Statistical Analysis Relating Well Yield to Construction Practices and Siting of Wells in the Piedmont and Blue Ridge Provinces of North Carolina

United States Geological Survey Water-Supply Paper 2341–A

Prepared in cooperation with the North Carolina Department of Natural Resources and Community Development

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879- 1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962- 1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971- 1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

Chapter A

Statistical Analysis Relating Well Yield to Construction Practices and Siting of Wells in the Piedmont and Blue Ridge Provinces of North Carolina

By CHARLES C. DANIEL III

Prepared in cooperation with the North Carolina Department of Natural Resources and Community Development

A statistical analysis of data from more than 6,200 water wells was made to identify geologic, topographic, and construction factors associated with high-yield wells

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2341

GROUND-WATER RESOURCES OF THE PIEDMONT-BLUE RIDGE PROVINCES OF NORTH CAROLINA

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government

UNITED STATES GOVERNMENT PRINTING OFFICE : 1989

For sale by the Books and Open-File Reports Section,
U.S. Geological Survey, Federal Center,
Box 25425, Denver, CO 80225

Library of Congress Cataloging in Publication Data

Daniel, Charles C., III
Statistical analysis relating well yield to construction practices and siting of wells in the Piedmont and Blue Ridge provinces of North Carolina.
(U.S. Geological Survey water-supply paper ; 2341–A)
Supt. of Docs. no. : I 19.13:2341A)
"Prepared in cooperation with the North Carolina Department of Natural Resources and Community Development."
Bibliography: p
1. Water, Underground—North Carolina—Statistical methods. 2. Wells—North Carolina—Statistical methods. 3. Water-supply—North Carolina—Statistical methods. I. North Carolina. Dept. of Natural Resources and Community Development. II. Title. III. Series.
TD224.N8D36 1989 628.1'14'09756 88-600118

CONTENTS

FIGURES

TABLES

METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound unit	By	To obtain SI unit
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	.003785	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	3.785	liter per minute (L/min)
	.003785	cubic meter per minute (m^3/min)
	Flow per Length	
gallon per minute per foot [(gal/min)/ft]	12.418	liter per minute per meter [(L/min)/m]
	.01242	cubic meter per minute per meter [(m^3/min)/m]

ALTITUDE DATUM

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

Statistical Analysis Relating Well Yield to Construction Practices and Siting of Wells in the Piedmont and Blue Ridge Provinces of North Carolina

By Charles C. Daniel III

Abstract

A statistical analysis was made of data from more than 6,200 water wells drilled into the fractured crystalline rocks of the Piedmont, Blue Ridge, and western edge of the Coastal Plain where crystalline rocks underlie sediments at shallow depths. The study area encompassed 65 counties in western North Carolina, an area of 30,544 square miles, which comprises nearly two-thirds of the State. Additional water supplies will be needed in western North Carolina as population and industrial development continue to increase. Ground water is an attractive alternative to surface-water sources for moderate to large supplies. The statistical analysis was made to identify geologic, topographic, and construction factors that are associated with high-yield wells.

It is generally believed that the crystalline rocks of the Piedmont and Blue Ridge provinces yield only small amounts of water to wells, that water is obtained from vertical fractures that pinch out at a depth of about 300 feet because of lithostatic pressure, and that the function of a large diameter well is primarily for storage. These concepts are reasonable when based upon the fact that the average well drilled in these rocks is a domestic well, 125 feet deep, 6 inches or less in diameter, and located on a hill or ridge. However, statistical analysis shows that wells in draws or valleys have average yields three times those of wells on hills and ridges. Wells in the most productive hydrogeologic units have average yields twice those of wells in the least productive units. Wells in draws and valleys in the most productive units average five times more yield than wells on hills and ridges in the least productive units.

Well diameter can have a significant influence on yield; for a given depth, yield is directly proportional to well diameter. Maximum well yields are obtained from much greater depths than previously believed. For example, the average yield of 6-inch diameter wells located in draws and valleys can be expected to reach a maximum of about 45 gallons per minute at depths of 500 to 525 feet; for similarly located 12-inch diameter wells, the average yield can be expected to reach a maximum of about 150 gallons per minute at depths of 700 to 800 feet.

INTRODUCTION

Additional water supplies will be needed in the Piedmont and Blue Ridge provinces of North Carolina (fig. 1) as population and industrial development continue to increase. Municipal and industrial water supplies are derived almost exclusively from surface water sources. However, the potential for further development of surface water is limited, and ground water is an attractive alternative for moderate to large water supplies.

Ground water has many attractive features as a source of supply. Ground water in the crystalline rocks of the Piedmont and Blue Ridge provinces has a relatively low cost of development (Cederstrom, 1972).Generally, ground water in these areas is of good chemical quality and requires little treatment. Because of the large quantity of water in storage, the ground-water system usually can sustain moderate yields during seasonal dry periods. The use of ground water generally permits other land-use activities if they do not impede the infiltration of recharge or diminish water quality.

The crystalline rocks that underlie the Piedmont and Blue Ridge are reputed to furnish only small quantities of ground water. This impression is the outgrowth of drilling large numbers of domestic wells that do not represent efforts to obtain quantities of water beyond the minimum requirement of 2 to 10 gallons per minute (gal/min). About 70 percent of all wells drilled in the Piedmont and Blue Ridge are for domestic supply, and most were located and drilled without regard to geology,topography, and optimal construction. In spite of these shortcomings, a significant number of wells yield a few tens to a few hundreds of gallons per minute. Additional high-yield wells likely can be developed at carefully selected sites throughout the area.

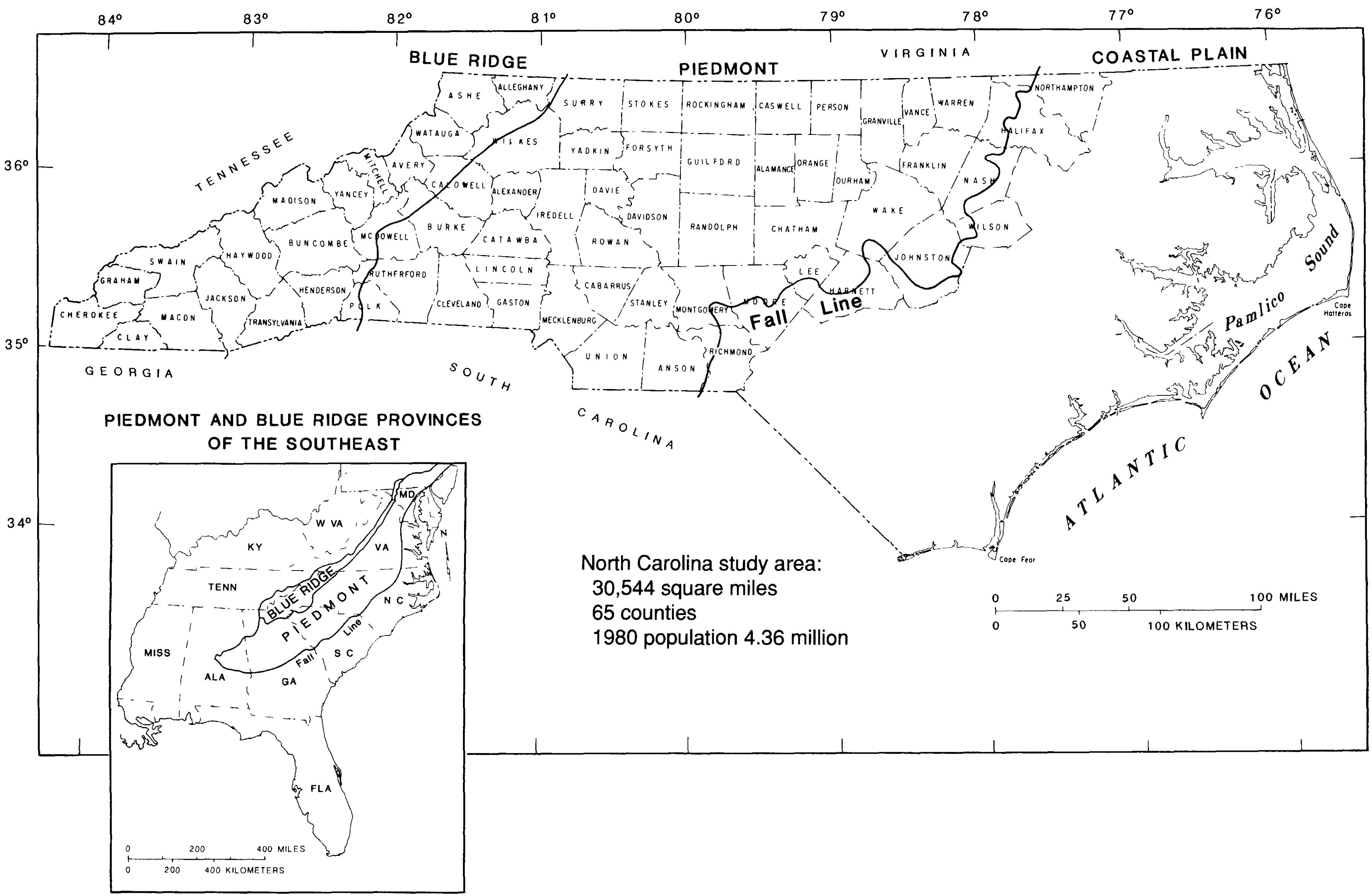


Figure 1. Area of investigation showing counties and physiographic provinces.

