 33°07'13" | 84°20'54" | H | 305 | P | 67 | 6 | 15 | 08-15-80 | H | A |
| 11Y027 | Ed Edwards (1983 well) | 33°07'10" | 84°20'54" | H | — | — | — | — | — | - -83 | I | A |
| 11Y028 | Zebulon, Elkins Creek | 33°07'28" | 84°20'49" | F | 595 | S | 36 | 7 | 50 | 02- -91 | U | A |
| 11Y029 | Robert Anderson | 33°05'56" | 84°20'53" | F | 505 | P | 48 | 6 | 6 | 10-05-81 | I | B |
| 11Y030 | John Edwards | 33°06'26" | 84°19'35" | S | 405 | P | — | 6 | 30 | 07- -91 | H | C |
| 11Y031 | Joseph Kuprain | 33°07'20" | 84°20'17" | F | 505 | P | 16 | 6 | 4 | 04-27-87 | U | B |
| 11Y032 | Joseph Kuprain | 33°07'20" | 84°20'17" | F | — | P | — | — | — | — | — | B |
| 11Y033 | Doug Mangham | 33°05'41" | 84°20'57" | S | 305 | P | 50 | 6 | 5 | 10-31-89 | H | B |
| 11Y034 | Pike County High School | 33°05'20" | 84°20'39" | F | 305 | S | 60 | 6 | 12 | — | I | B |
| 11Y035 | Will Ferrell | 33°07'28" | 84°18'52" | F | 250 | S | — | 6 | 200 | — | U | C |
| 11Y036 | Will Ferrell | 33°07'28" | 84°18'51" | F | 25 | C | 25 | 30 | — | — | U | C |
| 11Y037 | Will Ferrell | 33°07'27" | 84°18'52" | F | 50 | C | 50 | 30 | — | - -89 | H | C |
| 11Y038 | Sullivan's Store | 33°04'04" | 84°20'37" | F | 305 | — | 100 | 6 | 100 | — | H | C |

Table 1.—Inventory of wells within a 3-mile radius of Zebulon, Georgia—Continued

[gal/min, gallons per minute. Topographic setting: V, valley; F, flat; S, hillside; H, hilltop; U, undulating; W, upland draw. Use of water: I, irrigation; H, domestic; P, public supply; U, unused; S, livestock; Z, other; —, information not available; Casing material; S, steel, P, polyvinylcarbon, C, Cement]

| Well number | Station name | Latitude | Longitude | Topographic setting | Depth of well (feet) | Casing material | Casing depth (feet) | Casing diameter (inches) | Yield (gal/min) | Date drilled | Water use | Geologic unit (plate 2) |
|-------------|---------------------------|-----------|-----------|---------------------|----------------------|-----------------|---------------------|--------------------------|-----------------|--------------|-----------|-------------------------|
| 11Y039 | Steve Shields | 33°04'03" | 84°20'38" | F | 305 | — | — | — | 40 | — | H | C |
| 11Y040 | Rounds | 33°04'47" | 84°21'44" | F | 300 | — | — | 6 | 8 | — | H | B |
| 11Y041 | Margie-Pennistone Bledsoe | 33°05'10" | 84°21'38" | H | 305 | P | 48 | 6 | 30 | — | H | B |
| 11Y042 | Colwell (Flowing well) | 33°04'16" | 84°22'28" | F | 130 | P | 40 | 6 | 100 | — | S | A |
| 11Y043 | Earl (Barn well) | 33°05'16" | 84°18'46" | U | 300 | S | — | 6 | 25 | — | S | C |
| 11Y044 | Earl (Barn well) | 33°05'16" | 84°18'46" | U | — | C | — | 30 | — | — | S | C |
| 11Y045 | Earl (House well) | 33°05'14" | 84°18'49" | U | — | P | — | 6 | 250 | — | Z | C |
| 11Y046 | Earl (House well) | 33°05'14" | 84°18'49" | U | — | C | — | 30 | — | — | H | C |
| 11Y047 | Hurd | 33°05'17" | 84°18'57" | U | — | C | — | 30 | — | — | H | C |
| 11Y048 | Mike Ward | 33°07'19" | 84°20'24" | S | 205 | P | 27 | 6 | — | 08-03-89 | — | A |
| 11Y049 | Jerry Spinks | 33°05'38" | 84°20'58" | H | 186 | P | — | 6 | 28 | - -89 | H | B |
| 11Y050 | John Edwards | 33°06'23" | 84°19'37" | H | 330 | P | 85 | 6 | 10 | 03-22-91 | — | C |
| 11Y053 | Harold Rawlins (springs) | 33°05'12" | 84°19'43" | S | — | — | — | — | — | — | U | C |
| 11Y056 | Brannon (Pine Hill farms) | 33°06'57" | 84°19'05" | F | — | — | — | — | 35 | — | H | C |
| 11Y057 | Jim Trawick | 33°05'49" | 84°20'45" | F | 205 | P | 20 | 6 | 30 | — | U | B |
| 11Y058 | Pasley | 33°05'35" | 84°21'04" | F | 286 | — | — | 6 | 55 | - -89 | H | B |
| 11Y059 | Jim Trawick | 33°05'52" | 84°20'48" | S | 305 | — | — | — | 0 | — | — | B |
| 11Y060 | Jim Trawick | 33°05'50" | 84°20'47" | F | 605 | — | 18 | 6 | 0 | — | — | B |
| 11Y061 | Jim Trawick | 33°05'51" | 84°20'45" | F | 605 | — | 20 | 6 | 0 | — | — | B |
| 11Y062 | Jerry Colwell | 33°05'53" | 84°20'38" | F | 305 | — | — | — | 0 | — | — | B |
| 11Y063 | Jerry Colwell | 33°05'53" | 84°20'37" | F | 305 | — | — | 6 | 12 | — | — | B |
| 11Y064 | Jerry Colwell | 33°06'32" | 84°20'36" | F | 300 | P | 5 | 6 | 75 | — | — | B |
| 11Y065 | Jerry Colwell | 33°06'33" | 84°20'39" | F | — | — | — | — | 10 | — | — | B |
| 11Y066 | Jerry Colwell | 33°06'32" | 84°20'35" | F | — | — | — | — | — | — | — | B |
| 11Y067 | Edwards Lake Well | 33°06'34" | 84°20'28" | F | — | — | — | — | 60 | — | U | B |

The growth rate in Pike County has steadily increased during the past decade. The population of Pike County increased from 8,937 in 1980 to 10,224 in 1990, which is an increase of 12.6 percent. The city of Zebulon had a population of 1,035 in 1990 (Beatrice Piddock, U.S. Department of Commerce, Bureau of Census, oral commun., 1992).

The average annual precipitation in the Pike County area during 1991 was 47.22 in., and the maximum precipitation occurred during the winter and mid-summer months (National Oceanic and Atmospheric Administration, 1990). The 30-yr average precipitation in Pike County is 52.56 in.

