GEOLOGY, GROUND WATER, AND WELLS OF GREENVILLE COUNTY, SOUTH CAROLINA

STATE OF SOUTH CAROLINA
DEPARTMENT OF NATURAL
RESOURCES

WATER RESOURCES DIVISION
REPORT 8

1995

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by

H. Lee Mitchell

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GEOLOGY, GROUND WATER, AND WELLS OF GREENVILLE COUNTY, SOUTH CAROLINA

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ABSTRACT

Reservoirs and streams are the main sources of water supply in Greenville County, S.C., but wells furnish water to about one-tenth of the county's 132,000 households. About 20 percent of the wells are large-diameter, shallow, generally low-yielding, bored wells that produce water from the saturated zone of the residual saprolite. The other 80 percent are mainly 6-inch drilled wells that produce their water from a network of bedrock fractures beneath the saprolite. The drilled wells have a median yield of less than 10 gallons per minute. The low yields discourage consideration of wells as realistic water supplies where large quantities are needed; however, yields are considerably higher for wells carefully sited and drilled for maximum production.

Information on 1,828 6-inch drilled wells and 566 24-inch bored wells was analyzed for this report. The median bored-well depth is 50 feet, and the median drilled-well depth is 200 feet. The median depth of drilled-well casings is 54 feet—this is approximately the saprolite thickness.

For bored wells, the median water level is 27 feet below land surface, and for drilled wells it is 30 feet. Saturated thickness of the saprolite in bored wells has a median value of 26 feet. For drilled wells, the median saturated thickness is less, at about 23 feet.

Topography is an important factor influencing the yield of drilled wells. Generally, wells in draws and valleys have higher yields than those on hillsides or hilltops. Proximity to lineaments is also helpful.

The ground water quality is generally good, with most wells having slightly acidic water; pH ranges from 5 to 7.8, but almost 90 percent of well samples had a pH less than 7. Most of the water is soft, and elemental concentrations usually are low, although iron can sometimes be troublesome.

Many tools are available for improving the understanding of the Piedmont hydrogeology in Greenville County. These include borehole geophysical logs, water quality analyses, pumping tests, geological maps, and lineament analysis.

NOTE: Data from the ground water records of the South Carolina Department of Natural Resources are available for Greenville County on diskette, in either dBase IV or ASCII format. Pumping test data are available in WordPerfect format (version 6.0). The data can be obtained from the SCDNR-WRD Piedmont Office in Greenville or from the Main Office of the SCDNR-WRD in Columbia, for a nominal fee.

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INTRODUCTION

PURPOSE AND SCOPE OF REPORT

The ground water resources of Greenville County, S.C., and their relationships to hydrogeological, geomorphic, and climatological factors are presented in this report. Water is plentiful and generally accessible to most users, because of a large and efficient surface water system that serves a majority of the county and some communities in bordering counties. A smaller percentage of the county population is served by water wells. Because of the ease of access to surface water, ground water is generally not considered as a source of water supply. Increasing population growth, with accompanying commercial and industrial expansion, is putting greater demands on the available water supply, and it is important to better understand not only where the alternative supply (that is, ground water) is located, but how better to use it and, in addition, how to protect this valuable resource.

The well information in this report reflects only a fraction of the water wells in Greenville County, but it is a representative and useful group from which information about ground water in Greenville County, and in the Piedmont in general, can be analyzed and understood. To that end, this study covers:

1. A description of all wells inventoried,
2. A description of the hydrogeology,
3. A description of the ground water quality,
4. A description of standard and new techniques used in locating groundwater.

By understanding these facets of Greenville County's ground water, better efforts to find, use, and protect it can be made.

ACKNOWLEDGMENTS

The author gratefully acknowledges the cooperation of well drillers, consulting engineers, home owners, industrial and government workers, and others who supplied well-construction and pumping-test data and other information without which this report would not have been possible. Special appreciation is extended to Mr. Jim Anthony of The Cliffs at Glassy and to Mr. Russell C. Ashmore, Jr., of Ashmore Brothers, Inc. , for permission to conduct pumping tests on their respective properties and for providing personnel to help run the tests. Many thanks go to report reviewers Charles C. Daniel, III, U. S. Geological Survey, Raleigh, N.C., Joseph A. Harrigan, Rust Environment and Infrastructure, Inc., Greenville, S.C., and Dr. Kenneth A. Sargent, Geology Department, Furman University, Greenville, S.C. Their suggestions and observations were extremely helpful and much appreciated.

POPULATION, AREA, AND WATER SUPPLY

Greenville County is located near the northwestern extremity of South Carolina, bordering the North Carolina line and lying west of Spartanburg and Laurens Counties and east of Pickens and Anderson Counties (Fig. 1). It is the most populous county in the State, with 320,167 residents (1990 Census, U.S. Bureau of the Census, *in* South Carolina Division of Research and Statistical Services, 1992a). At 797 square miles in area it is the twelfth largest of the State's 46 counties. With 9.2 percent of the State's population and 2.5 percent of the total land area, Greenville County has a population density of almost 402 persons per square mile, the densest in South Carolina.

Most of Greenville County's residents are supplied by surface reservoirs in the county and neighboring Pickens County. The city of Greenville has the largest water system in the State. Although the surface-water systems supply a majority of the population, a sizeable percentage relies on ground water. According to the 1990 U.S. Census, there were 131,645 residential units in Greenville County; 10,075 of these used drilled wells and 2,648 used dug or bored wells, for a total of about 9.7 percent (South Carolina Division of Research and Statistical Services, 1992b). Another 412, or 0.3 percent, had some other source, such as spring, stream, lake, or cistern, as their main water supply. Municipal or other public water-supply systems supplied 118,510 residences (90 percent) (South Carolina Division of Research and Statistical Services, 1992b). If these figures are rounded for ease of use, it may be assumed that about 10 percent of households in Greenville County, or approximately 13,000 residences, use well water for their primary water supply.

Greenville County's public water-supply systems reach almost all of the county's communities (either through the Greenville Water System, Greer Water System, or other smaller systems that purchase their water from the Greenville system). Many rural households and other users rely on ground water.

The ground water supply is generally plentiful except in certain areas of the county where it is difficult to drill wells and obtain appreciable supplies. The water quality is also usually good, although in some places it has high iron or other elemental concentrations.

PREVIOUS INVESTIGATIONS

Some previous geologic work has been done in Greenville County as part of regional studies, the first from as early as the 19th century; the best known is the geologic map of the Piedmont and Blue Ridge ("Crystalline Rocks") of South Carolina (Overstreet and Bell, 1965). Koch (1968) borrowed from their work but also

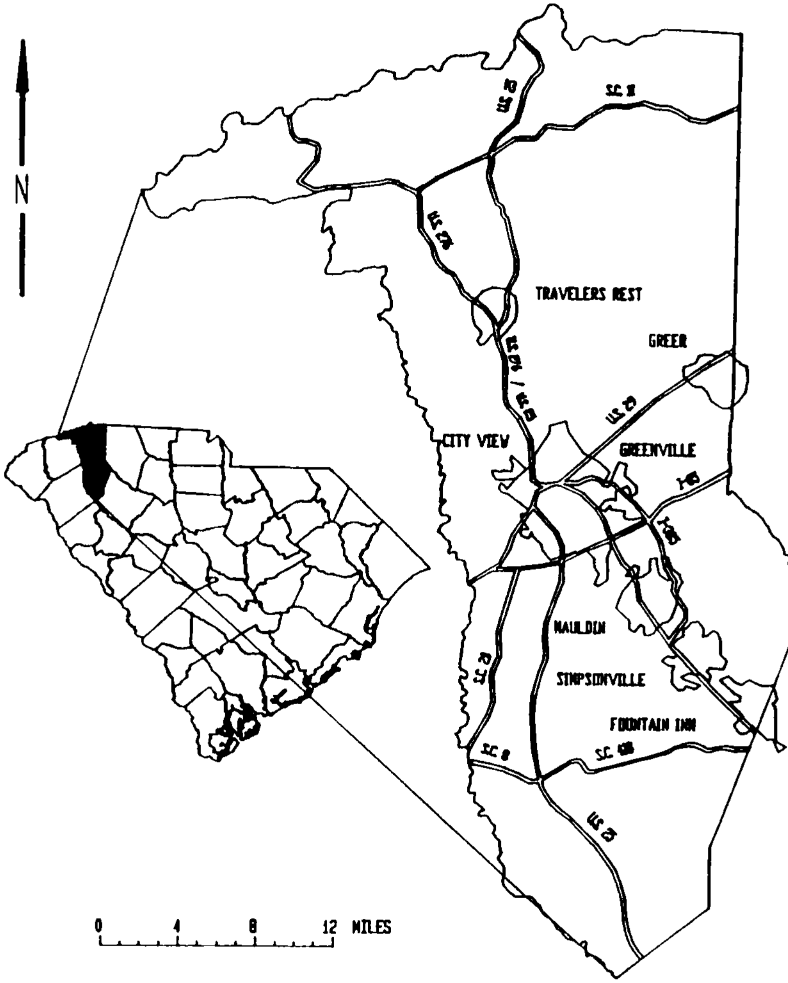

Figure 1. Cities and major roads of Greenville County, and location of Greenville County in South Carolina.

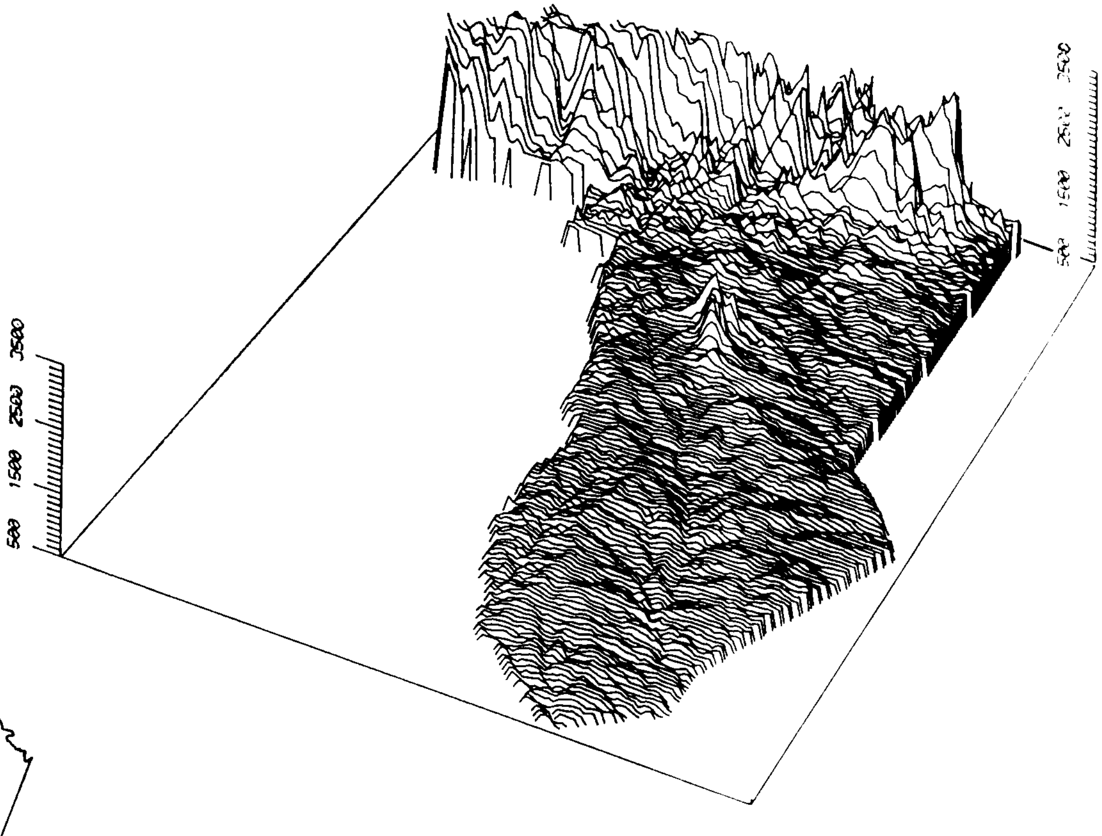

Figure 2. Topography of Greenville County. The Blue Ridge physiographic province begins at about 1,500 feet above sea level (northern part of county), and the Piedmont physiographic province is south of it. The rise in the center of the county is Paris Mountain.

contributed his own field investigations to a geologic map of Greenville County. Hadley and Nelson (1971) produced a geologic map of the Knoxville 1° x 2° quadrangle, which encompasses the northern one-third of Greenville County. Nelson, Horton, and Clarke (1987) put together a generalized tectonic map of the Greenville 1° x 2° quadrangle, and a geologic map of the quadrangle was produced in 1989 by the same authors; this quadrangle encompasses the southern two-thirds of Greenville County. Garihan and others (1988 and 1990) reported results of detailed mapping of faults, lineaments, and cataclastic rocks in the northern part of the county. The above-mentioned reports and maps were used to construct the geologic map for this report (see Plate).

The first hydrological report in the area was that of Siple (1946). Stock and Siple (1969) also had a water quality analysis and a hydrograph of precipitation and water level for one well in Greenville County. Several other reports dealt briefly with the hydrogeology of Greenville County as a part of regional studies; Aull and Duncan (1967), Campbell (1969), and South Carolina Water Resources Commission (1980, 1983a, and 1983b). Patterson and Padgett (1984) reported on the water quality of the Piedmont bedrock aquifers, and Speiran and others (1987) also reported on ground water quality of the entire State. Two reports from the U. S. Department of Energy National Uranium Resource Evaluation project published ground water and stream sediment geochemical data on the Greenville 1° x 2° quadrangle (Ferguson, 1978) and the Knoxville 1°x 2° quadrangle (Baucom and Ferguson, 1978), which include Greenville County. Another publication from the same project released data for the States of North and South Carolina (Sargent and others, 1982). Snipes (1981), Snipes and others (1983 and 1984), and Stafford and others (1983) reported on the hydrogeology of several Piedmont counties adjacent to Greenville County and briefly touched on some features in the county itself. Koch (1968) wrote the most detailed work on the hydrogeology of Greenville County. In that report he analyzed the hydrology as it relates to topography, surface geology, saprolite thickness, location and orientation of faults, fractures, bedding, and schistosity. Koch also tabulated 688 wells in the county, and described water quality analyses for several wells.

CLIMATE

Most of Greenville County's climate is characterized as temperate, with mild winters and warm summers. During fall, winter, and spring, the weather is controlled dominantly by the west-to-east motion of fronts, cyclones, and air masses, while in the summer air-mass exchanges are infrequent and tropical air from the coast persists in the area for long periods (Landers, 1975). Prevailing winds are from the northeast in fall and winter and from the southwest in spring and summer, with average windspeed of about 8 miles per hour. The northeast-southwest trending mountain ridges apparently affect the wind direction; the mountains also serve to protect the county from the full effects of the cold air masses moving southeastward from Canada during the winter (National Climatic Data Center, 1991).

Average annual precipitation in Greenville County is more than 75 inches in the northern part of the county, 55 to 60 inches in the central portion, and less than 50 inches in the southern part; the higher elevations in northwestern Greenville County have the State's highest average rainfall, with as much as 80 inches annually (Purvis and others, 1987). Annual precipitation totals vary directly with elevation, decreasing to the southeast. The driest month in northern Greenville County (Caesars Head) is October, with normal precipitation of 5.87 inches; the wettest month in this area is March, with 8.50 inches. In the east-central part of Greenville County (Greenville-Spartanburg Airport) November is the driest month, with 3.21 inches, and the wettest month is March, with 5.87 inches (Purvis and others, 1987).

Average annual temperatures for Greenville County generally range from about 56 degrees F in the northern part to about 60 in the southern part. The coldest temperatures occur in January, and daily means range from about 36 degrees F in northern Greenville County to about 41 degrees F in the central part of the county and slightly higher in southern Greenville County. The warmest normal temperatures are in July when daily means range from about 71 degrees F in the north to about 88 degrees F in centralGreenville County and slightly higher in the southern part (Purvis and others, 1987).

PHYSIOGRAPHY

Greenville County is located in the Piedmont Upland of the Piedmont physiographic province, except for the northernmost part of the county which is in the Blue Ridge physiographic province on the eastern slope of the southern Appalachian Mountains (Koch, 1968). The Blue Ridge physiographic province coincides approximately but not precisely with the Blue Ridge geologic province (Soller and Mills, 1991); the northern extremity of Greenville County is in the Blue Ridge physiographic province, but no part of the county is in the Blue Ridge geologic province (see Geologic Map (Plate), Fig. 2, and Fig. 3). The Brevard fault zone, which cuts through Oconee County west of Greenville County, is the geologic boundary between the Blue Ridge and Piedmont geologic provinces (Fig. 3). It was formed during the

Taconian Orogeny, in the Middle to Late Ordovician period (Horton and McConnell, 1991). The mountainous area of northern Greenville County constitutes the southeastern boundary of the Blue Ridge physiographic province, which is the Blue Ridge Escarpment. There are several theories on the formation of this escarpment, the most recent by Clark (1993). He suggested that the Escarpment has developed progressively from northeast to southwest, mostly by processes of weathering, headward erosion, and stream piracy by Atlantic-slope streams (southeast-flowing) of ancient, formerly northeast-flowing streams (Clark, 1993). As the weathering proceeded to the southwest, it caused a progressive spatial separation of isolated mountains and mountain masses on the northeast and then more rugged, increasingly imperfect escarpment development on the southwest (at least in North Carolina, and probably also in South Carolina). The overall picture is that of a gradually widening wedge between the main landmass on the northwest and the monadnocks and inselbergs created on the southeast, with the wedge being wider on the northeast and narrowing to the southwest, gradually moving to the southwest (Clark, 1993). Most of the erosion and geomorphic changes have occurred during the Quaternary period.

Elevations in northern Greenville County range from 1,200 to over 3,000 feet above sea level, with the highest point at 3,357 feet at Coldbranch Mountain in the northwestern tip of the county. The Blue Ridge physiographic province is a region of dissected, rugged mountains and narrow valleys, with local relief of several hundred to a few thousand feet from valley floor to ridge crest (Smith and Hallbick, 1979). Several other mountains, such as Table Rock, Caesars Head, and Glassy Mountain, rise prominently above the valley floors in the Blue Ridge part of Greenville County, with valley floors sloping to the south-southeast. As a group, the mountains have a general east-northeast trend.

The remainder of the county is in the Piedmont physiographic province and lies at elevations between 600 and 1,500 feet above sea level, with gently rolling to hilly slopes and narrow stream valleys. Local relief is usually in the tens of feet but ranges to hundreds of feet, and again the land slopes to the southeast (Smith and Hallbick, 1979). An exception to the general topography of the area is Paris Mountain, which rises in the center of the county to an elevation of 2,067 feet. The lowest elevation in the county is about 570 feet, where the Saluda River leaves Greenville County at its southern tip, where it intersects with Abbeville, Anderson, and Laurens Counties.

The rivers draining Greenville County are the Enoree, Reedy, Saluda, and Tyger, all of which flow into the Santee River basin. The major streams in Greenville County drain predominantly to the southeast, and most of their tributaries join them at roughly right angles, to parallel the general northeasterly trend of the mountains and hills (Fig. 4). There are two exceptions to the general southeasterly drainage. First are Lake Lanier and the streams that feed it in the northeast corner of the county, which drain northeastward into North Carolina and the North Pacolet River, which then turns to the southeast. Second is the North Saluda River in north-central Greenville County, which flows to the southwest before joining the South Saluda River at the Greenville-Pickens County line, where the Saluda River flows to the southeast.

GEOLOGY

STRUCTURE AND ROCK TYPES

Greenville County lies wholly within the Inner Piedmont block of the Piedmont geologic province, and is underlain by a suite of igneous and metamorphic rocks. The Inner Piedmont block is separated from the Blue Ridge geologic province on the northwest by the Brevard fault zone and from the Kings Mountain belt on the southeast by the Lowndesville and Kings Mountain shear zones (Horton and McConnell, 1991). The dominant structural features of the Inner Piedmont block are four or five stacked sheets thrusting westward (Nelson and others, 1987). Three of these thrust sheets underlie Greenville County and are, in ascending order, the Six-Mile, Paris Mountain, and Laurens thrust sheets (Horton and McConnell, 1991, and Nelson and others, 1987). The principal rock types in these thrust sheets are schist, gneiss, and amphibolite. The metamorphic grade is the sillimanite zone of the amphibolite facies, and on the northwest and southeast the rocks are of lower grade (Butler, 1991). The Caesars Head Granite also covers a large part of Greenville County and is dominantly a biotite granitoid gneiss or gneissic granitoid (Nelson and others, 1989).

Several faults, lineaments, and diabase dikes cut through the rocks of Greenville County. Most of the faults and lineaments trend generally northeast-southwest, but most dikes trend northwest-southeast (Garihan and others, 1988, Koch, 1968, and Overstreet and Bell, 1965). A few of the faults and lineaments are over a mile long and several are greater than 20 miles in length. These faults and lineaments are mapped predominantly in northern Greenville County; their extent southward is unmapped, but they extend into North Carolina and into Spartanburg County on the east and Pickens County on the west (see Geologic Map).

A mantle of residual weathered bedrock, saprolite, overlies all the bedrock, and streams are bedded in deposits of Quaternary alluvium.

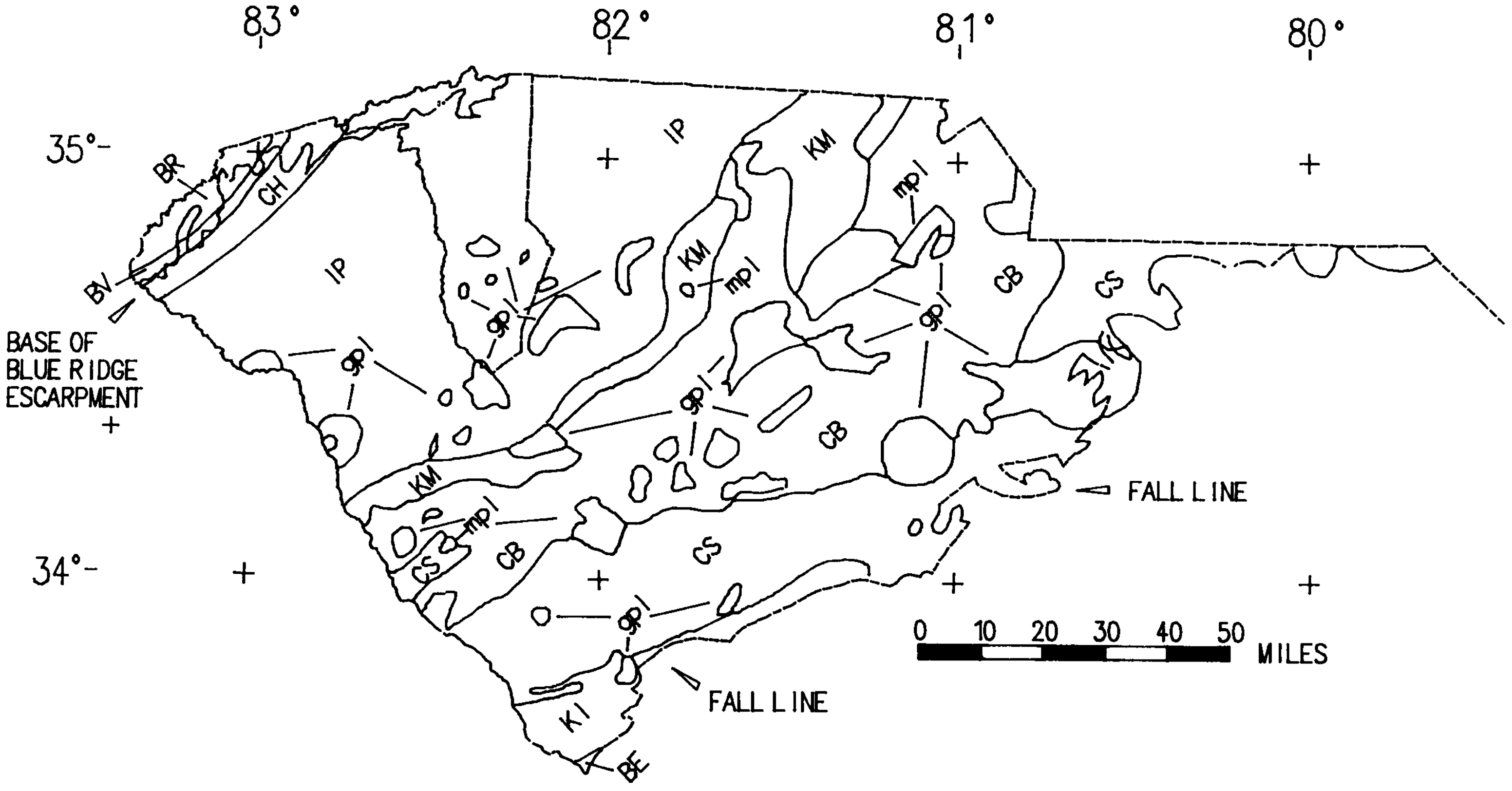

Figure 3. Geology of the South Carolina Piedmont and Blue Ridge, and physiographic boundaries. The Blue Ridge Escarpment separates the Blue Ridge physiographic province from the Piedmont physiographic province to the southeast. The Brevard belt (Brevard fault zone) is the boundary between the Blue Ridge geologic province and the Piedmont geologic province. The Fall Line separates the Piedmont physiographic and geologic provinces from the Coastal Plain physiographic and geologic provinces to the southeast. The Coastal Plain is not shown on this map. Units of the Blue Ridge geologic province: BR, Blue Ridge belt; BV, Brevard belt (Brevard fault zone). Units of the Piedmont geologic province: CH, Chauga belt, IP; Inner Piedmont belt; KM, Kings Mountain belt; CB, Charlotte belt; CS, Carolina Slate belt; KI, Kiokee belt; BE, Belair belt; gpl, granitic and monzonitic plutons; mpl, mafic plutons; diabase dikes and pegmatite dikes not shown. Adapted from Overstreet and Bell (1965), South Carolina Water Resources Commission (1983a), and Clark (1993).

DESCRIPTION OF GEOLOGIC UNITS

Two 1° x 2° quadrangles cover Greenville County, and consequently there are two geologic maps of different dates and surficial geological interpretations: the Knoxville 1° x 2° quadrangle (Hadley and Nelson, 1971) and the Greenville 1° x 2° quadrangle (Nelson and others, 1989). The Knoxville map covers approximately the northern one-third of Greenville County and the Greenville map covers the remaining two-thirds. Some of the units appear similar enough in lithologic descriptions to attempt to correlate across map borders, such as the Caesars Head Quartz Monzonite of Hadley and Nelson (1971) and the Caesars Head Granite of Nelson and others (1989). Indeed, the name Caesars Head Quartz Monzonite is no longer used and instead has been replaced by the Caesars Head Granite to conform with IUGS classification and nomenclature of igneous rocks[1] (Horton and McConnell, 1991). The lithologic boundaries and contacts do not match, however, and other units are so different at the map border that correlation between the two maps is difficult. For example, the Caesars Head Quartz Monzonite of the Knoxville map and the Caesars Head Granite of the Greenville map do not touch at the border except in a small area in the western part of the county; the major parts of the units are separated by the migmatite and biotite-hornblende granodiorite of the Knoxville map. Since it is outside the scope of this study to correlate the geologic units across different quadrangles, each map is left in its original form for the surficial units, even if the name on the original map is no longer in use. Diabase dikes have been added to the map in this report from other sources, as have faults and lineaments. For references on the following geologic descriptions, see "Sources" on the Geologic Map (Plate).

Caesars Head Quartz Monzonite (cqm)

This is the dominant geologic unit in northern Greenville County and the second largest in area in the county. It is a massive gneissic biotite quartz monzonite and granodiorite, medium to coarse grained, grading to and similar to the less foliated phase of the Henderson Gneiss. It may locally contain very large tabular megacrysts of microcline.

Henderson Gneiss (hg)

Consisting of biotite-microcline augen gneiss, medium to coarse grained, and generally well foliated, the Henderson Gneiss occurs in Greenville County only in the extreme western tip. It grades southeastward to a coarser and less foliated phase.

Henderson Gneiss, Less-Foliated Phase (hgg)

This is similar to the Henderson Gneiss above except for being less foliated and more coarse texturally. It occupies a northeast-southwest band between the Henderson Gneiss on the west and paragneiss on the east.

Biotite-Hornblende Granodiorite (bgd)

This unit occupies a small area in northeastern Greenville County on the 35° latitude line. It is weakly foliated and consists of a medium-grained, mesocratic granodiorite and tonalite, with a composition that is mostly biotite-rich but commonly also contains hornblende.

Migmatite (mgm)

Migmatite is the second most common unit in the northern part of the county; it is mostly paragneiss and schist containing 15 to 35 percent leucocratic granitic material of variable composition in sheets, lenses, and dikes ranging in width from an inch to a few feet. It occurs mostly in the northeastern part of Greenville County north of the 35° parallel but also in the extreme north-central portion of the county.

Paragneiss and Schist (pgs)

Scattered across the northern part of Greenville County but mostly in the northwest, this unit is a heterogeneous assemblage of interlayered biotite-quartz-feldspar gneiss, amphiobolite, muscovitic or garnetiferous quartzite, and biotite-garnet-sillimanite schist.

Layered or Stratified Rocks of the Six Mile Thrust Sheet

This sheet is the lowermost of the stacked thrust sheets. The stratigraphic order of the units within each sheet is uncertain, however. The first four of the following five units occur as small, usually isolated bodies in the western part of Greenville County; the fifth unit is a larger body in the same area.

Biotite-muscovite schist (CZs). This unit is interlayered with subordinate layers of sillimanite-mica schist and amphibolite.

Sillimanite-mica schist (CZss). This is a minor unit within the biotite-muscovite schist.

Garnet-quartz rock (gondite) (CZgs). This rock

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[1] An internationally adopted classification of plutonic rocks by the IUGS (International Union of Geological Sciences) Subcommission on the Systematics of Igneous Rocks (Bates and Jackson, 1987, p. 350).

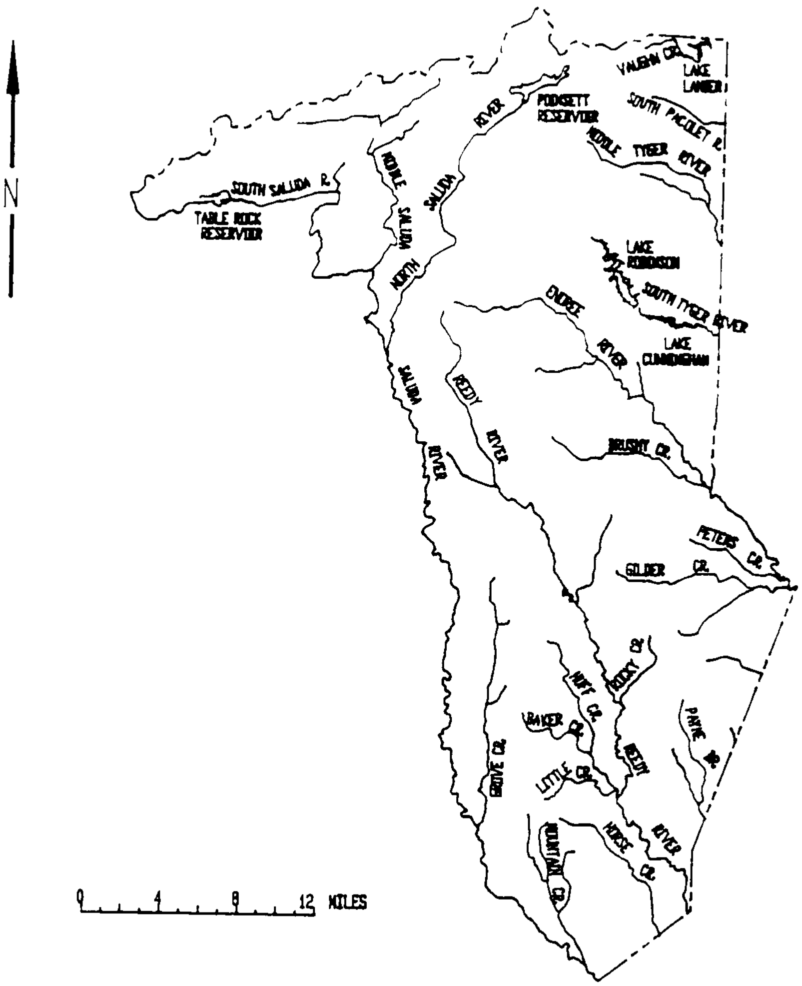


Figure 4. Major streams and reservoirs of Greenville County.

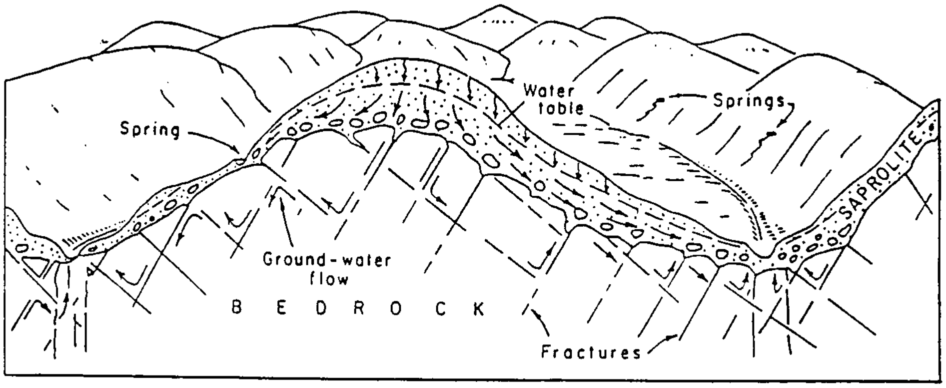


Figure 5. Typical Piedmont landforms and hydrology (from Heath, 1980).

grades locally into garnet-bearing quartzite.

Amphibolite (CZas). This amphibolite is a minor unit within the biotite-muscovite schist.

Biotite-plagioclase-quartz gneiss (CZbs). This rock unit contains subordinate biotite-muscovite schist, megacrystic biotite gneiss, amphibolite, rare garnet-quartz rock, and granitoid gneiss.

Intrusive Rocks of the Six Mile Thrust Sheet

Two intrusive units, the Caesars Head Granite and biotite granitoid gneiss, cover a major portion of the area of this thrust sheet.

Caesars Head Granite (SOch). This is mainly a gneissic granitoid, or biotite granitoid gneiss, of Early Silurian to Ordovician(?) age (an age of Devonian to Silurian is given by McSween and others, 1991). It occurs across the center of Greenville County, just south of the 35° parallel. This unit is equivalent to the Caesars Head Quartz Monzonite (cqm) to the north, and Caesars Head Granite is the preferred name now given to that unit. As previously explained, however, unit boundaries do not match across the two 1° x 2° maps, and it is outside the scope of this report to attempt correlating and interpreting units across those boundaries.