Results of studies in several areas of the Piedmont, both within and outside North Carolina, show that the ground-water system can support large well yields. For example, Daniel and Sharpless (1983) reported finding more than 300 wells in an eight-county area of central North Carolina that produce 50 gal/min or more. Cressler and others (1983) found a substantial number of wells in the Georgia Piedmont that yield more than 100 gal/min and some that yield nearly 500 gal/min. They also found 66 mainly industrial and municipal wells that had been in use for periods of 12 to more than 30 years without experiencing declining yields. Similarly, Cederstrom (1972) found that yields of 100 to 300 gal/min are not uncommon for bedrock wells in the Piedmont and Blue Ridge provinces from Maine to Virginia.

To evaluate the potential for large ground-water supplies in the Piedmont and Blue Ridge provinces of North Carolina, the U.S. Geological Survey—in cooperation with the North Carolina Department of Natural Resources and Community Development—conducted a 5-year study of ground-water resources in the region. This report is part of that study.

Purpose and Scope

This report describes a statistical analysis of data from a large number of water wells in the Piedmont and Blue Ridge provinces of North Carolina. The analysis was undertaken to identify factors that are associated with high-yield wells.

The statistical analysis was made by using hydrologic, geologic, topographic, and well-construction data that were obtained from records of more than 6,200 water wells. The wells are in an area including all of the Piedmont and Blue Ridge provinces in the State and an adjoining narrow strip at the western edge of the Coastal Plain province where a number of wells draw water from Piedmont crystalline rocks at shallow depth beneath the sedimentary cover. The study area encompassed 65 counties in North Carolina, an area of 30,544 square miles (mi^2), which comprises nearly two-thirds of the State (fig. 1).

The records of water wells, obtained from published sources, were used to compile information on well yields and water levels; use of the water; well-construction variables such as total depth, diameter, and casing depth; and the siting of wells in relation to topography and geology. A total of 14 geologic terranes considered to be hydrologically significant were identified in the study area. Within these terranes are 21 major rock types of igneous, metaigneous, metasedimentary, metavolcanic, and sedimentary origin that are considered to have quantifiable hydrogeologic properties. Because of their hydrogeologic properties, these major rock types are designated herein as hydrogeologic units.

The data on both geologic terranes and hydrogeologic units were obtained largely from the work, both published and unpublished, of other investigators. Field studies were kept to a minimum.

Previous Investigations

Between 1946 and 1971, a total of 14 reconnaissance ground-water investigations (fig. 2) were completed that provided information on ground-water resources in all the counties in the Piedmont and Blue Ridge provinces of North Carolina. All but one of these reports (Peace and Link, 1971) were prepared by the U.S. Geological Survey in cooperation with various North Carolina State agencies. Included in the 14 reports, which were the main sources of data for this report, are maps showing well locations in each county and tables of well records providing details of well construction, yield, use, topographic setting, water-bearing formation, plus miscellaneous notes.

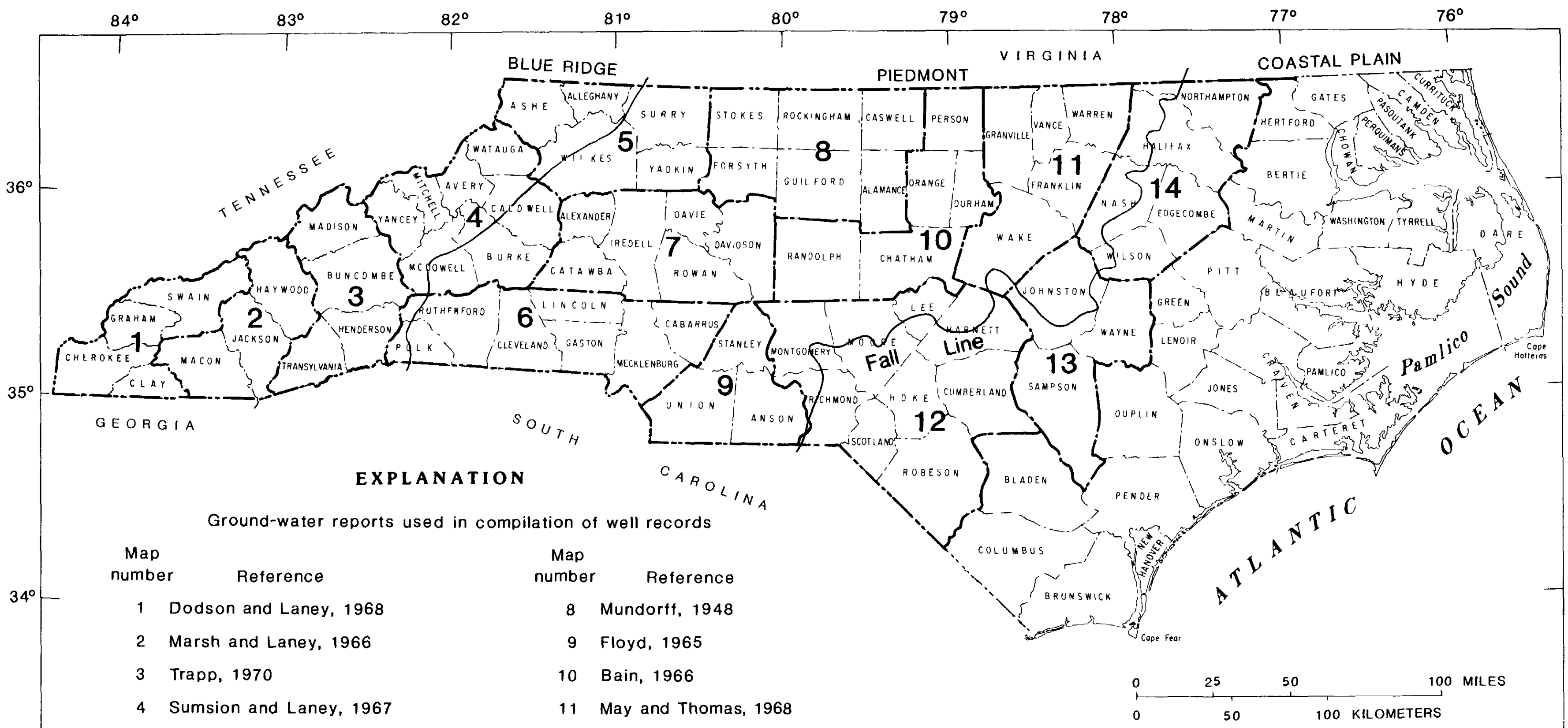
DESCRIPTION OF THE STUDY AREA

Physiography

North Carolina lies in three physiographic provinces of the southeastern United States (fig. 3): the Blue Ridge, the Piedmont, and the Coastal Plain (Fenneman, 1938).

The Blue Ridge province in western North Carolina contains the greatest mountain masses, highest altitudes, and the most rugged topography in eastern North America. The province is marked by steep, forest-covered slopes that are cut by numerous small stream valleys. More than 40 peaks are greater than 6,000 feet (ft) in altitude and another 82 peaks are between 5,000 and 6,000 ft in altitude (Conrad and others, 1975). The province is bounded on the west in Tennessee by the Ridge and Valley province. On the east, the boundary of the Blue Ridge with the Piedmont province is marked by the escarpment of the Blue Ridge front—a prominent topographic feature thought in part to be associated with faulting. The Blue Ridge front rises more than 1,700 ft above the Piedmont surface at the North Carolina-Virginia border and reaches a maximum relief of nearly 2,500 ft in central North Carolina.