In Pike County, water withdrawal totalled about 1.69 Mgal/d during 1990 (Fanning and others, 1992). About 72 percent (1.21 Mgal/d) was withdrawn from ground-water sources, and 28 percent (0.48 Mgal/d) was withdrawn from surface-water sources. Of the 1.21 Mgal/d withdrawn from ground-water sources during 1990, 50 percent was used for domestic and commercial purposes, 27 percent for public supply, 15 percent for irrigation, and 8 percent for livestock. Of the surface water, 43 percent was used for livestock, 36 percent for public supply, and 21 percent for irrigation. The city of Zebulon withdrew approximately 0.17 Mgal/d from Elkins Creek in 1990, which accounted for about 36 percent of all surface water used in Pike County (Fanning and others, 1992).

Methods of Investigation

A geologic map was constructed to provide data on the geologic, hydrogeologic, and hydrochemical aspects of the study area. Field studies include identification of major rock type(s), structural features, weathering characteristics, and topographic setting. The description of rock types included the identification of major, minor, and accessory minerals in relative percentage comparison, and compositional characteristics and variations, such as foliation or layering. The mapping of structural features included the orientation (strike and dip), spacing, and degree of development of foliation, joints, and other fractures. The notation of weathering characteristics included the development and degree of differential weathering along geologic contacts, compositional changes or structural features, and the overall depth of weathering and competence of regolith. Saprolite, weathered material within the regolith that retains geologic textures and structure, is common in the study area. The presence of saprolite at land surface rather than unweathered rock is common in the Piedmont region of northern Georgia, and mapping saprolite characteristics was an important part of the hydrogeologic evaluation. Topographic setting also was noted at each outcrop.

Data for wells in the study area were compiled from records of the city of Zebulon, the Pike County Health Department, the County Extension Office (University of Georgia), local well drillers, individual well owners, published reports, and the USGS data base. Well data from these sources were field verified and plotted on USGS 7 1/2-minute topographic maps and assigned a USGS well number. The wells were field-checked to verify the location and determine if water could be sampled at the well head (table 1). Additional information, such as verification of well-construction data, variations in yield, water quality, or other information, was obtained from individual well owners. Geologic information, including nearby rock outcrops, were noted, and cuttings were collected from recently drilled wells, where available. Also, during the well inventory, areas that may be potential sources of contamination were mapped.

Water samples were collected from eight wells in the study area and analyzed in the field; seven of these also were analyzed in the USGS laboratory. The eight wells were selected because of their high yield (greater than 25 gal/min). Water was sampled at spigots as close to the wellhead as possible, in advance of the pressure tank. The wells were purged until a minimum of three well volumes had been removed, or until specific conductance and pH were stable, to ensure that the water sample was representative of the aquifer. Two wells did not have pumps and were sampled using a brass bailer. The bailer was lowered to a depth below the well casing, and water samples were collected.

Field measurements of water temperature, specific conductance, pH, and dissolved oxygen were made during purging and sampling of each well. Alkalinity also was determined in the field using titration methods. In addition, samples were qualitatively analyzed in the field for ferrous iron, ferrous plus ferric iron (total), and sulfide concentrations using colorimetric methods. Water samples collected for laboratory analyses (USGS, Atlanta, Ga.) of total iron were preserved using nitric acid and analyzed using atomic adsorption spectrometry. Water samples collected for other analyses were not treated, and were analyzed using ion chromatography. Samples were not filtered, so that *total* concentrations rather than *dissolved* concentrations are reported here. Iron concentrations reported from the Pike County Extension Services (University of Georgia) were analyzed using inductively coupled plasma spectrometry (William Cauldwell, Pike County Extension Service, oral commun., August 1991).

Previous Studies

A few regional studies have evaluated ground-water resources in crystalline rock hydrogeologic settings in the Piedmont physiographic province of the Southeastern United States. The major objectives of those studies were to formulate concepts regarding the availability of ground water and determine possible controlling factors affecting well yield and ground-water quality. Conceptual models of hydrogeologic frameworks of the crystalline rock aquifers in this region have evolved as data-base information increases.

Ground-Water Availability

Herrick and LeGrand (1949) inventoried a large number of wells in the Atlanta region and conducted regional geologic mapping to determine possible factors influencing ground-water availability and quality. They concluded that the availability and quantity of ground water in the Metropolitan Atlanta area depends largely on such factors as rock type, structural features, degree of weathering, and topography. A discussion of geologic settings where conditions were favorable for high-yielding wells was outlined for a variety of rock types, geologic structural conditions, and topographic settings. Although the study represented a reconnaissance rather than a detailed evaluation, Herrick and LeGrand (1949) recognized that variations in the rock character and attitude strongly influence the availability of ground water, and distinct differences can be observed within intervals of feet, or even inches, in the Piedmont region.

Carter and Herrick (1951) evaluated water use and sources of water supply (including surface water) in the Metropolitan Atlanta area and estimated future water-supply needs. Historically, dug wells were the sources of water supply in the Atlanta area until the late 1800's, when surface-water sources were developed to meet increasing water-supply demands. The report examined the relations between ground-water availability and certain geologic factors, such as joints, faults, and other fractures. The investigators evaluated well yield, total depth of wells, and the importance of aquifer tests in assessing sustained yield and potential well interference. One of the conclusions of the report was that the potential for ground-water development in the Atlanta area was considerable, and wells could serve as sole sources of water supply for rural communities and industrial needs throughout the Piedmont region.

LeGrand (1967) proposed a rating system, based on topographic setting and soil (regolith) thickness, to assess ground-water conditions in the Piedmont and Blue Ridge physiographic provinces of the Southeastern United States. LeGrand developed the concept of a statistical percentage chance of obtaining a certain yield under various conditions. Actual quantifiable estimates were said to be difficult because well yields were found to vary substantially within 100 ft of lateral distance. LeGrand also stated that fractures seemed to diminish with increasing depth, and the relation between well yield and depth was not simple to determine.

Cressler and others (1983) conducted a regional ground-water study in the Atlanta area to assess the availability of ground water in crystalline rocks and to devise methods for locating sites for high-yielding wells that could serve as alternative sources of water supply. Results from this study indicated that the highest well yields were in areas having local increases in aquifer permeability. High-yielding wells in the Atlanta area seemed to be associated with contact zones between rocks of contrasting lithology, closely spaced joints or fractures associated with faults, folds, or structural features, stress-relief (horizontal) fractures, and drainage features controlled by local structural characteristics. Cressler and others (1983) showed that high-yielding wells were not present only in areas having thick regolith, such as valleys or topographic lows, but also in areas having thin regolith, such as ridges or steep slopes. The investigators reported that topographic drainage features may or may not be related to underlying water-bearing features in the rocks. From data gathered using borehole geophysical logs of the wells, Cressler and others (1983) determined that the size, spacing, and interconnection of water-bearing openings differed greatly from one rock type to another. The range in well yield within a water-bearing unit was highly variable, and high-yielding wells were present in each unit. Local features in the rocks generally control well yield.

Radtke and others (1986) conducted a ground-water study in an 11-county area near Athens, Ga., to assess the occurrence and availability of ground water and determine whether ground water was a viable alternative or supplemental resource. Geologic controls on well yield were examined throughout the study area. Radtke and others (1986) found that contact zones between rock units and within multilayered rock units contribute substantially to well yield. Other geologic features, such as stress-relief fractures, faults, and shear zones, were determined to improve well yield. To a lesser degree, factors such as rock type, depth of weathering, regolith thickness, and topographic setting, were determined to influence well yields. The authors also concluded that the dendritic drainage pattern in the study area was superimposed, and overall, did not represent geologic structural control.