Biotite granitoid gneiss (SOsg). This rock occurs in a narrow north-south band in western Greenville County, along the eastern extremity of the Six Mile thrust sheet.

Layered or Stratified Rocks of the Paris Mountain Thrust Sheet

The three following units are of Early Cambrian and/or Late Proterozoic age, but the stratigraphic relationship between these units is unknown.

Sillimanite-mica schist (CZsp). This is the largest unit in areal extent in Greenville County, and it occupies a broad northeast-southwest trending band from the center to the southern part of the county. It constitutes the vast majority of the Paris Mountain thrust sheet.

Amphibolite (CZap). This unit consists of two small bodies in the southwestern part of the county.

Quartzite (CZqp). There are two small bodies of quartzite at the central eastern edge of the county.

Intrusive Rocks of the Paris Mountain Thrust Sheet

Granite gneiss (Pzpg). Several small to moderate size (up to approximately 5 miles in diameter) plutonic bodies of Paleozoic age occur within the Paris Mountain thrust sheet. Some of these plutons have an elongated northeast-southwest trend.

Layered or Stratified Rocks of the Laurens Thrust Sheet

This is the uppermost thrust sheet in Greenville County and consists of two units of Early Cambrian and/or Late Paleozoic age.

Biotite (hornblende-sillimanite-microcline-muscovite) gneiss (CZgl). This rock is interlayered with schist, quartzo-feldspathic gneiss, quartzite or quartz-muscovite schist, granitoid gneiss, granodiorite gneiss, amphibolite, and metagabbro. It occurs in three small- to moderate-sized bodies in the southeastern part of the county.

Amphibolite (CZal). This unit occurs as one small, north-northeast to south-southwest trending body in the southeastern part of Greenville County.

Intrusive Rocks of the Laurens Thrust Sheet

Granite gneiss (Pzgf). In Greenville County, this unit dominates the Laurens thrust sheet, covering most of the southeastern part of the county. It is the third-largest unit in areal extent in Greenville County.

Diabase Dikes

Some diabase dikes are present in the northern part of the county, striking generally northwest-southeast, but the majority are in the middle to southern portion of Greenville County (Garihan and others, 1988, Koch, 1968, and Overstreet and Bell, 1965). One dike has been mapped striking northeast to southwest in southeastern Greenville County (Koch, 1968).

Regolith

Regolith is the surface mantle composed of soil, alluvium, and saprolite. Saprolite is the clayey residuum derived from in-place chemical weathering of the bedrock. Because the regolith covers the entire surface, and is derived from the bedrock, it is not shown on the map as a separate unit. There are very few exposures of the bedrock itself, which is usually identified from its weathered residuum (saprolite) at or near the surface. The majority of the regolith layer is saprolite, and for hydrogeological purposes the amount of soil and alluvium are considered to be negligible.

GROUND WATER

OCCURRENCE

The ground water hydrology of Greenville County, as in most of the Piedmont, is controlled by a dual-aquifer system: saprolite and fractured bedrock. The overlying weathered bedrock, saprolite, ranges in thickness from 0 to 100 feet or more, but it averages about 60 feet. This clayey mantle has high porosity but low transmissivity. As such, it serves as a storage reservoir for the water infiltrating from precipitation. Underlying the saprolite is the unweathered bedrock, which can serve as a water reservoir if it is substantially fractured. Fractures in the bedrock act as conduits carrying water from the overlying saprolite (Figs. 5 and 6). There is a transitional zone between the two units that varies from inches to several feet in thickness. Rarely is the contact between saprolite and bedrock sharp and absolute, but rather there is a gradual lessening of the weathering effects and an increase in competency of the bedrock. Where the gradation from saprolite to bedrock is sharp and occurs over a short vertical distance, the boundary is often itself a source of ground water. Where there are few fractures or a scarcity of water in the fractures, the transition zone is sometimes the only viable source of water.

DRILLED AND BORED WELLS IN THE SOUTH CAROLINA PIEDMONT

In Greenville County, and in the Piedmont of South Carolina in general, there are two main types of wells used for water supply. The majority of wells constructed today are drilled, but there are many bored wells (Fig. 7). Of 2,831 records for Greenville County on file at the Water Resources Division office of the South Carolina Department of Natural Resources in Greenville, 1,828 are 6-inch diameter drilled wells, and 566 are 24-inch bored wells.

Drilled wells may range from 4 to 8 inches in diameter, and most are 6 inches. They are cased through the saprolite and into the bedrock. Most domestic wells are cased with PVC (polyvinyl chloride) pipe, which is resistant to the corrosive effects of the acidic ground water. Public-supply wells are required to be constructed with steel or galvanized steel casing, which is stronger and not as susceptible to breaking under the stress of emplacement as are the PVC casings. Public-supply wells must be grouted the entire depth of the casing down to bedrock (South Carolina Department of Health and Environmental Control, 1981). Domestic wells and others not intended for public supply are required to have at least the top 20 feet of annular space surrounding the casing grouted (South Carolina Department of Health and Environmental Control, 1985). Beneath the casing, the well bore is open to the bedrock and any fractures that may be encountered. Submersible pumps are almost always used in drilled wells and are emplaced anywhere from a few feet off the bottom in poorly producing wells to a few feet below the static water level in high-yielding wells. The definition of drilled wells, besides including those drilled by present-day rotary air hammer rigs, also includes those done in earlier days by cable tool and mud rotary rigs.

Bored wells do not penetrate the bedrock and are cased with 24-inch-diameter concrete pipe in 2-foot vertical sections. The annular space between the casing and the well bore is grouted either to at least 20 feet or, as in most of the newer bored wells in Greenville County, the top 6 to 10 feet is grouted, with a variance allowed by the South Carolina Department of Health and Environmental Control (SCDHEC, 1989). SCDHEC regulations do not allow bored wells to be used as public-supply wells. Submersible pumps are used in the deeper bored wells, but many are equipped with above-ground jet pumps. The definition of bored wells also includes hand-dug or otherwise augered large-diameter wells.

Drilled wells derive their water from fractures in the bedrock (Figs. 5, 6, and 7) and consequently must be carefully sited to ensure a location with sufficient fractures. The saprolite, which consists mostly of clay, has a very low hydraulic conductivity but at the same time is highly porous and serves as a water reservoir. The fractures are supplied with water by the saprolite reservoir above and are connected with other fractures that may extend a great distance.

Bored wells, on the other hand, receive their water only from the surrounding saprolite. Water enters at the bottom of the well through a gravel filter emplaced before the casing is installed. Being shallow, bored wells are more susceptible to droughts or other problems (such as pumping interference by nearby wells) that lower the water table below the pump level. Also, if not properly constructed and protected, bored wells are more susceptible to contamination because of their large diameter and shallow depth.

METHODS OF INVESTIGATION

All well records in this report are from the files of the South Carolina Department of Natural Resources, Water Resources Division, formerly the South Carolina Water Resources Commission. Most of the older records came from the U. S. Geological Survey Office in Columbia, S.C. Almost 690 wells inventoried for a report by Koch (1968) are included in this report. They have county numbers GRV-1 to GRV-701, with a few gaps in the numbering. Since 1968, many more wells have been added to the files.

Most information on wells constructed for other than

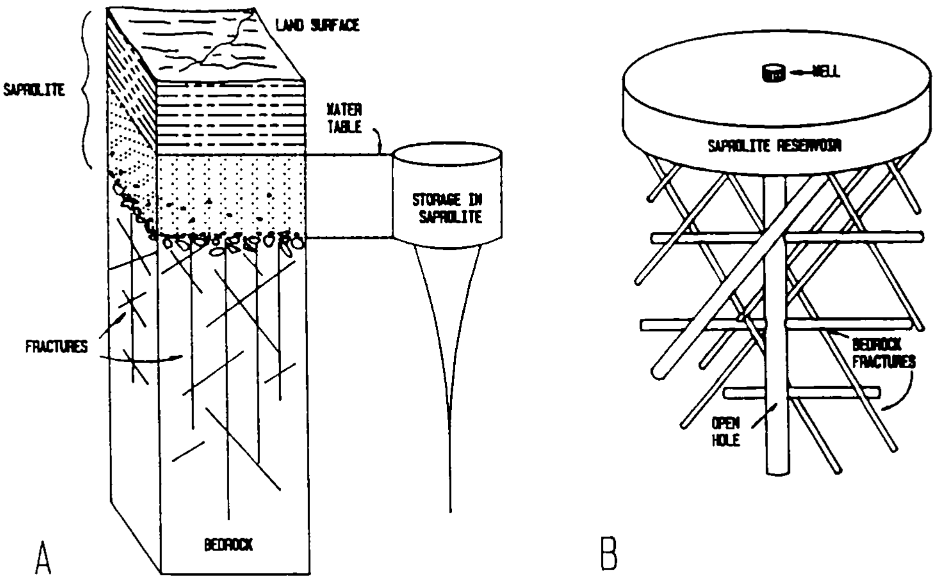


Figure 6. (A) Relationship of storage in saprolite to storage in fractured bedrock. (B) Schematic diagram of reservoir/pipeline system of typical Piedmont saprolite/bedrock aquifer (both figures after Heath, 1980).

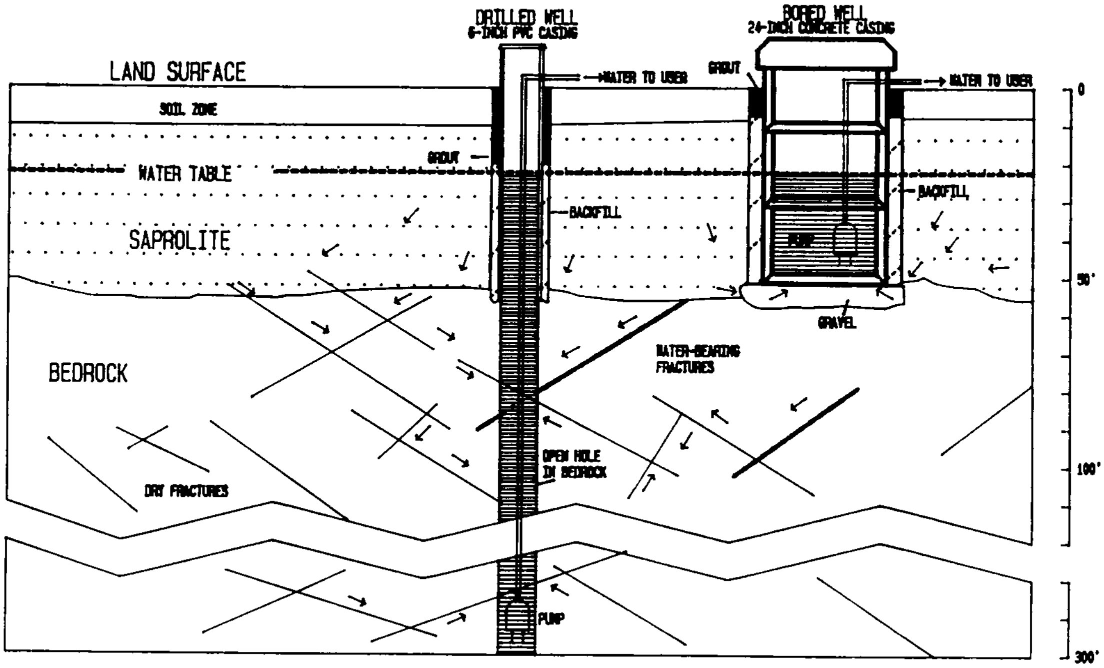


Figure 7. Typical domestic drilled and bored wells in the South Carolina Piedmont. Arrows indicate direction of water flow during pumping. For diagram clarity, not all concrete-casing joints are shown.

public-water supplies has come from well drillers in the form of SCDHEC's Ground Water Protection Division water well records (SCDHEC form 1093). These forms are completed by drillers and submitted to SCDHEC. Copies are forwarded to the Water Resources Division of the Department of Natural Resources (SCDNR-WRD). Much well information has also been gathered from field inventories, from well-site selection work, and from direct contacts with owners, drillers, consultants, and others. Currently, there are 2,825 well records and 6 records of springs for Greenville County.

Location Grid and Well-Numbering System

The well records of the SCDNR-WRD are filed in paper form and are summarized in a computerized database. All well records have two identification numbers. One is the county number assigned sequentially to each well recorded in a county well file. County numbers are assigned permanently to wells, even if the well is abandoned or destroyed.

Each well is also assigned a grid number, which is an identifier that locates the well on a State-wide grid in the SCDNR-WRD data-base. The grid number is also permanently assigned, except in cases of mistaken location, in which case a corrected grid number would be assigned. This identification number locates each well by 5-minute and 1-minute grids (Figs. 8 and 9). 5-minute grids are identified by capital letters corresponding to latitude divisions (letters A through MM, north to south) and numbers for longitude divisions (1 through 59, east to west). 1-minute grids are identified by lower-case letters a through y. Following is a description of the grid-numbering system.

Accurately located wells. Wells that are reliably located to the nearest second have their full latitude and longitude coordinates recorded and are identified by a three-digit 5-minute identifier and a two-digit 1-minute identifier. For example, the well with coordinates 34°54'23" latitude and 82°15'42" longitude is assigned the grid number 46E-a1, as it was the first well inventoried in that 1-minute grid. The next accurately located well inventoried within that 1-minute grid is assigned the number 46E-a2, and the next would be 46E-a3, and so on.

Wells located to nearest 5 seconds. Most of the wells inventoried for the earlier report on Greenville County (Koch, 1968) were located to the nearest 5 seconds; for example, well number 1 (GRV-1) in that report has coordinates of 34°56'25" latitude and 82°24'30" longitude. Though these wells technically do not fit the category of the above-mentioned wells located to the nearest second, they have been assigned regular grid numbers. GRV-1 is therefore also identified as 47D-p1. Some wells from the earlier inventory have been field located more recently and their latitudes and longitudes have been amended as needed.

Tentatively located wells. Many wells are located on the basis of small-scale hand-drawn maps supplied by drillers on their report forms, or through telephone conversations with owners, or other similar methods that allow estimating a general location but not a pinpoint coordinate. Unless these wells are field located by reliable sources, they are assigned tentative locations only. If the wells can be located to the nearest minute of latitude and longitude they are identified with a 'z' following the 1-minute grid identifier letter. The seconds columns are left blank in their latitude and longitude coordinates; therefore a well that is known only to be within the 1-minute grid 46C-e would be assigned the number 46C-ez1 (the first well inventoried in that grid in the tentative category) and its coordinates would be listed as 35°04'—" latitude and 82°19'—" longitude.

Wells located to the nearest 5 minutes only are assigned a 'z' in their 1-minute grid identifier but with no preceding 1-minute letter, and they are not given latitude and longitude coordinates; for example, 46C-z1. Wells that are not known even to the nearest 5 minutes but only to be within a county are assigned a 'Z' after the three-letter county abbreviation, and a sequential number, in the grid identifier; for example, GRVZ-1 (not to be confused with the county number). When a well with a tentative grid identifier is later located more accurately, the grid number will be changed accordingly, and the full latitude and longitude recorded. The county number does not change, however, as it is assigned permanently to a well regardless of its location in the county.

Data Acquisition and Verification

Records in the files cover wells of all ages, types, and conditions, in addition to various levels of data reliability. Many well records are generated from site-intensive field studies, with accurate location and construction information. At the other extreme of reliability, records may be based only on correspondence or telephone conversations with drillers or owners. Some records are very old, and new records arrive frequently on recently drilled wells. The sheer number of well records available for Greenville County precluded site visits for every well or even a large percentage of them, but certain procedures are followed to maintain as much control over data accuracy and reliability as possible.

The large majority of well records on file are domestic wells drilled in the last several years. Using the drillers' directions and/or hand-drawn maps on the forms, and sometimes contacting the drillers or owners, these wells are located to the nearest minute, if possible.

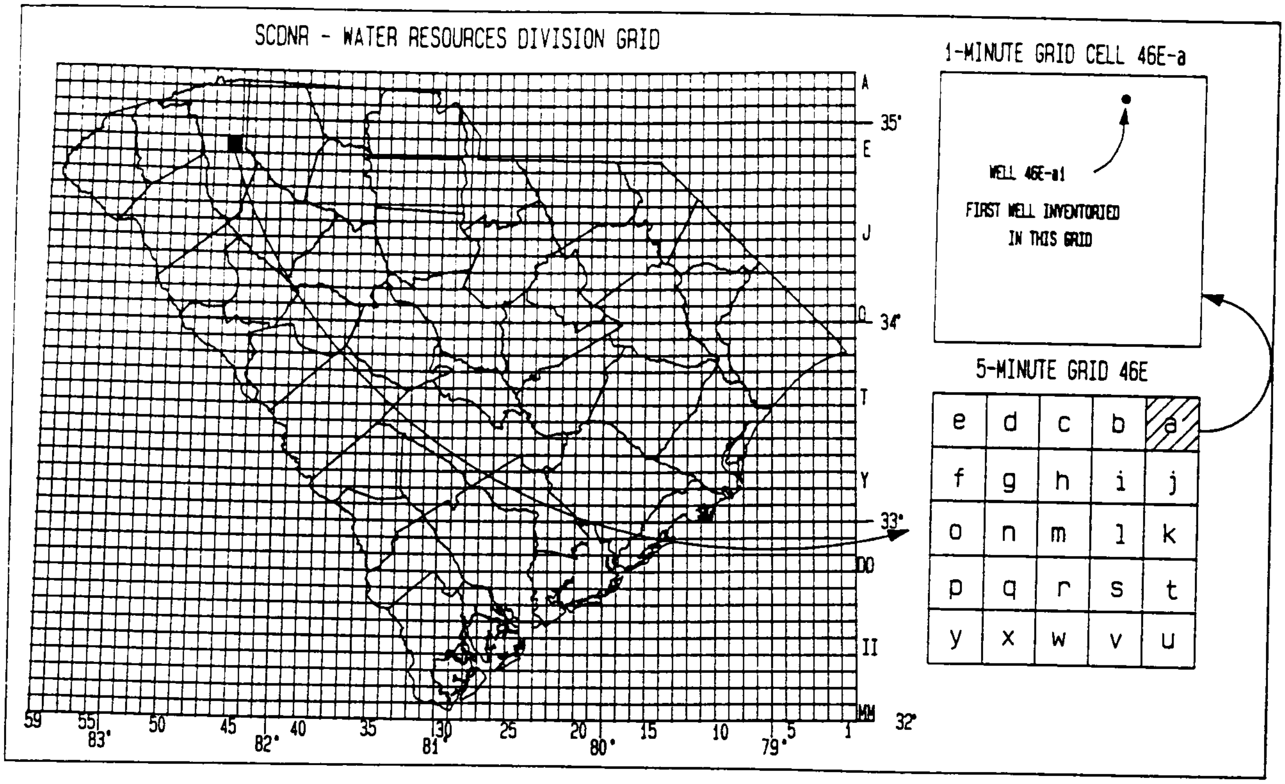


Figure 8. Well-numbering system.

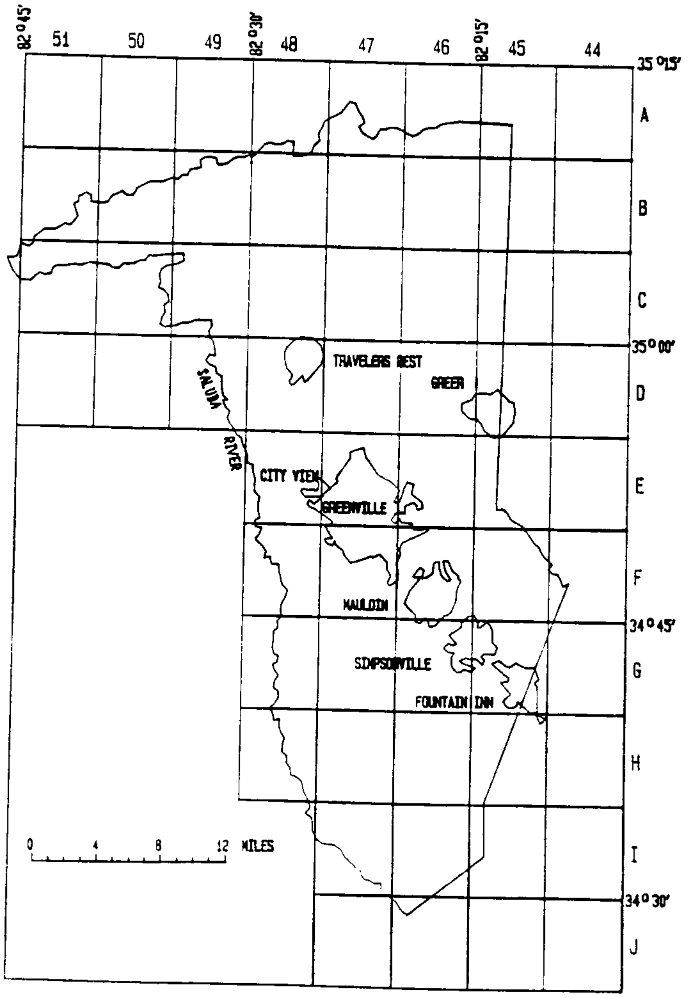


Figure 9. Greenville County and the 5-minute grid system.

Some well locations are inadequately described and therefore may be located to only the nearest 5 minutes.

For the well sites that are visited, locations are marked on U. S. Geological Survey 7.5-minute topographic maps or on Greenville County orthophotoquad sheets (usually with contour line overlays). Scales of these maps are 1:24,000 and 1:4,800, respectively. Coordinates (latitude and longitude) for the wells are determined from these maps. Some well locations are surveyed by the engineering contractor or consultant, especially for public-supply or large industrial wells, and this information is used for determining the well coordinates. Site elevation and topography are also determined from this location information. Some drillers indicate on their forms the site topography. All wells located to the nearest second are assigned a geologic unit.

Depending on the statistical information desired, varying levels of reliability would filter out certain unusable wells. For example, in determining whether a well's geologic unit had any statistical significance on the other properties of the well, such as yield, drilled depth, or casing depth, only those wells that are accurately located and assigned geologic units could be used. On the other hand, for example, determining the median depths of all the wells in Greenville County does not require that all the wells be accurately located, but only that a particular set of information (total depth on each well) be available.

WELLS IN GREENVILLE COUNTY

There are presently 2,825 well records on file for Greenville County. Of these, 8 have no location information, 27 are located to within 5 minutes of latitude and longitude, 1,844 are located to within 1 minute, and the remainder, 946, are located to the nearest 1 second or 5 seconds.

Important and useful information on wells includes the total depth, casing depth, diameter, water level, and yield. Also important are the well-site topography and the geologic unit (indicated as 'aquifer' in the data base). Other information in the data base includes land surface elevation, water level elevation with respect to mean sea level, well-construction method, and water use (see data diskette for listing of all available data). Another important value is the saturated saprolite thickness, which is the thickness of the saprolite layer above the bedrock which is saturated with ground water. This is calculated by subtracting the static water level from the casing depth (casing depth is approximately the same as the saprolite thickness). Few wells have all the desired data but a majority have the most critical information. There are two main types of well construction, drilled and bored. The summaries and discussions herein follow this division.

For statistical analysis, emphasis is placed on wells drilled originally for production purposes, whatever their final disposition may be. That is, wells included in this analysis are those which were drilled or bored with the intention of producing water, whether for public or domestic or other supply, even though the well may have been a dry hole or a very low-yielding well. Conversely, wells drilled solely for water level observation or water quality monitoring, such as those at hazardous waste sites, underground storage tank sites, or landfills, for example, are excluded from the statistical evaluation.

The majority of drilled wells in Greenville County are 6 inches in diameter. A very few are of smaller diameter (less than 20 wells in the files) and a few are greater in diameter; 21 are 8-inch wells (see "Drilled and Bored Wells in the South Carolina Piedmont" for discussion of well diameters and construction types). For the sake of simplicity and uniformity, in the analysis of drilled wells only the 1,828 6-inch drilled production wells are used in the statistical tables (64.7 percent of all the well records).

The analysis of bored wells deals with only those bored wells that are 24 inches in diameter; there are 566 in the records for Greenville County (20 percent of all the well records). A sizable minority are 48 inches in size (41), and there are 15 36-inch wells and a few other bored or dug wells of varying sizes, but these are excluded from the statistical analysis.

This means that in a total of 2,825 wells, there are 2,394, or 84.7 percent, included in the statistical summaries. This high percentage is more than enough to give a realistic and representative view of the wells in Greenville County.

6-INCH DRILLED WELLS: DISTRIBUTION BY WELL PROPERTIES

There are eight statistical summaries for the drilled wells: well depth, casing depth, stated yield, water level, saturated thickness, site topography, aquifer (as denoted by surficial geologic unit), and 5-minute grid location.

Total Depth

Almost all the 6-inch wells have known total depths (1,823 of 1,828); depths range from 22 to 1,085 feet (Fig. 10). The mean depth is 234 feet and the median depth is 200 feet. The disparity between these values indicates a small number of disproportionately deep wells. Median values are more reliable than mean in analyzing the statistics, since they are not subject to possible distortion, as are mean values, because of a few high or low values outside of the general trend.

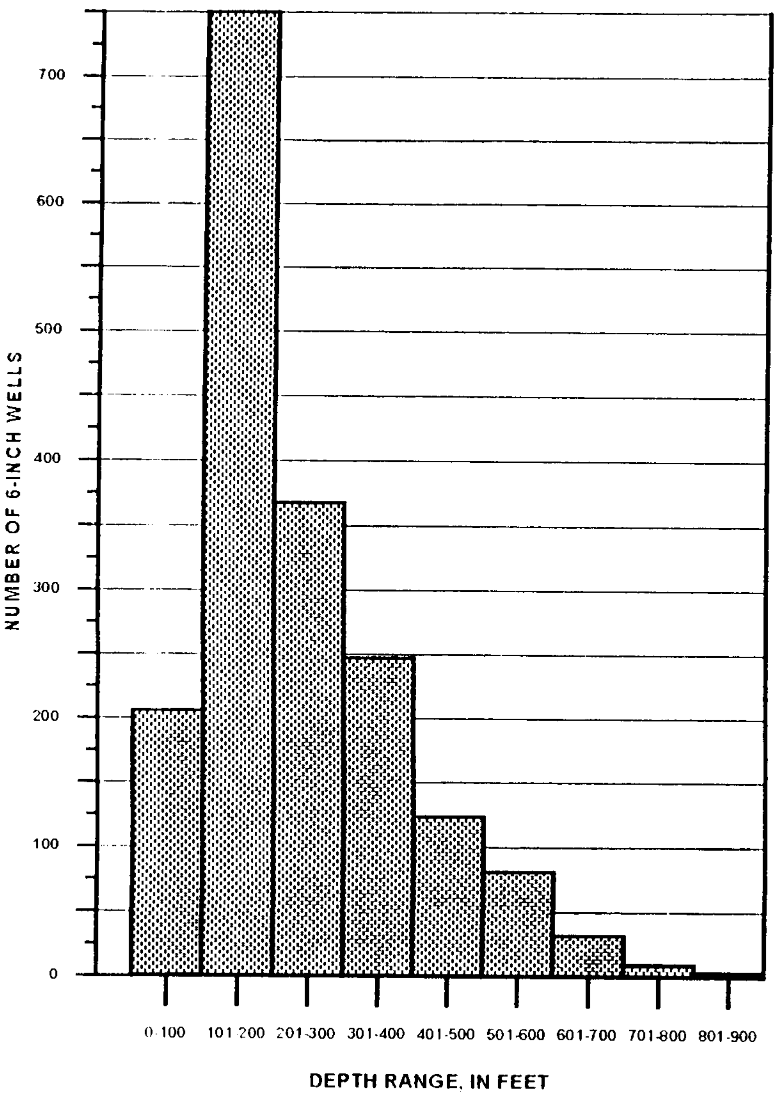


Figure 10. Depths of 6-inch drilled wells in Greenville County. One well is 1,085 feet deep (not shown on graph).

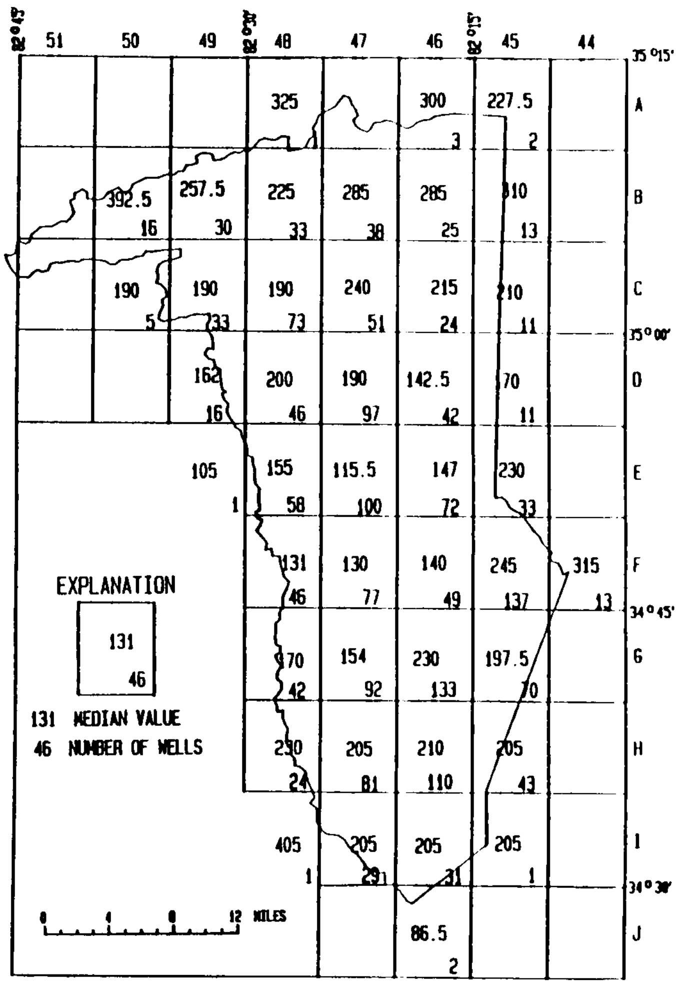


Figure 11. Median depths, by 5-minute grid, of 6-inch drilled wells in Greenville County.

A histogram of the well depths shows that the greatest number of 6-inch wells are between 101 and 200 feet deep (Fig. 10). The distribution of median depths is shown in Figure 11.

Casing Depth

Drilled wells are cased through the saprolite, the overlying layer of weathered residual rock. Casing is usually set about a foot into bedrock; consequently, casing depth information allows a fairly accurate estimate of saprolite thickness. Of the 1,828 6-inch wells, 1,686 (92 percent) have data on casing depths. Of these 1,686 casings, 1,088 are made of PVC, 7 are steel, 68 are galvanized steel, and 523 are unknown or not recorded.

The median depth for all 6-inch diameter casings is 54 feet, with a range of 5 to 208 feet (Fig. 12).

Yield

Yield is a term that needs to be defined because yield can be used to describe a wide range of values. For public supply, long-term sustainable yield defines the pumping rate for the well. Short term yields are estimated by drillers and are most often the yield reported. Accurate long-term well yields are difficult to ascertain, for pumping tests of several hours duration with pumping rate and water-level measurements are needed for estimating long-term yield. Such tests are rarely made in Greenville County because they are required by SCDHEC only for public-supply wells. Usually, for other than public-supply wells, a rudimentary test is made by drillers while the drill stem is still in the well, in which the formation water is forced out of the hole by air pressure from the drilling rig and the resulting flow is measured over a short interval of time. The short-term yield values thus obtained are used to determine if there is sufficient yield for the customer's needs or if more drilling is necessary. Often the flow is not measured but is estimated, the driller relying on experience to gage the yield. These short-term yields can be misleading since they may not indicate the true capacity of the water supply.

Of 1,828 wells, 1,617 (88 percent) have yield information. More than half of these wells have yields less than 10 gpm (gallons per minute) (Fig. 13). The median yield for all wells is 9 gpm. Figure 14 indicates the distribution of median yields in the county. The highest values are in grid 50C, in the northwest; but these are for only five wells. In the east-central part of the county, at grid 45E, is the next highest set of yield values. Most of the other higher-yielding wells are in the south-central region of Greenville County.

An important point is the fact that the majority of these wells are domestic wells or other wells without large yield demands, which are drilled in locations and to depths more dependent on owners' property size and economic constraints than on conditions suited to maximize well yield. Once a well driller achieves a minimum desired yield for a home owner, for example, it is unlikely the owner would want to pay more to go deeper or drill another well in search of more water, as long as the driller is confident of the yield achieved at that point. Conversely, wells sited and drilled to achieve maximum yield, such as those for municipalities and industries, will tend to have higher yields.

Static Water Level

Static water levels are known for 1,305 of a total of 1,828 wells, or 71 percent. This is the least reported of the four well-construction variables (well depth, casing depth, yield, and water level).

While not as prone to errors of procedure or estimation as well yield, static water level nevertheless is subject to measurement variations dependent on time and use. Most static water levels are measured by drillers soon after drilling, often before the water levels have had time to stabilize after the drilling and "air-blowing" yield test. Water levels measured a day or so after drilling generally show a foot or more rise compared to the level measured soon after drilling. A more important variable is the seasonal change in the water level. Generally, water levels are lowest in the dry months, during late fall and early winter, and are highest in the wet months, usually early spring and early summer. Water levels may vary as little as 3 or 4 feet over a few years to almost 20 feet over the same period in a different area of the Piedmont, even given the same precipitation (Mitchell, 1992).

The median static water level for all wells is 30 feet below land surface. Nearly half of the water levels are in the interval between 20 to 40 feet below land surface (Fig. 15). Deeper wells generally have deeper water levels (Fig. 16).

Saturated Thickness

The saturated thickness of saprolite is a value found useful by Daniel and Sharpless (1983) for predicting relative performance of wells. This value is simply the depth to the static water level subtracted from the saprolite thickness at the site (as indicated by casing depth). Obviously, where the static water level is deeper than the casing depth, the saprolite saturated thickness is zero. Generally, the greater the saturated thickness of the saprolite ground water reservoir, the higher the yields of wells, all other factors being equal. In records of the 1,828 drilled 6-inch wells, 1,251 had saturated-thick-

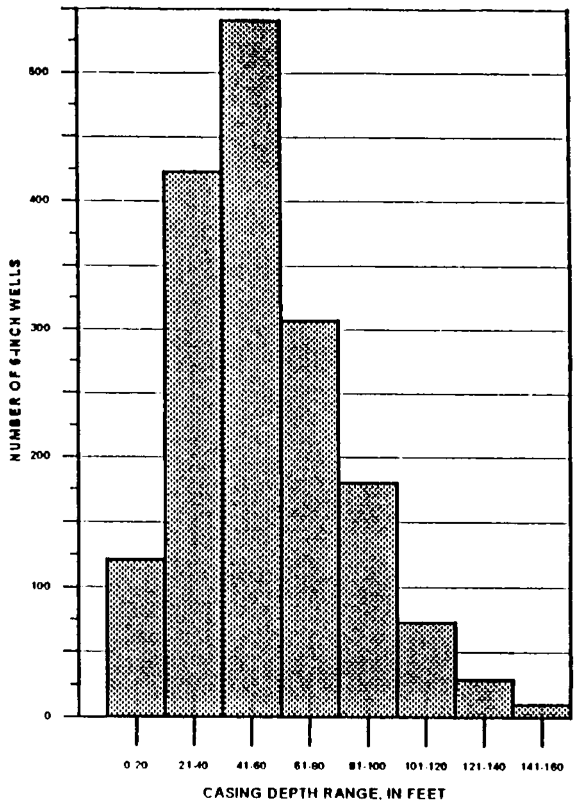


Figure 12. Casing depths of 6-inch drilled wells in Greenville County. Three wells, not shown, have casing depths greater than 160 feet.