The topography of the Piedmont consists of low, well-rounded hills and long, rolling, northeast-trending ridges. The tops of many ridges and interstream divides are relatively flat. They are thought to be remnants of the Piedmont peneplain, an ancient erosional surface of low relief. More recent erosion and downcutting by streams has dissected the Piedmont peneplain and created a local topographic relief of 100 to 200 ft between interstream divides and stream bottoms. The Piedmont surface is 300 to 600 ft



EXPLANATION

Ground-water reports used in compilation of well records

Map number	Reference	Map number	Reference
1	Dodson and Laney, 1968	8	Mundorff, 1948
2	Marsh and Laney, 1966	9	Floyd, 1965
3	Trapp, 1970	10	Bain, 1966
4	Sumsion and Laney, 1967	11	May and Thomas, 1968
5	Peace and Link, 1971	12	Schipf, 1961
6	LeGrand and Mundorff, 1952	13	Pusey, 1960
7	LeGrand, 1954	14	Mundorff, 1946

Figure 2. Study areas of reconnaissance ground-water investigations that were the sources of well data for this study.

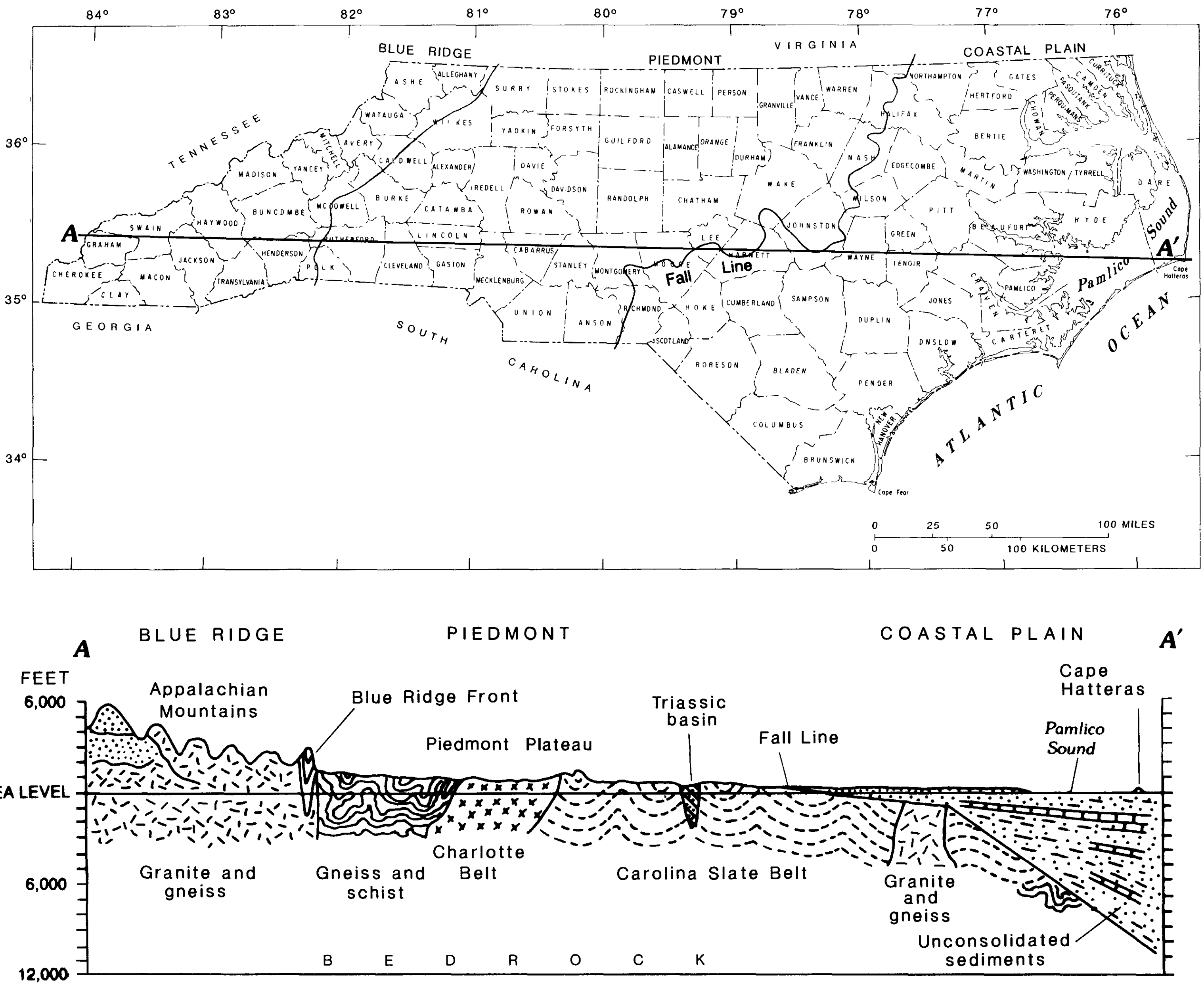


Figure 3. Physical setting of the ground-water system in North Carolina (modified from Heath, 1980).

in altitude along the eastern border and rises gradually to the west to about 1,500 ft in altitude at the foot of the Blue Ridge front.

Scattered across the rolling Piedmont surface are remnants of once higher mountains that because of their resistance to erosion stand as much as 500 to 1,600 ft above the local land surface. Some form prominent lines of hills. Others are isolated hills and mountains, called monadnocks, that stand alone above the Piedmont surface and, although more common in the western Piedmont, are found throughout the province.

The Piedmont is bounded on the east by the Fall Line where the hard crystalline rocks of the Piedmont give way to the softer sedimentary rocks of the Coastal Plain province. At the Fall Line, the swift-flowing streams of the Piedmont enter the Coastal Plain over a zone of rapids and low falls.

The Coastal Plain has little relief in contrast to the adjoining Piedmont. It is marked by sluggish streams flowing in broad valleys cut into predominantly sand and clay units that thicken seaward from a feather edge at the Fall Line. Along the western edge of the Coastal Plain, the sediments are underlain at shallow depth by crystalline Piedmont rocks (fig. 3).

Geology

The geology of the Piedmont and Blue Ridge is extremely complex. All major classes of rocks—metamorphic, igneous, and sedimentary—are represented, although metamorphic rocks are the most abundant. The metamorphic and igneous rocks range in composition from felsic to ultramafic and range in age from Precambrian in the Blue Ridge to Triassic and Jurassic in the Piedmont. The metamorphism of the rocks varies in grade from low rank to high rank; that is, varying in degree of recrystallization and destruction of the original texture; many have been folded and refolded during multiple metamorphic and orogenic events. The rocks are broken and displaced by numerous faults and zones of shearing, some of which are many miles in length. Nearly everywhere are rock fractures without displacement called joints. The joints commonly cluster in groups orientated about one or more preferred directions. Within the crystalline rocks of the Piedmont are downfaulted basins (grabens) filled with sedimentary rocks of Triassic age.

Three or more periods of igneous intrusion (Fullagar, 1971) have resulted in the emplacement of plutonic bodies that range in size from batholiths down to dikes, sills, and veins. Most intrusions have been metamorphosed, deformed, and fractured, but some are massive and have little or no foliation. All rocks have been subjected to uplift, weathering, and erosion, which resulted in the widening of fractures and the formation of new openings such as stress-relief fractures. These breaks in the otherwise solid rock are the conduits for ground-water flow. All of the events and processes that are part of the geologic history of the area have given the hydrogeologic system properties that control the present-day movement and circulation of ground water.

Bedding and planes of metamorphic foliation generally are folded and tilted and can have almost any attitude and orientation. Fractures, bedding, and foliation create inhomogeneities in the rocks and result in permeability that is usually greatest parallel to bedding, foliation, and zones of fracture concentration; permeability is usually least at right angles to the plane of these features.