Daniel (1990) conducted a statistical analysis of well data and evaluated site-selection criteria for wells in the Piedmont and Blue Ridge physiographic provinces of North Carolina. The analyses showed that certain geologic, topographic, and well-construction characteristics were related to well yield. Site-selection criteria included hydrogeologic unit (rock type), saturated regolith thickness, and an analysis of drainage lineaments related to fractures and joints. Conceptual models of local hydrogeologic systems were developed in test areas to guide selection of the most favorable well sites. Reconnaissance geology, including the mapping of structural features, was conducted after areas were selected from the regional hydrogeologic unit map. Fractures also were inferred from drainage lineament patterns or mapped locally. Daniel (1990) determined that the most favorable site for well drilling was in a topographic low or in a drainage feature that was structurally controlled. Results of test drilling showed that above-average yields could be obtained where favorable conditions existed; however, high-yielding wells also were drilled in less favorable areas.

The most recent regional ground-water study conducted in the Piedmont was by Clarke and Peck (1991) in a nine-county area (including Pike County) south of the Metropolitan Atlanta area. The study consisted of a general evaluation of the existing and possible future development of ground-water resources. Data collection consisted of the compilation of geologic, hydrologic, and water-quality data. An extensive inventory of wells and springs was conducted. The study followed the same method of defining hydrogeologic units based on variation of rock types used by Cressler and others (1983). Several high-yielding wells were inventoried. The study showed that ground water is a viable resource that has been underutilized in the variety of hydrogeologic settings in the area.

Ground-Water Quality

Most studies conducted for the purpose of evaluating ground-water availability also included the collection of some ground-water quality data. Herrick and LeGrand (1949) determined that the quality of ground water was related to rock type. They found high iron concentrations associated with biotite gneisses and schists. Ground water from granitic rocks showed low mineralization compared to water from amphibolites/hornblende gneisses, which contained elevated concentrations of calcium and magnesium. Sulfate concentration in ground water was related to gypsum and pyrite in various rock types.

Several other studies addressed the relation of certain rock types to ground-water quality. Carter and Herrick (1951) related hardness of ground water to mafic rocks, such as amphibolites/hornblende gneisses, and determined that granitic rocks contained softer water. The investigators stated that hardness and high concentrations of iron, manganese, and silica were common ground-water quality problems in well water in the Piedmont. Stewart and others (1964) conducted a study of wells and springs at the Georgia Nuclear Laboratory site in Dawson County, Ga., and found high iron concentrations in water from wells tapping mica schist, amphibolite schist, and gneiss. McCollum (1966) discussed ground-water quality in Rockdale County where high iron concentrations were detected in water from some wells open to biotite gneiss and garnet mica schist. Cressler and others (1983) noted that water from wells open to mafic rock types had higher concentrations of iron, magnesium, manganese, dissolved solids, and possibly chloride, and a higher pH than water from wells open to granitic rocks in the Metropolitan Atlanta area.

Well and Spring Numbering System

In this report, wells and springs are numbered based on USGS 7 1/2-minute topographic maps. Topographic maps in Georgia are assigned a number and letter designation beginning at the southwestern corner of the State. Numbers increase eastward through 39, and letters advance alphabetically northward through "Z," then become double letter designations "AA" through "PP." The letters "I," "O," "II," and "OO" are not used. Wells and springs inventoried in each quadrangle are numbered consecutively, beginning with 1. Thus, the fourth well or spring scheduled in the 10Y quadrangle is designated 10Y004.

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GEOLOGY

The Zebulon area (plate 2) is underlain by crystalline rocks that have undergone intense metamorphism and deformation. Mineralogy, textural variations, structural features, and overall rock types can vary within a few feet. Most rocks in the Piedmont Province of northern Georgia also have undergone intense weathering, resulting in the presence of saprolite at land surface.

Regional Geology

The Piedmont Province of northern Georgia consists of complexly folded and faulted metamorphosed sedimentary, volcanic, and plutonic rocks that have been intruded by granitic plutons. The geology of the Piedmont south of Atlanta was described by Atkins and Higgins (1980) and Higgins and others (1984, 1988). Higgins and others (1988) grouped rocks in the Zebulon area into the Zebulon and Atlanta thrust sheets of uppermost Precambrian to lower Ordovician age. An assemblage of purplish-weathering garnetiferous, aluminosilicate schists interlayered with ocher-weathering amphibolites and less prevalent granites and biotite gneisses have been identified in the study area. A sillimanite-grade schist unit having thin layers of gondites (spessartine-quartzite) was identified as the Barrow Hill Formation by Higgins and Atkins (1981).

Local Geology

The most common rock type in the study area is an aluminosilicate schist, composed chiefly of sillimanite, muscovite, biotite, quartz, and feldspar (in ascending relative percentages) and having trace amounts of graphite, garnet, pyrite, and magnetite. Other mappable rock types are granitic rocks, amphibolites, hornblende gneisses, and gondites. The granitic rocks vary from a porphyritic or weakly foliated granite to a compositionally layered granitic gneiss. Primary minerals in the granitic rocks are biotite, quartz, and feldspar. Amphibolites and hornblende gneisses consist chiefly of hornblende and plagioclase, the former having a higher percentage of hornblende. The gondites generally consist of garnet, quartz (quartzite), and magnetite. Pegmatites (mainly metamorphic in origin) and quartz veins also were noted in the study area. Igneous pegmatites, although not really extensive, were more common in the schists in the northeastern part of the study area. Pegmatitic zones within the granitic rocks were common in the southwestern part of the study area.

Three mappable geologic unit, designated A, B, and C (plate 2), were delineated in the study area. The unit divisions discussed in this report represent mappable rock groups (geologic units) that were correlated on the basis of dominant rock types and are not considered to be hydrogeologic units.

Unit A

Unit A consists of a sillimanite-muscovite-biotite-quartz-feldspar schist interlayered with amphibolites/hornblende gneisses having scattered gondite pods (table 2). Quartz veins and metamorphic pegmatitic zones within the schist generally are thin (less than one foot in width) and concordant. A few larger igneous pegmatites were noted in the northern part of unit A. The schist also is locally graphitic, having scattered garnets and magnetite, and has local evidence of sulfide weathering (iron oxide in cubic-shaped vugs). Textural variations are present within the schist throughout the study area and also in a single outcrop.

Table 2.—*Lithologic and structural characteristics of geologic units in the Zebulon area, Georgia*

| Geologic unit | Major rock types | Secondary rock types | Structural features | Weathering characteristic |
|---------------|---|---|---|--|
| A | schists amphibolites hornblende gneisses | gondites quartz veins pegmatites | strong foliation and jointing | moderately to deeply weathered |
| B | granitic rocks schists | amphibolites/ hornblende gneisses | strong foliation and jointing in schists; common jointing in granitic rocks | well-developed differential weathering |
| C | schists gondites | not applicable | strong foliation and jointing in schists; common jointing in gondites | moderately to deeply weathering |

Foliation and jointing are well developed in the schist in unit A; however, the orientation and degree of inclination (dip) vary both locally and areally (plate 2). Many topographic lineaments seem to be structurally controlled, and local drainage features probably are parallel to the orientation of foliation and joints.