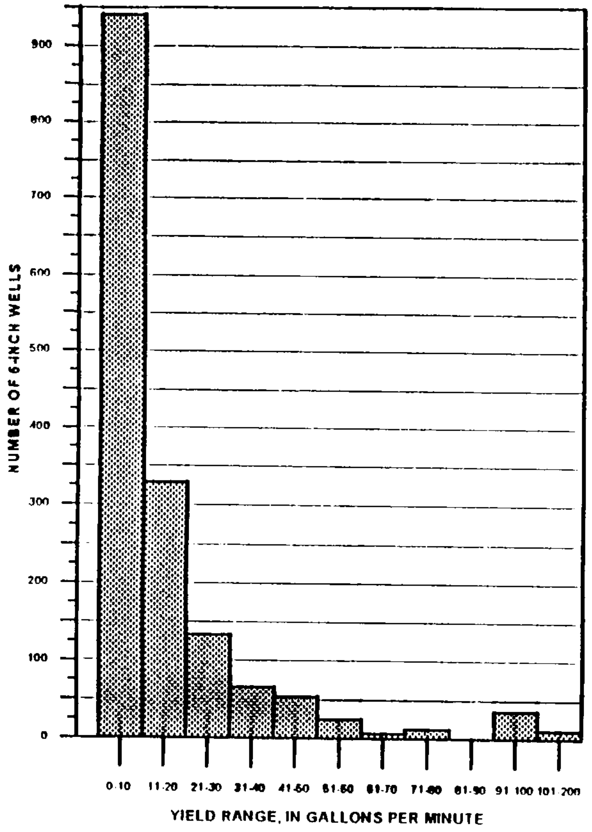


Figure 13. Yields of 6-inch drilled wells in Greenville County.

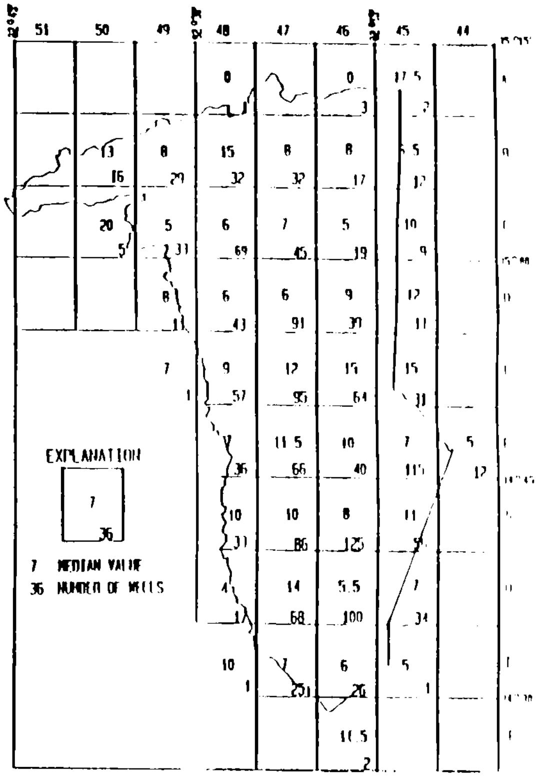


Figure 14. Median yields, by 5-minute grid, of 6-inch drilled wells in Greenville County.

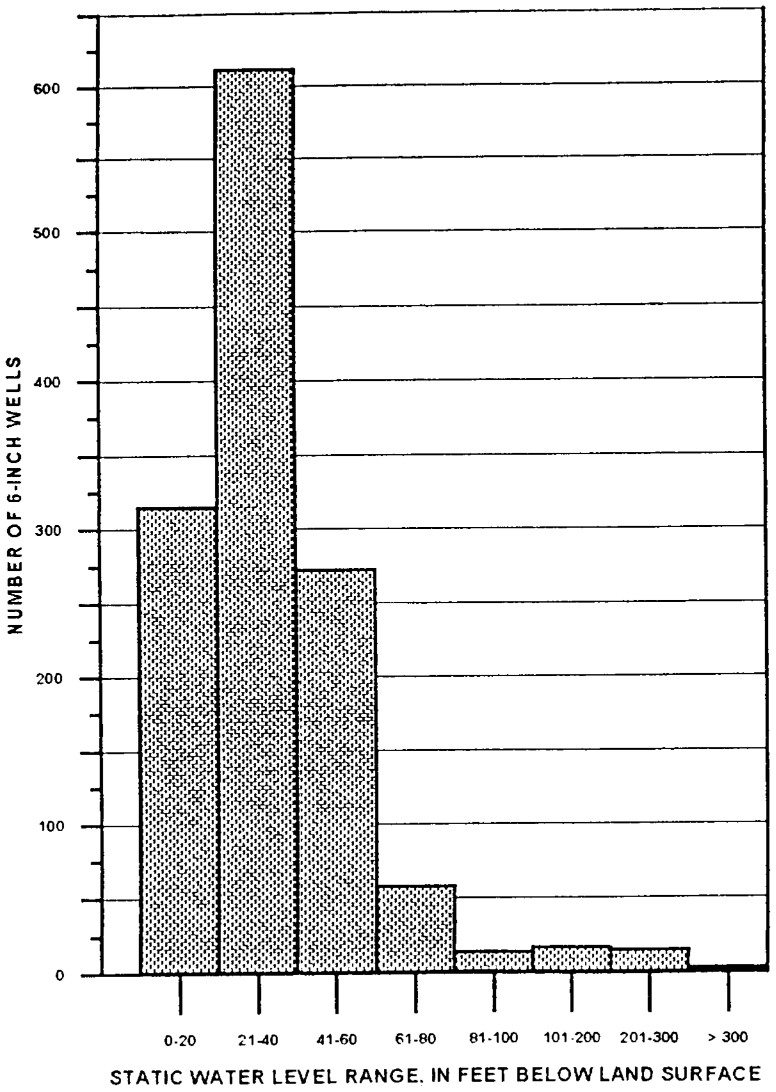


Figure 15. Static water levels in 6-inch drilled wells in Greenville County.

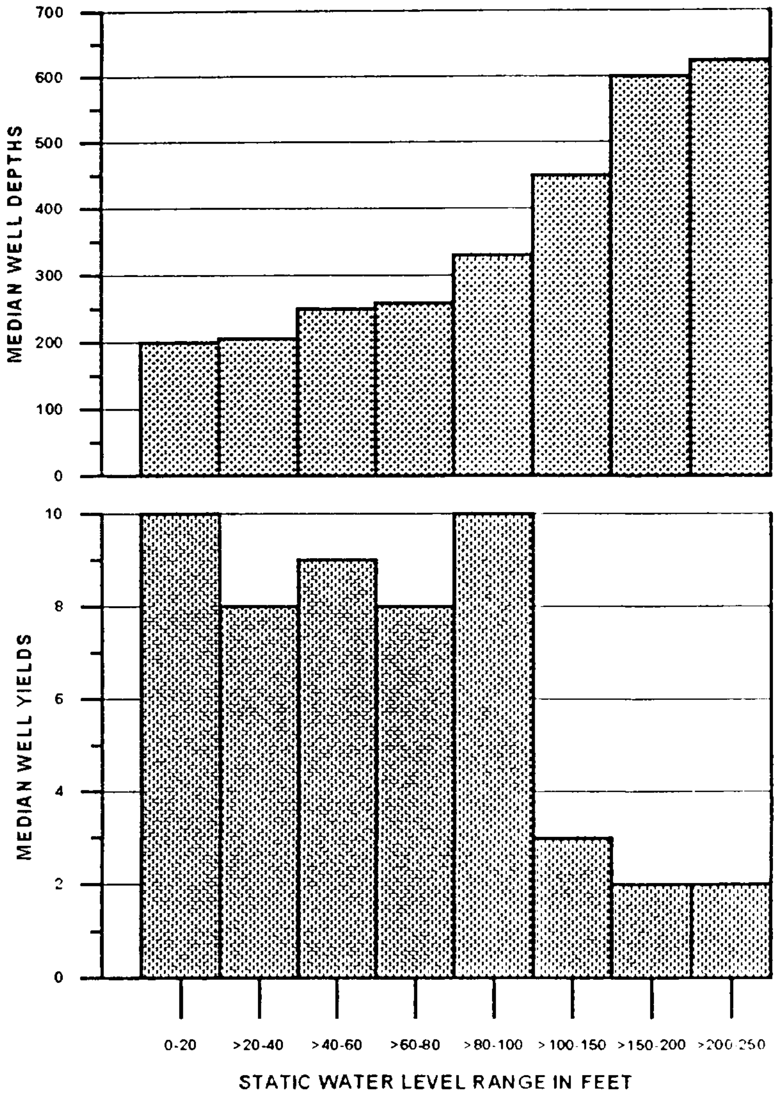


Figure 16. Variation in static water level with median well depth and with median well yield for 6-inch drilled wells in Greenville County.

ness values calculated (Fig. 17; data for the other 577 wells lacked either the casing depth or static water level, or both). The median saprolite saturated thickness is 26 feet. There is a fairly even distribution of the saturated thickness values across the county, although the greater values are slightly more predominant in the south, and several grids in the northeastern part of the county have less than the median thickness (Fig. 18).

Topography

In previous work done in Greenville County, as in the rest of the Piedmont, the topography was concluded to be very important in well siting. Wells with the greatest yields are usually located in valleys, wells on slopes and flat areas are lower in yield, and the lowest yielding wells are those on hills (Koch, 1968).

An analysis was made, with respect to topographic situation and well yield, for 669 wells having both yield and topographic situation information (Fig. 19). Results are similar to those of Koch's (1968). Within this set of wells, the largest number were drilled on slopes (282, or 42 percent) and the next largest on flat areas (173, or 26 percent). Of course, in the hilly Piedmont most flat areas actually are very gentle slopes, so in a sense these two categories are similar and merge together. Hills also account for a large number of wells (121, or 18 percent), and this is probably due to homeowners desiring wells next to their homes on the hilltops. Prime real estate does not necessarily mean ideal well sites, however. Wells on hills have the lowest production values of any of the topographic categories. Wells drilled in draws account for only 9 percent of the wells in known topographic categories, and valley wells constitute less than 5 percent.

Most wells in Greenville County are for domestic use and are drilled not for maximum well yield but for convenience of location and may be constrained by economic and geographic (property boundary) limitations (Fig. 19). If a well produces an adequate amount for the homeowner's satisfaction, the topographic situation of the well is of small concern.

Figure 19 shows the results of grouping well use by topographic situation. The top graph displays median yields of all 6-inch drilled wells for which the information was available (Table 1). Wells drilled for maximizing the available water supply with minimum cost and effort, such as those for public-water supply systems and

Table 1. Median yields of 6-inch drilled wells with respect to topographic situation

	Valley	Draw	Flat	Hillside	Hilltop	No topographic designation	All topographic situations
All 6-inch drilled wells							
Median yield	15	15	10	10	7	8	9
Number of wells	31	66	208	312	131	949	1617
Domestic-supply wells							
Median yield	10	8	8	10	7	8	8
Number of wells	22	25	130	250	104	865	1343
*Maximum-yield wells							
Median yield	21	29.5	15	20	7	22	20
Number of wells	7	20	32	29	15	49	152

*Mostly public-supply wells, but also includes wells for the following purposes: commercial, industrial, irrigation, institutional, livestock, and recreational.

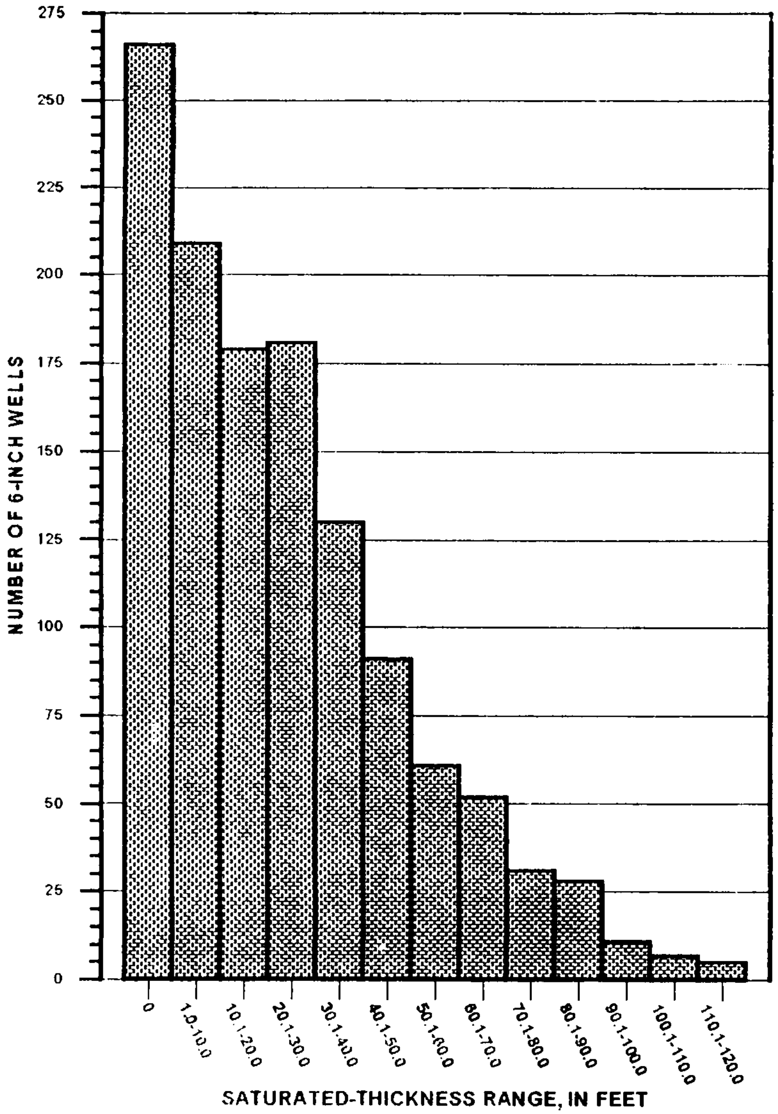


Figure 17. Saturated thickness of saprolite in 6-inch drilled wells in Greenville County.

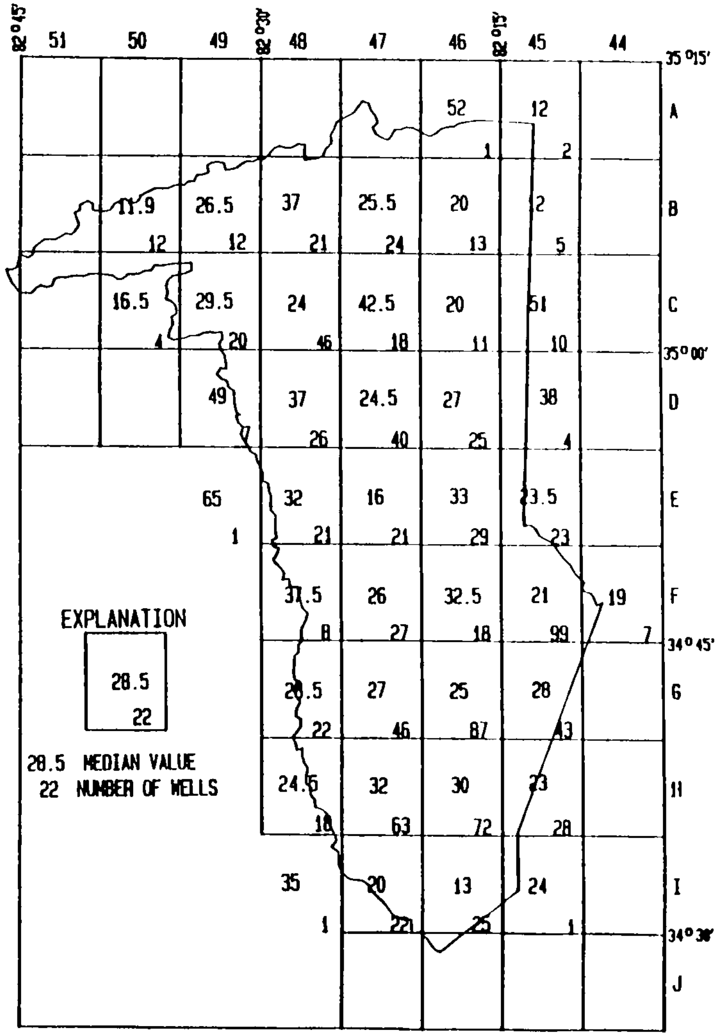
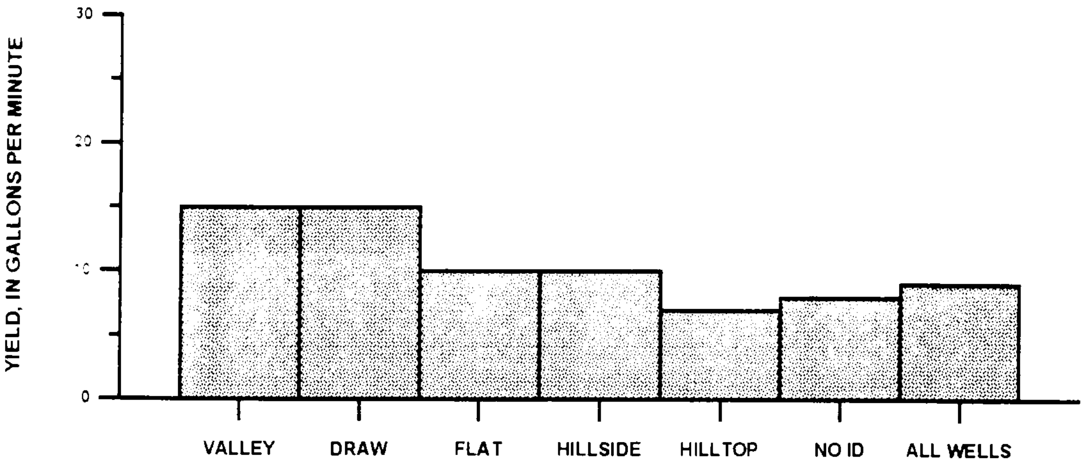
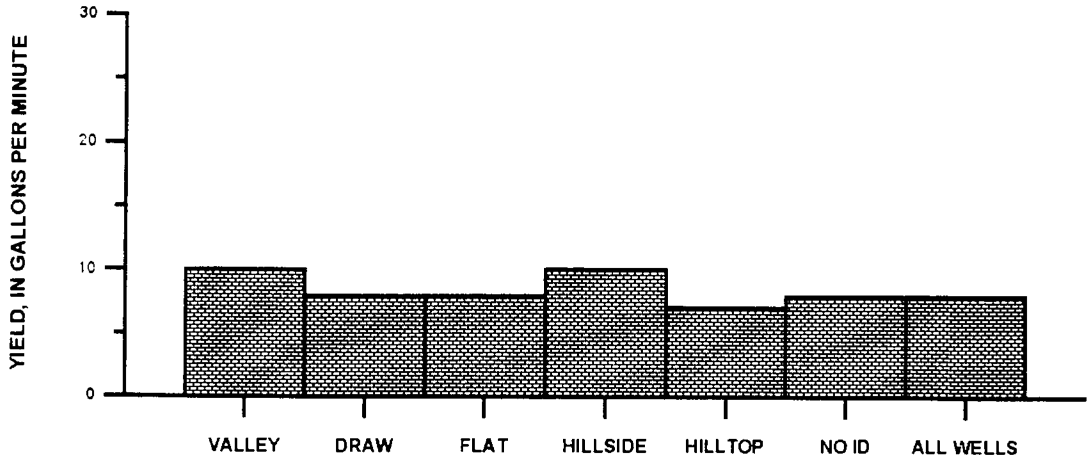


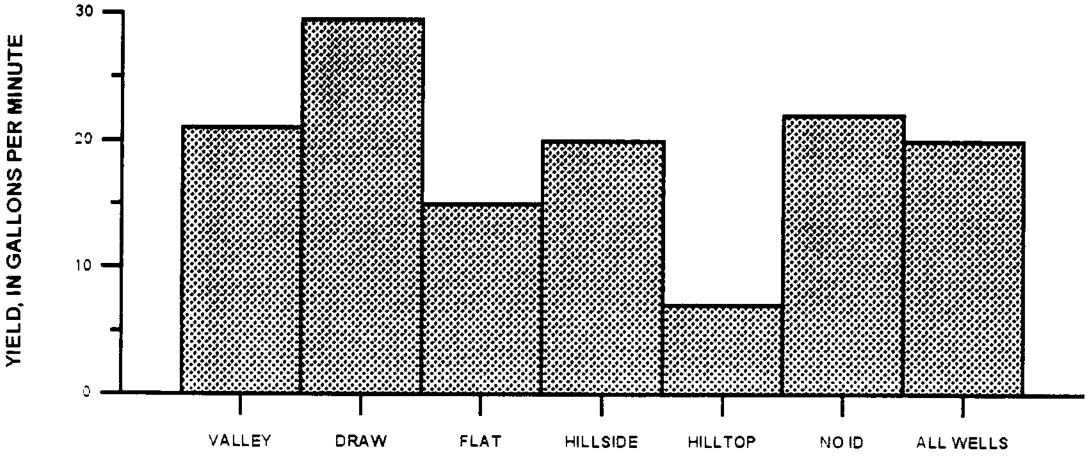
Figure 18. Median saprolite saturated thickness in 6-inch drilled wells in Greenville County.



ALL 6-INCH DRILLED WELLS



6-INCH DRILLED DOMESTIC WELLS



6-INCH WELLS DRILLED FOR MAXIMUM YIELD

Figure 19. Median yields of 6-inch drilled wells with respect to topographic location. Top graph represents all wells, middle graph represents domestic wells, and bottom graph represents wells generally located to maximize yields (commercial, industrial, irrigation, institutional, livestock, recreational, and public-supply).

industries, are usually sited with more care and foresight and, consequently, produce more water. Not only do these wells produce more water in general, but they have higher specific capacities and also produce more gallons per minute per foot of well depth (Fig. 19).

These more carefully sited wells have significantly different topographic characteristics. The percentage of wells drilled on hills, slopes, and flat areas is less, and the percentage of wells drilled in draws and valleys is more than double that among all wells. Well yields have increased also, as a result of the siting designed to increase the yields.

Geology

Surficial geologic units were assigned to the 960 wells that are accurately located. For the statistical analysis, only those units represented by five or more wells were used. There are 40 units penetrated by wells, but only 12 of these have at least 5 wells in them. As such, there are 633 wells in these 12 geologic units, or aquifers (Table 2 and the Plate). Aquifers here do not include the overlying saprolite reservoir but only the fractured bedrock.

Wells drilled along or near faults (within 300 feet) were categorized as such. For example, wells with the rock unit name "Caesars Head Quartz Monzonite and faults" (cqm/f) identify wells in that unit drilled alongside or near faults in the unit. Likewise, wells drilled in units overlain by Quaternary alluvium are noted; for example, sillimanite-mica schist of the Paris Mountain Thrust Sheet and Quaternary alluvium (CZsp/Qal). Also, wells located along the contact between sillimanite-mica schist and granite gneiss of the Paris Mountain Thrust Sheet (CZsp/Pzpg) are so identified. Finally, some units may be of similar rock type but have different names because of being located in different map quadrangles. Caesars Head Quartz Monzonite (cqm) north of the 35° parallel and the Caesars Head Granite (SOch) south of the parallel are essentially the same unit, but their unit boundaries do not necessarily match at the map borders. As it is out of the scope of this report to attempt to reconcile these differences, the names and boundaries have been left as they were originally reported on the geologic maps. See further discussion in the Geology section of this report. If not for these divisions and those mentioned earlier, there would be fewer geologic units to distribute among the wells.

There is a total of 633 wells for which the rock unit in which they were drilled is identified. Of these, more than half (319) are in the areally largest unit, sillimanite-mica schist, which is located predominantly in a wide band extending northeasterly across the center of the county. No other rock unit comes close in number of wells drilled; the next-largest group has 81 wells in granite gneiss of the Paris Mountain Thrust Sheet, which consists of several separate bodies spread out within the sillimanite-mica schist.

The deepest median depth for wells, by geologic unit, is in the Caesars Head Quartz Monzonite, at 212 feet. This depth may be more of a function of the relief and elevation than the geology, as most of this unit lies at higher elevations in the northern part of the county. The median elevation of wells in this unit is 2,002 feet, whereas wells in a similar unit to the south, the Caesars Head Granite, have a median elevation of 1,068 feet. The median well depth in this unit is 125 feet. The shallowest median depth is 98 feet, in migmatite, which strikes generally east-northeast, and lies between the Caesars Head Quartz Monzonite and the Caesars Head Granite.

There are 558 wells in known geologic units that have yield data (Table 2). Of these, the largest group, again, is the sillimanite-mica schist, with 279 wells and a median yield of 10 gpm. The highest median yields are from wells in biotite gneiss, at 40 gpm; however, there are only five wells in this unit, so this value may be high. The next-highest median yield is 12 gpm, and three geologic units share this value. The lowest median yield is 4 gpm in the Caesars Head Granite.

Overall, the median yield for most units ranged from about 4 gpm to 12 gpm, and the median depth for most units ranged from approximately 100 feet to 140 feet (Fig. 20).

Geography (5-Minute Grids)

To completely cover Greenville County, 47 5-minute latitude-and-longitude grids are required (see Figs. 8 and 9). Of these grids, 17 are completely within the county and 30 are partial, as they are located along the county border. Wells are drilled in all 17 of the complete grids and in 19 of the partial grids.

The two grids having the highest number of wells with depth information are 45F, with 137 wells, and 46G, with 133 wells (Table 3). The median depths of these wells are 245 and 230 feet, respectively. These two grids and grid 46H, with 110 wells, are areas bordering the Interstate Highway 385 corridor which are not completely reached by the Greenville Water System. These are areas of rapid growth, a conclusion supported by the fact that more than 31 percent of drilled wells in these grids have been constructed since the beginning of 1990. Other grids in the area, although lower in total number of wells, also have high percentages of new wells; 43, 47, and 48 percent, respectively, of wells drilled in grids 47H, 45H, and 47I were drilled since 1990. Other fast-

Table 2. Distribution of 6-inch drilled wells in Greenville County with relation to geologic unit, depth, yield, saprolite thickness, and saturated saprolite thickness

Surface Geologic Unit	Wells with depth data	Median depth of wells (feet)	Wells with yield data	Median yield of wells (gpm)	Wells with saprolite and saturated saprolite thickness data	Median saprolite thickness (feet)	Median saturated saprolite thickness (feet)
Ceasars Head Quartz Monzonite (cqm)	58	212	55	8	32	40.5	8.9
Ceasars Head Quartz Monzonite and faults (cqm/f)	6	159	5	12	< 5	*	*
Biotite-plagioclase-quartz gneiss of the Six Mile Thrust Sheet (CZbs)	45	140	40	11	10	27	1.5
Biotite-plagioclase-quartz gneiss of the Six Mile Thrust Sheet and Quaternary Alluvium (CZbs/Qal)	15	105	13	8	< 5	*	*
Boitite gneiss of the Laurens Thrust Sheet (CZgl)	11	180	5	40	< 5	*	*
Sillimanite-mica schist of the Paris Mountain Thrust Sheet (CZsp)	319	125	279	10	101	45	18
Sillimanite-mica schist and granite gneiss of the Paris Mountain Thrust Sheet (CZsp/Pzpg)	25	135	21	12	10	62.5	17.9
Sillimanite-mica schist of the Paris Mountain Thrust Sheet and Quaternary Alluvium (CZsp/Qal)	7	120	6	9	< 5	*	*
Migmatite (mgm)	10	98	9	10	< 5	*	*
Granite gneiss of the Laurens Thrust Sheet (Pzgf)	41	133	37	6	17	46	30
Granite gneiss of the Paris Mountain Thrust Sheet (Pzpg)	81	108	74	12	29	50	2
Ceasars Head Granite (SOch)	15	125	14	4	< 5	*	*

* No medians were calculated from groups of less than 5 wells.

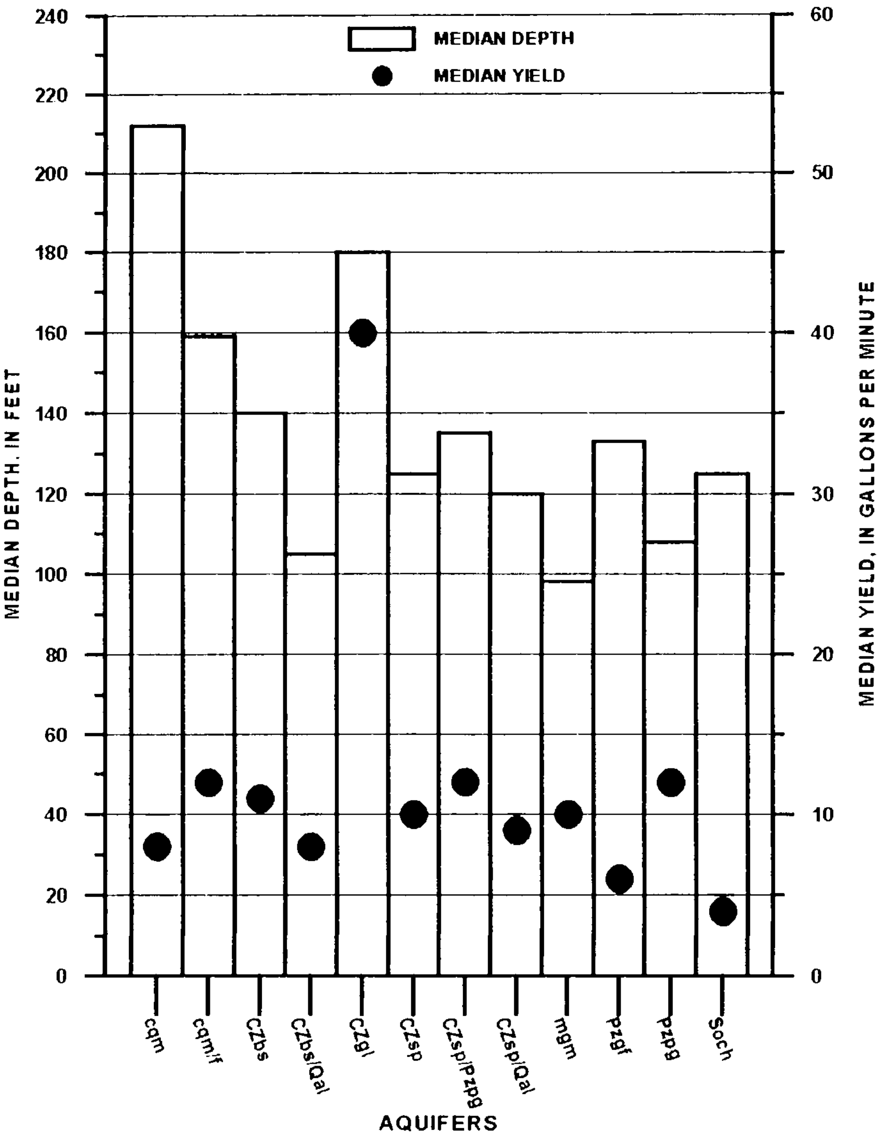


Figure 20. Median depths and yields of 6-inch drilled wells in the aquifers of Greenville County.

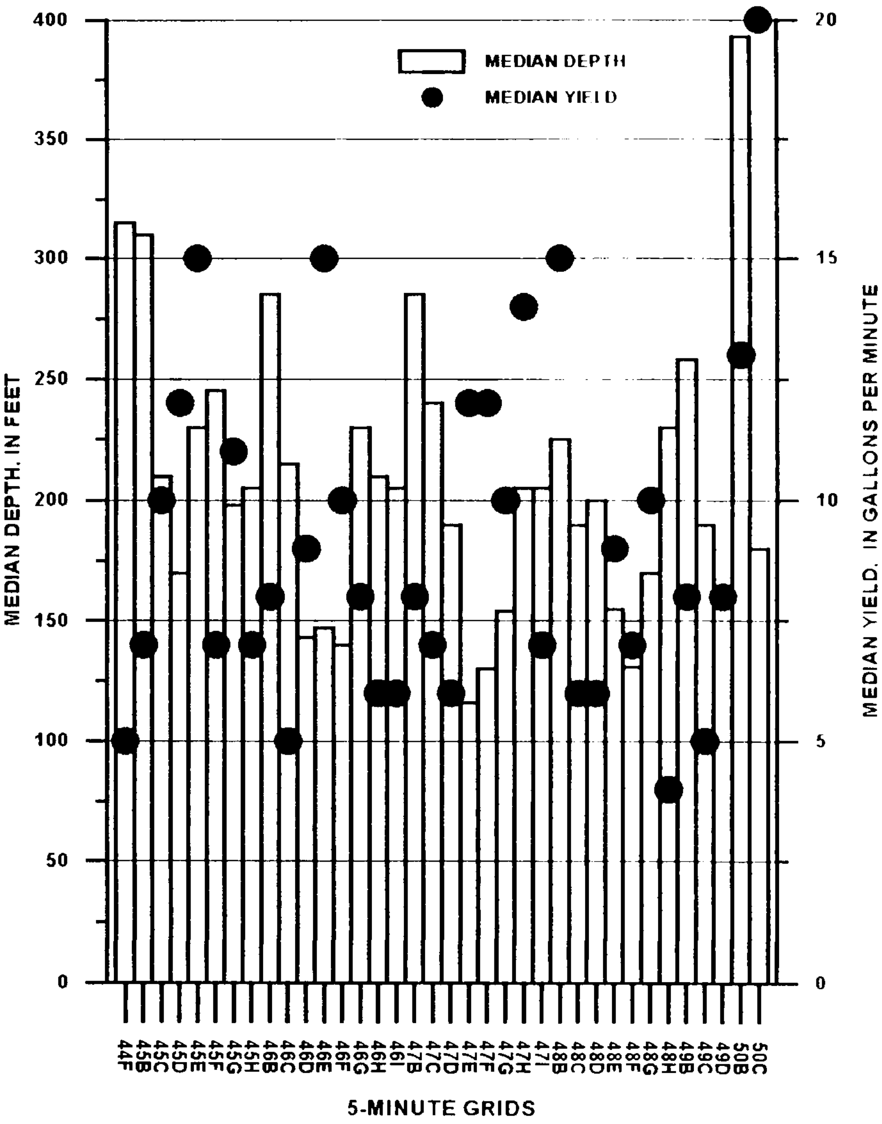


Figure 21. Distribution of median depths and median yields, by 5-minute grids, of 6-inch drilled wells in Greenville County.