Bedrock may be exposed at land surface on steep slopes, rugged hilltops, or in stream valleys, but nearly everywhere else it is overlain by unconsolidated material that may reach depths greater than 100 ft. Collectively this unconsolidated material, which is composed of saprolite, alluvium, and soil, is referred to as regolith. Saprolite is clay-rich, residual material derived from in-place weathering of the bedrock. When the bedrock weathers to form saprolite, the relict structures generally are retained, and the directional properties of permeability are also retained. In many valleys, the saprolite has been removed by erosion, and bedrock is exposed or thinly covered by alluvial deposits. Soil is present nearly everywhere as a thin mantle on top of both the saprolite and alluvium. The water-storing and transmitting characteristics of bedrock and regolith and the hydrologic relation between them determines the water-supply potential of the ground-water system in the Piedmont and Blue Ridge provinces.

Hydrogeologic Units

Within the Piedmont and Blue Ridge of North Carolina there are hundreds of rock units that have been defined and named by various conventions more in keeping with classical geologic nomenclature than hydrologic terminology. The geologic nomenclature does little to reflect the water-bearing potential of the different units. To overcome this shortcoming and to reduce the number of rock units to the minimum necessary to reflect the differences in water-bearing potential, a classification scheme based on origin, composition, and texture was devised (table 1). The rationale behind the hydrogeologic units shown in table 1 is the hypothesis that these factors would be linked not only to a rock's primary porosity but also to its susceptibility to the development of secondary porosity in the form of fractures and solution openings. The composition and texture would also determine, in part, the rate and depth of weathering of these units and the water-bearing properties of the resulting regolith.

The origin of the hydrogeologic units is indicated by the rock class (igneous, metamorphic, or sedimentary) or

Table 1. Classification and lithologic description of hydrogeologic units in the Piedmont and Blue Ridge provinces of North Carolina

Symbol	Hydrogeologic unit	Lithologic description
		IGNEOUS INTRUSIVE ROCKS
IFI	Igneous, felsic intrusive	Light-colored, mostly granitic rocks, fine- to coarse-grained, some prophyritic, usually massive, locally foliated; includes granite, granodiorite, quartz diorite, quartz monzonite, alaskites.
III	Igneous, intermediate intrusive	Gray to greenish-gray, medium- to coarse-grained, massive rocks of dioritic composition; includes assemblages of closely associated diorite and gabbro where they are too closely associated to be mapped separately.
IMI	Igneous, mafic intrusive	Dark-greenish-gray to black, medium- to coarse-grained intrusive bodies; primarily gabbroic in composition, includes closely associated gabbro and diorite where they are too closely associated to be mapped separately, ultramafic rocks, diabase, dunite.
		METAMORPHIC ROCKS
		Metaigneous Rocks (Intrusive)
MIF	Metaigneous, felsic	Light-colored, massive to foliated metamorphosed bodies of varying assemblages of felsic intrusive rock types; local shearing and jointing are common.
MII	Metaigneous, intermediate	Gray to greenish-gray, medium- to coarse-grained, massive to foliated, well-jointed, metamorphosed bodies of dioritic composition.
MIM	Metaigneous, mafic	Massive to schistose greenstone, amphibolite, metagabbro and metadiabase, may be strongly sheared and recrystallized; metamorphosed ultramafic bodies are often strongly foliated, altered to serpentine, talc, chlorite-tremolite schist and gneiss.
		Metavolcanic Rocks (Extrusive-Eruptive)
MVF	Metavolcanic, felsic	Chiefly dense, fine-grained, light-colored to greenish-gray felsic tuffs and felsic crystal tuffs, includes interbedded felsic flows. Felsic lithic tuffs, tuff breccias, and some epiclastic rocks; recrystallized fine-grained groundmass contains feldspar, sericite, chlorite, and quartz. Often with well-developed cleavage, may be locally sheared; phyllitic zones are common throughout the Carolina slate belt.
MVI	Metavolcanic, intermediate	Gray to dark-grayish-green tuffs and crystal tuffs generally of andesitic composition; most with well-developed cleavage; also includes interbedded lithic tuffs and flows of probable andesitic and basaltic composition and minor felsic volcanic rocks.
MVM	Metavolcanic, mafic	Grayish-green to dark-green, fine- to medium-grained andesitic to basaltic tuffs, crystal tuffs, crystal-lithic tuffs, tuff breccias and flows; pyroclastic varieties may contain lithic fragments; usually exhibits prominent cleavage; alteration minerals include chlorite, epidote, calcite, and tremolite-actinolite.
MVE	Metavolcanic, epiclastic	Primarily coarse sediments including interbedded graywackes and arkoses and minor conglomerates, interbedded argillites and felsic volcanic rocks; much of the sequence is probably subaqueous in origin and most of the rocks were derived from volcanic terranes.
MVU	Metavolcanic, undifferentiated	Volcanic rocks of all origins (extrusive and eruptive) and compositions (felsic to mafic) interbedded in such a complex assemblage that mapping of individual units is not practical.
		Metasedimentary Rocks
ARG	Argillite	Fine-grained, thinly laminated rock having prominent bedding plane and axial plane cleavage; locally includes beds of mudstone, shale, thinly laminated siltstone, conglomerate, and felsic volcanic rock.
GNF	Gneiss, felsic	Mainly granitic gneiss; light-colored to gray, fine- to coarse-grained rocks, usually with distinct layering and foliation, often interlayered with mafic gneisses and schists.
GNM	Gneiss, mafic	Mainly biotite hornblende gneiss; fine- to coarse-grained, dark-gray to green to black rock, commonly with distinct layering and foliation, often interlayered with biotite and hornblende gneisses and schists, and occasional amphibolite layers.
MBL	Marble	Fine- to medium-grained, recrystallized limestone and dolostone; found primarily in the Blue Ridge belt.
PHL	Phyllite	Light-gray to greenish-gray to white, fine-grained rock having well-developed cleavage; composed primarily of sericite but may contain chlorite; phyllitic zones are common throughout the Carolina slate belt and probably represent zones of shearing although displacement of units is usually not recognizable.

Table 1. Classification and lithologic description of hydrogeologic units in the Piedmont and Blue Ridge provinces of North Carolina—Continued

Symbol	Hydrogeologic unit	Lithologic description
QTZ	Quartzite	Metasandstone, often feldspathic to highly feldspathic, thin- to thick-bedded with occasional graded bedding, includes meta-arkose and metaconglomerate; often interbedded with mica schist, phyllite, and slate.
SCH	Schist	Schistose rocks containing primarily the micas muscovite or biotite or both, occasional sericite and chlorite schists; locally interlayered with hornblende gneiss and schist, commonly with distinct layering and foliation.
SLT.....	Slate	Fine-grained metamorphic rock formed from such rocks as shale and volcanic ash, possesses the property to part along planes independent of the original bedding (slaty cleavage).
		MISCELLANEOUS
TRI	Triassic sedimentary rocks	Mainly red beds, composed of shale, sandstone, arkose, and conglomerate (fanglomerate near basin margins).
CPL.....	Coastal Plain basement	Undifferentiated crystalline basement rocks of igneous and metamorphic origin overlain unconformably by sedimentary sands, gravels, clays, and marine deposits.

subclass (metaigneous, metavolcanic, or metasedimentary). The composition of the igneous, metaigneous, and metavolcanic rocks is designated as felsic, intermediate,or mafic except for the addition in the metavolcanic group of epiclastic rocks and compositionally undifferentiated rocks. These last two groups were necessary because of the significant areas of epiclastic rocks where reworking by sedimentary processes and admixture of terrigenous sediment during deposition made the rocks texturally distinct and the other areas where the complex and small-scale stratigraphic changes made differentiation of separate units impractical. Composition is also shown in the metasedimentary units of gneiss, marble, and quartzite. The other metasediments are designated primarily on the basis of texture (grain size, degree of metamorphism, and development of foliation).

The two miscellaneous classifications account for the sedimentary rocks within the Triassic basins and the undifferentiated crystalline basement rocks east of the Fall Line that are overlain unconformably by sediments of Cretaceous age and younger.

By using the classification scheme in table 1 and the most recent geologic maps available (fig. 4), a hydrogeologic unit map was compiled for the study area. Part of this map for Guilford and Alamance Counties in the north-central Piedmont (fig. 1) is shown in figure 5. Well-location maps were later superimposed on this hydrogeologic unit map, and the units corresponding to the well locations were coded and entered into a computerized data file for analysis to determine the well yields in each unit.