The sillimanite schist in unit A is moderately to deeply weathered (in this report, moderately weathered refers to structured saprolite within a depth of 5 ft below land surface). Deeply weathered refers to the lack of structured saprolite within 5 to 10 ft below land surface. In general, structural features are retained in the saprolite of unit A. Rock resistance to weathering in this unit, in descending order is: quartz veins, gondites, amphibolites, hornblende gneisses, pegmatites, and schists.

Additional, commonly local, identifiable characteristics of unit A include various mineralogical associations and weathering features. Biotite and muscovite can be intermingled; however, zones of biotite concentrations are common in this unit. Where the sillimanite percentage increases, the schist seems to weather to a more fibrous texture. In general, coarser grained or distorted textures were more resistant to weathering. High-sillimanite and high-biotite schists can be interlayered as separate rock types in this unit; however, this generally does not result in differential weathering along compositional boundaries. Iron-oxide accumulations were observed along joint surfaces in this unit. Scattered pods of feldspathic saprolite having weathered-out iron-bearing minerals also were noted in unit A.

Unit B

Unit B (plate 2) consists of granitic rocks interlayered with aluminosilicate schists and amphibolites/hornblende gneisses (table 2). Isolated gondite pods, some containing magnetite, also are present in this unit. The granitic rocks consist chiefly of biotite, quartz, and feldspar. The texture of the granitic rocks varies from very coarse-grained and porphyritic granite, to a medium-grained, compositionally layered biotite gneiss. The gneissic texture may be the result of shearing in some areas. The coarser grained, generally equigranular granite is most common in the study area. Some igneous pegmatites are associated with the granitic rocks. The schists are similar in composition to those in unit A, having a larger concentration of muscovite compared with biotite. The amphibolites/hornblende gneisses and gondites also have a similar mineralogical composition to those in unit A. Scattered, highly feldspathic saprolite (different rock types or compositional change) containing iron stains also is present in both units A and B. Quartz veins and pegmatites were noted within the granitic rocks and within the schists; the latter being of a smaller scale and of metamorphic origin. Garnets and graphite are present locally in the schists.

The granitic rocks of unit B generally are resistant to weathering, whereas the schists are moderately to deeply weathered. More resistant, biotite-rich layers are present in the schist. Halloysite has accumulated along joints in the schists during the weathering processes. Resistant pods containing quartz and feldspar also are scattered in this unit. Rock resistance to weathering in this unit, in descending order, are quartz veins, granitic rocks, gondites, amphibolites, hornblende gneisses, pegmatites, and schists. Differential weathering is well developed in this unit.

The orientation of the granitic rocks in unit B generally is concordant with the schists; orientation and degree of inclination of both rock types vary both locally and areally (plate 2). Jointing is prevalent in granitic outcrops, presumably from stress-relief processes. In the schists, jointing is common and locally is sometimes well developed.

Unit C

Unit C (plate 2) consists chiefly of a muscovite-sillimanite-quartz-feldspar schist containing significant gondite pods or layers (table 2). Quartz veins and metamorphic pegmatitic zones generally are thin and concordant within the schist. Sillimanite concentrations were identified in the pegmatitic zones. Graphite and evidence of the weathering of sulfides were noted in isolated areas in the schist. Magnetite is scattered within the gondites. Scattered igneous pegmatites also are present in the schist. This geologic unit has a higher percentage of sillimanite and muscovite compared to the schists in units A and B.

Compared to the other schists in units A and B, the saprolite from the weathering of the schist in unit C generally appears purplish and more fibrous in texture as a result of increased sillimanite. A similar highly feldspathic rock having iron stains also is scattered in this unit, as in the other geologic units. Rock resistance to weathering in this unit, in descending order, are quartz veins, gondites, pegmatitic zones, and schist.

Foliation and jointing in the schist in unit C generally are well developed. The gondites are highly jointed and generally concordant with the schist. As with units A and B, the orientation and degree of inclination of the rocks in unit C vary both locally and areally (plate 2). Crenulations also were observed locally in the schist.

GROUND-WATER RESOURCES

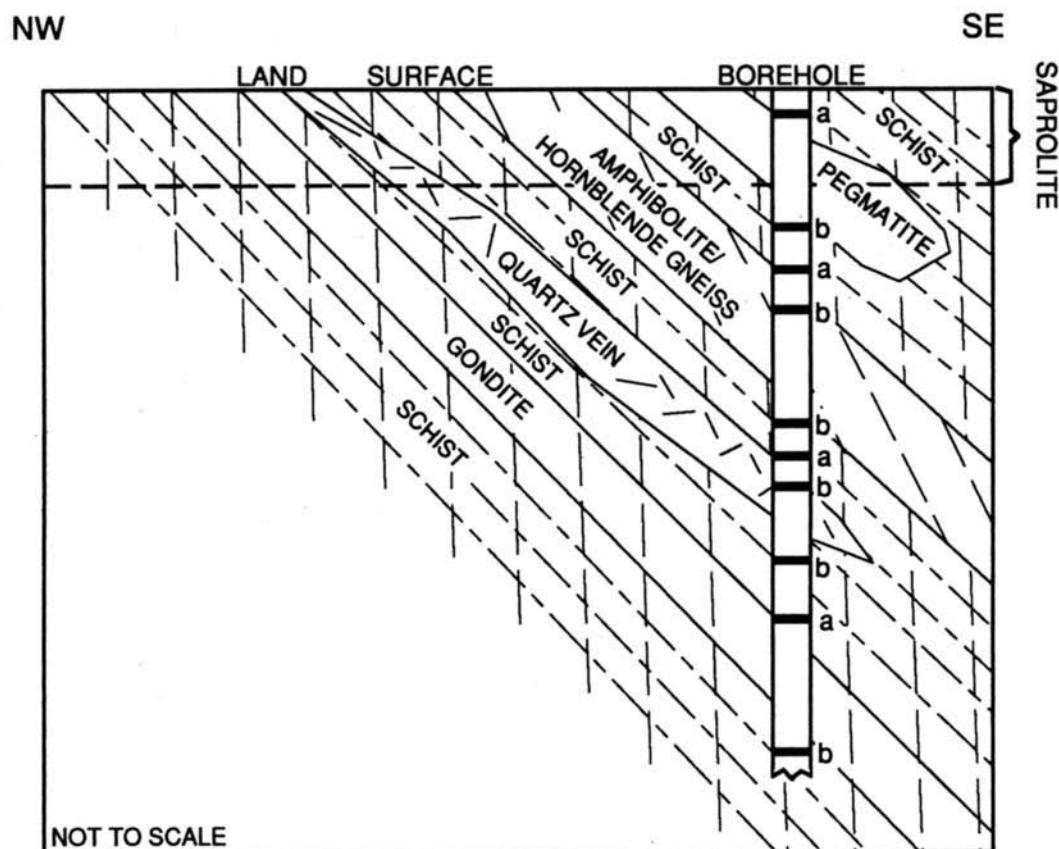
The metamorphic and igneous rocks of the Piedmont Province have little or no primary porosity, and low intrinsic permeability. Differential weathering along geologic features, such as lithologic contacts, foliation, joints, fractures, faults, folds, quartz veins, and pegmatites, produces openings that enhance permeability and enable the storage and flow of ground water.