Table 3. Distribution of 6-inch drilled wells on the 5-minute grid maps of Greenville County

5-minute grid	Wells with depth data	Median well depth	Wells with yield data	Median well yield
44F	13	315	12	5
45B	13	310	12	7
45C	11	210	9	10
45D	11	170	11	12
45E	33	230	31	15
45F	137	245	115	7
45G	70	198	56	11
45H	43	205	34	7
46B	25	285	17	8
46C	24	215	19	5
46D	42	143	39	9
46E	72	147	64	15
46F	49	140	40	10
46G	133	230	125	8
46H	110	210	100	6
46I	31	205	26	6
47B	38	285	32	8
47C	51	240	45	7
47D	97	190	91	6
47E	100	116	95	12
47F	77	130	66	12
47G	92	154	86	10
47H	81	205	68	14
47I	29	205	25	7
48B	33	225	32	15
48C	73	190	69	6
48D	46	200	43	6
48E	58	155	57	9
48F	46	131	36	7
48G	42	170	33	10
48H	24	230	17	4
49B	30	258	29	8
49C	33	190	33	5
49D	16	162	11	8
50B	16	393	16	13
50C	5	180	5	20

growing areas with high rates of well drilling include grids 47C and 47B (the area between Travelers Rest and Tigerville and north of Tigerville along Highway 11), with rates of 51 percent and 42 percent, respectively, of wells drilled since the start of 1990. Fifty-seven percent of the wells drilled in grid 49B (River Falls and Cleveland) have also been put in since early 1990. Conversely, only 2 wells out of a total of 100 in grid 47E, where most of the city of Greenville is located, have been drilled since 1990. Other grids adjacent to the city of Greenville also had low drilling rates in recent years. The main reasons, of course, are that piped city water is available in these areas and new construction is not as prevalent as in the outlying areas.

The deeper wells are mostly in the mountainous northern part of the county, and the shallowest wells are in the center, extending from the southwest to the northeast (Figs. 11 and 21). The distribution for median yields is more random, with little grouping of yield values, except for several grids in the east-central part of the county in the 12- to 15-gpm range (Figs. 14 and 21). There is little correlation between median depths and median yields as grouped by grids.

Summary of 6-Inch Drilled Wells

Six-inch drilled wells account for about 65 percent of all the wells in the records for Greenville County. Median depths are 200 feet for the wells and 54 feet for casing. Other median values are 30 feet below land surface for static water level, 26 feet for saprolite saturated thickness, and 9 gpm for well yield.

There are a few more drilled wells in the southern part of the county than in the northern part. Well depths tend to be greater in the north, whereas yields are generally higher in the south-central area. There is an even distribution of saturated thicknesses across the county, except that those in the south tend to be slightly greater.

Yields increase when care is taken to site wells in favorable topography, such as valleys and draws, and near lineaments or other signs of fracture and fault zones. Median yields for most of the rock units ranged only between 8 and 12 gpm. The extremes were biotite gneiss of the Laurens Thrust Sheet at 40-gpm median yield (but the small population of five wells perhaps makes this statistically insignificant) and the Caesars Head Granite, with a 4-gpm median yield.

24-INCH BORED WELLS: DISTRIBUTION BY WELL PROPERTIES

Four statistical summaries are available for the bored wells: well depth, water level, saturated thickness, and 5-minute grid location. Casing depth is not treated as a separate variable here because it is the same as total depth in a bored well. Yield, topography, and aquifer (surficial geologic unit) are not analyzed for bored wells because there were not enough wells identified by these parameters for a valid statistical analysis.

Total Depth

Almost all the bored wells in the records have known depths (563 of 566), and they range from 14 to 85 feet (Fig. 22). The median depth is 51 feet. The greatest number of 24-inch bored wells are between 51 and 60 feet in depth, with more than 35 percent in this depth range

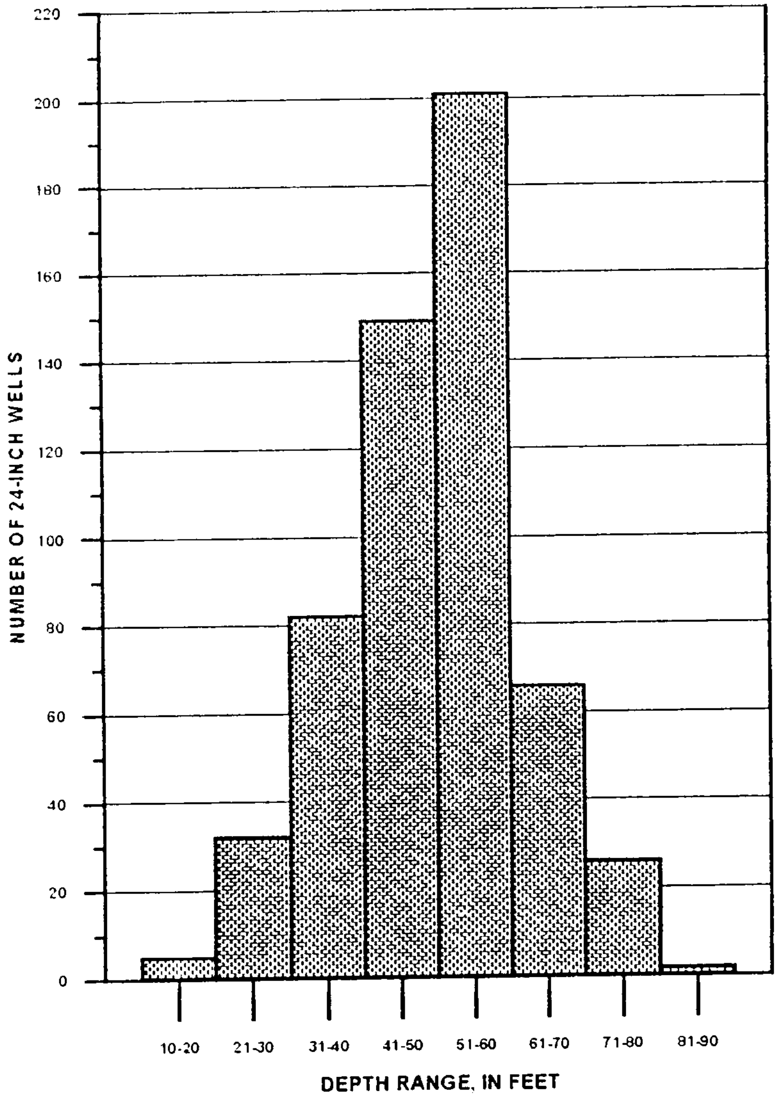


Figure 22. Depths of 24-inch bored wells in Greenville County.

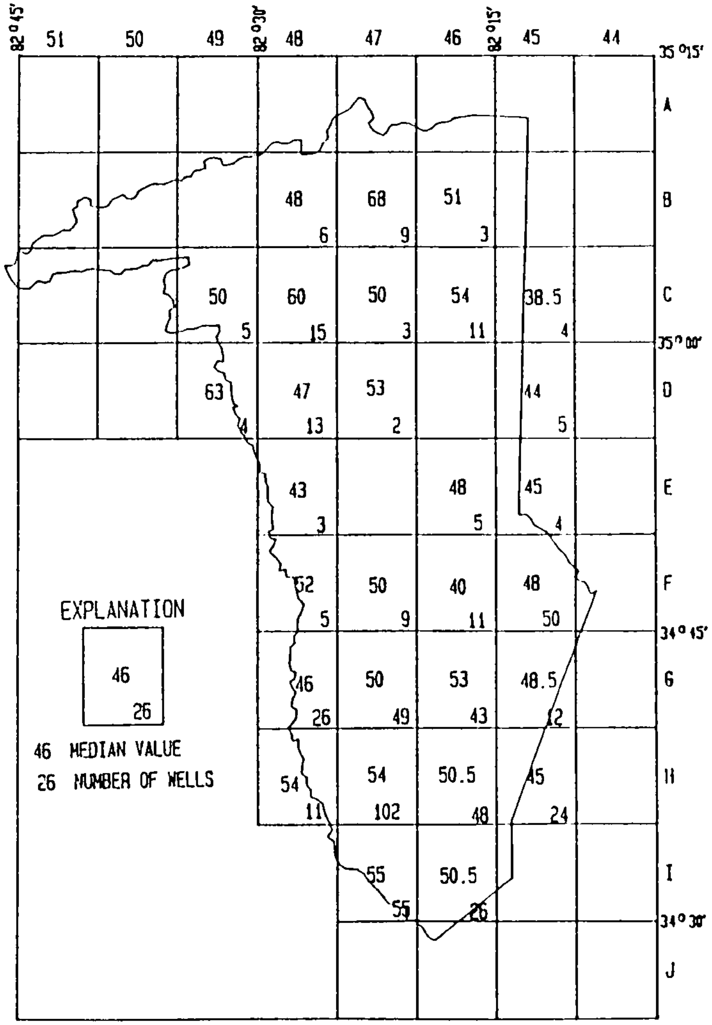


Figure 23. Median bored-wells depths in Greenville County.

(Fig. 22). More than 26 percent are between 41 and 50 feet. Most of the deeper wells are in the northern and northwestern parts of the county, and the shallower wells are generally along the county's eastern borders with Spartanburg and Laurens Counties (Fig. 23).

Static Water Level

Static water levels are known for 508 of 566 bored wells, or 90 percent. The median water level is 27 feet below land surface. Most static water levels in bored wells are more than 20 but less than 30 feet deep; these account for almost 46 percent of all water levels (Figs. 24 and 25). This value is, of course, critical to drillers, for it allows them to know how much usable water there is in a bored well. Since bored wells are much shallower than most drilled wells, the depth to the static water level can be a large percentage of the well's total depth. The higher the water level is (the closer to land surface), the greater will be the usable (water-producing) depth of the well. Bored wells with deep water levels generally have a smaller margin of safety in droughts, as their water levels may decline below the pump intake. This is especially true of wells bored during wet periods, as generally high water levels at those times may give a false sense of expected year-round water level. Conversely, wells bored during dry times but which have a high water level can generally be expected to at least maintain the high water level throughout the year. Users of bored wells should therefore be especially mindful of seasonal variations in water level and also of periodic drought and high-precipitation times.

Saturated Thickness

Saturated thickness in bored wells, which is the thickness of the saturated saprolite, is calculated by subtracting the static water level from the depth of bored wells (assuming that the bottom of the bored well reached the bottom of the saprolite). As important as this property is in drilled wells, it is absolutely critical in bored wells. The greater the saturated thickness, the greater the potential volume of water the well has to draw on, since it has no access to underlying bedrock fractures as do drilled wells. Of the 563 bored wells, 506 (90 percent) had information on saturated thickness. The median saturated thickness is 23 feet. Almost half of the bored wells have saturated thicknesses between 15 feet and 25 feet (Fig. 26). In general, the greater the saturated thickness, the deeper the bored well is, and correspondingly, the shallower the water level.

Across most of Greenville County there is a fairly even distribution of saturated thickness (Fig. 27). An exception is in the extreme northern part of the county, where saturated thicknesses are generally less than average, at about 15 to 17 feet. Here the wells are deeper than general (Fig. 23) and the static water levels are also deeper (Fig. 25). Conversely, in the southeastern area of the county, saturated thicknesses are greater than average, about 23 to 25 feet; in this area the depths of the wells are slightly less than average but the saturated thicknesses are greater than average because the static water levels are shallower than average for the county.

Geography (5-Minute Grids)

Most bored wells are located in the southern part of the county, especially below 34°30' latitude (Fig. 23). As noted previously, conditions such as water level and saturated thickness are generally more favorable in this area than in the northern area. There is also a larger population in this area not served by the municipal water system and, consequently, more dependent on wells. The 5-minute grid with the highest number of bored wells in it is 47H, with 102 wells, and the next highest is in grid 47I with 55 wells (note that almost half of this grid is in Anderson County to the southwest and that only wells in Greenville County are counted here). The three grids immediately to the north, northeast, and east of 47H are also high in numbers of bored wells (Fig. 23).

In general, wells bored in the northern part of Greenville County had greater depth, deeper static water level, and less saturated thickness; the median saturated thickness for these wells is usually about half the median static water level depth and about one-third the median well depth (Fig. 28). Farther south, however, the median depth decreases, and median water level depth and median saturated thickness approach each other. In only one grid, 45C, did median saturated thickness actually exceed median water level depth.

Summary of 24-Inch Bored Wells

Twenty-four-inch bored wells constitute about 20 percent of the wells in the records for Greenville County. The median depth is 51 feet, static water level is 27 feet, and saprolite saturated thickness is 23 feet. There are many more bored wells in the southern part of the county than in the central or northern areas, partly because of the lack of a municipal water system in much of the southern area. Well depths are greater in the north than in the other areas. Static water levels are somewhat shallower in the south, and, consequently, saturated thicknesses are greater.

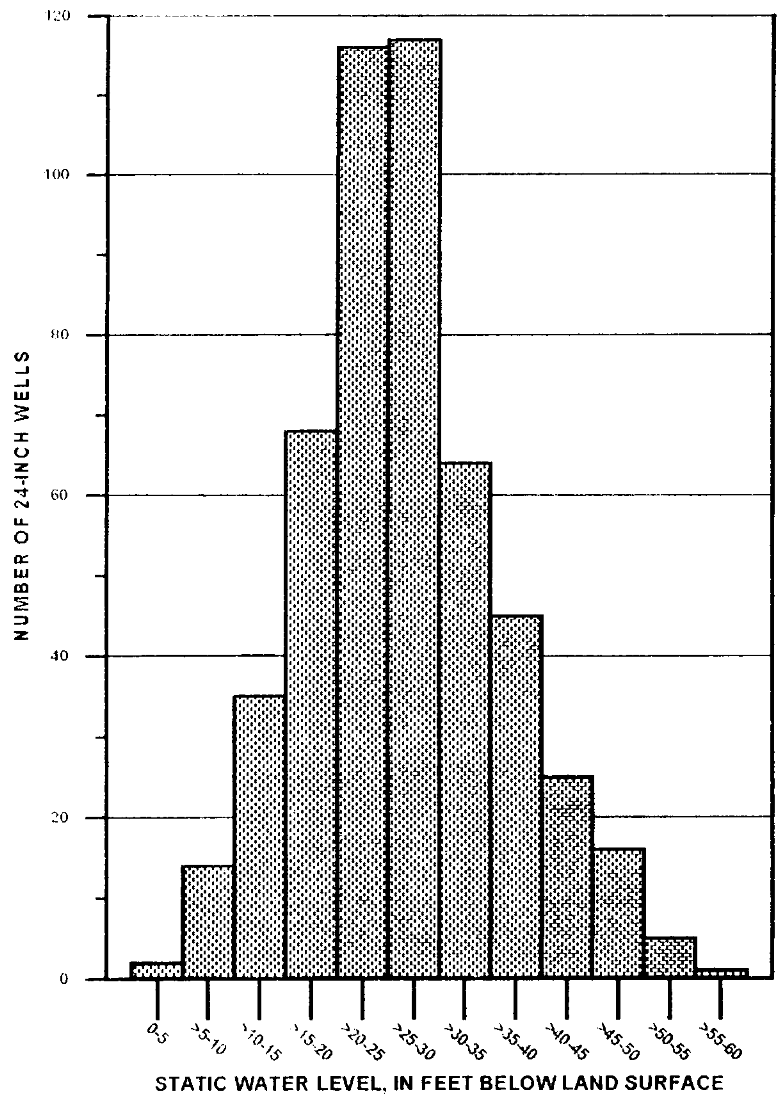


Figure 24. Static water level variation in 24-inch bored wells in Greenville County.

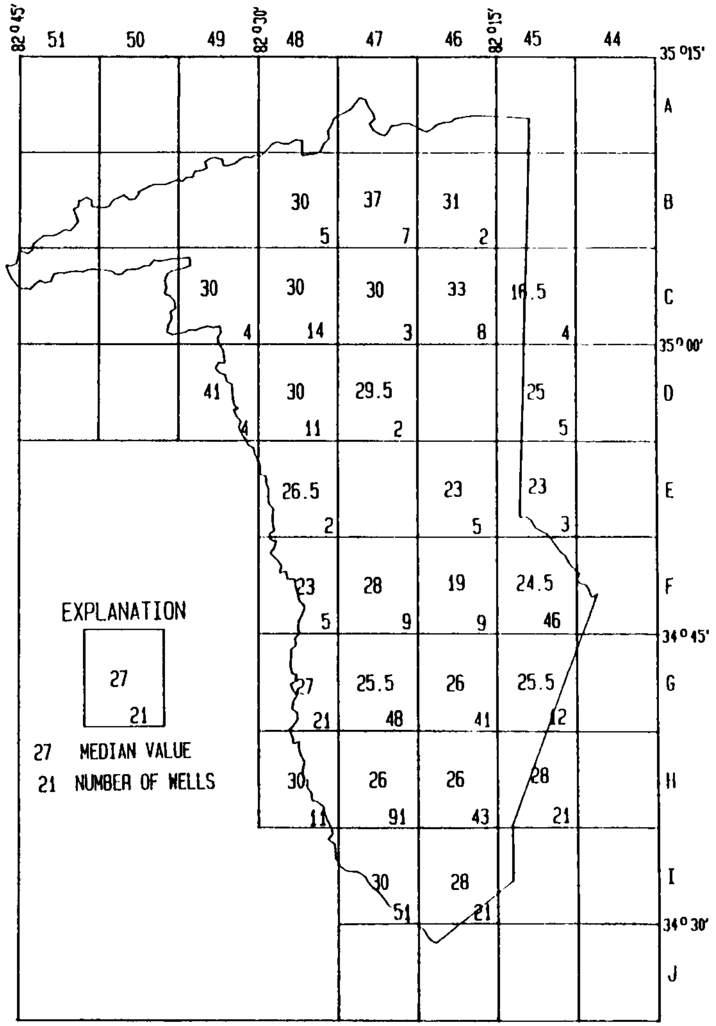


Figure 25. Median static water levels in bored wells.

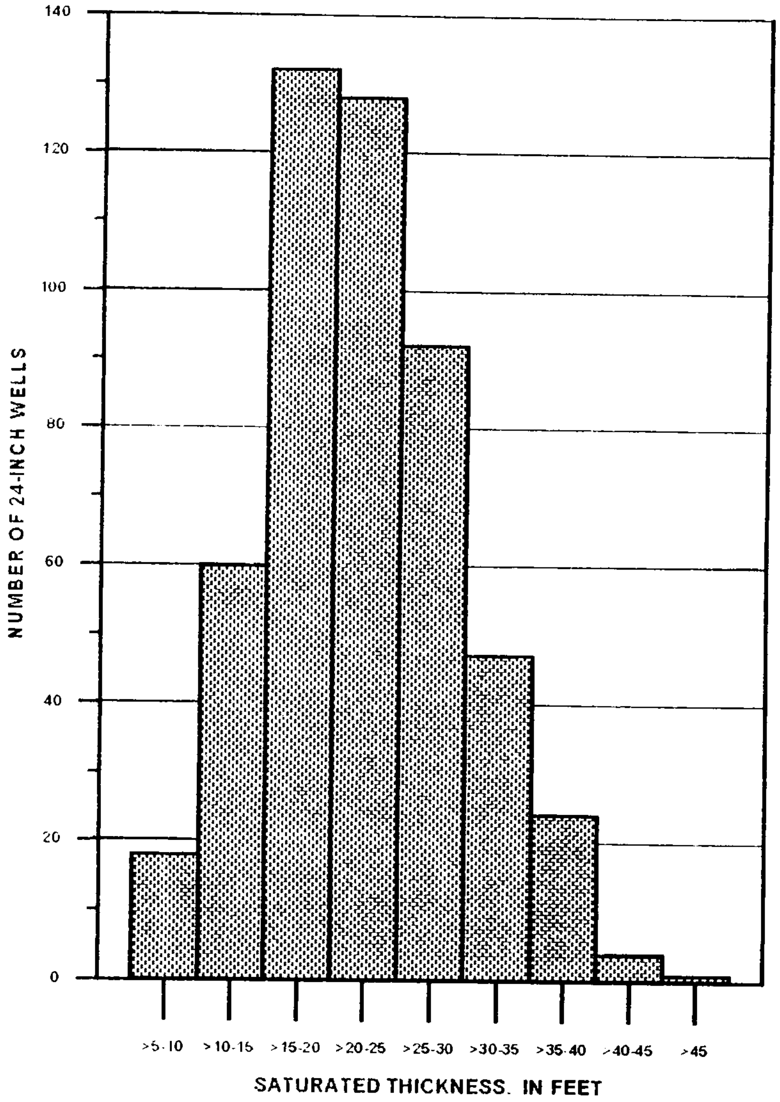


Figure 26. Saturated-thickness variation in 24-inch bored wells in Greenville County.

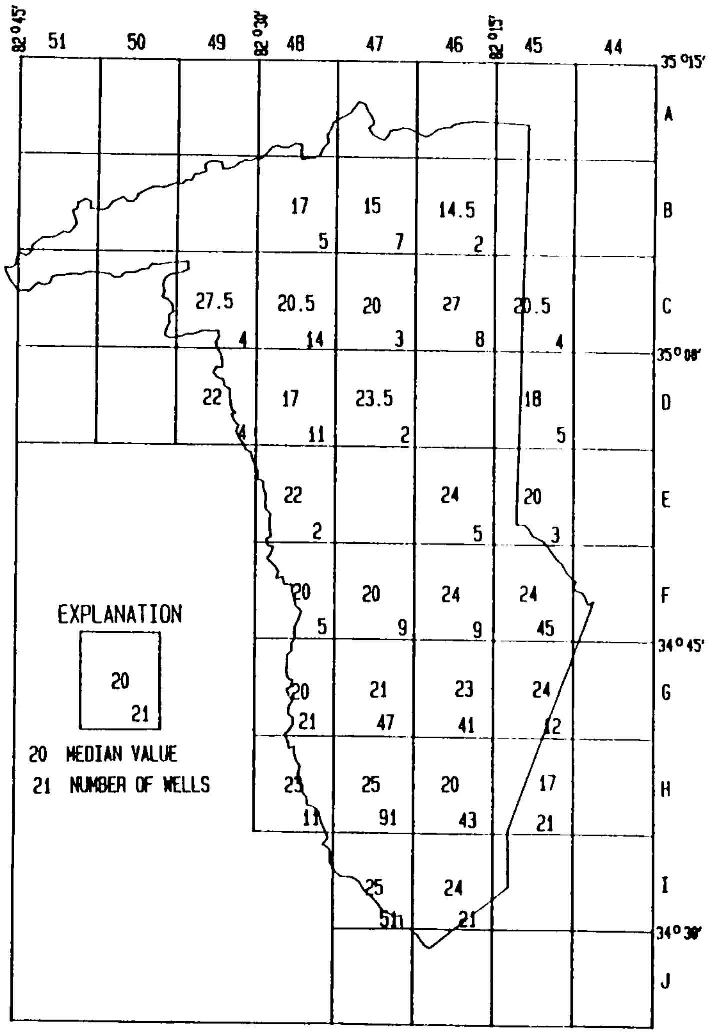


Figure 27. Saturated-thickness variation in bored wells.

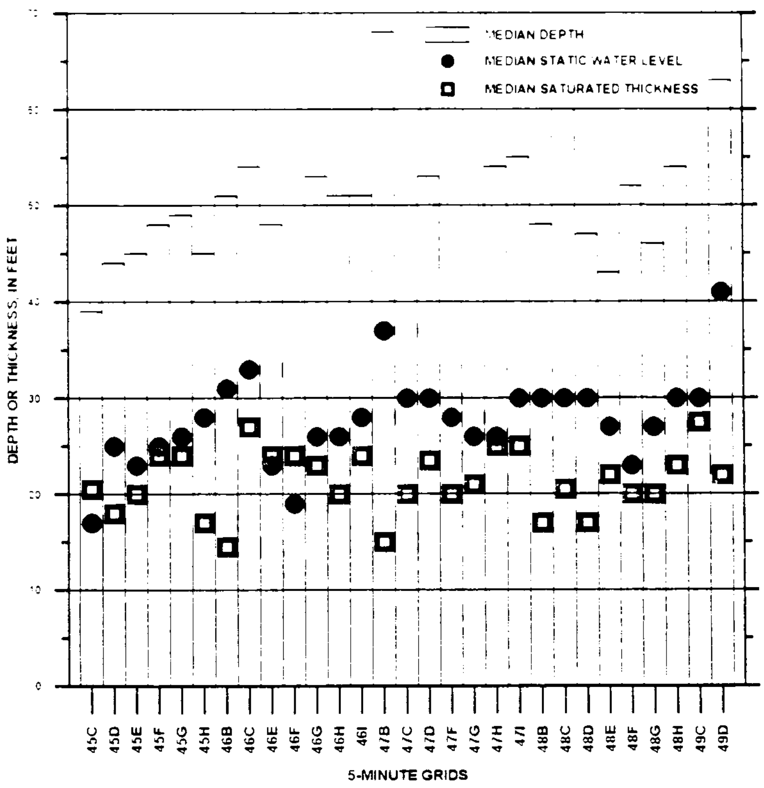


Figure 28. Areal variation in relationship of depth, static water level, and saturated thickness for 24-inch bored wells.

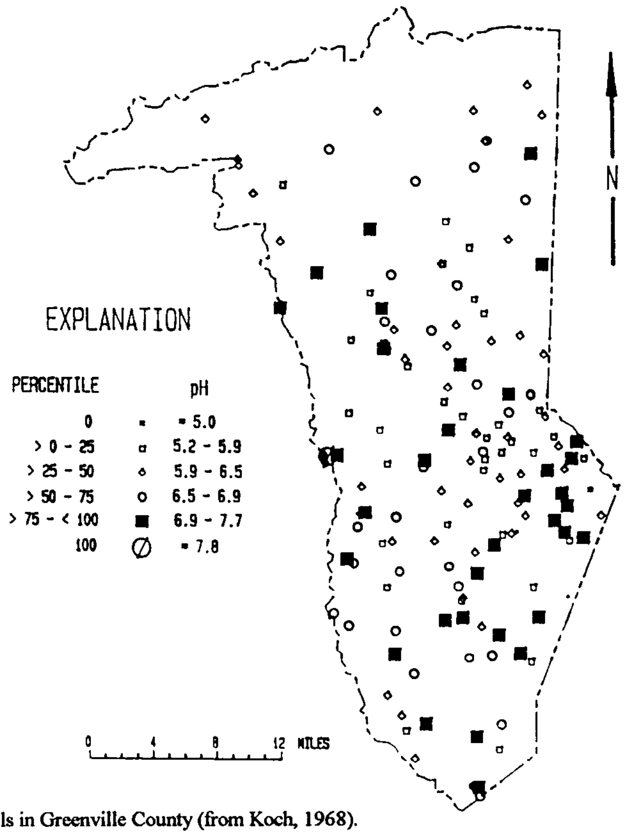


Figure 29. Variation in pH for wells in Greenville County (from Koch, 1968).

WATER QUALITY

Water-quality samples were not analyzed for this report, so previously collected data were studied. Koch (1968) reported on about 150 water samples from wells in Greenville County. Samples were analyzed for pH, hardness, and total iron (Table 4).

Table 4. Water quality analyses for Greenville County (from Koch, 1968)

Property/element	Number of samples	Range	Median
pH	152	5-7.8	6.5
Hardness	154	7-323	34
Total iron	151	0-10	0.2

Note: pH is in standard units, hardness and total iron are in milligrams per liter.

These characteristics are among the most important in determining the usability of the water. Most well water in the Piedmont is somewhat acidic (pH less than 7), and this is true in Greenville County; most pH values were below 7; only 36 of 152 samples had pH equal to or higher than 7. There appears to be little correlation of ground water pH with the rocks in which the wells were drilled. The low-pH wells are scattered alongside the high-pH wells in the same areas. An exception exists for some predominance of the slightly higher pH values in the southeastern area, in the Laurens Thrust Sheet granite gneiss and northwest of its contact with sillimanite-mica schist of the Paris Mountain Thrust Sheet (Fig. 29 and Plate [Geologic Map of Greenville County).

Most of the well water sampled in Greenville County is soft (Table 4). Since calcium and magnesium are the main elements causing hardness, it is reported in milligrams per liter (mg/L) of calcium carbonate (in which magnesium can substitute for calcium). Water having between 60 and 120 mg/L of CaCO3 is considered moderately hard, and 14 of 154 wells had water of that hardness; only 4 wells had harder water. Nearly 90 percent of the wells sampled had soft or very soft (less than 60 mg/L) water. As with pH, there is little apparent correlation between hardness and the rock units in Greenville County (Fig. 30).

Iron, even in very small quantities, is known for its tendency to stain fixtures and to impart bad taste to water. This is especially true if it exists in concentrations above 0.3 mg/L. Of the wells sampled, 48 percent had iron at or above this threshold. See Table 4 for the range and median values of iron concentration. Most of the high-iron samples came from wells in the central part of the county, in sillimanite-mica schist and granite gneiss of the Paris Mountain Thrust Sheet (Fig. 31). The median iron values are predominantly in the northern part of the county, in the Caesars Head Granite and migmatite. The lowest values are found intermixed with the highest ones in sillimanite-mica schist and granite gneiss of the Paris Mountain Thrust Sheet and, in the southeastern part of the county, in granite gneiss of the Laurens Thrust Sheet (Fig. 31).

Another source of ground water quality data is the National Uranium Resource Evaluation of the U. S. Department of Energy (Table 5). The values for pH are similar to those published by Koch (1968), with the ranges and medians of pH being closely similar. The distribution across the county is different, however (Figs. 29 and 32). Most of the higher pH measurements are in the north, especially in water from the Caesars Head Quartz Monzonite, and the lower pH values are scattered, with no apparent correlation to rock type.

Table 5. Water quality analyses for Greenville County. Data from the National Uranium Resource Evaluation, U.S. Dept. of Energy (Baucom and Ferguson, 1979, and Ferguson, 1978)

Property/element	Number of samples	Range	Median
pH	76	5.1-7.8	6.6
Conductivity	76	5-200	33.5
Alkalinity	76	0.01-0.6	0.06
Aluminum	76	12-725	24.5
Bromine	67	4-3,257	47
Chlorine	68	3,200-41,200	6350
Magnesium	39	130-5,020	960
Manganese	70	1-226	13.5
Sodium	58	780-20,480	2820
Uranium	75	0.002-83.19	0.03

Note: pH is in standard units, alkalinity is in milliequivalents per liter, conductivity is in µmhos per centimeter, and elements are in parts per billion.

Two useful water quality properties are electrical conductivity and alkalinity. Conductivity, or specific conductance, is the ability of a substance to conduct an electric current (Hem, 1985, p. 66). In solutions as dilute as most ground water, the specific conductance varies almost directly with the amount of dissolved minerals (Driscoll, 1986, p. 93). Water with relatively high specific conductance can corrode iron and steel, even though other properties of the water may not indicate a corrosion problem (Driscoll, 1986, p. 94). Alkalinity of the water (from which bicarbonate concentration is determined) is the capacity of solutes in a solution to react with and neutralize acid, or the capacity of the solution to react with hydrogen ions (Hem, 1985, p. 106, 109).

Conductivity and alkalinity have similar distribu-

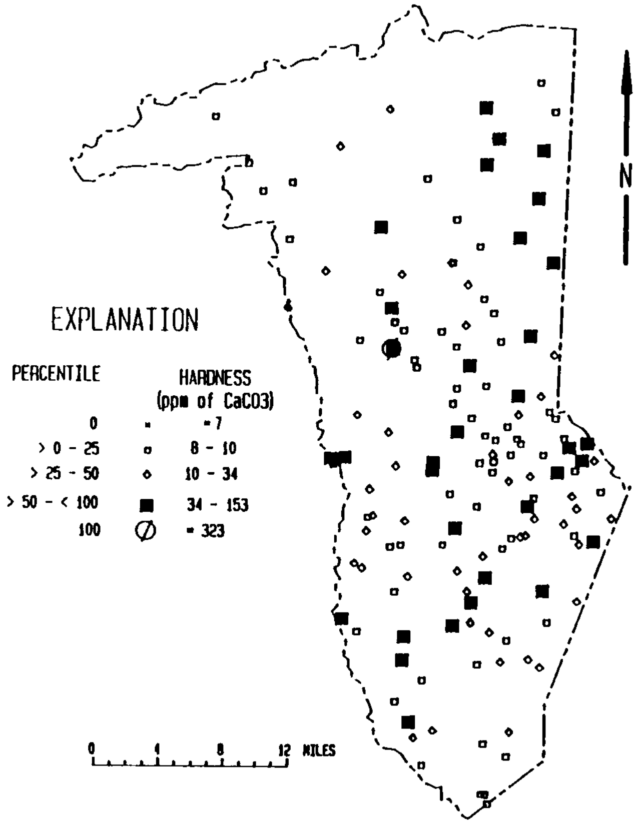


Figure 30. Variation in hardness for wells in Greenville County (from Koch, 1968).

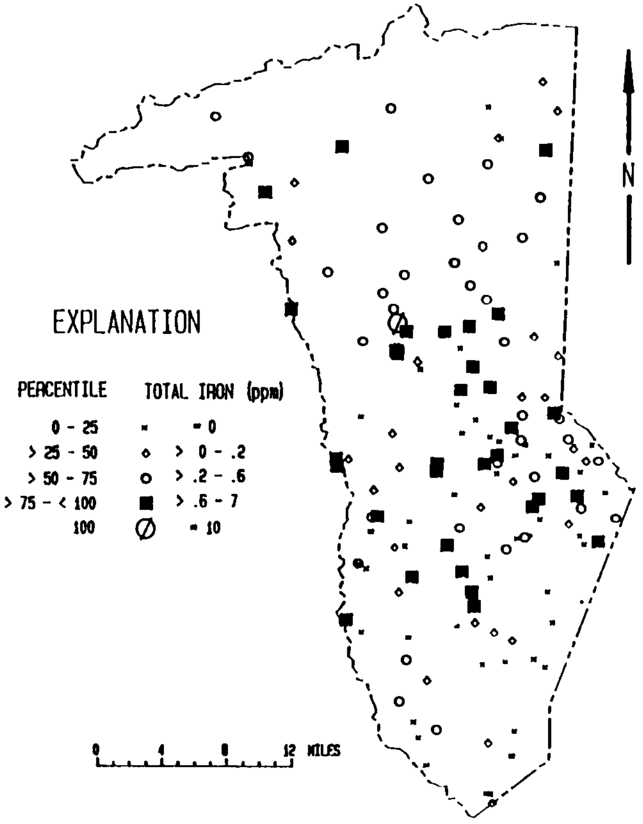


Figure 31. Variation in total iron for wells in Greenville County (from Koch, 1968).