Geologic Belts and Terranes

The Piedmont and Blue Ridge have been divided into a number of northeast-trending geologic belts (fig. 6). Within a belt, rocks are to some degree similar to each other with respect to general appearance, metamorphic rank, structural history, and relative abundance of igneous, metaigneous, metasedimentary, and metavolcanic rocks (Butler and Ragland, 1969). Areally, the most significant are the Blue Ridge, Inner Piedmont, Charlotte, Carolina slate, and Raleigh belts. Two geologic terranes important to this study have been added to the generally recognized belts. These are the Triassic basins and the Coastal Plain immediately east of the Fall Line. A brief summary of the belts and the hydrogeologic units that constitute the belts is given in table 2. Wells tapping rocks within these belts and terranes were analyzed to determine well yields within each area.

COMPILATION OF THE DATA BASE AND STATISTICAL PROCEDURES

Information on 6,224 wells was compiled from published sources (fig. 2) and statistically analyzed to identify relations between well yield and various geologic, topographic, and construction factors. This compilation contained well records from every county in the 65-county study area and included 419 wells that derive water from crystalline rocks buried beneath the thin sedimentary cover along the western edge of the Coastal Plain (fig. 3).

Information Categories in the Data Base

Specific types of information categories (variables) in the data base included (1) the county where the well is located, (2) the published well number, (3) the total depth of the well, (4) well diameter, (5) casing depth, (6) static water level below land surface, (7) yield, (8) intended use when drilled, (9) the topographic setting of the well site, (10) the hydrogeologic unit into which the well is drilled, (11) the geologic belt or terrane in which the hydrogeologic unit is found, and (12) the reference to the published report

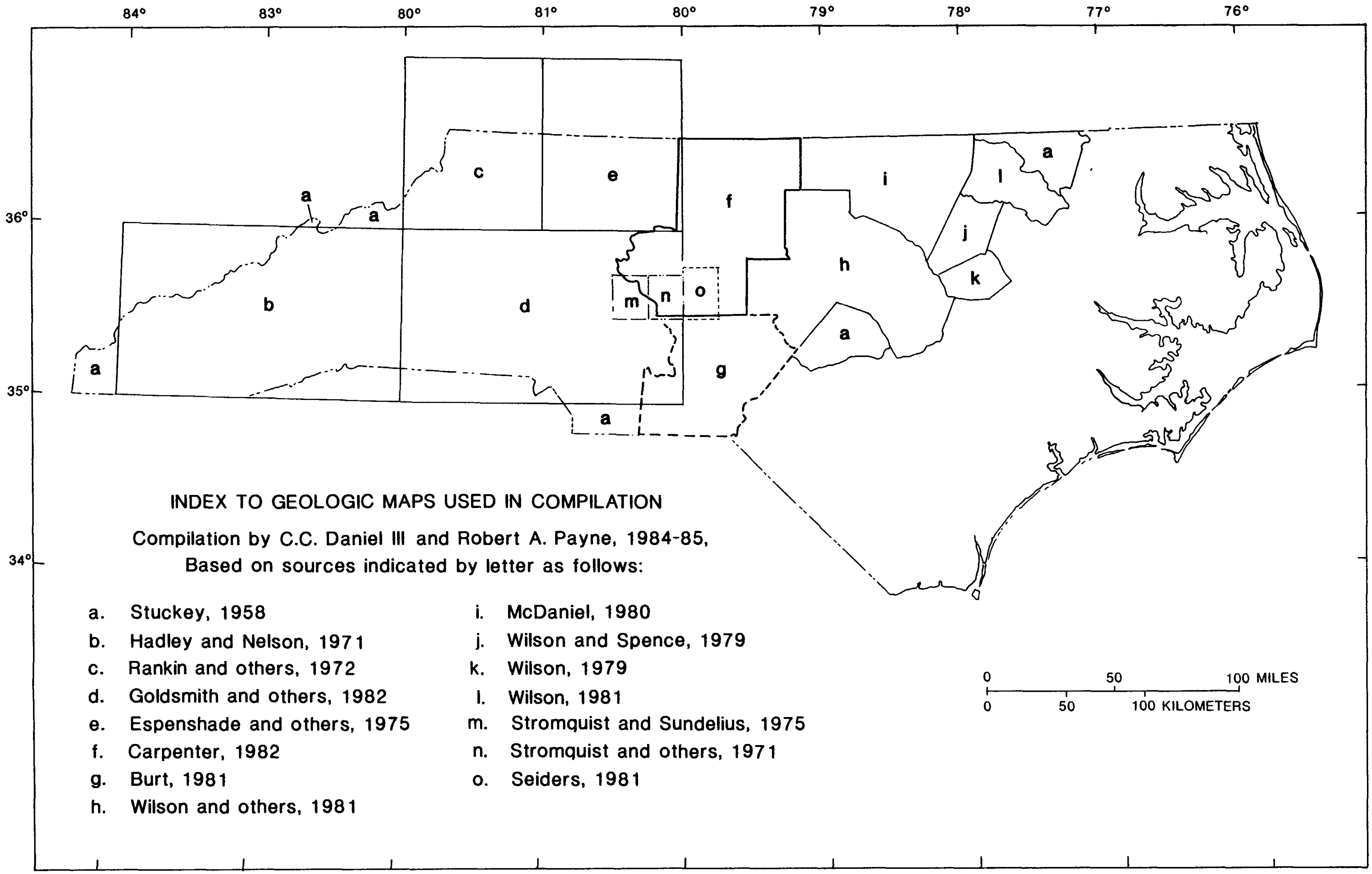


Figure 4. Areas of geologic maps used in compilation of the hydrogeologic unit map of the Piedmont and Blue Ridge provinces.

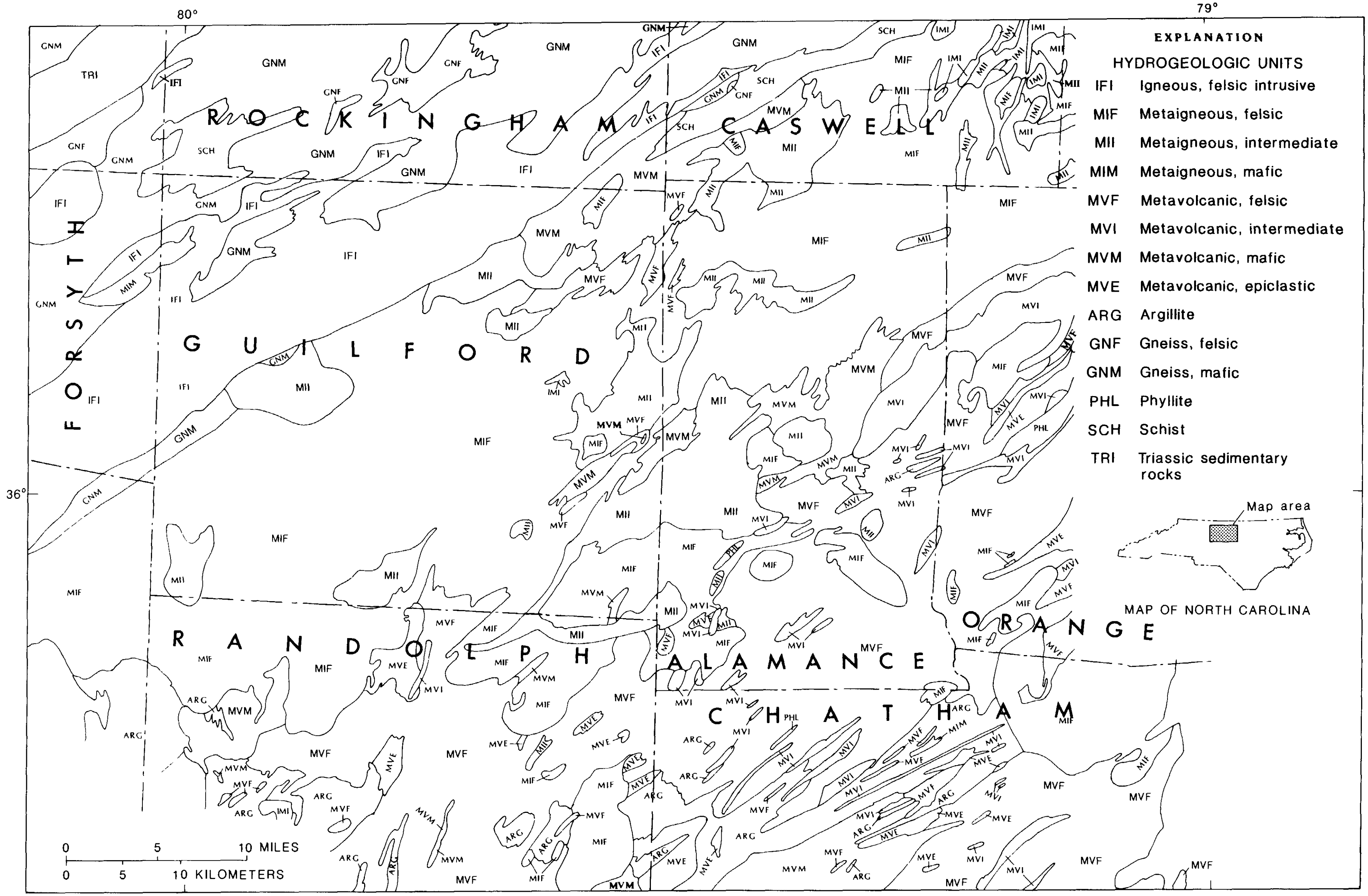


Figure 5. Hydrogeologic unit map of Guilford and Alamance Counties and vicinity in the north-central Piedmont of North Carolina.