Relation of Geology to Occurrence and Availability of Ground Water

Prior to the collection of well-yield and ground-water quality data, conceptual interpretations were developed regarding ground-water availability based on observations recorded during geologic mapping. Each geologic unit is interpreted as having different characteristics that could affect well yield and ground-water quality.

Unit A

Rocks in some parts of unit A have characteristics, such as well-developed foliation and prominent jointing, that could enhance ground-water storage and flow; and hence, these features may increase well yield (table 3). Figure 2 is a conceptual hydrologic section showing water-bearing zones that could be encountered by a drilled borehole penetrating geologic unit A. (The letter "a" designates potential water-bearing zones along rock-type contacts, and the letter "b" represents water-bearing zones along structural features, such as foliation and jointing.) Differential weathering along geologic contact zones could result in potential water-bearing zones. Discontinuous features, such as quartz veins (fig. 2), pegmatitic zones (metamorphic), and igneous pegmatites, also may enhance ground-water movement because these features tend to weather differently than do country rock (typically schist in the study area). Igneous pegmatites are common in unit A in the northeastern part of the study area. Differential weathering along structural features, such as foliation and joints (fig. 2), also could enhance well yield. Textural variations, absence of well-developed jointing, and limited differential weathering, which result in reduced potential well yield, also are observed in unit A. Also, the foliation in this unit can be nearly vertical, lessening the possibility of tapping a potential water-bearing zone with a single drilled borehole.



EXPLANATION

- POTENTIAL WATER-BEARING ZONE
 - a Lithologic contact
 - b Structural feature
- — — FOLIATION--Parallel to dip of rock
- — — JOINT--Degree of dip is variable

Figure 2.-- Diagrammatic hydrogeologic section of geologic unit A.

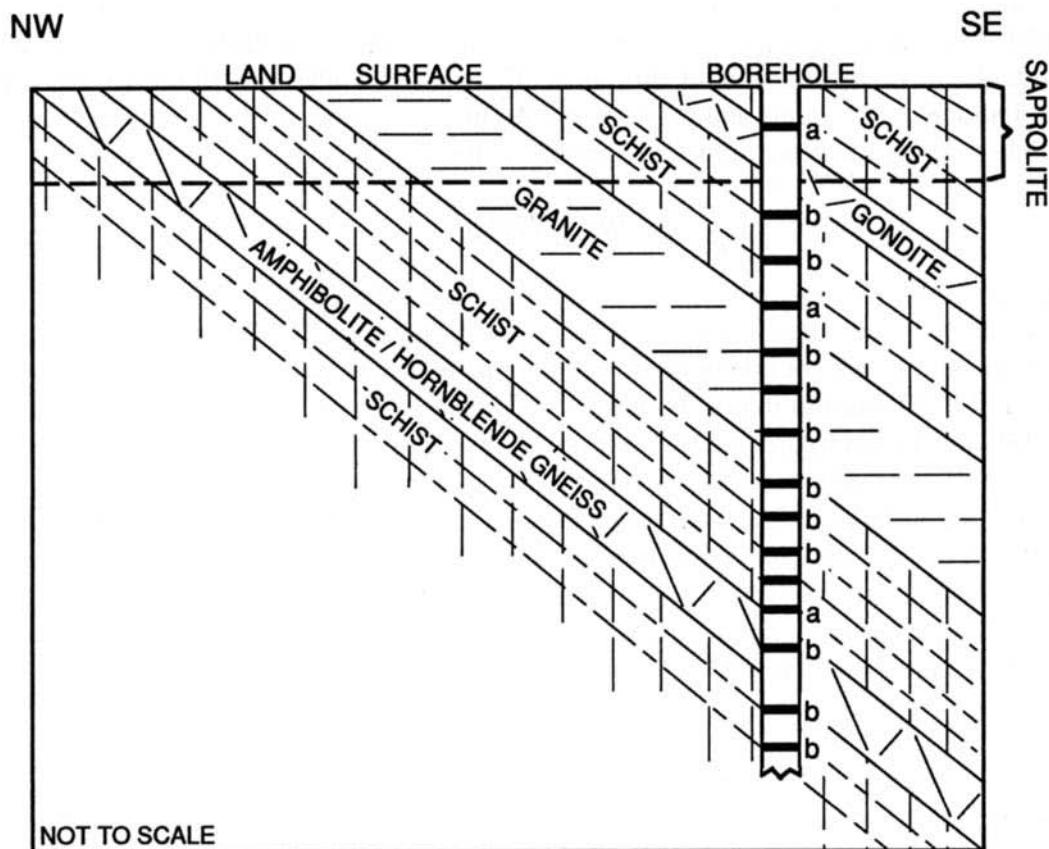
Table 3.—*Hydrogeologic characteristics of geologic units in the Zebulon area, Georgia*
[gal/min, gallons per minute]

| Geologic unit | Well yield range (gal/min) | Ground-water quality | Topographic setting and drainage | Favorable hydrogeologic conditions |
|---------------|----------------------------|---|----------------------------------|--|
| A | 4 to 125 | moderate probability of high high concentrations of iron | hillside | well-developed foliation and jointing; correlation of structural features with topographic lineaments. |
| B | 0 to 75 | relatively low ¹ probability of high high concentrations of iron | flat | well-developed differential weathering along geologic contacts; well-developed foliation and jointing. |
| C | 6 to 250 | relatively high probability of high concentrations of iron | flat | well-developed differential weathering along geologic contacts; well-developed foliation and jointing; correlation of structural features with topographic lineaments. |

¹ “Low” and “high” refer to a relative comparison to the secondary maximum contaminant level for iron of 0.3 mg/L (U.S. EPA, 1992)

Unit B

Granitic rocks are more resistant than the schist in unit B (table 3) and probably are nearly impermeable boundaries for ground water (fig. 3). The granitic or mafic rocks tend to be relatively homogeneous, and can weather somewhat uniformly with depth, resulting in reduced ground-water movement. However, near-surface, stress-relief jointing (fig. 3) commonly is observed in the granitic rocks. If the joints persist in depth, substantial amounts of water can be withdrawn from these water-bearing zones. Joints noted in saprolitic-schist outcrops generally persist with depth in the Piedmont Province (fig. 3) and can enhance ground-water occurrence. As in unit A, the more resistant quartz veins in unit B tend to fracture easily, and also can enhance ground-water availability and flow.



EXPLANATION

- POTENTIAL WATER-BEARING ZONE
 - a Lithologic contact
 - b Structural feature
- — — FOLIATION--Parallel to dip of rock
- — — JOINT--Degree of dip is variable

Figure 3.-- Diagrammatic hydrogeologic section of geologic unit B.

Unit C

The potential for ground-water availability in unit C seems most favorable where weathered schist is interlayered with the more resistant gondites (differential weathering) (table 3). Ground-water storage and flow also could be augmented by well-developed foliation and jointing (fig. 4) observed throughout this unit. Features that also contribute to ground-water availability include quartz veins and pegmatites. As in unit A, textural variations and disoriented or steep foliation most likely would reduce ground-water movement.