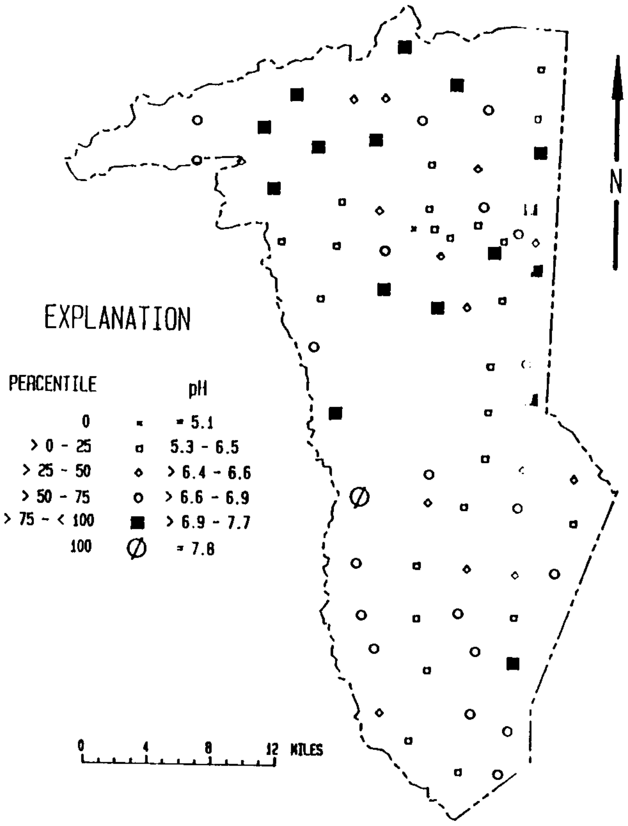


Figure 32. Variation in pH for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978). See also Figure 29.

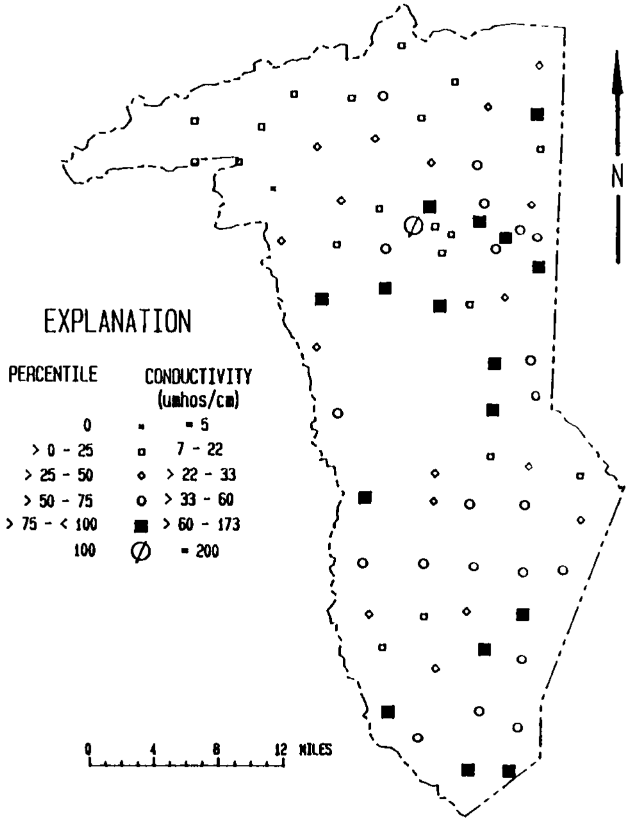


Figure 33. Variation in electrical conductivity for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978). See also Figure 29.

tion patterns across the county, with most of the higher values concentrated in the central-northeast and the southeast. No clear correlation exists as to rock type, especially for the central-northeast clustering, which covers several rock types (Table 5 and Figs. 33 and 34).

Two halogen elements, chlorine and bromine, have similar distribution patterns (Figs. 35 and 36). Their higher concentrations are predominantly in the eastern and southern parts of the county. Bromine has most of its higher values in sillimanite mica-schist of the Paris Mountain Thrust Sheet, while chlorine's higher concentrations extend northward into the migmatite and Caesars Head Granite also.

The metals aluminum, magnesium, manganese, and sodium exhibit similar distributions in well water samples of the county. Their higher concentrations are clustered mainly in the Caesars Head Granite and migmatite and biotite-hornblende granodiorite, in a band stretching southwest to northeast across the upper middle part of the county, and in the sillimanite-mica schist of the Paris Mountain Thrust Sheet in the south (Figs. 37, 38, 39, and 40). Their lowest concentrations are in the Caesars Head Quartz Monzonite in the northern part of the county.

The heavy metal uranium has a somewhat similar distribution to that of the lighter metals, with most of the higher values in sillimanite-mica schist of the Paris Mountain Thrust Sheet (Fig. 41).

PUMPING TESTS

Almost all the drilled wells on record for Greenville County have a stated yield in gallons per minute. This yield estimate is usually based on air-lift tests done at the time of drilling. While these estimates provide the driller with an approximation of the short-term capacity of the well, long-term capacity and performance can be better predicted from results of a pumping test. Such a test consists of pumping a well at a constant rate for a given period of time and measuring the water level during and after the pumping. A nearby nonpumping well whose water level can be monitored during the test is desirable (but not required) for gaging the effect of the pumping well on other wells and on the aquifer itself. If the test is conducted correctly, a fairly reliable projection of the well and aquifer capacities and limitations can be made.

The longer a pumping test is run, the more reliable are the resulting data. Typically, pumping tests run 24 hours, and water level recovery after pumping is stopped should be measured for the same length of time. Some tests are run for 48, 72, or more hours. Sometimes a 24-hour test may not be long enough to detect a problem such as storage in large horizontal fractures, which may give a misleading high capacity for a well. Testing for a longer period of time may reveal the existence of such hidden storage systems, allowing for correction of the well's capacity to a smaller, although more realistic value (Caswell, 1986). Even short tests can be useful, however, if basic requirements are met during the testing, such as maintaining pumping at a constant rate.

Before the actual pumping test begins, a reasonable estimate of the well's yield, beyond that done by the initial air-lift test, should be determined, so that the longer test will provide useful information. This can be done by a series of short step-drawdown pumping tests, in which the rate of pumping is increased several times (steps), preferably in the same increments. Usually consisting of three or four steps, each step of the test is an hour to a few hours long, depending on how long it takes for the time-drawdown plot to become nearly flat. The time interval should be the same for each step. At the end of each step the discharge is increased and the test is continued (another way is to stop the pumping, measure water level recovery, and at a given consistent time interval, restart the test at the greater pumping rate). These steps are continued until the amount of pumping exceeds the well capacity to replenish itself (as indicated by the plot of the drawdown data). The pumping rate for the longer test should be the rate, as indicated by the step-drawdown test, that allows maximum discharge without overpumping the well. The well's water level should be allowed to recover to static water level or nearly so before the long pumping test begins.

TESTS MADE FOR THIS STUDY

Few pumping tests go completely as planned; but even where problems occur, if the overall test is conducted in a consistent and accurate manner, useful results can usually be obtained. Two pumping tests conducted by the author for this report are examined and then compared to several other pumping tests made by drillers on public supply wells.

In the first example, a 24-hour test was run at well 45E-f1/GRV-735 on May 8 and 9, 1992. Preliminary testing had indicated an ideal rate of about 22 gpm for the test. After the earlier testing, the water level was allowed to recover before pumping began. The data obtained during and following pumping are plotted in Figures 42 through 44.

The well was drilled in sillimanite-mica schist of the Paris Mountain Thrust Sheet, on a slight slope. The median well depth of all 6-inch drilled wells (153 total) in this lithologic unit and topography is 121 feet, and the median casing depth is 45 feet. Median yield is 10 gpm, and median static water level is 34 feet below land surface.

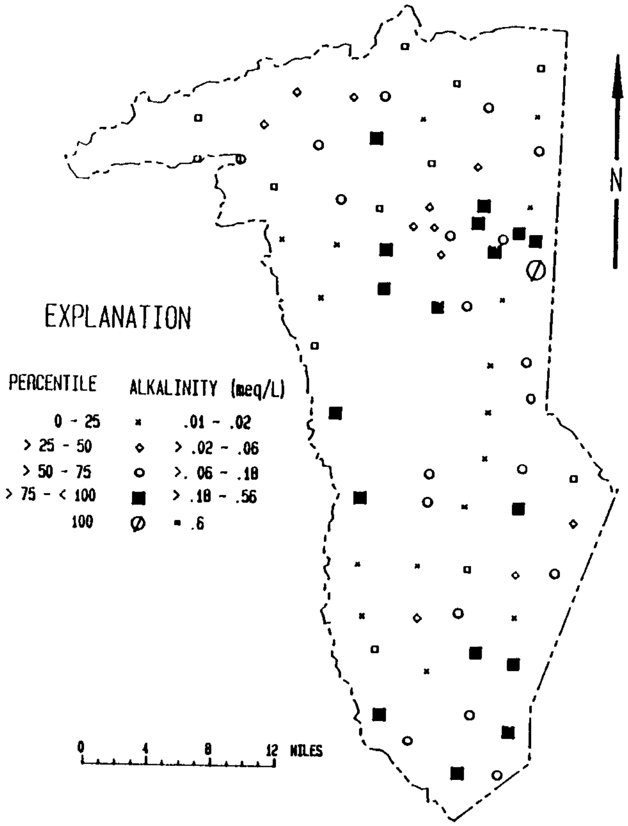


Figure 34. Variation in alkalinity for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978).

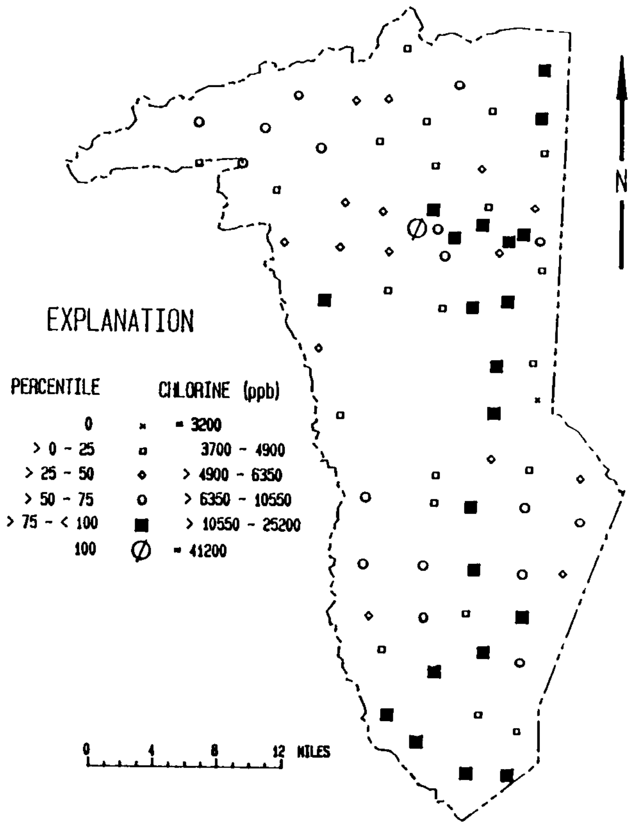


Figure 35. Variation in chlorine for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978).

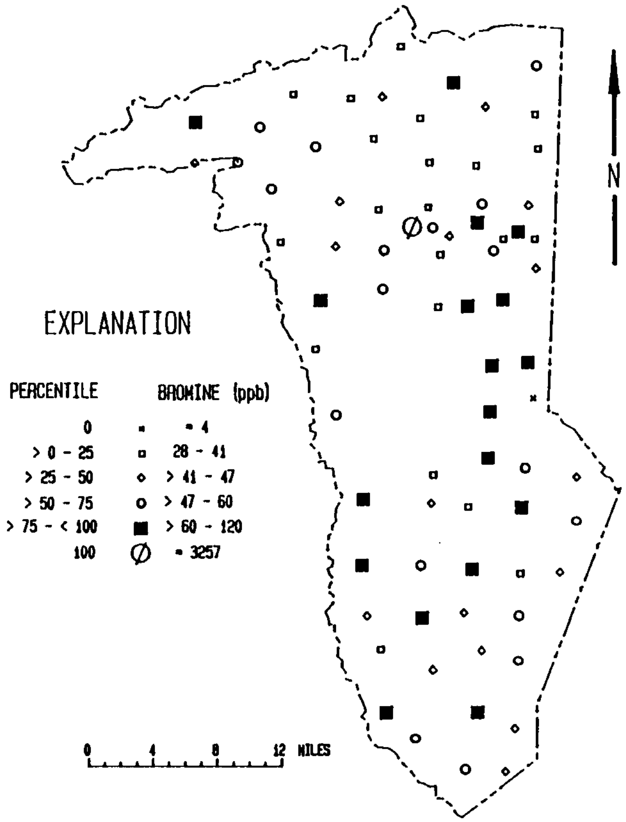


Figure 36. Variation in bromine for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978).

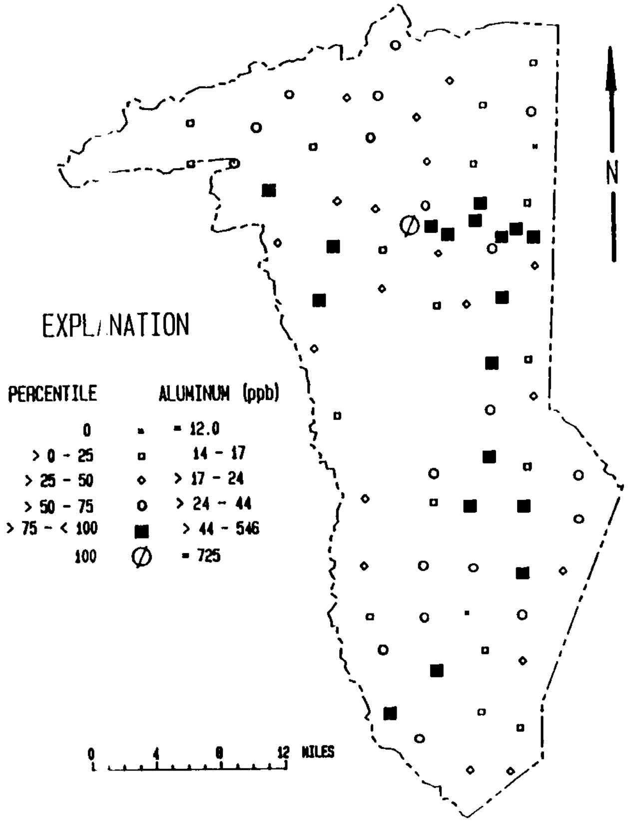


Figure 37. Variation in aluminum for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978).

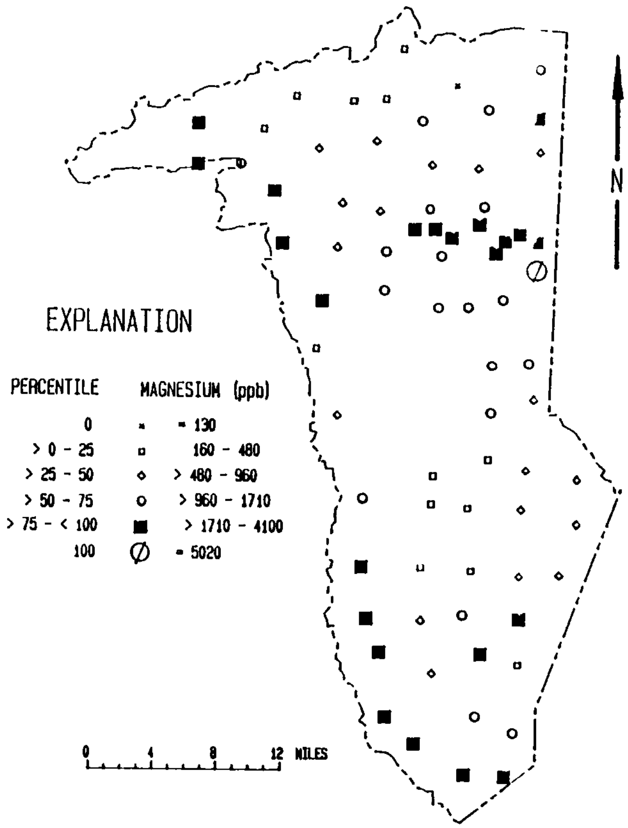


Figure 38. Variation in magnesium for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978).

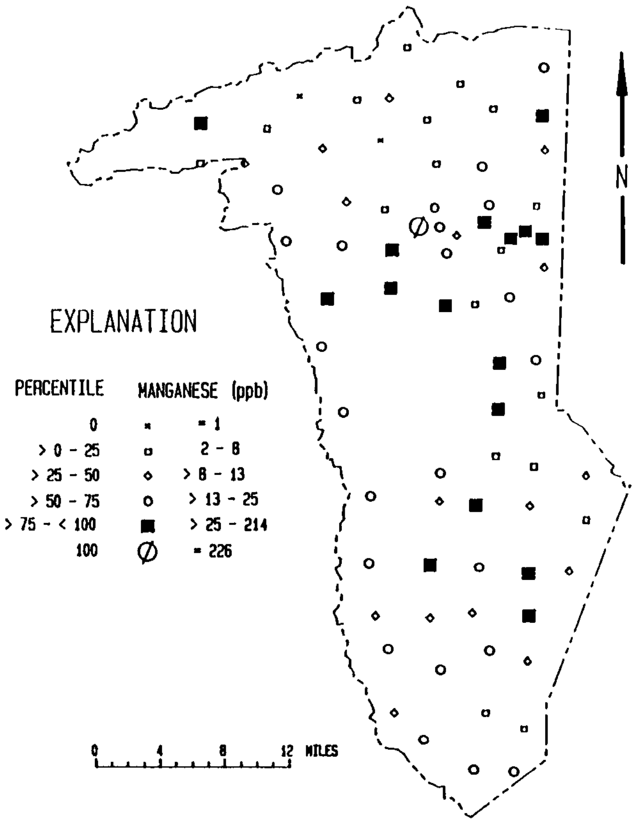


Figure 39. Variation in manganese for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978).

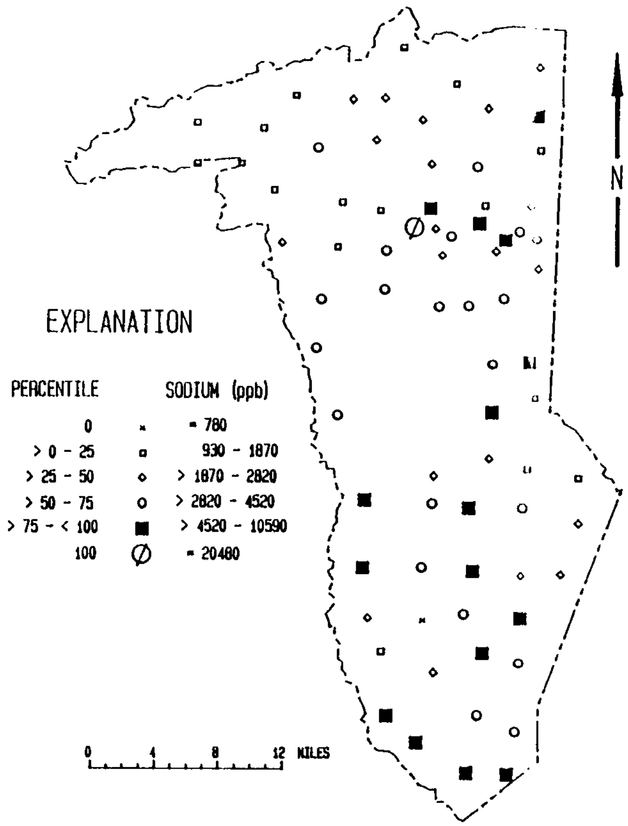


Figure 40. Variation in sodium for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978).

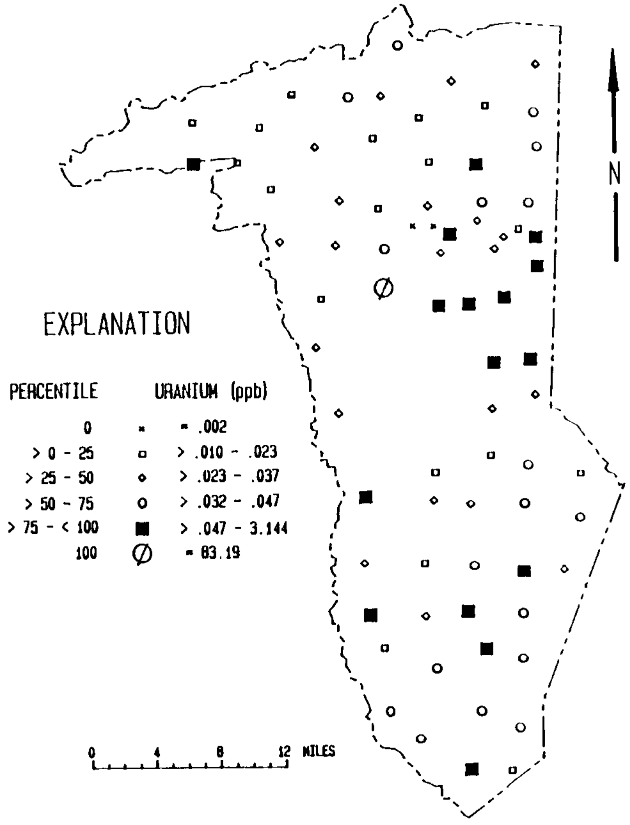


Figure 41. Variation in uranium for wells in Greenville County (from Baucom and Ferguson, 1979, and Ferguson, 1978).

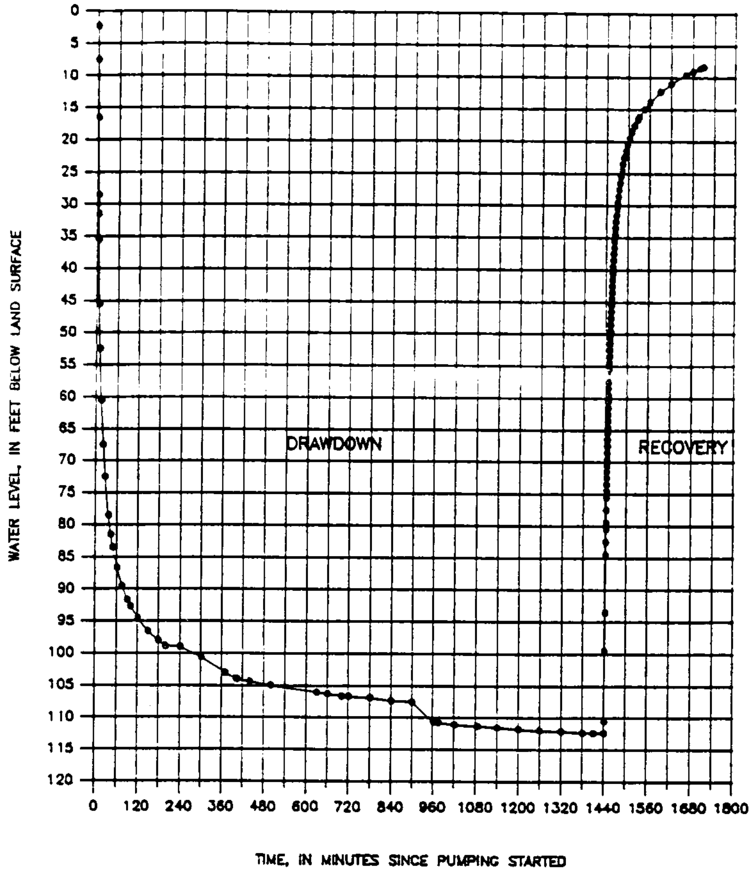


Figure 42. Pumping test of well 45E-fl/GRV-735; pumping rate 22.5 gpm, with small fluctuations.

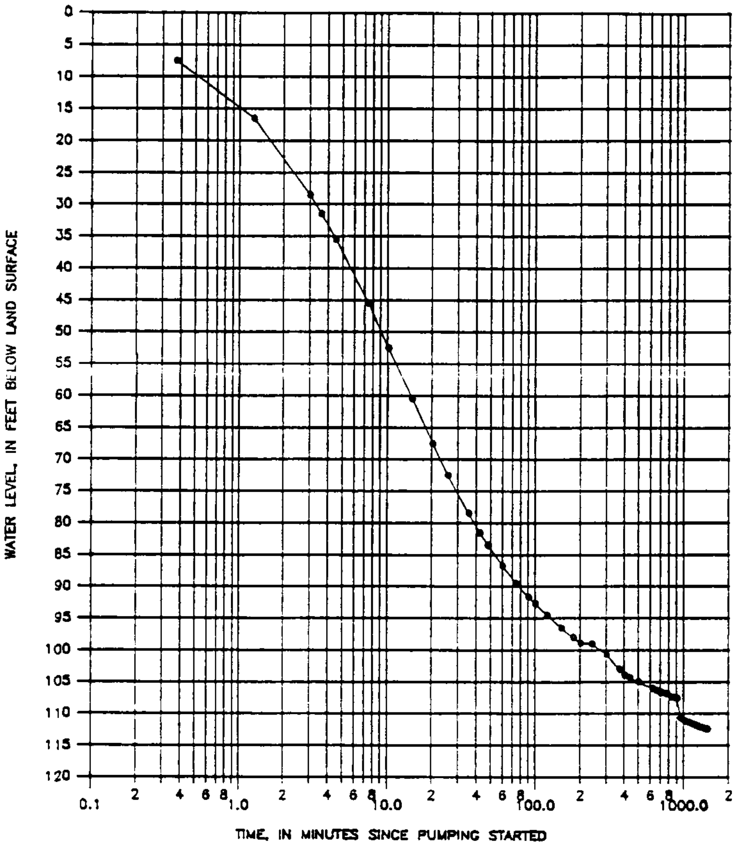


Figure 43. Semilogarithmic plot of drawdown data for well 45E-fl/GRV-735 pumping test.

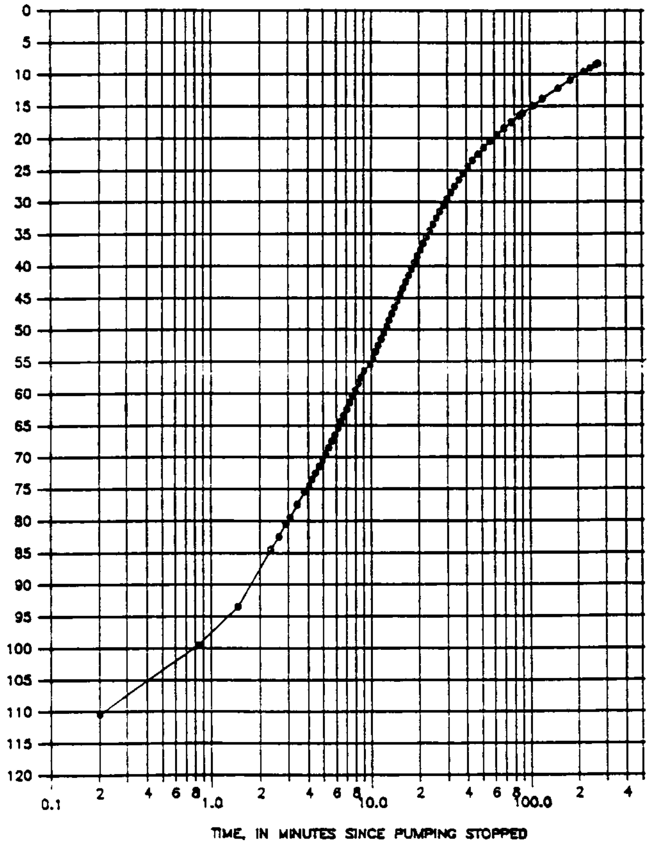


Figure 44. Semilogarithmic plot of recovery data for well 45E-fl/GRV-735 pumping test.

This well is 6 inches in diameter and 289 feet deep. It is cased to 74 feet and the pump is set at about 250 feet depth. Pumping started at 7:30 p.m. at a rate of 22.5 gpm; the static water level was 2.27 feet below land surface. Water levels were monitored by hand with an electric water-level tape, and the pumping rate was monitored by a flow meter. The pumping period was 24 hours.

The recovery phase began at 7:30 p.m. on May 9 when the pump was shut off. The water level was monitored for the next 4½ hours (Fig. 44). In this time the water level rose from 112.42 feet to 8.21 feet.

The fact that the slope of the drawdown curve was flattening at about 112 feet indicates that pumping could have continued at the present rate for many more hours, if not days, without exhausting the well, since the pump was at 250 feet. The pumping rate could even have been increased. Total drawdown was 110.15 feet, and at 22.5 gpm for 24 hours this gives a specific capacity of 0.2 gpm per foot. The semilog plots of drawdown and recovery are nearly identical when superimposed, confirming the accuracy of the test.

The second pumping test made by the author was at the Cliffs at Glassy development on Glassy Mountain in the northeastern part of the county. The well was drilled in June 1990 to a depth of404 feet and cased to 36 feet (well 47B-j2/GRV-2172). It was drilled 6 inches in diameter, then reamed to 8 inches. The geologic unit is Caesars Head Quartz Monzonite (Caesars Head Granite), and the topography is a draw. Initial driller estimates were that the well produced about 200 gpm, although a later pumping test by the driller ended at 75 gpm (see Fig. 54). Another well also drilled for the development, located 160 feet to the west-southwest was used as an observation well (47B-j3/GRV-2173; depth 500 feet, 8-inch diameter to 110 feet, and 6-inch diameter to the bottom).

For other 6-inch drilled wells in this geologic unit and topographic situation (20 total), median values are 314 feet for well depth and 22 feet for casing depth; yield is 17 gpm, and static water level is 12 feet below land surface.

The pumping test by the author began at 1:50 p.m. on June 11, 1992, after several hours of preliminary testing to ascertain a sustainable pumping rate. The static water level was 5.45 feet in the pumping well and 3.16 feet in the observation well (Fig. 45). Water levels were monitored by two pressure-transducer probes connected to a data logger that recorded measurements at 5-minute intervals. The pumping rate was monitored with a flow meter and controlled by a valve on the outlet pipe. This test was run for 14 hours at 96 gpm.

The linear drawdown plot produced a classic flattening-out curve above 53 feet; the observation well showed a similar but much shallower curve (Fig. 45). In the semilogarithmic plot, the observation well line slope is unexpectedly flat as opposed to the curve described by the pumping-well drawdown (Fig. 46). When the pump was turned off, recovery began immediately in the main well but lagged for a few minutes in the observation well (Figs. 45 and 47). The two recovery plots have similar slopes after 1 hour. Pumped-well and observation-well plots should exhibit the same slopes if both wells are producing from the same zone. The plots of the two wells, although similar, have some differences, especially at the beginning of pumping and of recovery, that may indicate a poor connection between the two wells. The differences are not obvious on the linear plots but are apparent on the semilog plots.

In examining the drawdown plots, a very slight anomaly in the pumped-well curve can be seen at 44 feet and 45 minutes. Pumping rate records were reviewed to rule out the possibility that pumping rate decreased for a while, which may have caused this anomaly. There was no evidence of pumping rate changing at this point. Rather, it may have been caused by the draining of a fracture immediately beneath the casing that can be seen in the caliper log of this well (see Fig. 55). The rate of decline in the water level was briefly slowed as, apparently, a water-filled fracture drained into the well. This fracture is not seen on the recovery plots, but that is because the automatic readings were 5 minutes apart, and this fracture was passed by the declining water level between the 5- and 10-minute readings early in the recovery period.

Total drawdown, in the 14 hours of the test, was 47.09 feet, at 96 gpm. The specific capacity was 2.0 gpm per foot of drawdown and probably would have been little different if the test had run for 24 hours. This test can be compared to one made by the driller at the same well (see Fig. 54). That was a 24-hour test which began at 150 gpm and ended at 75 gpm. The total drawdown was 44 feet; this level was reached 720 minutes (12 hours) into the test and remained there for the following 12 hours. Specific capacity cannot be accurately calculated here because of the varying pumping rate. However, an approximation can be made by taking the lowest pumping rate (75 gpm) and dividing it by the drawdown, which gives a specific capacity of 1.7 gpm/foot. Interestingly, there seems to be a change in the slope of the line of the driller's drawdown plot at about 45 feet, just as in the pumping test made by the author. This supports the likelihood of a large water-bearing fracture at that depth in the well.

The two pumping tests made by the author were at constant pumping rates to better quantify the performance of the wells. Specific capacities and drawdowns were determined for given pumping rates. The drawdown curves were used to verify that the pumping level

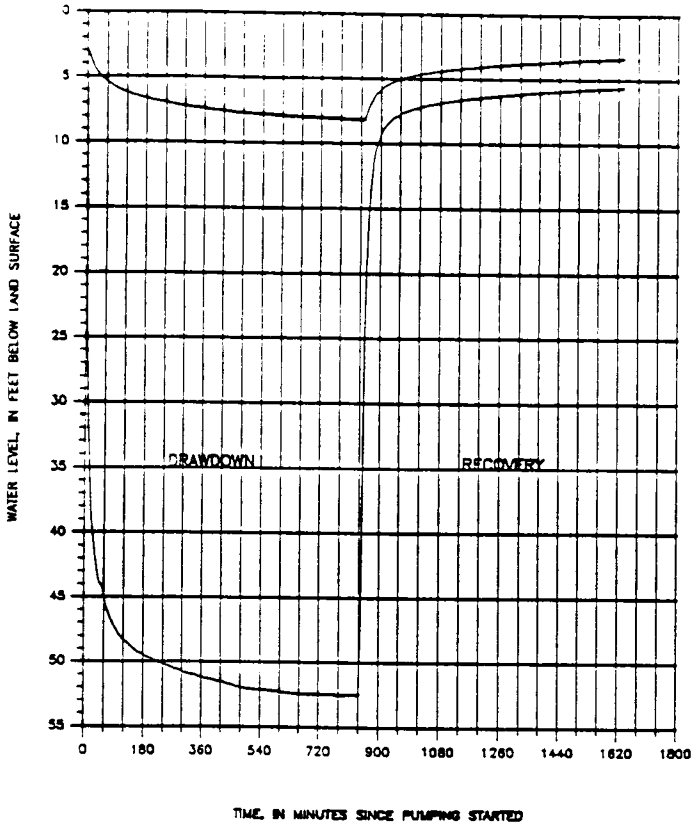


Figure 45. Pumping test at Glassy Mountain. Pumping well is 47B-j2/ GRV-2172 (lower graph). Observation well is 47B-j3/GRV-2173 (upper graph).