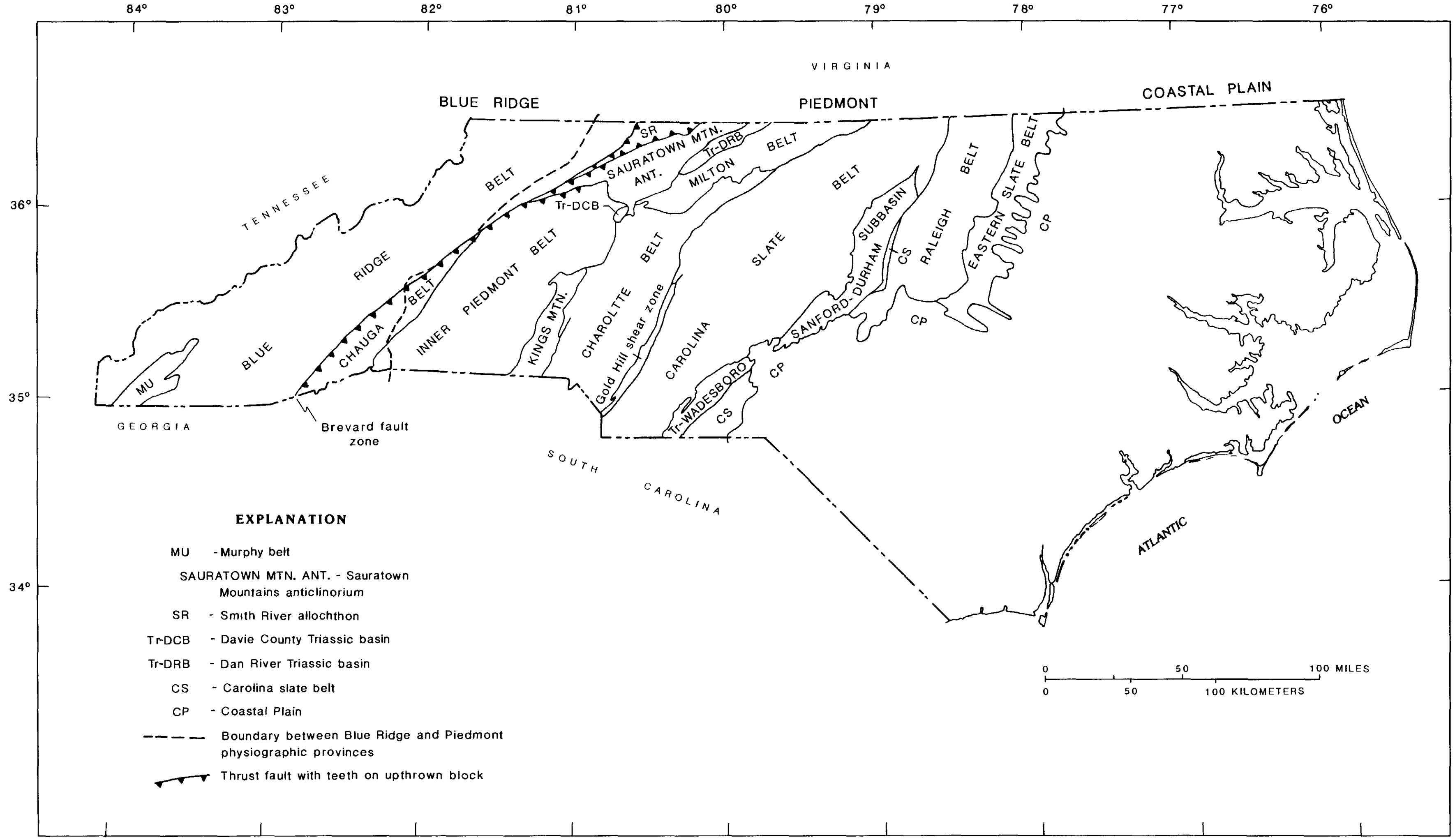


Figure 6. Geologic belts, terranes, and some major structural features within the Piedmont and Blue Ridge provinces of North Carolina (from Brown and Parker, 1985).

Table 2. Geologic belts and terranes of the Blue Ridge, Piedmont, and Coastal Plain provinces of North Carolina
[The hydrogeologic units are described in table 1]

Belt or terrane	Letter designation	Boundaries	Dominant hydrogeologic units
Murphy belt	MU	Surrounded by metasedimentary rocks of Blue Ridge belt.	SCH, SLT, MBL.
Blue Ridge belt	BR	Sedimentary rocks of Ridge and Valley on northwest and Brevard fault zone on southeast.	GNF, GNM, SCH, QTZ, PHL.
Chauga belt (includes Brevard fault zone).	CA	Blue Ridge belt on northwest, Inner Piedmont on southeast.	GNF, GNM.
Inner Piedmont belt	IP	Chauga and Blue Ridge belts on northwest, Kings Mountain and Charlotte belts on southeast.	GNM, MIF.
Smith River allochthon.	SR	Blue Ridge belt on northeast and Sauratown Mountains anticlinorium on southeast.	GNF.
Sauratown Mountains anticlinorium.	SA	Smith River allochthon on northwest, Inner Piedmont belt on southwest, and Dan River Triassic basin and Milton belt on southeast.	GNM, GNF, QTZ.
Kings Mountain belt	KM	Inner Piedmont belt on northwest and Charlotte belt on southeast.	SCH, MIF, GNF.
Charlotte belt	CH	Kings Mountain and Inner Piedmont belts on northwest, Milton belt on north, Gold Hill shear zone and Carolina slate belt on southwest.	MII, MIF, MIM, IFI, MVU.
Milton belt	MI	Igneous and metaigneous rocks of Charlotte belt on south, Carolina slate belt on southeast, Dan River Triassic basin and Sauratown Mountains anticlinorium on northwest.	GNM, GNF.
Gold Hill shear zone	GH	Metavolcanic and metaigneous rocks of Charlotte belt on northwest and metavolcanic rocks of Carolina slate belt on southeast.	PHL.
Carolina slate belt	CS	Gold Hill, Charlotte, and Milton belts on northwest, Coastal Plain on southeast.	ARG, MVE, MVU in southwestern half of belt—MVF, ARG, MVU, MIF, MII in northeastern half of belt.
Raleigh belt	RA	Bordered by Carolina slate belt rocks on east and west, Coastal Plain sediments on the south.	MIF, GNF, SCH.
Triassic basins	TR	Several bodies of sedimentary rock downfaulted into the metamorphic crystalline rocks of the Piedmont.	TRI.
Coastal Plain	CP	Western edge of Coastal Plain province.	CPL.

from which the well record was obtained. The total number of entries for each variable is shown in table 3.

For inclusion in the data base, a well had to satisfy certain requirements. The well had to be drilled into bedrock, and the yield and location had to be known. All wells in the resulting compilation are cased to the top of bedrock and have no screened or slotted intervals in the regolith, and nearly all are finished as open holes drilled into bedrock. A small number of wells included in the data base have casing, slotted casing, or screen extending into bedrock to prevent fragmental rock debris from entering the well bore. An extreme example is a well that is 600 ft deep and is cased to the bottom of the hole. No other well has more than 300 ft of casing, and only 157 wells, or 2.5 percent, are cased to within the bottom 5 ft of the well.