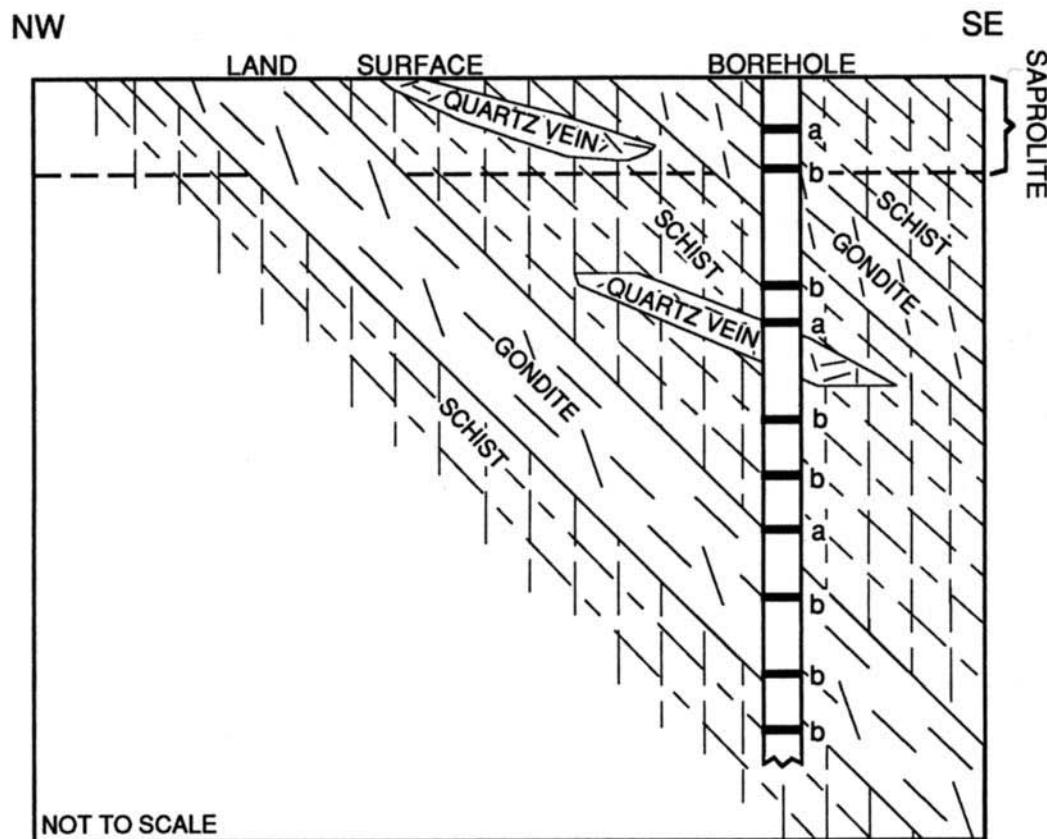
Well Yield

High-yielding wells (greater than 25 gal/min) are present in each of the three geologic units mapped in the study area (table 1, plates 1 and 2); however, low-yielding wells, including some dry boreholes, also were inventoried in each unit. Well yields range from about 6 to 125 gal/min in unit A, 0 to 75 gal/min in unit B, and 6 to 250 gal/min in unit C (table 3). This wide range of yield is not unusual for hydrogeologic settings in the Piedmont Province. As previously noted, geologic controls that affect well yield can vary in occurrence, orientation, and degree of development on a scale of a few tens of feet or less. Average yields were not computed in this study because of this high local variability in ground-water availability. Areally, well yields were found to vary on the scale of a few acres, most likely because of local geologic controls.

As with well yield, the depth of casing and total well depth vary within each geologic unit. Casing depth ranges from 12 to 133 ft in unit A, 5 to 115 ft in unit B, and 25 to 100 ft in unit C (table 1). Total well depth ranges from 42 to 605 ft in unit A, 186 to 605 ft in unit B, and 25 to 580 ft in unit C.

Casing depth generally is an indication of regolith thickness. The State of Georgia requires that casing be sealed to a depth 5 ft into solid bedrock for wells to be used for drinking-water supply (Georgia Environmental Protection Division, 1983). The regolith functions as a storage reservoir for precipitation and other surface-water sources that percolates into the ground. In general, areas having thicker regolith should have increased storage for ground water in the shallow subsurface, which could provide recharge to deeper water-bearing zones in the bedrock. Thicker regolith can provide recharge for sustained well yield; however, thick regolith is not necessarily indicative of higher well yields. For example, in unit B, well 11Y024 (table 1) has 115 ft of casing, or apparent regolith thickness, and yields only 10 gal/min; well 11Y064 has only 5 ft of casing and an estimated yield of 75 gal/min.

As with casing depth, total well depth may not be related to well yield. In some instances, by drilling to a greater depth, more water-bearing zones can be intersected; however, in the study area, yield does not substantially increase with depth. In unit A, wells 11Y001 and 11Y005 were drilled to depths of 505 and 250 ft, respectively, resulting in nearly the same yield of about 20 gal/min. In unit B, well 11Y063 was drilled to a depth of 305 feet and yielded 12 gal/min, and well 11Y064, having a similar depth of about 300 ft, yielded 75 gal/min.



EXPLANATION

- POTENTIAL WATER-BEARING ZONE
 - a Lithologic contact
 - b Structural feature
- — — FOLIATION--Parallel to dip of rock
- — — JOINT--Degree of dip is variable

Figure 4.-- Diagrammatic hydrogeologic section of geologic unit C.

Ground-Water Sampling Results

Chemical analyses of water sampled from wells in the Zebulon area (tables 4, 5) indicate that ground-water quality is similar to that reported for other wells in Pike County (Clarke and Peck, 1991). Except for two values of pH and iron, measured constituents were within the secondary maximum contaminant levels (SMCL) for drinking water established by the U.S. Environmental Protection Agency (EPA) (U.S. Environmental Protection Agency, 1992). Hardness (as CaCO_3) ranged from about 13 to 95 milligrams per liter (mg/L), which is classified as soft to moderately hard water, and pH ranged from 5.6 to 7.8. Specific conductance, which is an indicator of concentrations of dissolved solids in water, ranged from 60 to 220 microSiemens per centimeter ($\mu\text{S}/\text{cm}$). Alkalinity as total CaCO_3 ranged from 18 to 89 mg/L.

Wells 11Y049 and 11Y057 (plate 1) yielded water having pH of 6.1 and 5.6, respectively (table 4), both of which are below the SMCL range of 6.5 to 8.5 (U.S. Environmental Protection Agency, 1992); water from both wells also was low in specific conductance and alkalinity. Also, water from well 11Y049 contained 7.8 mg/L of dissolved oxygen, which may indicate rapid recharge from precipitation or casing leakage problems. Water from well 11Y049 also contained high concentrations of nitrogen and phosphorous and low concentrations of calcium, magnesium, sodium, and sulfate (table 5). The differences in the chemical properties and constituents in wells 11Y049 and 11Y057 compared to the other six wells sampled seem to indicate one or more of the following: (1) leakage of precipitation or surface water into the well casing; (2) tapping of a shallow aquifer; or (3) rapid recharge of the water-bearing zone that supplies water to the well.