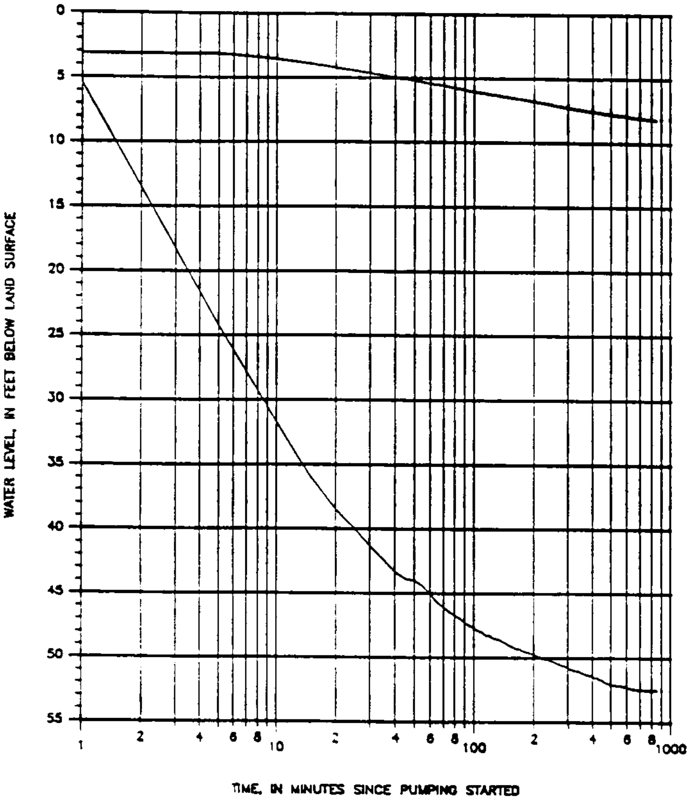


Figure 46. Semilogarithmic plot of drawdown data for pumping well 47B-j2/GRV-2172 (lower graph) and observation well 47B-j3/ GRV-2173 (upper graph).

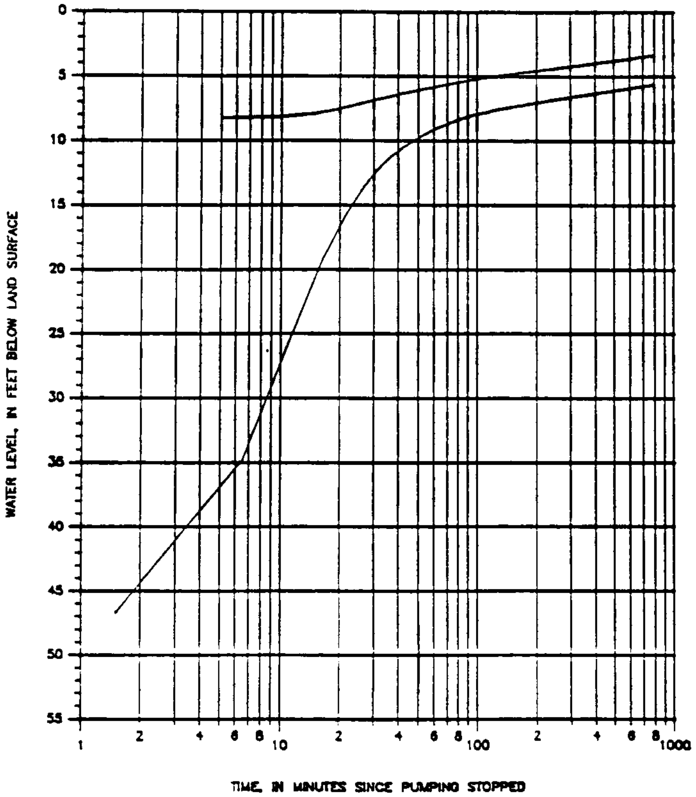


Figure 47. Semilogarithmic plot of recovery data for pumping well 47B-j2/ GRV-2172 (lower graph) and observation well 47B-j3/GRV-2173 (upper graph).

would not be lower than the pump's level, at least not for several continuous days of pumping.

In contrast, drillers ordinarily make pumping tests to determine maximum sustainable drawdown in a 24-hour period. By starting out with a higher pumping rate than that with which they finish the test, the wells are drawn down farther than they would normally be drawn down at a lower, constant rate. The drillers' tests are made as required by SCDHEC, for the purpose of insuring a margin of safety for public supply wells.

DRILLERS' PUMPING TESTS

Records are available for 33 pumping tests made in Greenville County by well drillers or owners (Table 6). Most of these are public supply wells, and the pumping tests are required by SCDHEC. These tests generally produce more accurate results than the yield estimates given by drillers for domestic wells, which are obtained by "blowing" the wells with compressed air while drilling. However, all of the test procedures leave much to be desired in their technique.

Many tests did not maintain a constant discharge (pumping rate); consequently, a meaningful assessment of the well's capacity is difficult to obtain. Results of some tests are surprising, if not doubtful; many pumping tests exhibit a constantly declining drawdown curve that suddenly levels out to a flat line for the remaining several hours of the test. Yet, some tests are useful in ascertaining well and aquifer characteristics for Greenville County. Following are descriptions of some typical pumping tests:

Well 50B-r8 had a 24-hour pumping test (Fig. 48). Pumping began at 25 gpm and stabilized at 15 gpm 4 hours into the test. The static water level was 24 feet below land surface, and after 2 hours and 40 minutes the pumping level was down to 358 feet, where it stayed for the duration of the test. It is difficult to understand how the water level could remain at such a constant level for 20 hours, and it seems probable that this is more an artifact of the record-keeping process than a result of actual conditions. It is possible that the water level rate decrease did slow down but perhaps not so completely. Because of the pumping-rate variation, the drawdown plot is difficult to use for accurate interpretation. For example, at 120 minutes into the pumping test the pumping rate was decreased from 20 gpm to 18 gpm (after starting at 25 gpm). There is a distinct change in the slope of the drawdown curve at this time. The recovery plot, on the other hand, can be analyzed with more certainty, since the recovery is totally natural, not dependent on pumping or other man-induced changes.

Table 6. Results of pumping tests made by drillers

SCDNR-Water Resources Division well	Pumping rate (gallons per minute)	Specific capacity (gpm per foot of drawdown)	Pumping time (hours)
45E-fl	24	0.08	24
45F-kz3	37	1.2	2
45F-w4	8	.04	24
45F-xz4	42	.67	24
45G-c4	20	.06	12
45G-wz4	20	.04	12
45G-wz5	10	.06	12
46B-fl	48	.87	24
46D-wz4	65	.12	24
46H-xz5	14	.90	6
47B-j2	75	1.2	24
47B-j3	81	1.7	24
47C-cz3	16	.03	24
47D-fz1	28	.30	24
47D-p11	29	.19	75
47D-q1	30	.13	24
47G-r1	35	.15	24
47G-s4	38	.28	12
48B-f2	30	.53	24
48B-vz3	17	.20	6
48B-x5	60	.60	8
48C-n5	15	.29	6
48G-a6	95	.55	23
48G-kz2	5	.02	24
49B-oz1	15	.71	24
50B-q1	30	.17	24
50B-r8	15	.04	24
50B-r9	20	.10	24
50B-s2	75	4.2	24
50B-s3	30	.11	4
50B-s5	11	.05	24
50B-wz1	65	6.5	24
50B-wz2	20	.09	24
Minimum	5	.02	2
Maximum	95	6.5	75
Median	29	.20	24

Recovery of well 50B-r8 was rapid, with the water level returning to beginning conditions in 5 hours (Fig. 49). The drawdown and recovery plots both contain irregularities that are probably caused by fractures that fill up with water and provide extra storage. When pumping begins, the discharge is temporarily made up of the actual well discharge plus the stored water in the fractures flowing into the well. After the stored water is depleted, the well draws down normally. For example, 1

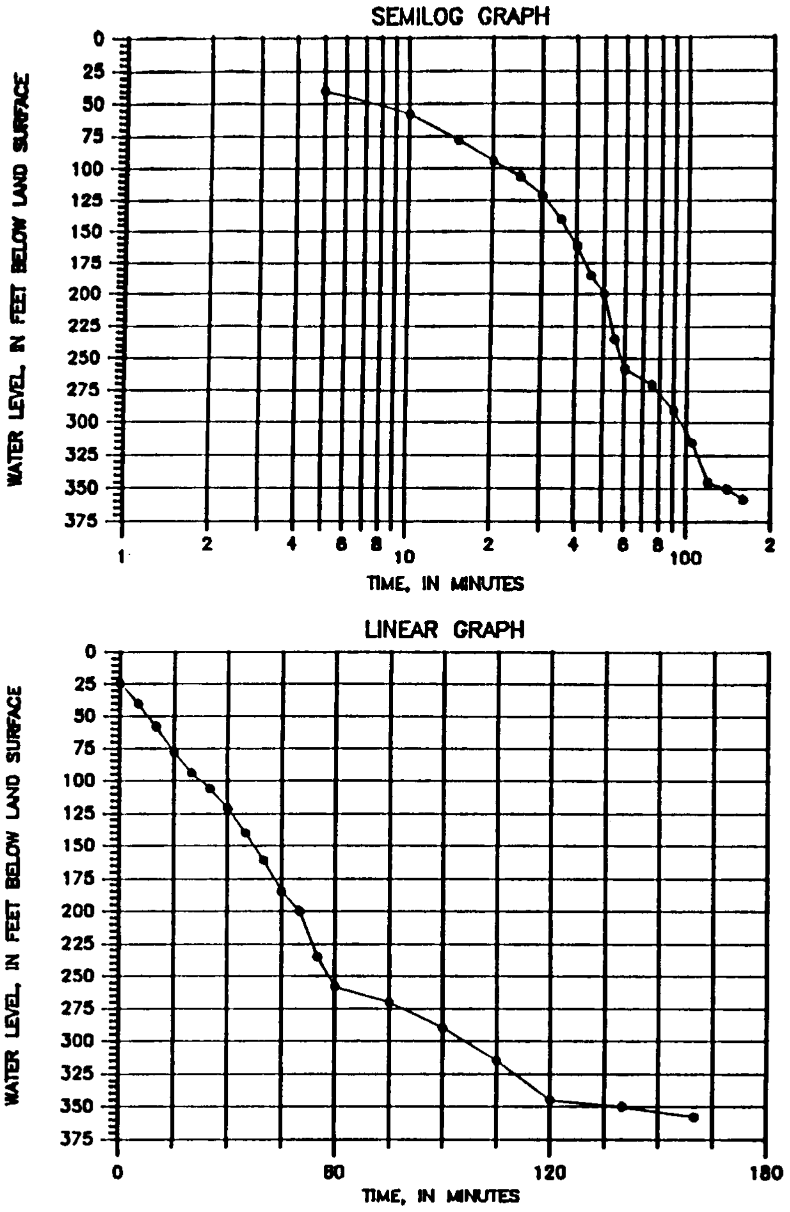


Figure 48. Drawdown in well 50B-r8/GRV-742, March 12-13, 1986. Well depth is 500 feet and test pump was set at 358 feet. Pumping started at 25 gpm and was gradually reduced to 15 gpm by 160 minutes. At this point the maximum pumping level was reached (358 feet, at the pump), and the water level and pumping rate are reported as constant for the duration of the 24-hour test.

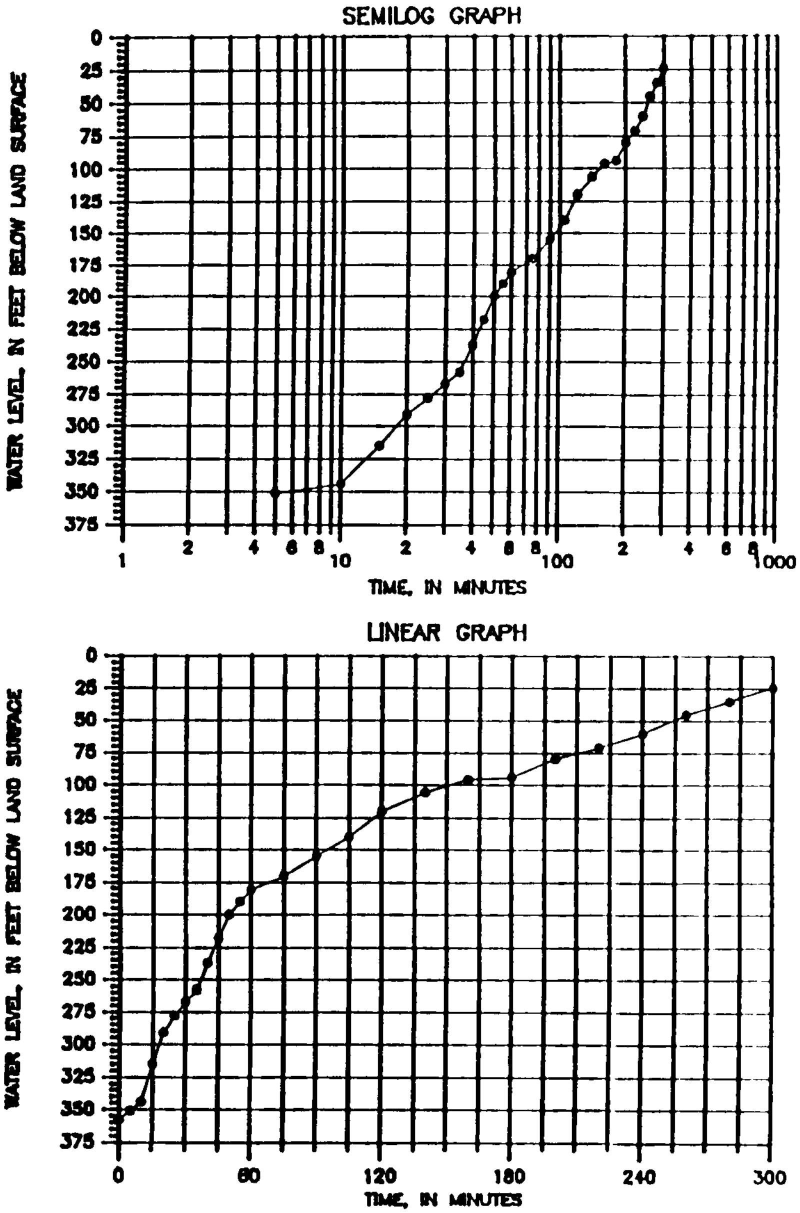


Figure 49. Recovery in well 50B-r8/GRV-742, March 13, 1986.

hour into the pumping test, at 258 feet, there is a distinct change in slope of the drawdown curve. This anomaly is also seen in the recovery curve, at the same depth (258 feet) at 35 minutes into the recovery period.

Unfortunately, the driller's log does not detail the occurrence of fractures to verify this interpretation, though water-bearing zones are listed at 30 and 305 feet. A nearby well, 50B-r9, exhibits similar behavior (Figs. 50 and 51). The drawdown and recovery plots for the pumping test at this well contain irregularities, but the shapes of the plots are not the same as for 50B-r8. The driller's log for 50B-r9 mentions a "water vein" at 35 feet and "cracks" (fractures) at 65, 82, and 165 feet. Some of these numbers match the plot, but some do not. The reason for the discrepancy is uncertain but may be related to the frequency with which water level measurements were made in the first few minutes of the recovery, as some irregularities may have been unrecorded. Also, some fractures may have been missed by the driller.

The drawdown curve for a pumping test at well 46B-f1 contains a major irregularity about 45 feet (Fig. 52). The decrease in the slope of the line might indicate a decrease in pumping rate, but the driller's pumping test record indicates only a minor change, from 68 gpm at 40 minutes to 67 gpm at 45 minutes (the test started at 72 gpm, decreased to 70.5 gpm at 30 minutes and 68 gpm at 35 minutes). The caliper log also indicates a large fracture from 45 to 47 feet depth (Fig. 53). The spontaneous potential, short normal resistivity, and single point resistance logs appear to confirm this fracture, although it is not evident on the gamma-ray log (Fig. 53). Other fractures are also indicated on the geophysical logs, especially the caliper, but evidently are not extensive enough to affect drawdown or recovery. This information would indicate that the fracture at 45-47 feet may be the producing one, at least of those fractures within the range of the drawdown test. On the other hand, the fracture may not necessarily be the producing zone, but a large fracture with water in storage, which drained out during the pumping test. The well is 500 feet deep, but maximum drawdown on the test reached only 80.5 feet below land surface. At this depth, and at 900 minutes into the test, the line flattened out. Here the pumping decreased to its lowest rate, 48.5 gpm, where it remained for the duration of the test (Fig. 52).

Geophysical logs also seem to confirm water-filled cavities on another well, 47B-j2, which was pumped for 24 hours at a rate beginning at 150 gpm and ending at 75 gpm (Fig. 54). A source of inflow seen on the drawdown plot in the 60-70 minute period is identifiable on the caliper log at 39 to 50 feet (Fig. 55). The gamma-ray log also shows a formation change at about this depth, and continuing to about 75 feet, so it is possible that a contact between different rock types could be a zone of increased water flow. This deeper contact would not necessarily increase the diameter of the well as a fracture would, and therefore it would not show up on the caliper log. The single-point resistance log, short- and long-normal resistivity logs, and, to a smaller extent, the spontaneous-potential log indicated some water-bearing zones. The 50-foot zone is difficult to identify, but there are some deeper anomalies, although whether they are water-bearing zones, or simply lithologic contacts, or weathered zones that washed out during drilling, is uncertain. These other possible water-bearing zones were detected on the electric logs below the deepest pumping level of the test, at 70, 105, 125, 150, 230, 300, and 345 feet; the zone at 230 feet appeared to be the most promising for water (Fig. 55). Pumping tests can be useful tools in evaluating a well's performance, especially if their results are analyzed in conjunction with other information such as detailed drillers' logs or geophysical logs. But it is essential that the tests be conducted in a useful manner. Many tests have highly variable pumping rates which obscure information about the actual well yield and water-bearing fractures. For example, well 47D-p11, a 292-foot deep well, had a 75-hour test, with the pumping rate varying intermittently between 25 and 47 gpm. Whenever the pumping rate increased the water level declined, and vice-versa; the effect of the highly variable pumping rate is dramatically evident in the drawdown curve (Fig. 56). It is unfortunate that no recovery data were gathered, for in many cases where the drawdown plot is unusable the recovery curve provides useful information.

There is a problem in determining the ideal type of pumping test to conduct in Piedmont aquifers. Public-supply wells are tested to satisfy maximum-demand predictions, not actual well capacity over extended time. Instead of varying the pumping rate in order to achieve a stable water level as is done now, pumping tests should be made at a constant pumping rate; if not for the entire test period, then at least in evenly-spaced or graduated steps, as in a step-drawdown test. This would allow for more accurate interpretation of the drawdown (and recovery) data, including analysis of irregularities.

WELL-SITING TECHNIQUES

DRAINAGE AND LINEAMENT ANALYSIS

For decades, well drillers and ground water scientists have known that one of the most important factors affecting well yield in the Piedmont is well-site topography (Bloxham and others, 1970; Daniel, 1987; Daniel and Sharpless, 1983; Johnson and others, 1968; LeGrand, 1967; Snipes, 1981; Snipes and others, 1983 and 1984). Valleys and draws are usually the best sites,

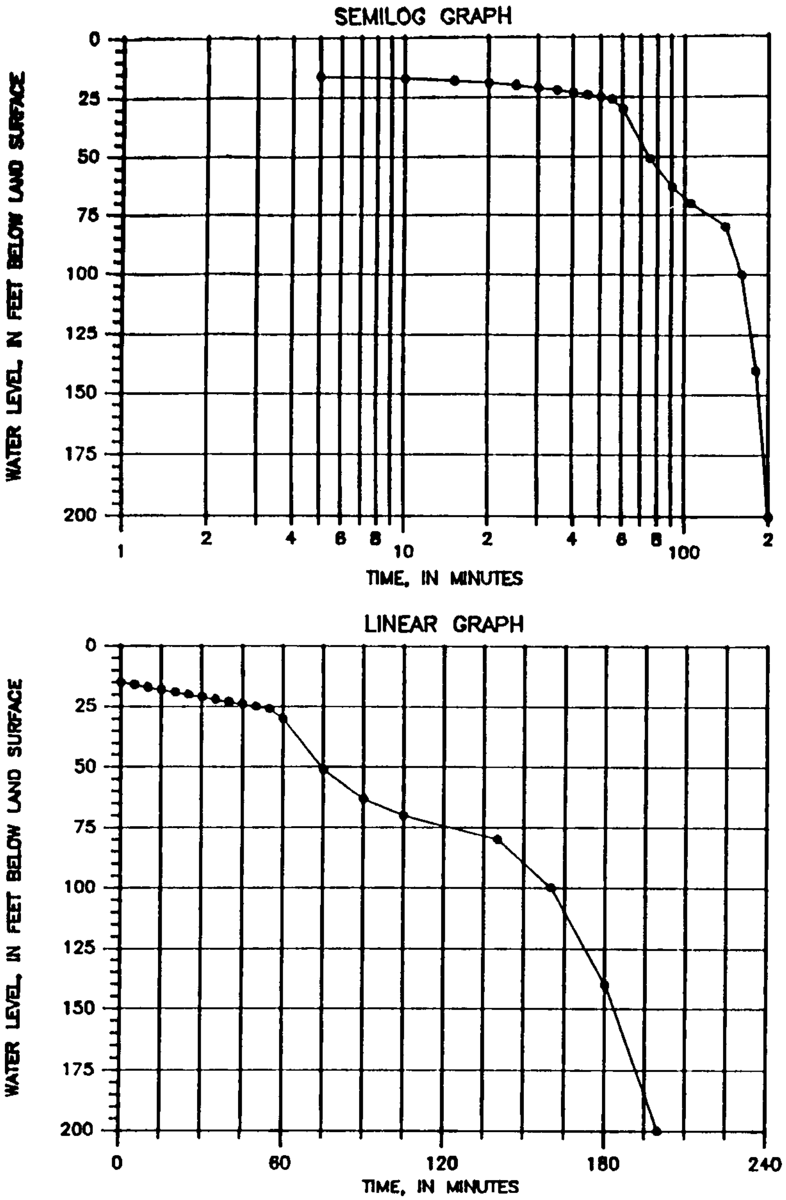


Figure 50. Drawdown in well 50B-r9/GRV-790, May 27-28, 1987. Well depth is 402 feet, and test pump was set at 200 feet. Pumping started at 40 gpm and was gradually reduced to 19.5 gpm by 240 minutes. Pumping level maximum of 200 feet (at pump) was reached at 200 minutes, pumping 21 gpm. From 240 minutes to the end of the 24-hour test, the pumping rate was reported to be 19.5 gpm and the pumping level remained at 200 feet.

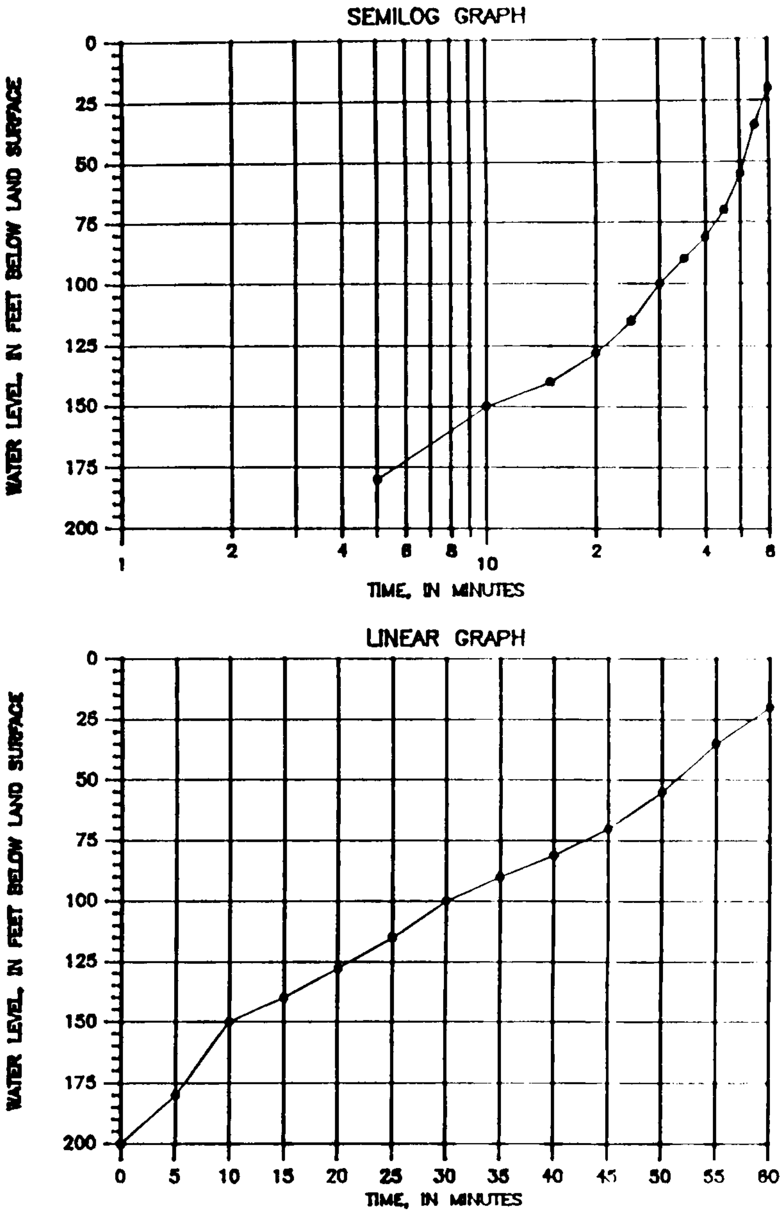


Figure 51. Recovery in well 50B-r9/GRV-790, May 28, 1987.

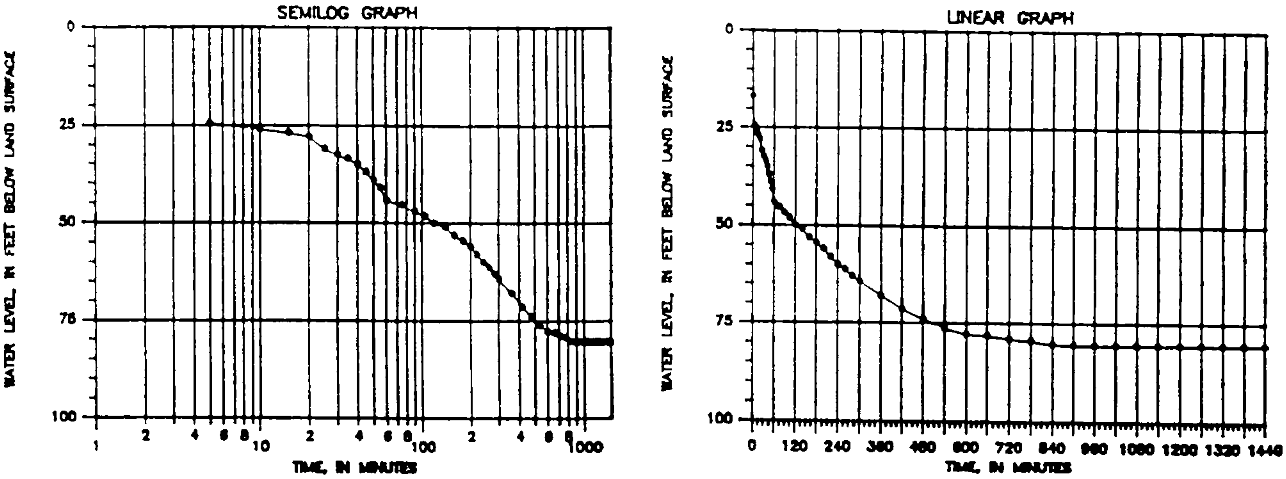


Figure 52. Drawdown in well 46B-f1/GRV-2170, August 6-7, 1990. Well depth is 500 feet; pumping began at 72 gpm, decreasing to 48.5 gpm at 900 minutes (15 hours), when the maximum pumping level of 80.5 feet also was reached.

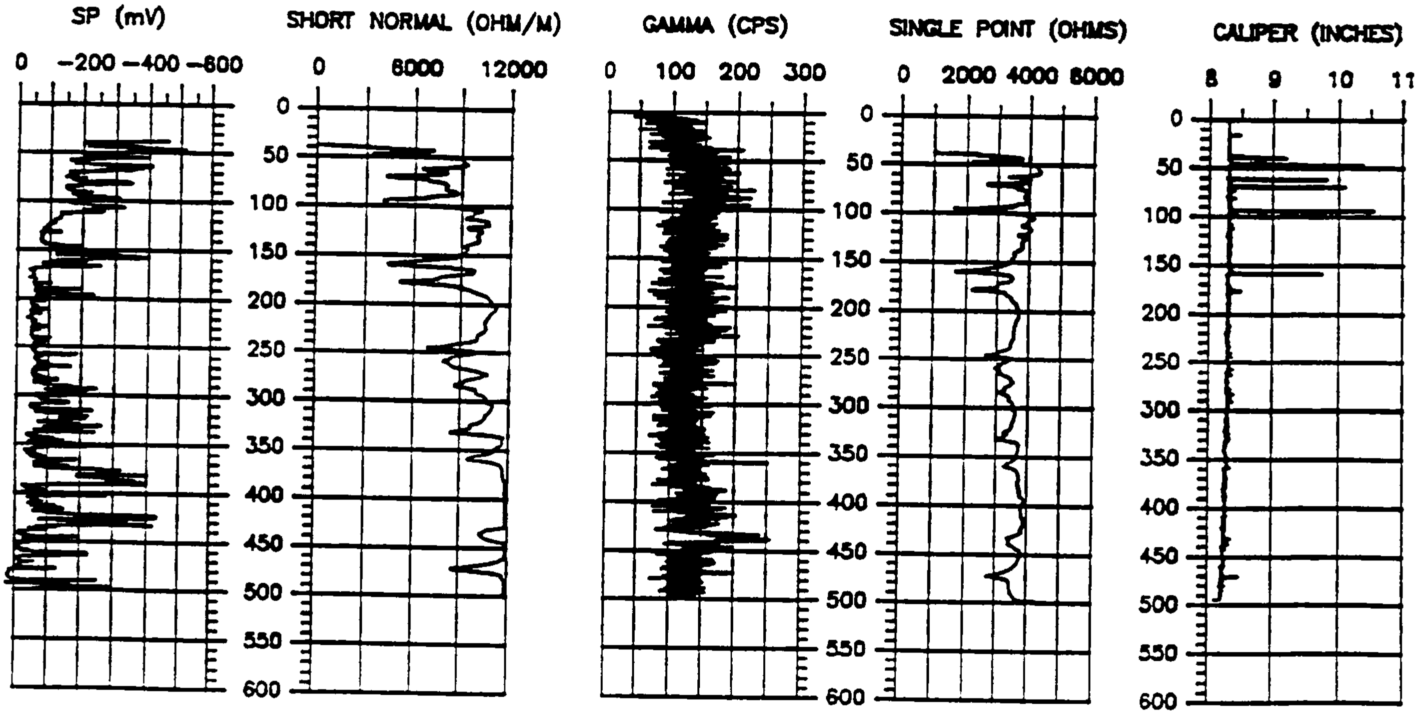


Figure 53. Geophysical logs of well 46B-f1/GRV-2170. Well depth is 500 feet, casing depth is 37 feet. Major fractures are at 40, 45-47, 62, 69, 93, and 159 feet.

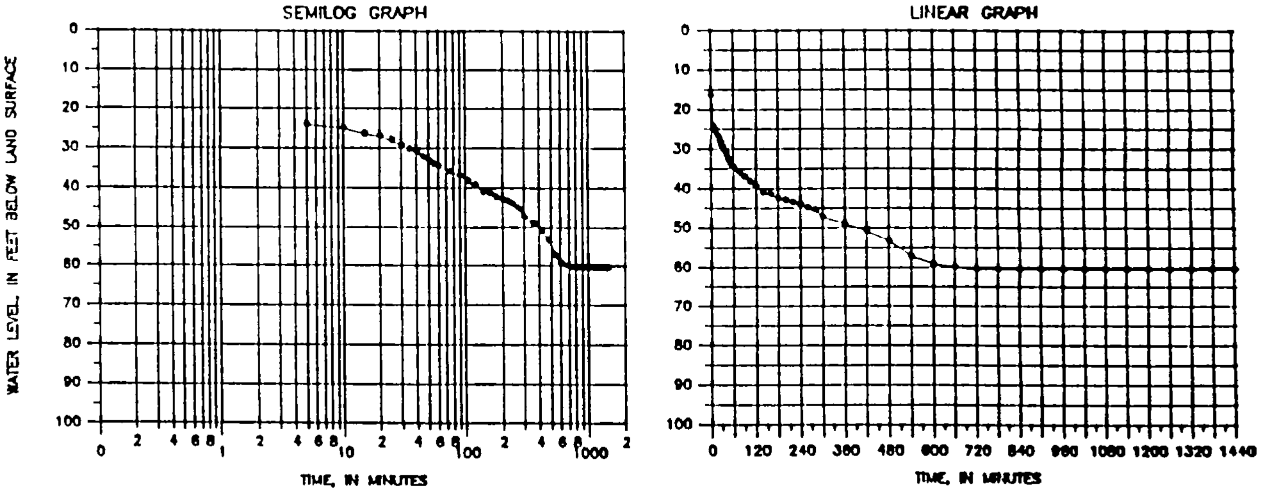


Figure 54. Drawdown in well 47B-j2/GRV-2172, August 13-14, 1990. Well depth is 404 feet, pumping began at 150 gpm, decreasing to 75 gpm at the maximum pumping level of 60.5 feet, at 720 minutes (12 hours) into the test.