Table 3. Total number of entries for each variable in the water-well data base

Variable	Total number of data entries
County	6,224
Well number	6,224
Total depth	6,204
Well diameter	6,060
Casing depth	4,038
Static water level	3,130
Yield	6,224
Use	6,205
Topographic setting	5,234
Hydrogeologic unit	6,224
Geologic belt	6,224
Reference	6,224

The wells range in diameter from 1.25 to 15 inches (in.), and most (69 percent) of the wells have diameters between 5.5 and 6.5 in. Only two drilled wells were as large as 15 in.

Large-diameter bored or dug wells were not included in the compilation because these wells are not typical of modern well construction. Nearly all new wells in the Piedmont and Blue Ridge are drilled by air rotary methods. Further, large-diameter wells are rarely dug below the top of bedrock and do not represent attempts to obtain quantities of water beyond that necessary for domestic supplies.

Transparencies were made of well-location maps given in the published sources (fig. 2) and overlaid on maps of the hydrogeologic units and geologic belts to assign the wells to the units and belts in which they occur. The hydrogeologic units reported in these publications were not entered into the data file because of the conflicting variety of names and naming conventions that were used by the many authors. The reported hydrogeologic units were not ignored, however. If a well was located on or near a contact between units used in this report, the published description helped guide the choice in the assignment of the unit and in some places pointed out the need for revisions to the hydrogeologic unit map. The published reports also were used to identify wells drilled into diabase dikes. Diabase dikes are common in the Piedmont (Reinemund, 1955; Weigand and Ragland, 1970; Ragland and others, 1983), but generally they are too narrow to accurately correlate with well locations at the scale of the maps being used. Wells drilled into diabase dikes are included in the igneous, mafic intrusive (IMI) hydrogeologic unit. By using a combination of the new maps and the published descriptions, each well in the data base subsequently was assigned to 1 of the 21 hydrogeologic units.

All data related to well construction, yield, topographic setting, and static water level were entered as reported. The intended use of each well was inferred from the listed owner and other information in the remarks column of the well-record tables. Wells were placed in one of three use categories: domestic, commercial-industrial, and public supply. Domestic wells serve single family residences or, at most, a small number of homes. The commercial-industrial category includes wells that serve businesses ranging in size from large mills and factories down to service stations and small shops. Public-supply wells serve municipalities, subdivisions, trailer parks, hospitals, churches, campgrounds, and other facilities having a relatively large number of users.

Every item of information was not available for every well. The static water level had the fewest number of data entries; water levels were reported for only slightly more than one-half of the wells. The second smallest number of entries was for casing depth; less than two-thirds of the well records had this information. The other variables had much more complete records. The effect of these incomplete records will be seen in the statistical analyses that follow, especially for computations that are based on more than one variable. For example, in a calculation of yield per foot of well depth by topographic setting, the variables yield, depth, and topographic setting had 6,224, 6,204, and 5,234 data entries, respectively. Yet the final computation was based on the 5,221 wells for which all three items of information were available. This was generally the pattern; the final computation was based on no more than and commonly fewer observations than the smallest number of variable entries.

Statistical Procedures

The data were statistically analyzed by using programs developed by the SAS Institute (SAS Institute, Inc., 1982a) that are available on the U.S. Geological Survey computer system in Reston, Va. The most commonly used SAS procedures were SORT, UNIVARIATE, RSQUARE, GLM, and ANOVA.

The SORT procedure (SAS Institute, Inc., 1982a) is a SAS utility procedure that sorts observations in a data set by one or more variables. In this study, the SORT procedure was used to sort the well data by topographic position, use, hydrogeologic unit, and geologic belt so that statistics could be computed for the sorted groups of data.

The UNIVARIATE procedure (SAS Institute, Inc., 1982a) produces simple descriptive statistics including the mean, median, range, standard deviation, and quantiles for numeric variables.

A SAS procedure called RSQUARE (SAS Institute, Inc., 1982b) was used for regression analysis because it allows many possible regressions to be fitted to the data and systematically analyzed to identify those combinations of variables that best explain the variation in the data. Those variables that repeatedly appeared in the models offering the highest r-square were further tested by using SAS procedure GLM (General Linear Models) (SAS Institute, Inc., 1982b), which uses the method of least squares to determine regression coefficients, intercepts, and statistical properties of the models being tested.

Analysis-of-variance tests using the procedure ANOVA (SAS Institute,Inc., 1982b) were made of the data in the topographic classifications, hydrogeologic unit classifications, and geologic belt classifications to determine if any of the apparent differences, or lack of differences, in mean values are statistically valid. Because the sample cells have unequal numbers of observations, Tukey's studentized range test, honestly significant difference (HSD) procedure (Steel and Torrie, 1960, p. 109–110), was used to make the multiple comparisons and to test for significant differences at the 0.95 confidence level. Unequal cell size was not the only reason for using Tukey's procedure. It is also a conservative test compared to other procedures such as Duncan's multiple-range test (Steel and Torrie, 1960, p. 107–109), which is most effective with samples of equal cell size, and controls for the experiment-wise error rate rather than on a percomparison basis. As a result, there is less chance that Tukey's procedure will declare some differences between means to be significant even when the means are a homogeneous set.

Duncan's multiple range test and the Duncan-Waller k-ratio t-test were also attempted on data sets that were manipulated to generate equal cell sizes. Equal cell sizes were generated by taking the percentile values of frequency distributions of data within a sample cell; this produced cells containing 100 observations. This transformation worked well for sample cells having large numbers of observations in a distribution that was not excessively skewed (skewness less than 4.0) and with similar values of skewness. When these two conditions were not met, the cell mean from the frequency distribution was different from the cell mean of the raw data. Because of this problem, the analysis-of-variance tests using Duncan's method and the Duncan-Waller method produced inconsistent results, although a pattern usually emerged that was similar to the results from Tukey's procedure. Because of the properties of Tukey's procedure, the nature of the data that were being tested, and for overall consistency, Tukey's HSD procedure was used for all analysis-of-variance tests described in this report. Further discussion of analysis of variance, including Tukey's HSD procedure, can be found in Steel and Torrie (1960) and SAS Institute, Inc.(1982b).

RELATION OF WELL YIELD TO CONSTRUCTION PRACTICES AND SITING OF WELLS

Results of the Analysis

The first group of statistics, presented in table 4, characterize the wells in the study area with regard to their physical and hydrologic characteristics. In the left half of the table, the average and median values of these characteristics are shown for wells in each of six topographic settings. The topographic settings are arranged in order of

Table 4. Average and median values of selected well characteristics according to topographic setting compared to statistics for all wells

Well characteristics	Topographic setting						All wells					
	Draw	Valley	Slope	Flat	Hill	Ridge	Average	First quartile	Median	Third quartile	Ninth dectile	Number of wells
Average yield[1] (gallons per minute)	33.3	25.7	17.1	16.8	10.8	9.7	17.2	5	10	20	36	5,234
Median yield (gallons per minute)	20	15	10	10	6	6						5,234
Average yield per foot (gallons per minute per foot)	.220	.205	.128	.131	.093	.086	.131	.038	.080	.165	.300	5,221
Median yield per foot (gallons per minute per foot)	.154	.143	.082	.083	.056	.058						5,221
Average depth (feet)	175.1	157.8	152.6	150.0	150.2	153.1	154.0	85	119	179.5	297.4	5,221
Median depth (feet)	134	104	118	119	117	112						5,221
Average casing (feet)	52.4	49.0	53.6	55.0	51.2	57.2	52.9	28	45	70	97	3,375
Median casing (feet)	46	40	47	50	43.5	42						3,375
Average water level (feet below land surface)	24.3	18.6	32.3	28.6	38.6	43.6	32.2	18	28	40	60	2,825
Median water level (feet below land surface)	20	15	28	25	34	40						2,825
Average saturated thickness of regolith (feet)	31.7	35.4	23.6	27.5	20.5	18.4	24.8	0	15	40	65	2,161
Median saturated thickness of regolith (feet)	25	29	14	19	9	10.5						2,161

[1]Unadjusted for differences in depth and diameter.

decreasing average (mean) yield. The statistics of well characteristics in the six topographic settings can be compared to statistics computed for all wells in the sample that are given in the right half of the table, which defines the frequency at which a given value of a well characteristic can be expected to occur. At the first quartile, 25 percent of the wells in the sample have values that fall below the given value; at the median or second quartile, half the wells have values below the given value; at the third quartile, 75 percent of the wells fall below the given value; and at the ninth dectile, 90 percent of the wells are below the given value.