Table 4.—*Selected field analyses of ground water from wells in the Zebulon area, Georgia*

[°C, degree Celsius; $\mu\text{S}/\text{cm}$, microSiemens per centimeter; mg/L, milligrams per liter; CaCO_3 , calcium carbonate; Fe^{2+} , ferrous iron; —, not analyzed; SMCL, U.S. Environmental Protection Agency, Secondary Maximum Contaminant Level; na, not applicable; ND, none detected; A, above U.S. Environmental Protection Agency, SMCL, for $\text{Fe}^{2+} + \text{Fe}^{3+}$; B, below U.S. Environmental Protection Agency, SMCL for $\text{Fe}^{2+} + \text{Fe}^{3+}$]

| Well number | Date sampled | Sampling method | Temperature, (°C) | pH | Specific conductance ($\mu\text{S}/\text{cm}$) | Dissolved oxygen (mg/L) | Alkalinity as CaCO_3 (mg/L) | Iron, Fe^{2+} (mg/L) | Iron, $\text{Fe}^{2+} + \text{Fe}^{3+}$ (mg/L) | Sulfide (mg/L) |
|-------------------|--------------|-----------------|-------------------|---------|--|-------------------------|--------------------------------------|-------------------------------|--|----------------|
| 11Y021 | 09-25-91 | pumped | 17.9 | 7.2 | 220 | 0.0 | 89 | ND | ND | 0.00 |
| 11Y034 | 09-25-91 | pumped | 19.0 | 7.8 | 170 | .0 | 78 | ND | ND | .00 |
| 11Y041 | 09-27-91 | pumped | 16.8 | 6.7 | 122 | .0 | 50 | ND | B | .00 |
| 11Y045 | 09-27-91 | pumped | 18.0 | 6.7 | 120 | .0 | 41 | A | A | .01 |
| 11Y049 | 09-26-91 | pumped | 17.0 | 6.1 | 60 | 7.8 | 21 | — | ND | .00 |
| 11Y057 | 09-26-91 | bailed | 17.0 | 5.6 | 101 | — | 18 | ND | ND | .00 |
| 11Y058 | 09-27-91 | pumped | 18.0 | 7.2 | 171 | .0 | 72 | B | B | .00 |
| 11Y064 | 09-26-91 | bailed | 17.9 | 6.5 | 130 | — | 47 | A | A | .00 |
| SMCL ¹ | na | na | na | 6.5–8.5 | na | na | na | na | .03 | na |

¹U.S. Environmental Protection Agency (1992).

Table 5.—Selected laboratory analyses of ground water from wells in the Zebulon area, Georgia

[Concentrations in milligrams per liter, Fe^{2+} , ferrous iron; Fe^{3+} , ferric iron; Ca, calcium; Mg, magnesium, K, potassium; Na, sodium; F, fluoride; Cl, Chloride; Br, bromine; N, NO_3 ; nitrate as nitrogen; P, PO_4 ; phosphate as phosphorus; SO_4 , sulfate; hardness as CaCO_3 ; MCL, maximum contaminant levels; SMCL, secondary maximum contaminant level; na, not applicable]

| Well number | Fe^{2+} Fe^{3+} | Ca | Mg | K | Na | F | Cl | Br | N, NO_3 | P, PO_4 | SO_4 | Hardness |
|-------------------|--------------------------------------|-----|-----|-----|-----|-----|-----|------|------------------|------------------|---------------|----------|
| 11Y021 | 0.04 | 33 | 3.0 | 2.6 | 10 | 0.8 | 5.5 | 0.04 | 0.02 | 0.021 | 5.6 | 95 |
| 11Y034 | .04 | 20 | 3.8 | 1.5 | 11 | 1.0 | 2.0 | .02 | .18 | .00 | 4.8 | 65 |
| 11Y041 | .02 | 16 | 1.8 | 1.3 | 7.6 | .3 | 2.6 | .02 | .00 | .02 | 9.2 | 47 |
| 11Y045 | 5.3 | 5.7 | 3.6 | 3.8 | 7.4 | .2 | 3.4 | .03 | .00 | .00 | 15.9 | 29 |
| 11Y049 | .02 | 3.7 | 0.9 | 2.0 | 3.5 | .1 | 1.8 | .02 | 1.78 | .09 | 0.7 | 13 |
| 11Y058 | .10 | 24 | 2.1 | 1.6 | 10 | 1.2 | 2.2 | .02 | .03 | .00 | 11.8 | 69 |
| 11Y064 | .90 | 13 | 3.7 | 3.8 | 6.6 | .2 | 3.1 | .04 | .00 | .00 | 10.1 | 47 |
| MCL ¹ | na | na | na | na | na | 4.0 | na | na | 10 | na | na | na |
| SMCL ¹ | .30 | na | na | na | na | 2.0 | 250 | na | na | na | 250 | na |

¹U.S. Environmental Protection Agency (1992).

Factors Affecting Ground-Water Quality

Although the availability and occurrence of ground water is commonly the focus of many water-resource investigations, the quality of water is a major concern in the development of public water supplies. High iron concentrations, most likely the result of the weathering of iron-bearing minerals in the rocks, were reported in water from several wells in the Zebulon area. Land-use factors, such as underground storage tanks and industrial storage areas, also can affect ground-water quality in the area.

Geology

Ground-water quality problems can occur in unit A. High iron concentrations were reported in water from several wells open to these crystalline rocks (table 1, plate 3). A hydrogen-sulfide (rotten egg) odor also was reported by the owner of one well. The schists of unit A locally contain substantial concentrations of biotite that upon weathering, may contribute iron into the ground-water system. Iron-oxide minerals were observed along the joint planes in the schists. Other sources of iron in the rocks of unit A include hornblende in the amphibolites/hornblende gneisses, garnets in the schists, and magnetite in the gondite pods. Oxidation and dissolution of sulfide minerals (primarily pyrite) occurring in these rocks produces the hydrogen-sulfide odor, and could contribute to the iron concentrations in ground water.

The overall lesser quantity of iron-bearing rocks in unit B could result in lower concentrations of total iron in ground water than in unit A. However, high iron concentration in ground water could result from the weathering of iron-bearing minerals, such as biotite, garnet, or pyrite in the schists, or from hornblende in the amphibolites/hornblende gneisses. The quality of water in unit C is of primary concern because of the presence of the gondites that contain magnetite (iron oxide). High iron concentrations were noted in water from some wells that are open to rocks in unit C (plate 3).

Sources of potential contamination

Ground water is susceptible to contamination from several sources. Landfills, sewage-treatment ponds, above- and below-ground storage tanks, chemical or pesticide storage areas, and septic tanks are some of the more common sources of potential contamination in the Zebulon area. Wells are particularly susceptible to contamination if located downgradient from these point source areas. Similarly, a well that has not been properly constructed and sealed also is potentially subject to contamination.