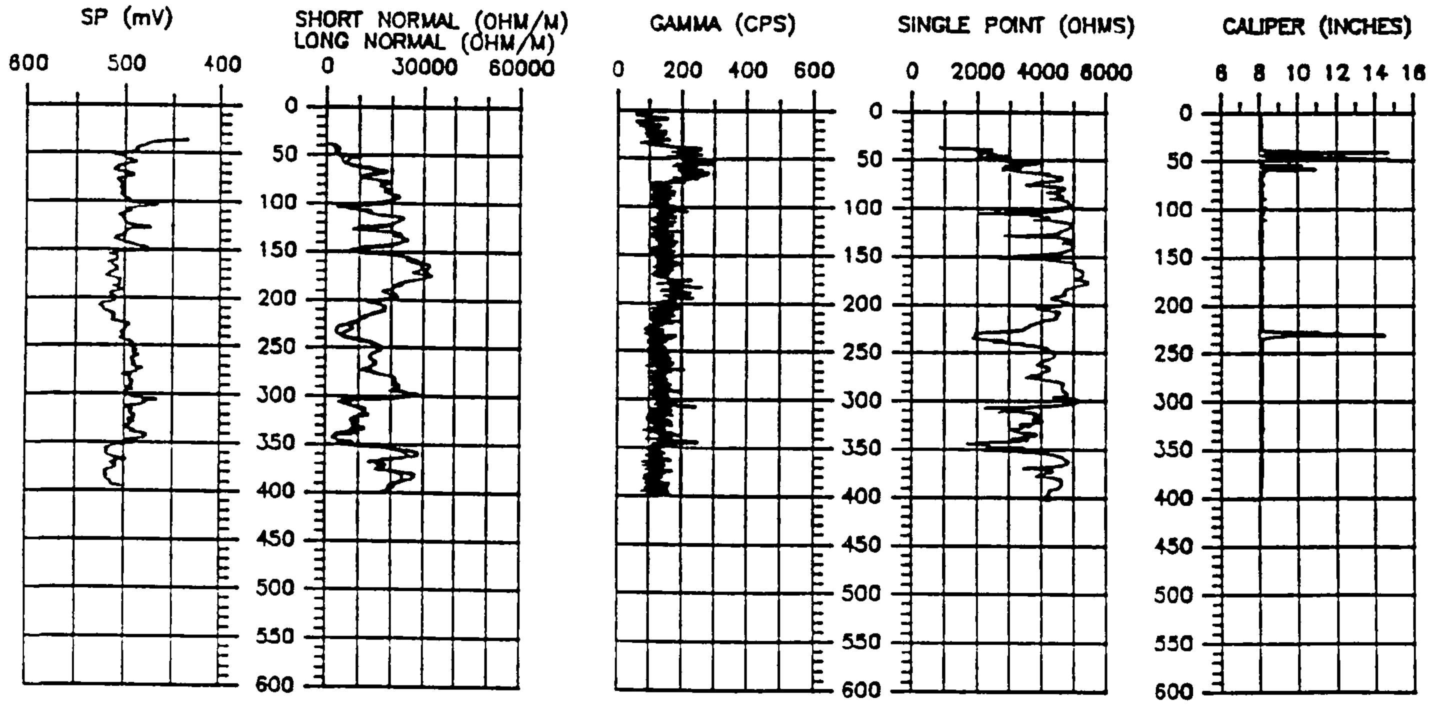


Figure 55. Geophysical logs of well 47B-j2/GRV-2172. Well depth is 404 feet, casing depth is 36 feet. Major fractures are at 39-50, 54-62, and 227-235 feet.

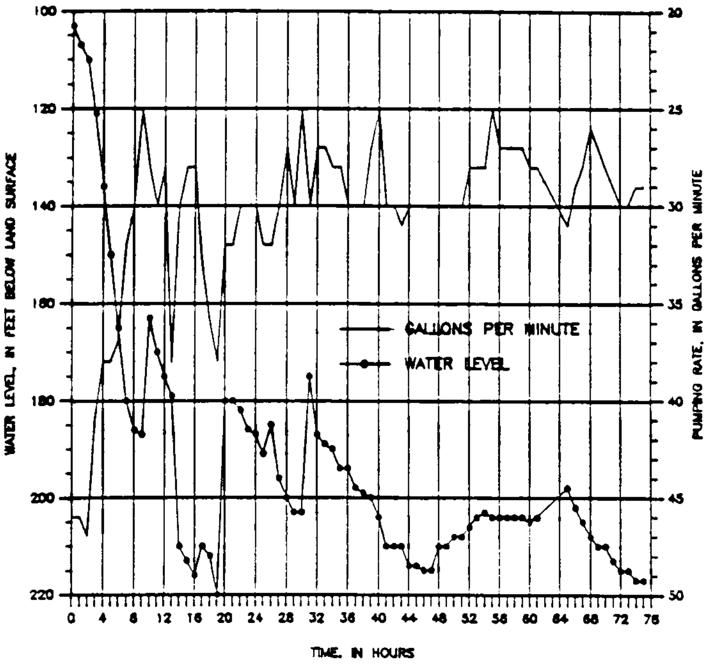


Figure 56. Drawdown in well 47D-pll/GRV-2030, July 26-29, 1977. Well depth is 292 feet. Four-hour gap from 61 to 65 hours was caused by a broken power generator.

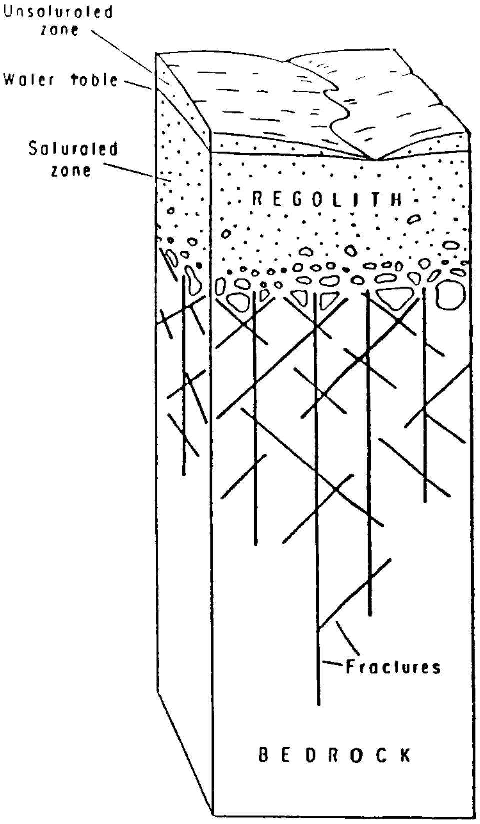


Figure 57. Principal components of the Piedmont ground water system (from Daniel and Sharpless, 1983). In Greenville County, the regolith (saprolite and overlying alluvium and soil) ranges in thickness from 0 to more than 200 feet, and median thickness of saprolite is 54 feet. The fracture zone may reach several hundred feet in depth.

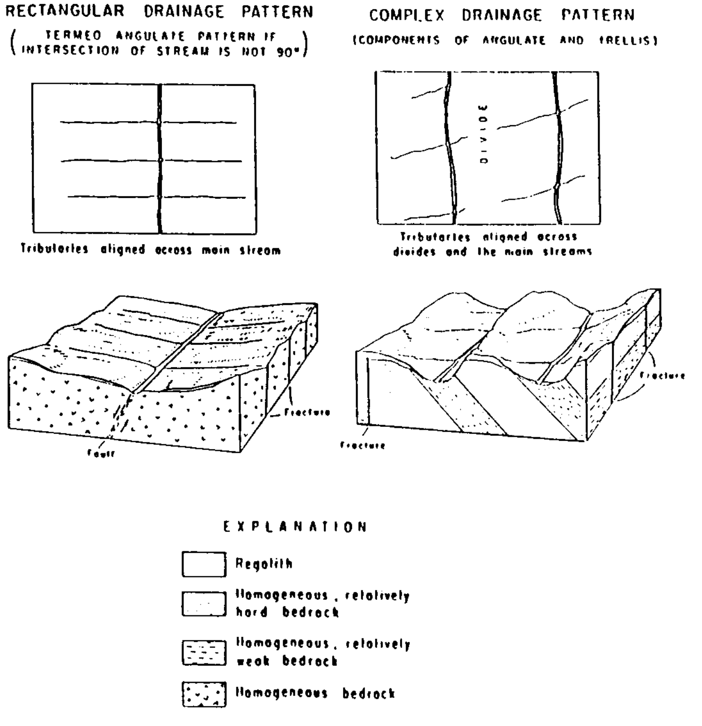


Figure 58. Some common drainage patterns and associated landforms of the Piedmont that generally are favorable to high well yields (from Daniel and Sharpless, 1983).

and hills and ridges are the least productive. Erosion of areas overlying fractured bedrock has led to the formation of valleys and draws; hills and ridges remain where fractures are less prevalent. The fractures act as a pipeline system that drains the overlying reservoir, the residual regolith (saprolite with overlying alluvium and soil) (Daniel and Sharpless, 1983, and Heath and Giese, 1980; Fig. 57).

An exception to valleys and draws being the best sites is reported by Snipes and others (1983) in Abbeville County, to the south of Greenville County in the Piedmont. At this location more high-yield wells were located along ridges than in valleys. The cause of this was attributed to structural control, as many of the ridges with the high-yield wells were located along synformal axes. Snipes and others (1984) also reported an exception to the general rule that fractures are more permeable and result in the formation of valleys and draws, in the case of the Pax Mountain Fault Zone. This fault, which is unusual in that it consists of quartz-rich microbreccia, strikes N80°E from Pickens County west of Greenville County, through Greenville County, and northeastward through Spartanburg County and into North Carolina (see Geologic Map [Plate]). Along the fault's southwestern exposure, it is expressed as a topographic depression, but in northern Greenville County it created Pax Mountain, a steep, narrow ridge with a height of 330 feet and a length of 1.6 miles. It continues as a more subtle ridge in neighboring Spartanburg County to the east. Most of the few wells in the fault zone were drilled with considerable difficulty and few produced usable yields (Snipes and others, 1984).

Also important to understanding ground water hydrogeology in the Piedmont are stream drainage patterns caused by underlying bedrock structure. Faults, fractures, joints, and related structures are usually angular or perpendicular to one another and are often sources of ground water in bedrock. Their surface expressions are streams and draws with rectangular or complex patterns (Fig. 58). Wells sited near these streams have higher yields than those near streams with trellis, dendritic, or radial drainage patterns (Cressler and others, 1983; Daniel and Sharpless, 1983; and Radtke and others, 1986; Fig. 59). Trellis patterns occur where alternating beds of resistant and nonresistant rocks are tilted and exposed on edge. The resistant rocks tend to form parallel ridges, whereas the less resistant rocks are cut by major streams (Daniel and Sharpless, 1983). Dendritic patterns, which resemble tree limbs in appearance, have randomly branching tributaries joining the main stream at irregular intervals and a variety of angles. They are usually the result of downcutting into massive bedrock or relict stream patterns being incised into uplifted terranes and suggest lack of structural control. Part of the reason for this is that there are few or no faults, fractures, or other linear and angular features, such as in unmetamorphosed granitic plutons. Radial drainage patterns may also result from uplift or erosional exposure of similar plutons, creating monadnocks and inselbergs (Fig. 59).

LeGrand (1967) provided a point system for determining the best well sites that is based on topography and soil (saprolite) thickness. He stated that "High-yielding wells are common where thick residual soils and relatively low topographic areas are combined, and low-yielding wells are common where thin soils and hilltops are combined." Johnson and others (1968) reported that saprolite thickness is an important indicator of well yield in Pickens County, but Snipes (1981) and Snipes and others (1983 and 1984) did not find any relationship between yield and saprolite thickness in several western South Carolina Piedmont counties. Lineaments and fracture traces were found to be correlated with increased well yields (the Snipes reports and Stafford and others, 1983). Snipes found that the median yield of wells located in fracture traces and lineaments was about twice the median yield of randomly located wells. Daniel and Sharpless (1983) stated that the "ideal well site would be located in the geologic unit having the greatest probability of high yields, have thick regolith, a high water table, be underlain by highly-fractured bedrock, and have a large contributing drainage area." They also explained the importance of having the greatest amount of saturated thickness of regolith, and because porosity and specific yield of the saprolite decrease with depth, a high water table is also important. In their area of study, the Upper Cape Fear River basin of North Carolina (Piedmont rock), the best well sites generally are along lineaments perpendicular to the geologic trend, between the hilltops and the stream valleys, part of the way up the valley flanks. An idealized well site is shown in Figure 60.

Caesars Head State Park case study: Caesars Head State Park, administered by the South Carolina Parks, Recreation, and Tourism Department (SCPRT), is located at Caesars Head, a prominent feature on the Blue Ridge Escarpment at an elevation of more than 3,000 feet in northern Greenville County. Since 1969 the State Park has used a well owned by the Caesars Head community, a small group of mostly summer- but several year-round residents, to supply a 72,000-gallon tank which serves the park and the community (well 50B-r4). Before 1969, community residents had used a spring-fed system since 1922. The well is situated in a draw, is 240 feet deep, and is cased to 18 feet depth. Its yield was reported at 100 gpm in 1976, but when tested 10 years later it yielded 70 gpm.

In late 1980 and early 1981, the park had three more

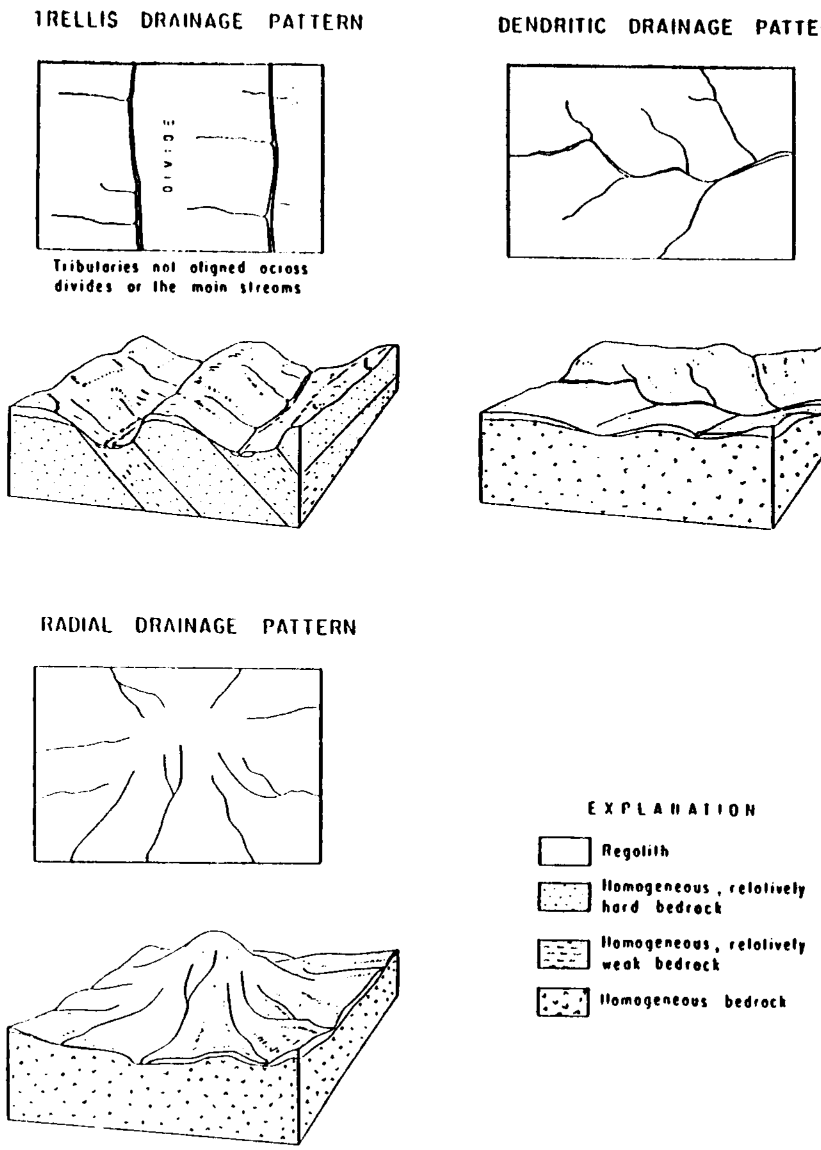


Figure 59. Some common drainage patterns and associated landforms of the Piedmont that generally are not favorable to high well yields (from Daniel and Sharpless, 1983).

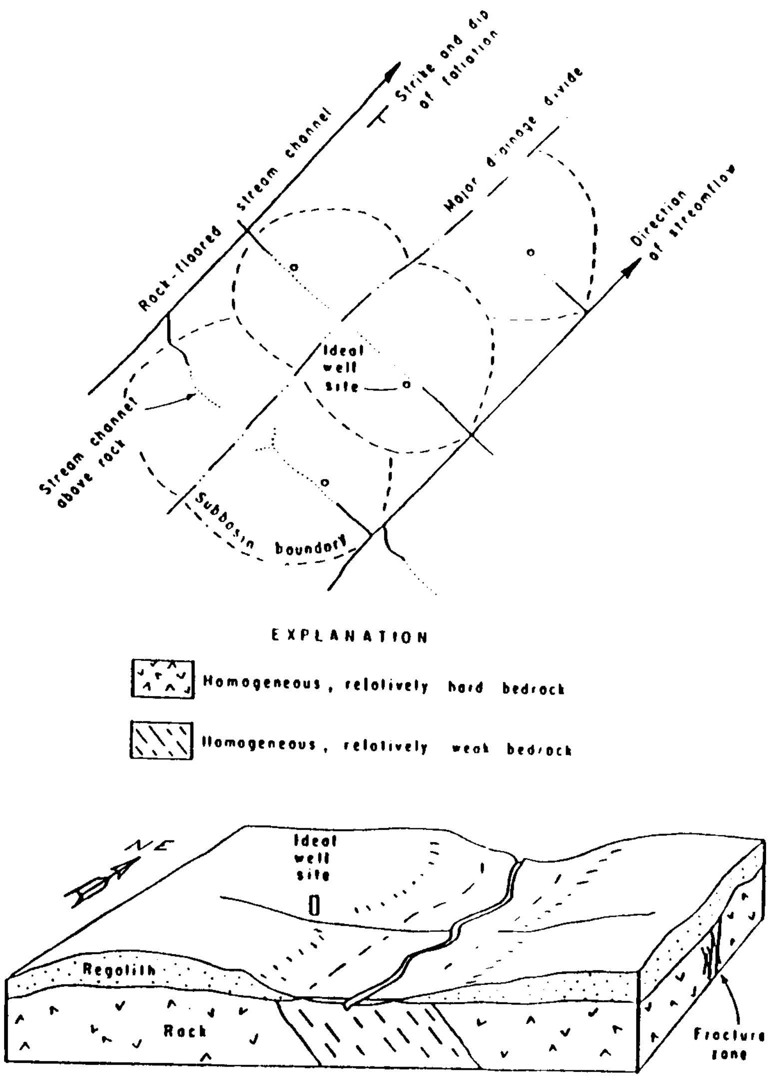


Figure 60. Generalized drainage pattern and associated landforms and hydrogeologic conditions typical of northwestern Guilford County, N.C., indicating an ideal Piedmont well site (from Daniel and Sharpless, 1983).

wells drilled in an attempt to construct a backup well. SCDHEC requires any public supply well system to have backup wells in case the main well has problems. These wells range in depth from 365 to 450 feet and are located either on a slope or at the heads of draws near the ridge top (wells 50B-r1, -r2, and -r3). The wells produced 2 gpm or less. One of these wells (50B-r1) was blasted with dynamite in an effort to increase its yield, but to no avail. Around 1985 the community also drilled two wells that were dry (wells 50B-r5 and -r6).

In December of 1985 SCPRT drilled another well to a depth of 450 feet; it produced more water than the other attempts but still less than 10 gpm (well 50B-r7). This was not enough for the park's needs.

The drought of 1986 caused the one good well to have pumping difficulties; its yield temporarily declined from 70 gpm to about 30 gpm. As a result, the search for a reliable backup well was renewed. The author was contacted by consulting engineers and SCPRT to seek a solution. Drilling records were examined, wells were logged, and topographic maps and airphotos with contour lines were studied to ascertain the location and extent of lineaments and fracture traces (Fig. 61 and Table 7). The 7.5-minute U. S. Geological Survey Maps, at a scale of 1 inch to 2,000 feet, were useful for determining the overall drainage patterns and lineament occurrences, but more useful were the larger-scale airphotos with the contour lines, which were at a scale of 1 inch to 400 feet. The larger scale permitted a contour interval of 10 feet, which shows much more detail than the 40-foot contour interval on the standard topographic maps.

Four options for a backup well were examined. One would have been to ream out the latest well drilled (well 50B-r7). It is in a draw and was producing less than 10 gpm, and studies by Caswell (1985) showed that increasing a drilled well's diameter in fractured-rock areas could substantially increase the well yield (subsequently, Daniel (1987) reported a direct correlation between well diameter and well yield—on average, in a producing well, the greater the diameter, the greater the yield in fractured-rock aquifers). However, this option was ruled out because of the difficulty and expense of reaming out a well, especially one of great depth (450 feet), and the risk that the resulting increased yield would still not be enough to meet the needs.

Another option was to hydrofracture the well. This procedure involves pumping water at high pressure into the well, near a fracture or fracture zone sealed off by packers, to open up the fractures and induce greater water flow (Voytek, 1986). The caliper log for this well indicated at least one fracture at depth and possibly another, as did the temperature and gamma-ray logs. This op-

Table 7. Construction Summary of wells at Caesars Head

SCDNR Water Resources Division well	Owner designation	Date drilled	Topography	Well depth (feet)	Casing depth (feet)	Yield (gpm)
50B-q1	SCPRT Raven Cliff Falls	6/9/87	Draw	600	37	30
50B-r1	SCPRT Caesars Head 1	11/27/80	Draw	450	28	2
50B-r2	SCPRT Caesars Head 2	12/1/80	Draw	365	26	2
50B-r3	SCPRT Caesars Head 3	2/10/81	Hillside	385	25	1
50B-r4	Caesars Head Comm. 1	6/24/76	Draw	240	18	70
50B-r5	Caesars Head Comm. 2	1985	Draw	300	unknown	0
50B-r6	Caesars Head Comm. 3	1985	Draw	200	20	0
50B-r7	SCPRT Caesars Head 4	12/20/85	Draw	450	17	10

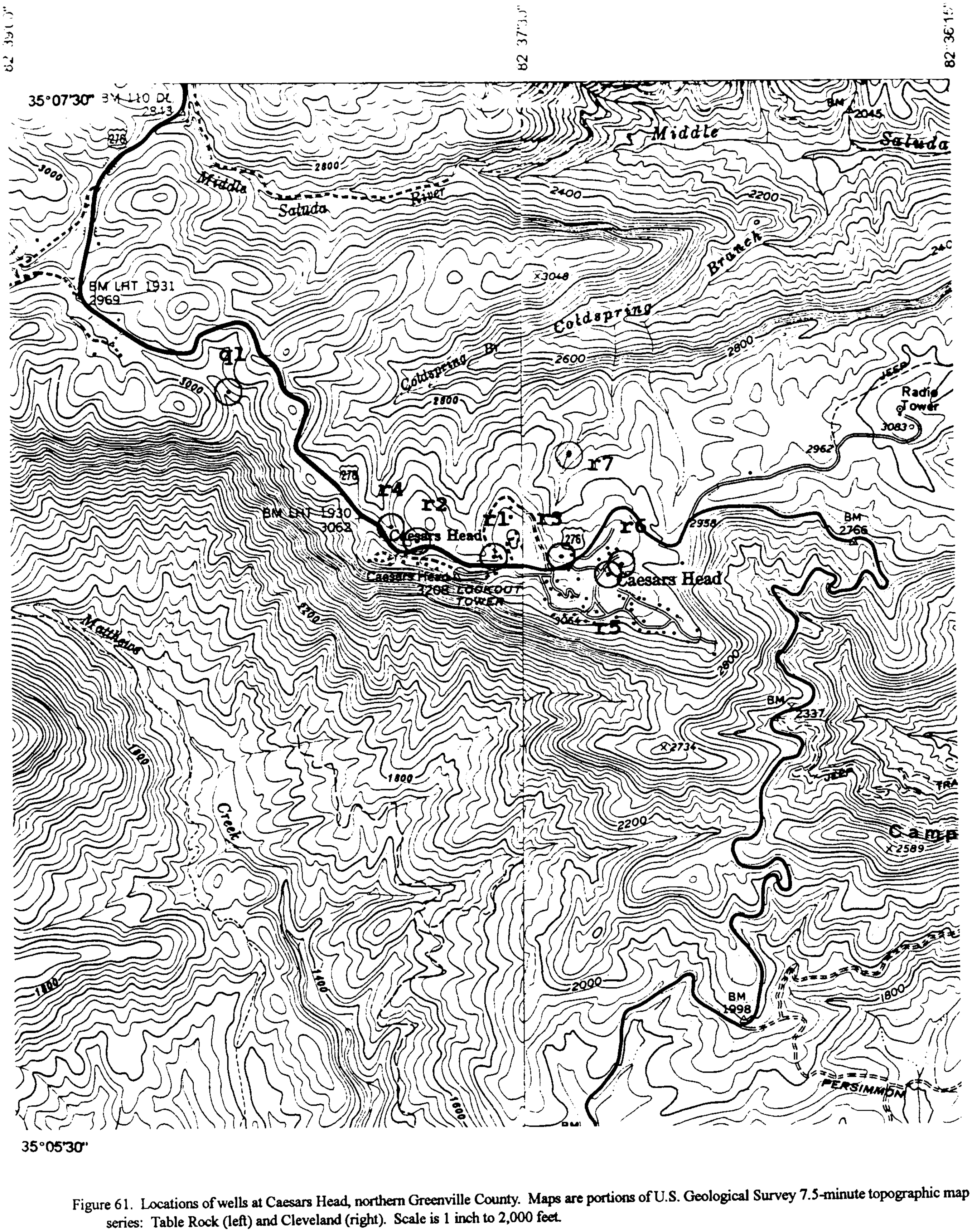


Figure 61. Locations of wells at Caesars Head, northern Greenville County. Maps are portions of U.S. Geological Survey 7.5-minute topographic map series: Table Rock (left) and Cleveland (right). Scale is 1 inch to 2,000 feet.

tion was decided against because little hydrofracturing had been done in the Piedmont of South Carolina, and even if it were successful an increase in yield to a usable amount was beyond the most optimistic projections.

A third option was to drill another well nearby in the same draw. This was not done because the well was already in what was judged to be the most favorable site in the draw, and there was little reason to believe that drilling another well nearby would produce any greater yield.

The fourth option was to drill a new well in a different site entirely. All the other wells had been drilled near the ridge top or on its northern slope, east or north of Caesars Head. A new site on the south-facing slope northwest of Caesars Head was selected (Fig. 62). This was done after analysis of topographic maps and contoured airphotos and visits to potential areas.

The well site is underlain by paragneiss and schist[1] and is in the valley of an east-southeast flowing stream that, in a few hundred feet, curves back to the south and south-southwest. The site is about 50 feet east of the intersection of the stream with a southward-trending draw. To the northwest of the site the stream is fairly straight for approximately 1,200 feet. The few exposures found showed foliation planes dipping generally to the east, toward the well site; this increases the favorability of the site, as recharge (from precipitation) would flow along these planes toward the well. Lithologies included biotite gneiss, hornblende gneiss, and quartzitic gneiss. Also found were several large pieces of massive quartz, indicating the presence of quartz veins, and boulders with large orthoclase or microcline (potassium feldspar) crystals, probably from pegmatite dikes. The presence of veins and dikes is favorable, as they often are water conduits.

Tributary streams farther to the northwest enter the main stream from the north-northeast and south-southwest, almost perpendicular to the trend of the main stream. Some tributaries have sharp (90-degree) bends in them, indicating structural control. Most of the joints in the stream were vertical. The recharge basin upstream of the well site is small at about .1 square mile, but considering the location near a ridge top, this is a fairly large area. It is also about twice the size of the next largest recharge basin in which a well was drilled (in this case, well 50B-r7).

All these factors made this a promising well site:
— the proximity of the site to a long straight stream segment and the presence of tributaries entering at sharp angles are probably indicative of structural control such as faults, joints, or fractures, which are all openings for ground water;
— the intersection nearby of a draw, increasing the likelihood of a drilled well at that site encountering a fracture, joint, or fault;
— foliation planes dipping towards the well site;
— fairly large (for the ridge top) recharge basin;
— the presence of pieces of massive quartz and of large potassium feldspar crystals, indicating quartz veins and pegmatite dikes.

The well was drilled in June of 1987 to a depth of 600 feet (well 50B-q1). Saprolite was about 37 feet thick and was cased off, and a large fracture was encountered at 414 to 430 feet. This fracture was the main water-producing zone, but it contained loose fragments, probably fault gouge, that continually fell into the well. The zone was screened to prevent further infilling and to allow the water to be used. The yield of this well is 30 gpm, and it is used now as a backup well for the park.

BOREHOLE GEOPHYSICS

Unlike wells in the Coastal Plain, where geophysical logs are commonly used to interpret lithologies and correlate units across wide areas, comparatively few wells in the Piedmont have such logs. This may be attributed to the difficulty in differentiating crystalline (igneous and metamorphic) rocks as opposed to sedimentary units and to the lesser importance of distinguishing between different units, since almost any unit in a crystalline rock well that produces water is welcome and used.

There are 26 wells in Greenville County with geophysical logs, all of which were logged by the Water Resources Division of the South Carolina Natural Resources Department (see Table 8). The most common tool used is the caliper log, which, besides its primary purpose of measuring the hole diameter, is useful in determining the location and number of fractures in the borehole (Figs. 63-66 and Gellici, 1992). The natural gamma-ray log is also frequently employed, although its interpretation is difficult (Figs. 63-66). It can be used to locate pegmatite dikes because of their higher content of radioactive material than the surrounding rock. This is important because it is often such dikes that are water-bearing zones. In another Piedmont county gamma-ray logs were used to find the fracture that was the source of radionuclide-rich water (Gellici, 1992).

Two other tools that are useful in the Piedmont, and in Greenville County, are the temperature and fluid-resistivity logs (Figs. 63-66). The temperature log may indicate a dominant water-bearing fracture in a flowing or pumping well, by showing where a change in water temperature gradient occurs (Gellici, 1992). Likewise, the fluid-resistivity log may indicate the same fracture by showing an abrupt change in the water's resistivity (Gellici, 1992).

Other logs are used to a lesser extent in the Pied-

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[1] See Description of Geologic Units In Introduction

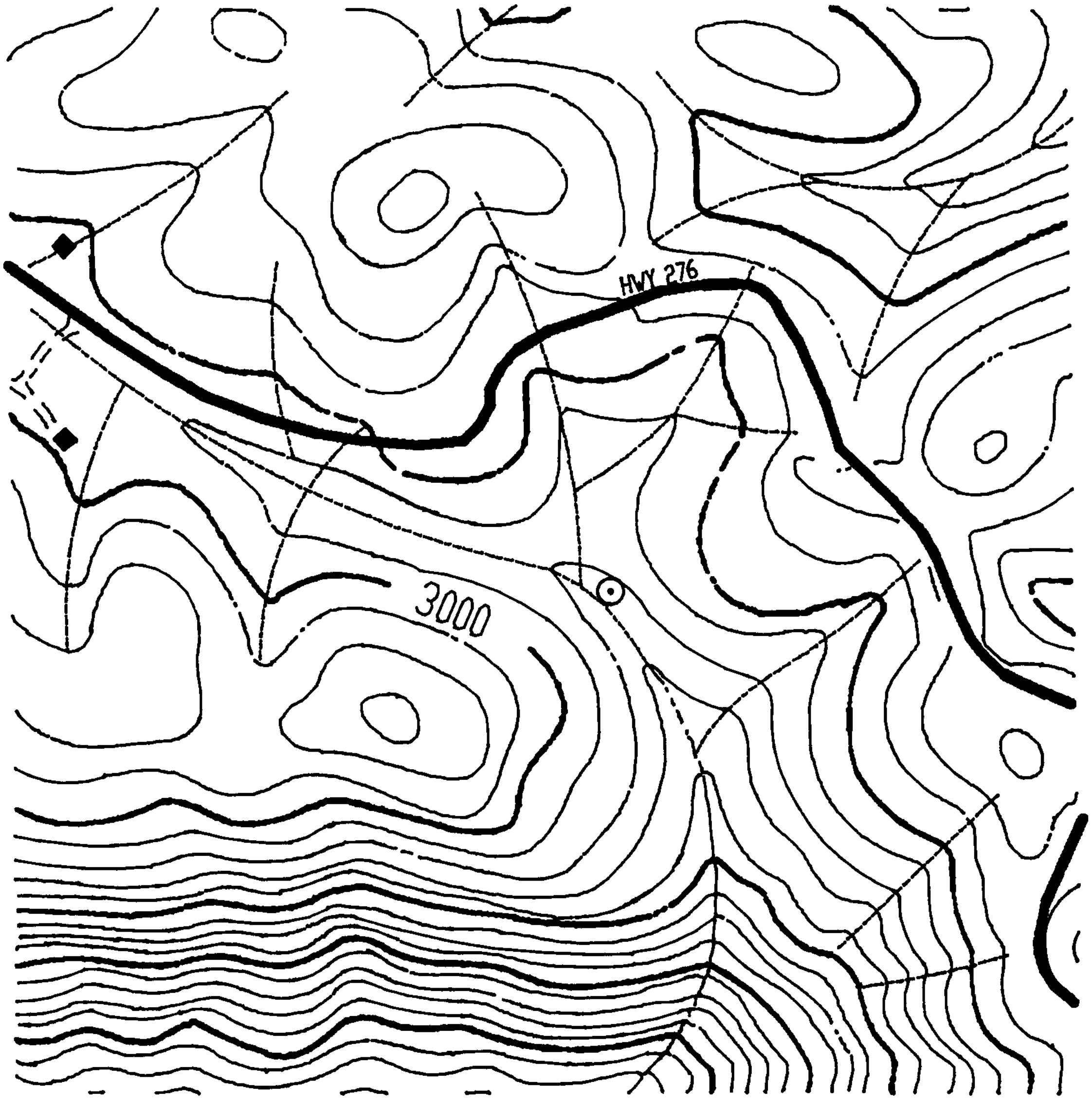

Figure 62. Site of successful well 50B-q1/GRV-792. Solid line is stream, dotted lines are draws, circle is well site. Scale is 1 inch to 400 feet; contour interval is 40 feet.

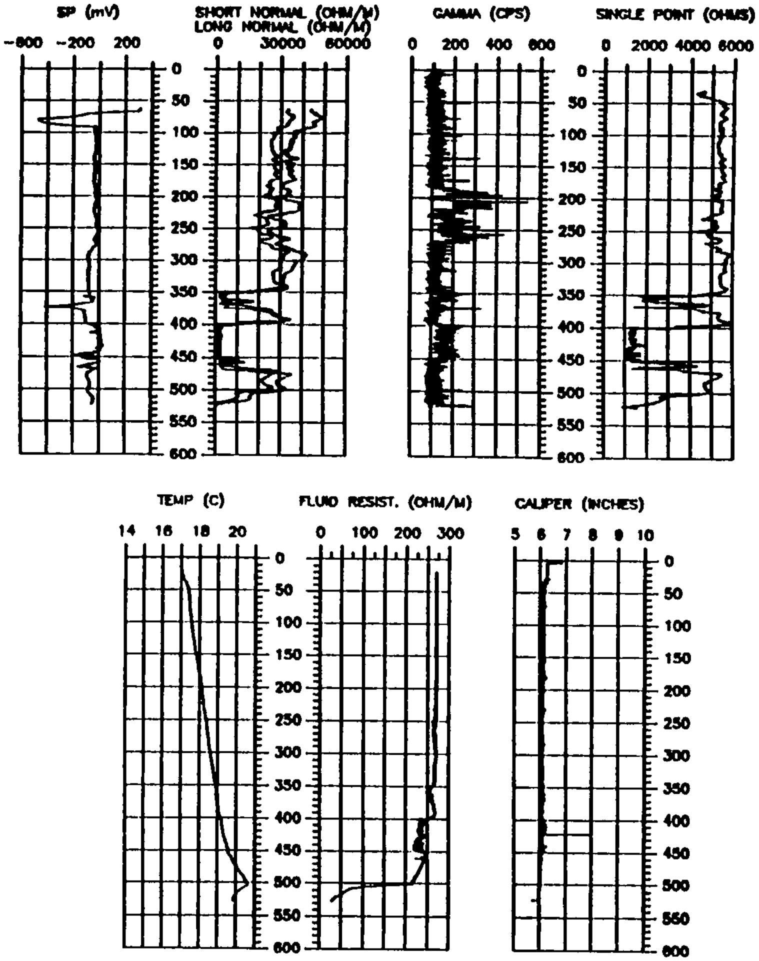

Figure 63. Geophysical logs of well 47D-n2/GRV-1554 before hydrofracturing. Depths are in feet.