Land-use features that can affect ground-water quality were identified (plate 3) within a 3-mi radius of Zebulon. The Pike County landfill, northwest of the city, is located on the drainage divide between Lewis Creek and a smaller unnamed creek. These creeks drain into Elkins Creek, the present (1991) water-supply source of Zebulon. Two sewage-treatment ponds also lie along small tributaries to Elkins Creek in the central and southwestern part of the city. Several gas stations and farms having above- and below-ground fuel-storage tanks were located and mapped. Areas where chemicals or pesticides are stored or mixed also were mapped.

SUMMARY AND CONCLUSIONS

Elkins Creek is the current (1991) primary source of water supply for the city of Zebulon, Pike County, Georgia. Population growth has increased water-supply demands, and with recent droughts (1980-82, 1986, and 1988), the availability of this surface-water source has been compromised. Also, periodic water-quality problems in water from Elkins Creek have caused concern. An investigation was completed to evaluate the occurrence and availability of ground water in crystalline rock of the Zebulon area and identify possible factors that affect well yield and ground-water quality. Results of this investigation could be used by water-resources managers to guide development and management decisions relating to ground water in the study area and in similar crystalline rock hydrogeologic settings.

Three geologic units having potentially different hydrogeologic characteristics are delineated: (1) an aluminosilicate schist interlayered with amphibolites/hornblende gneisses having scattered gondites; (2) granitic rocks interlayered with aluminosilicate schists and amphibolites/hornblende gneisses; and (3) an aluminosilicate schist having persistent gondite layers. High and low-yielding wells, including "dry" boreholes, were noted in each of the three geologic units in a variety of topographic settings in the study area. Well yields range from less than one to 250 gallons per minute. This wide range of yield is representative for hydrogeologic settings in the Piedmont physiographic province of northern Georgia. Geologic controls can differ on a local scale of a few tens of feet or less. Also, as commonly observed in the Piedmont Province, depth of weathering (inferred from casing depth) and total well depth are not related to well yield in the study area.

Geologic conditions considered to increase the availability of ground water are extensive differential weathering in the rocks along lithologic contacts, foliation, jointing, or other secondary features, such as quartz veins or pegmatites. Topographic features such as lineaments or drainage features having similar trends and relations to geologic factors also are considered favorable. Although well yield varies on a local scale, the presence of nearby high-yielding wells is important in the delineation of favorable areas.

Ground-water quality also is a concern because of the iron-bearing minerals in rocks in the study area. Water in several wells was reported to have high concentrations of iron, greater than the secondary maximum contaminant level of 0.3 milligrams per liter. Analyses of water sampled from selected wells also indicate a high variability in ground-water quality; iron concentrations (total) ranged from 0.02 to 5.3 milligrams per liter.

REFERENCES

Atkins, R.L., and Higgins, M.W., 1980, Superimposed folding and its bearing on geologic history of the Atlanta, Georgia, area, *in* Excursions in Southeastern Geology, Frey, R.W., *ed.*: America Geological Institute, Washington, D.C., v. 1, p. 19–40.

Carter, R.W., and Herrick, S.M., 1951, Water resources of the Atlanta Metropolitan area: U.S. Geological Survey Circular 148, 19 p.

Clark, W.Z., and Zisa, A.C., 1976, Physiographic map of Georgia: Georgia Geologic Survey, 1:200,000 scale, 1 sheet.

Clarke, J.S., and Peck, M.F., 1991, Ground-water resources of the south Metropolitan Atlanta region, Georgia: Georgia Geologic Survey Information Circular 88, 56 p.

Cressler, C.W., Thurmond, C.J., and Hester, W.G., 1983, Ground water in the greater Atlanta region, Georgia: Georgia Geologic Survey Information Circular 63, 144 p.

Daniel, C.C., III, 1990, Evaluation of site-selection criteria, well-design monitoring techniques, and cost analysis for a ground-water supply in Piedmont crystalline rocks, North Carolina: U.S. Geological Survey Water-Supply Paper 2341, chap. B, 35 p.

Durfor, C.N., and Becker, D., 1965, Public water supplies of the 100 largest cities in the United States, 1962: U.S. Geological Survey Water-Supply Paper 1812, 363 p.

Fanning, J.L., Doonan, G.A., and Montgomery, L.T., 1992, Water use in Georgia by county for 1990: Georgia Geologic Survey Information Circular 90, 98 p.

Georgia Environmental Protection Division, 1983, Rules for Safe Drinking Water, *in* Rules of Georgia, Department of Natural Resources, chap. 391-3-5, *revised* June 1989, p. 601–663.

Herrick, S.M., and LeGrand, H.E., 1949, Geology and ground-water resources of the Atlanta area, Georgia: Georgia Geologic Survey Bulletin 55, 124 p.

Higgins, M.W., and Atkins, R.L., 1981, The stratigraphy of the Piedmont southeast of the Brevard Zone in the Atlanta, Georgia, area, *in* Latest Thinking on the Stratigraphy of Selected Areas in Georgia, Wigley, P.B., *ed.*: Georgia Geologic Survey Information Circular 54-A, p. 3–40.

Higgins, M.W., Atkins, R.L., Crawford, T.J., Crawford, R.F., III, and Cook, R.B., 1984, A brief excursion through two thrust stacks that comprise most of the crystalline terrane of Georgia and Alabama: Georgia Geological Society Guidebook, 9th Annual Field Trip, 67 p.

Higgins, M.W., Atkins, R.L., Crawford, T.J., Crawford, R.F., III, Brooks, Rebekah, and Cook, R.B., 1988, The structure, stratigraphy, tectonostratigraphy, and evolution of the southernmost part of the Appalachian Orogen: U.S. Geological Survey Professional Paper 1475, 173 p.

LeGrand, H.E., 1967, Ground water in the Piedmont and Blue Ridge Provinces in the Southeastern United States: U.S. Geological Survey Circular 538, 11 p.

McCollum, M.J., 1966, Ground-water resources and geology of Rockdale County, Georgia: Georgia Geologic Survey Information Circular 33, 17 p.

National Oceanic and Atmospheric Administration, 1990, Climatological data annual summary, Georgia, 1990: U.S. Department of Commerce, Asheville, N.C., v. 94, no. 13.

Radtke, D.B., Cressler, C.W., Perlman, H.A., Blanchard, H.E., Jr., McFadden, K.W., and Brooks, Rebekah, 1986, Occurrence and availability of ground water in the Athens region, northeastern Georgia: U.S. Geological Survey Water-Resources Investigations Report 86-4075, 79 p.

Stewart, J.W., Callahan, J.T., and Carter, R.F., 1964, Geologic and hydrologic investigation at the site of the Georgia Nuclear Laboratory, Dawson County, Georgia: U.S. Geological Survey Bulletin 1133-F, 90 p.

U.S. Environmental Protection Agency, 1992, Final rule, National primary and secondary drinking water regulations-synthetic organic chemicals and inorganic chemicals: U.S. Federal Register, v. 57, no. 138 (sections 141.12, 141.32, 141.50, 141.51, 141.61 and 141.61 of part 141 and 143.3 of part 143), p. 31, 776-31, 849.

U.S. Geological Survey, 1991, Georgia floods and droughts in National Water Summary, 1988-89: U.S. Geological Survey: Hydrologic Events and Floods and Droughts Water Supply Paper 2375, p. 239-246.