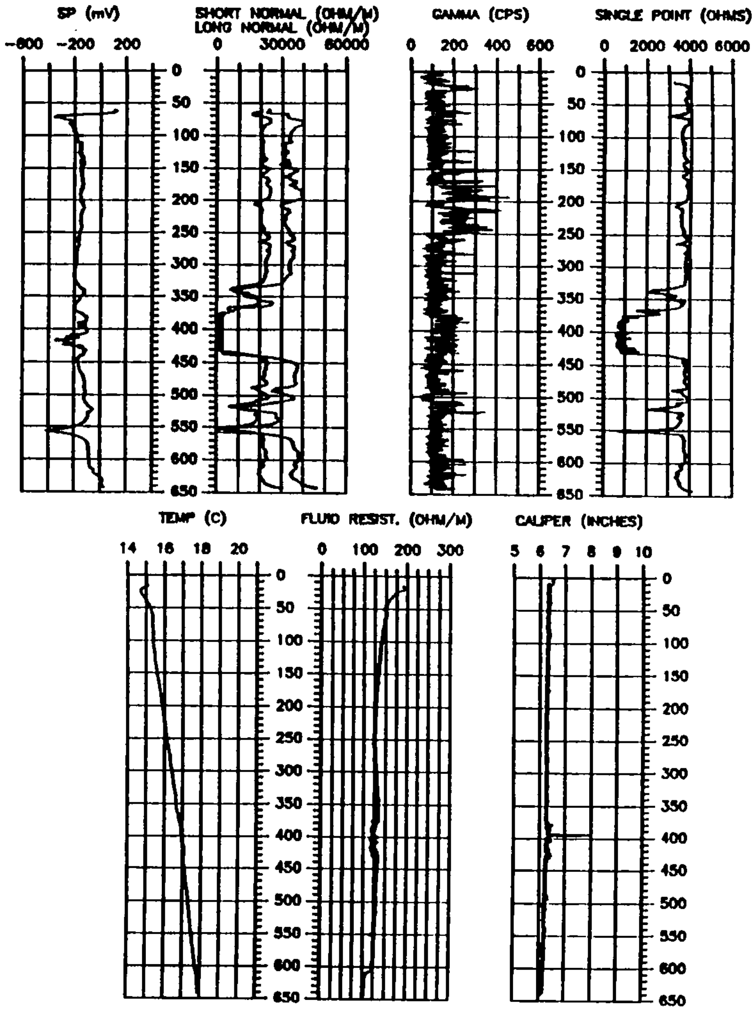

Figure 64. Geophysical logs of well 47D-n3/GRV-1556 before hydrofracturing. Depths are in feet.

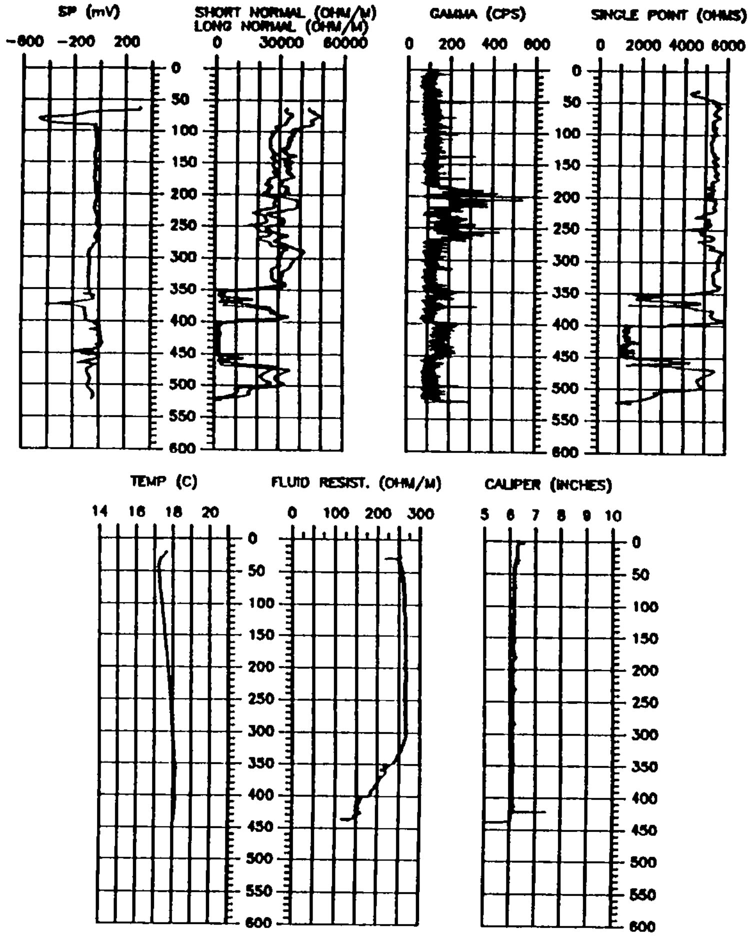

Figure 65. Geophysical logs of well 47D-n2/GRV-1554 after hydrofracturing. Depths are in feet.

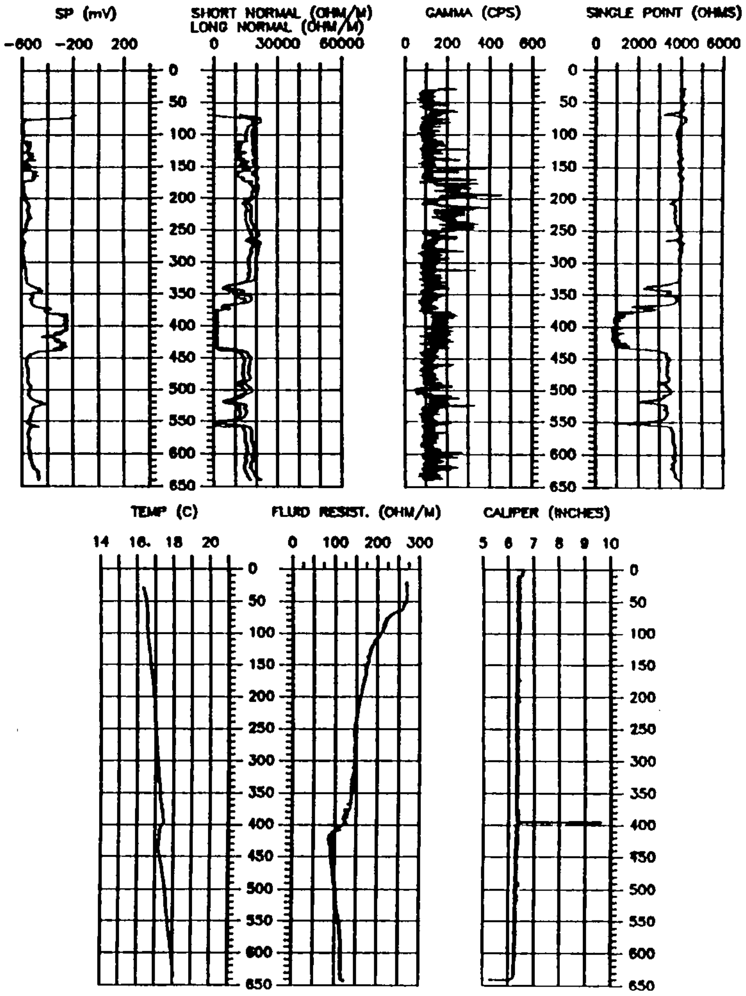

Figure 66. Geophysical logs of well 47D-n3/GRV-1556 after hydrofracturing. Depths are in feet.

Table 8. Geophysical logs in Greenville County

SCDNR-WRD well	ELEV (FT)	DEPTH (FT)	RES	ELS	ELN	ELT	TEM	FLR	SP	GAM	CAL
45F-l6	702	500		X			X	X		X	X
45F-l7	728	380		X			X	X		X	X
45F-l12	772	667	X	X					X	X	X
45F-m2	840	420		X			X	X		X	X
45F-m3	833	420		X			X	X		X	X
46B-f1	2470	500	X							X	X
46E-h1	948	80	X						X	X	X
46G-v4	805	600									X
46H-b1	835	322	X	X	X				X	X	X
46H-o1	838	262	X	X					X	X	X
47B-j2	2485	404	X	X	X		X	X	X	X	X
47B-j6	2480	500	X	X	X		X	X	X	X	X
47D-n2	1058	526	X	X	X	X	X	X	X	X	X
47D-n3	1055	645	X	X	X		X	X	X	X	X
47D-p5	1890	850									X
47D-p7	1955	782	X	X					X	X	X
48B-q1	1525	596	X	X	X		X	X	X	X	X
48B-q2	1510	600									X
48C-s2	1240	518									X
48C-s3	1240	686									X
49D-b1	1000	174					X	X		X	X
50B-r1	3150	450					X	X		X	X
50B-r6	3050	200		X			X	X		X	X
50B-r7	2905	450					X	X		X	X
50B-r9	2915	402		X			X	X	X	X	X
50B-s5	2920	327		X			X	X	X	X	X

RES, single-point resistance; ELS, short-normal resistivity; ELN, long-normal resistivity; ELT, lateral resistivity; TEM, temperature; FLR, fluid resistivity; SP, spontaneous-potential; GAM, gamma-ray; CAL, caliper.

mont, and represent the smallest number of geophysical logs in Greenville County. These include the so-called "electric" logs, which are spontaneous potential, resistance ("single-point"), and resistivity ("short normal", "long normal", and "lateral") (Figs. 63-66 and Gellici, 1992).

Geophysical logs can be used to establish the locations of water-producing fractures, and with detailed geological logs or samples, lithological compositions can be determined. By calibrating these logs with known geological information, geophysical logs can be used in the Piedmont to interpret lithologies of different units, or at least to determine contacts between units. More sophisticated logging tools, in addition to those previously discussed, such as high-resolution gamma-gamma density and acoustic bore-hole televiewer logs, have been used successfully to ascertain lithologies and fracture orientation in Piedmont (Carolina Slate belt) rocks in North Carolina (Stock, 1992).

Case Study: The following case study illustrates how geophysical logs were used. At a home site in Greenville County, a new well site was chosen by using a VLF (very low frequency radio wave) surface geophysical instrument, the WADI. The WADI is a passive electromagnetic instrument that measures the secondary magnetic field generated by the interference of very low frequency radio waves with subsurface electrical conductors (such as water-filled fractures). The VLF signals are broadcast around the world by military stations (for a detailed analysis of the use of VLF in the South Carolina Piedmont, see Harrigan, 1992). The old well had become unreliable and was not providing enough water for consistent use. This well (47D-n2/GRV-1554) was 526 feet deep and had a land-surface elevation of 1,058 feet above sea level. The original yield of the well is unknown. A caliper log clearly indicates a major fracture at 422 feet (Fig. 63).

The new well site is located less than 100 feet to the southeast, at an elevation of 1,055 feet (well 47D-n3/GRV-1556). Drilling was completed on June 10, 1989, to a depth of 645 feet. The caliper log of the new well indicates a fracture at a depth of 395 feet, which is an elevation of 660 feet (Fig. 64). This is apparently the same fracture detected in the other well, but it is 24 feet higher in elevation. Some minor fractures, such as those at 182 and 202 feet in well 47D-n2, seem to correlate with minor fractures at 150 and 174 feet in well 47D-n3. Although there are no geologist's logs or cutting samples available to determine the actual lithologies of the units, it is evident from other logs of the two wells, especially the single-point resistance and the short- and long-normal resistivity logs, that identical or at least correlatable units were logged, with a dip toward the old well on the northwest. The gamma-ray logs of the wells are almost identical, and they also indicate a horizontal difference of about 24 feet, with an apparent dip to the northwest. The fluid-resistivity logs also show a unit or fracture zone of almost identical extent, at 400 to 450 feet (658 to 608 feet elevation) in the old well (47D-n2) and at 375 to 430 feet (680 to 625 feet elevation) in the new well (47D-n3) to the southeast.

The new well did not produce enough water to be useful (less than 1 gpm). On June 27, 1989, it was hydrofractured in an attempt to increase its yield. This technique involved injecting water at high pressure (up to 3,000 psi) into the sealed well until fractures were forced open. The yield of well 47D-n3 improved to about 5 gpm, but more interesting was the effect on the old well 47D-n2. Before the procedure began, the static water level in the old well was 11.2 feet below land surface. During hydrofracturing of the new well, water began flowing out of the old well. After the procedure it stopped flowing, and after logging the old well again it was found to have filled in from a previous depth of 526 feet to 446 feet (Fig. 65 and Gellici, 1992). Presumably the fill was debris from the deep fracture, which apparently was also the conduit of pressurized water from the well being hydrofractured.

The new well was logged again after hydrofracturing (Fig. 66). The caliper logs show that the fracture in the new well had increased in size from 8 inches to almost 10 inches, but the fracture in the old well had decreased in size. In addition, the water in the new well flowed above land surface after the procedure and has continued to flow or remain very near land surface. The temperature logs in 47D-n3 indicate a sharper change in thermal gradient at the fracture after hydrofracturing than before (Figs. 64 and 66), suggesting improved flow. The fluid-resistivity logs indicate an increase in resistivity above the fracture zone after the hydrofracturing, showing a decrease in dissolved solids, perhaps due to increased flow. The gamma-ray and single-point resistance logs are essentially unchanged, but the spontaneous-potential and the short- and long-normal resistivity logs are substantially different after the hydro-fracturing. The spontaneous-potential log showed a significant increase in negative potential, and both resistivity logs indicated large decreases in resistivity. Why this is so is unknown, for in the old well the spontaneous-potential and resistivity logs remained basically unchanged after hydrofracturing (Figs.63 and 65).

WATER LEVEL FLUCTUATIONS AND THE EFFECTS OF PRECIPITATION

A direct relationship exists between precipitation and ground water levels in the Piedmont. Previous work in two areas at opposite ends of the South Carolina Piedmont indicate that, at least in those two areas (Cherokee and Oconee Counties), the response of water levels in wells to precipitation is rapid, usually on the order of hours or days (Mitchell, 1992). Cumulative precipitation departures from normal[1] were correlated with water levels in two wells for a period of 3½ years (March 1986 to September 1989). Both wells were drilled into bedrock, with the saprolite cased off, and both have caliper logs indicating the presence of fractures.

Hydrographs of precipitation data for the two areas are similar, indicating similar climatic conditions and patterns (Fig. 67). This is not surprising, since the distance between the areas is only about 90 miles. Hydrographs of the two wells also are similar in pattern, emphasizing the direct relationship between precipitation and well water levels. There is also a close similarity between these hydrographs and those for Greenville.

Greenville County is situated about midway between Cherokee and Oconee Counties. The observation well monitored is U. S. Geological Survey well GRV-709 (SCDNR-WRD number 46E-h1) at Brushy Creek Elementary School, and the precipitation data are from the Greenville-Spartanburg Airport National Weather Service Office (Station ID 383747) about 4 miles east of the well. Hydrographs of the observation well and precipitation gage are closely similar to those of the two other areas (Fig. 68). The similarity is especially apparent when comparing hydrographs of the 4 years covered at the Cherokee and Oconee sites (Fig. 69). All three precipitation-departure hydrographs can be seen to affect the water level in the observation wells near them. The well in Cherokee County indicated at certain times a rapid response to precipitation, on the order of hours of response time. The water levels were read by automatic recorder every 6 minutes, so it was possible to record every change in water level over very short periods of time. The well in Oconee County, however, had its water level measured manually on a sporadic basis, so very small responses of its water level to precipitation were impossible to identify. The Greenville well water levels are recorded as daily mean values, so the best response the water levels could show in relationship to precipitation is on the order of days. The averaging of values also tends to mask any possible short-term or sudden response to change. Nevertheless, a good correlation does exist, on at most a response time of just a few days, between the Greenville observation well and the precipitation gage.

All three hydrographs for the precipitation departures follow the same basic climatologic pattern: the driest month is November, the next-driest October; and the wettest month is March, with the next-wettest July. The general overall pattern is high rainfall from early spring to early summer and low rainfall from late fall to early winter.

One of the interesting findings of the earlier work was that although water level hydrographs for the Cherokee and Oconee sites were similar and followed the same general pattern in rising and falling, the order of magnitude of the changes was different. For example, the maximum fluctuation in the period of record for the Oconee well was only 4.4 feet, but the Cherokee well experienced fluctuations, over the same time, of as much as 18 feet. This is especially interesting, when considering that the cumulative departure from normal precipitation in Oconee was 54 inches below normal, while that in Cherokee was a maximum of 19 inches below normal. In Greenville, the maximum cumulative departure for precipitation in the years 1986 to 1989 was only about 2 inches below normal, and the maximum fluctuation in water level for the Greenville well was about 7 feet.

In considering these unusual numbers, it must be kept in mind that in the period of record of the Cherokee and Oconee sites, two of the worst droughts ever recorded in the South Carolina Piedmont occurred in 1986 and 1988. Since that time there has been a gradual return to normal levels for precipitation, and in the late summer of 1994 precipitation in the Greenville area was well above normal. From 1970 to July 1994, the departure from normal precipitation was mostly positive. The droughts of 1986 and 1988 brought the numbers down below normal, and since 1989 the precipitation has remained at about normal levels. The observation well (46E-h1/GRV-709) has been recording since the end of 1974, and since then has shown a maximum fluctuation in water level of 11.5 feet, from a high in October 1984 to the lowest level in February 1989.

In summary, while levels of precipitation form similar patterns across the South Carolina Piedmont, the actual amount, or magnitude, differs greatly from one area to another. Also, the effect of precipitation on ground water levels is similar in pattern and in seasonal trends across the Piedmont, but the magnitude of water level change is highly variable. Whether this is because of differences in the hydraulic properties of the aquifer, or possibly even well construction, is not known.

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[1] Calculated by subtracting measured daily precipitation values from normal daily precipitation values (monthly normals divided by the number of days in the given month), and adding (accumulating) the results daily, whether negative or positive. Periods of drought show downward trends, and periods of precipitation show upward trends.

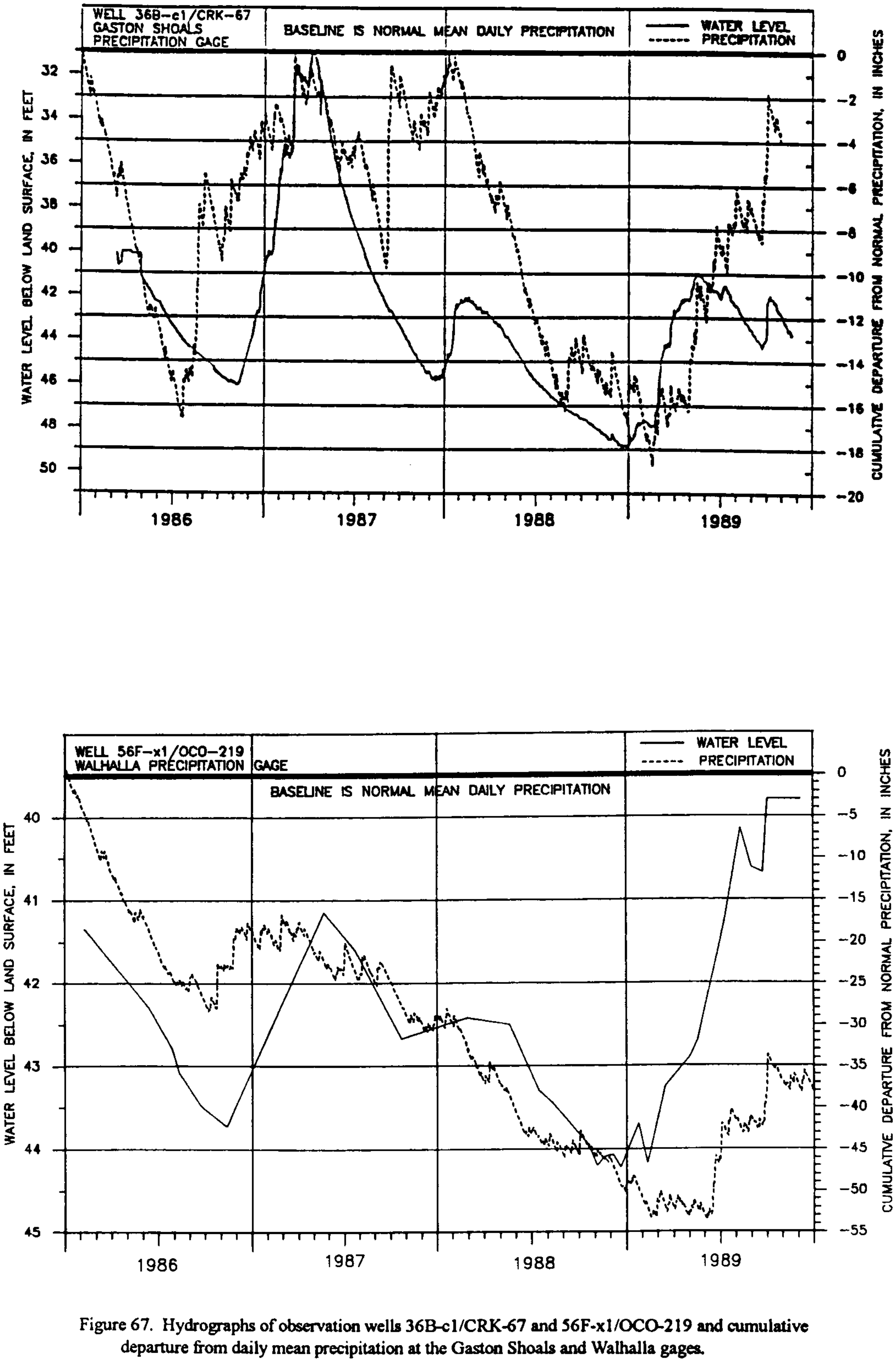

Figure 67. Hydrographs of observation wells 36B-c1/CRK-67 and 56F-x1/OCO-219 and cumulative departure from daily mean precipitation at the Gaston Shoals and Walhalla gages.

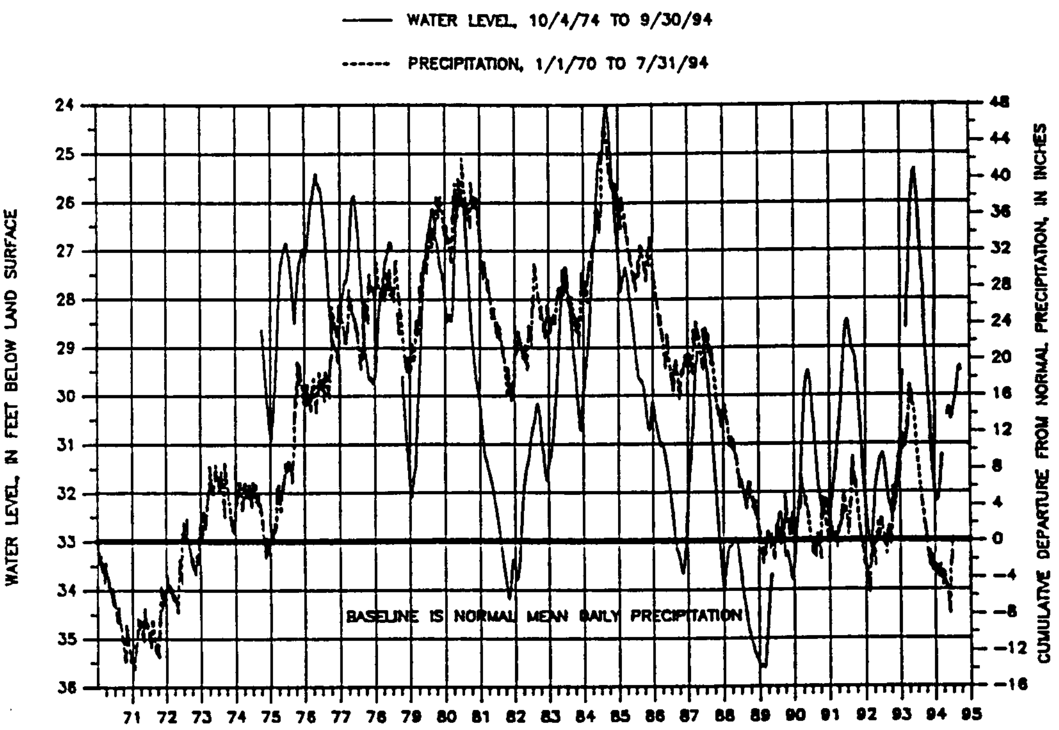

Figure 68. Relationship of daily mean water levels in observation well 46E-h1/GRV-709 to cumulative departure from normal precipitation at the Greenville-Spartanburg airport weather-service station.

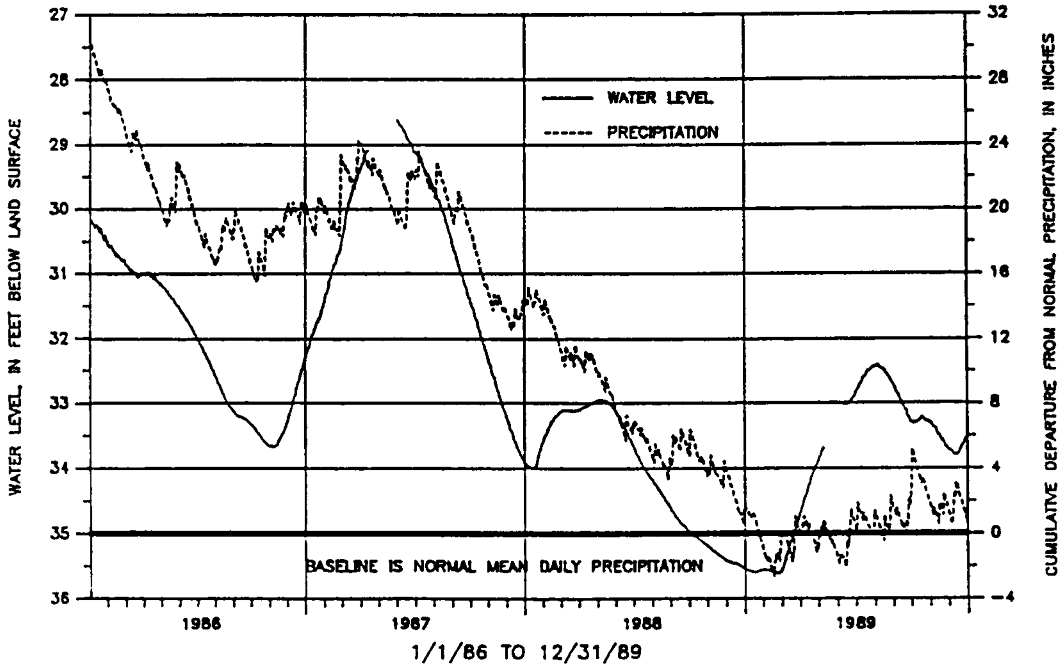

Figure 69. Four-year hydrographs of observation well 46E-h1/GRV-709 and departure from normal daily mean precipitation at the Greenville-Spartanburg airport weather-service station.

CONCLUSIONS

Surface reservoirs and streams furnish most of the water used in Greenville County, including the municipal water system of the city of Greenville. Less prolific but important to much of the populace are the subsurface reservoirs of ground water. As in most Piedmont counties, the wells do not yield copious amounts of water, and, for that reason—in addition to the relative ease and economy of surface-water supply—ground water is not looked at as a viable supply for large users. The reasons for the generally low yields of drilled wells are tied not only to the hydrogeology and other natural factors but also to the fact that a large majority of the wells drilled are for domestic use that do not require large amounts of water. Limited by financial and geographical constraints, owners of domestic wells are understandably reluctant to pay for more drilling than is necessary to provide sufficient water for their needs. Municipal, industrial, public-supply, and other large users, however, can achieve substantial yields (70 or more gallons per minute[1]) if they have access to adequate geographic and geologic criteria and knowledge of how to go about choosing the best site in a given area. Large water users who decide on whether to drill wells in a certain area on the basis of the overall average well yield may be doing themselves a disservice. They need instead to examine the yields of those wells that are sited to achieve maximum yield: that is, those for other large water users already established, as mentioned earlier.

The climate of Greenville County provides the amount of precipitation necessary to maintain the recharge to the ground water system. Indeed, in times of drought that cause surface reservoirs in some rural areas to become dangerously low, a deep well can provide the necessary water.

The quality of the ground water is somewhat acidic (low pH), as is most Piedmont ground water, because of the low buffering capacity of the igneous and metamorphic rocks that make up the fractured bedrock aquifer. The ground water is typically soft, and the water is generally of very good quality. It needs only minor treatment, if any, to remove possible objectionable materials, such as iron, or to moderate the corrosiveness of the acidic water. The vast majority of domestic well owners do not treat their ground water, but use it as it is. Many public suppliers, however, treat their water to comply with SCDHEC and EPA standards, some of which are aesthetic in nature.

Tools are available for better understanding the hydrogeology of the ground water of Greenville County. These include geophysical logs, surface geophysical techniques, geological maps (especially of lineaments and fracture traces), pumping tests, and water quality analyses. These tools should be utilized in an efficient manner, and the information gathered must be studied thoroughly and made easily available for others to learn from it.

In short, the ground water resources of Greenville County are more plentiful than usually realized, and they are of good quality, but they are underutilized, perhaps due to a lack of knowledge about them and fear of relying on a resource traditionally believed to have meager potential.

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[1] This is about 100,000 gallons per day, which is the lower limit for mandatory reporting to the State under the Water-Use Reporting and Coordination Act of 1982 (formerly reported to the Water Resources Commission; since State agency restructuring by the Legislature in 1994, SCDHEC has been the responsible agency); consequently this is an arbitrary but achievable number for wells in Greenville County. About 4 percent of the 6-inch drilled wells in the county have reached this yield. About one-third of these are the high-capacity users, such as public-supply, industrial, and irrigation users, although they account for only about 10 percent of all the 6-inch drilled wells in Greenville County.

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SOUTH CAROLINA DEPARTMENT OF NATURAL RESOURCES
WATER RESOURCES DIVISION REPORT 8

DESCRIPTION OF THE GEOLOGIC UNITS OF GREENVILLE COUNTY

Knoxville 1° X 2° Geologic Map
Inner Piedmont Belt
Paleozoic (?)

cqm Caesars Head Quartz Monzonite: Massive gneissic biotite quartz monzonite and granodiorite, medium to coarse grained, variably equigranular to porphyritic; gradational to and locally similar to the less foliated phase of Henderson Gneiss. Locally contains very large tabular megacrysts of microcline.

hg Henderson Gneiss: Biotite–microcline augen gneiss, medium to coarse grained, generally well foliated, locally fluorite bearing. Finer grained and more foliated adjacent to Brevard fault zone. Grades southeastward to a coarser and less foliated phase, hgg.

bgd Biotite–hornblende granodiorite: Medium grained, mesocratic granodiorite and tonalite, weakly foliated; composition varied, mostly biotite rich but commonly also contains hornblende.

mgm Migmatite: Mostly paragneiss and schist containing 15 to 35 percent leucocratic granitic material of varied composition in sheets, lenses, and dikes an inch to a few feet wide.

Age Unknown

pgs Paragneiss and schist: A heterogeneous assemblage of interlayered biotite–quartz–feldspar gneiss, amphibolite, muscovitic or garnetiferous quartzite, and biotite–garnet–sillimanite schist.

Greenville 1° X 2° Geologic Map
Six Mile Thrust Sheet
Layered or stratified rocks
(Stratigraphic order uncertain)

CZs Biotite–muscovite schist: Interlayered with subordinate layers of sillimanite–mica schist (CZss), and amphibolite.

CZss Sillimanite–mica schist

CZgs Garnet–quartz rock (gondite): Locally gradational into garnet–bearing quartzite.

CZas Amphibolite

CZbs Biotite–plagioclase–quartz gneiss: Contains subordinate biotite–muscovite schist (CZs), megacrystic biotite gneiss (CZps), amphibolite (CZas), rare garnet–quartz rock (CZgs), and granitoid (SOsg)

Intrusive Rocks

SOch Caesars Head Granite (Early Silurian to Ordovician?): Biotite granitoid gneiss or gneissic granitoid, mainly.

SOsg Biotite granitoid gneiss

Paris Mountain Thrust Sheet
(Stratigraphic order uncertain)
(Early Cambrian and/or Late Proterozoic)

CZsp Sillimanite–mica schist
CZap Amphibolite
CZqp Quartzite

Intrusive Rocks

Pzpg Granite gneiss (Paleozoic)

Laurens Thrust Sheet
Layered or stratified rocks
(Stratigraphic order uncertain)
(Early Cambrian and/or Late Proterozoic)

CZgl Biotite (hornblende–sillimanite–microcline–muscovite) gneiss: Interlayered with schist, quartzo–feldspathic gneiss, quartzite or quartz–muscovite schist, granitoid gneiss, amphibolite and metagabbro.

CZal Amphibolite

Intrusive Rocks

Pzgf Granite gneiss

Other

Qal Quaternary alluvium (overlies older rocks)

Mesozoic Brittle Faults and Lineaments

GR	Green River fault	BC	Bobs Creek fault	WS	West Lake Summit fault
ES	East Lake Summit fault	BP	Blakes Peak fault	JC	Joels Creek fault
G	Gap Creek fault	RF	River Falls fault	OCC	Oil Camp Creek lineament
DF	Devils Fork fault	CT	Colt Creek fault	P	Poinsett fault
M-G	Melrose-Gosnell fault	CC-SB	Cox Creek-Short Branch fault	RS	Rocky Spur lineament
HM	Hogback Mountain fault	CR	Chestnut Ridge lineament	CP	Cross Plains fault
PM	Pax Mountain fault	BM	Bullard Mountain fault		

SOURCES

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SEE "LOCATION GRID AND WELL-NUMBERING SYSTEM" IN REPORT FOR EXPLANATION OF LETTER-AND-NUMBER GRID ON MAP.
SEE FIGURES 1 AND 9 FOR LOCATIONS OF CITIES AND HIGHWAYS.

GEOLOGY OF GREENVILLE COUNTY, SOUTH CAROLINA