The yield per foot of well depth and saturated thickness of regolith are computed characteristics. The yield per foot is the yield divided by the total depth of the well. The saturated thickness of regolith is the difference between the depth of casing and the depth of the static water level. If the water level in a well was below the bottom of the casing, the saturated regolith thickness of that well was considered to be zero.

In the computation of the saturated thickness of regolith, casing depth was used to estimate regolith thickness. The depth of surface casing in a drilled well is a good approximation of regolith thickness in the Piedmont and Blue Ridge (Daniel and Sharpless, 1983; Snipes and others, 1983). Surface casing is usually set no more than 1 or 2 ft into fresh bedrock, just below the interface between it and the overlying regolith. Wells drilled in North Carolina since passage of the North Carolina Well Construction Act of 1967 (Heath and Coffield, 1970), however, are required to have a minimum of 20 ft of casing, regardless of how shallow the bedrock may be. Casing data from these wells can lead to overestimated regolith thickness. Fortunately, from a statistical standpoint, many of the records used in this study were for wells drilled prior to 1967. Records of casing depths as shallow as 1 ft for wells on bare-rock exposures are included in the data compilation. These data better reflect the natural range of depths to bedrock and thus provide for a more accurate approximation of regolith thickness.

The data in table 4 show a general pattern of decreasing yield, yield per foot, and saturated thickness of regolith at higher topographic settings (ridges and hilltops). The depth to the water table follows the opposite pattern. The amount of casing and the well depth do not show any apparent relation to topographic setting except that wells in draws average from 17 to 25 ft deeper than wells in other topographic positions.

Analysis-of-variance tests of the data in the six topographic settings of table 4 were made in two steps, first on the data in the six settings and then on grouped data where significant differences were not found. In the first analysis, casing depth was not statistically different in any of the six topographic settings. The average depths for wells on slopes, flats, hills, and ridges were also statistically the same. The yield and depth of wells located in draws was statistically different (greater) from the yield and depth of wells located in valleys and other topographic settings. The remainder of the data tended to cluster in three topographic groups made up of those wells in draws and valleys, on slopes and flats, and on hills and ridges. It is important to point out that analysis-of-variance tests on yield per foot data indicate that wells in draws and valleys are statistically one group, because of adjustment of the yield to account for the differences in well depth in these two topographic settings. This finding is also an indication of the relation between well yield and well depth that will be described in more detail.

In the second part of the analysis, the data were merged according to the three principal topographic groups identified in the first part of the test. Analysis of variance on the grouped data still found no difference in casing depth, nor did well depths on slopes and flats differ from well depths on hills and ridges. Because the statistical tests showed that the yield per foot for wells in draws was the same as for wells in valleys, the yield and depth data for wells in these settings were combined. The remainder of the data fell into one of the three topographic groups and were statistically distinct from the other groupings for a given variable. Yields of wells in draws and valleys average nearly three times the yields of wells on hills and ridges. The highest yielding wells also were the wells having the greatest saturated thickness of regolith and the highest water level.

Statistics showing the depth to the water table, casing depth, and saturated thickness of regolith for various topographic settings in the three physiographic provinces in the study area are given in table 5. The influence of topography on the depth to the water table is apparent. The effect of the higher relief and more rugged topography in the Blue Ridge is reflected by the greater depths to the water table than in comparable topographic settings in the Piedmont. An unexpected finding is the similarity of the saturated thickness of regolith in the Piedmont and Blue Ridge. This may be due in part to compensating conditions created by differences in rainfall and relief in the two provinces. Generally, there is more rainfall and more ground-water recharge in the Blue Ridge than in the Piedmont. But there also is greater relief, and presumably steeper ground-water gradients, in the Blue Ridge that results in greater ground-water discharge. Although there is less rainfall in the Piedmont (Eder and others, 1983), the lower relief results in lesser rates of ground-water discharge. Thus, the amount of ground water in long-term storage in the two provinces is roughly equal.

Although the data for casing depth in table 4 indicate little difference between wells in different topographic settings when the study area is considered as a whole, the data in table 5 show that there is an increase in casing depth at higher topographic settings in the Blue Ridge. For wells in the Piedmont, there is no apparent relation between

Table 5. Summary statistics defining depth to water, casing depth, and saturated thickness of regolith according to topographic group in the Blue Ridge and Piedmont physiographic provinces

[Statistics for wells penetrating bedrock beneath the western edge of the Coastal Plain sediments are given for comparison]

Well characteristic	Blue Ridge					Piedmont					Coastal Plain[1]	
	Draws and valleys	Slopes and flats	Hills and ridges	All wells	Number of wells	Draws and valleys	Slopes and flats	Hills and ridges	All wells	Number of wells	All wells	Number of wells
Average water level (feet below land surface)	23.4	37.5	62.9	37.1	507	22.1	29.3	36.8	31.3	2,326	18.8	145
Median water level (feet below land surface)	18	35	50	30	507	20	25	32	27	2,326	15	145
Average casing (feet)	50.1	57.7	66.6	56.8	698	52.7	53.2	50.0	52.0	2,684	71.7	293
Median casing (feet)	43	55	60	53.5	698	45	46	41	44	2,685	63	293
Average saturated thickness or regolith (feet)	32.2	27.6	20.8	28.0	422	33.6	24.6	20.4	24.0	1,749	47.7	112
Median saturated thickness of regolith (feet)	28	20	10	20	422	28	15	9	13	1,749	44.5	112

[1]Topography of bedrock surface cannot be determined. Influence of topography on well yield in Coastal Plain is unknown.

Table 6. Relation of selected well characteristics to the use of the well

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

Use of well	Percentages of wells according to use in selected topographic settings						Statistical summary of well characteristics according to use					Number of wells
	Draw	Valley	Slope	Flat	Hill	Ridge	Average yield (gal/min)	Average yield/foot (gal/min)/ft	Average depth (ft)	Average casing (ft)	Average water level (ft)	
Domestic	47.5	54.5	71.5	72.0	82.0	83.6	11.6	0.117	123.6	51.8	30.8	4,408
Commercial-industrial	31.0	27.9	13.8	12.5	7.8	3.3	27.7	.161	216.5	60.9	31.2	872
Public	21.5	17.6	14.7	12.5	10.2	13.1	33.9	.171	229.8	69.2	34.7	905

casing depth and topographic setting. This difference may be due to the greater relief in the Blue Ridge.

In relation to use (table 6), more than one-half the wells in draws were commercial-industrial or public supply, and nearly one-half the wells in valleys were in the same two use categories. At the other topographic extreme, more than 80 percent of the wells on hills and ridges were domestic supply wells. The yields of domestic wells average about one-third the yields of the commercial-industrial and public-supply wells and are about 100 ft shallower. Information on well diameter (not shown) also indicated that domestic-supply wells had the smallest average diameters and public-supply wells had the largest. Fewer than 2 percent of domestic wells were 8 in. in diameter or larger, whereas 20 percent of the commercial-industrial and 26 percent of the public-supply wells were 8 in. or larger. The implication of the data in this table is that public-supply and commercial-industrial wells are more likely to be sited and constructed in an effort to obtain as much water as possible, whereas many domestic wells are at sites on hills and ridges selected for setting and view. Also, many secondary roads tend to follow the low ridgelines and drainage divides connecting the better drained agricultural land, and many rural homesites are near these roads.

The summary statistics strongly suggest a relation between well yield and well depth and diameter, a definite relation between topographic group and several well characteristics, including yield, and an apparent cultural bias in the siting and construction of wells related to the intended use of the well.

The relation of well yield to rock type, which has been described by many past authors, also may be distorted by cultural bias in siting and construction. For example, in the upper Cape Fear River basin, as described by Daniel and Sharpless (1983), the most productive rock unit is the mafic-volcanics unit. They showed a concentration of high-yield wells in central and northwestern Alamance County coinciding with the area underlain by the mafic-volcanics. Historically, this area has been a major center of textile manufacturing and has a number of factories and mills. The smaller towns have public water systems furnished by wells, and many of the mills have, or have had, their own ground-water supply systems. Thus, the area underlain by the mafic-volcanics unit may have appeared to be the most productive simply because it contained more large-diameter, deep wells than any other area in the basin.

The relation between well yield and well depth and diameter is indicated in figure 7, where average yield,

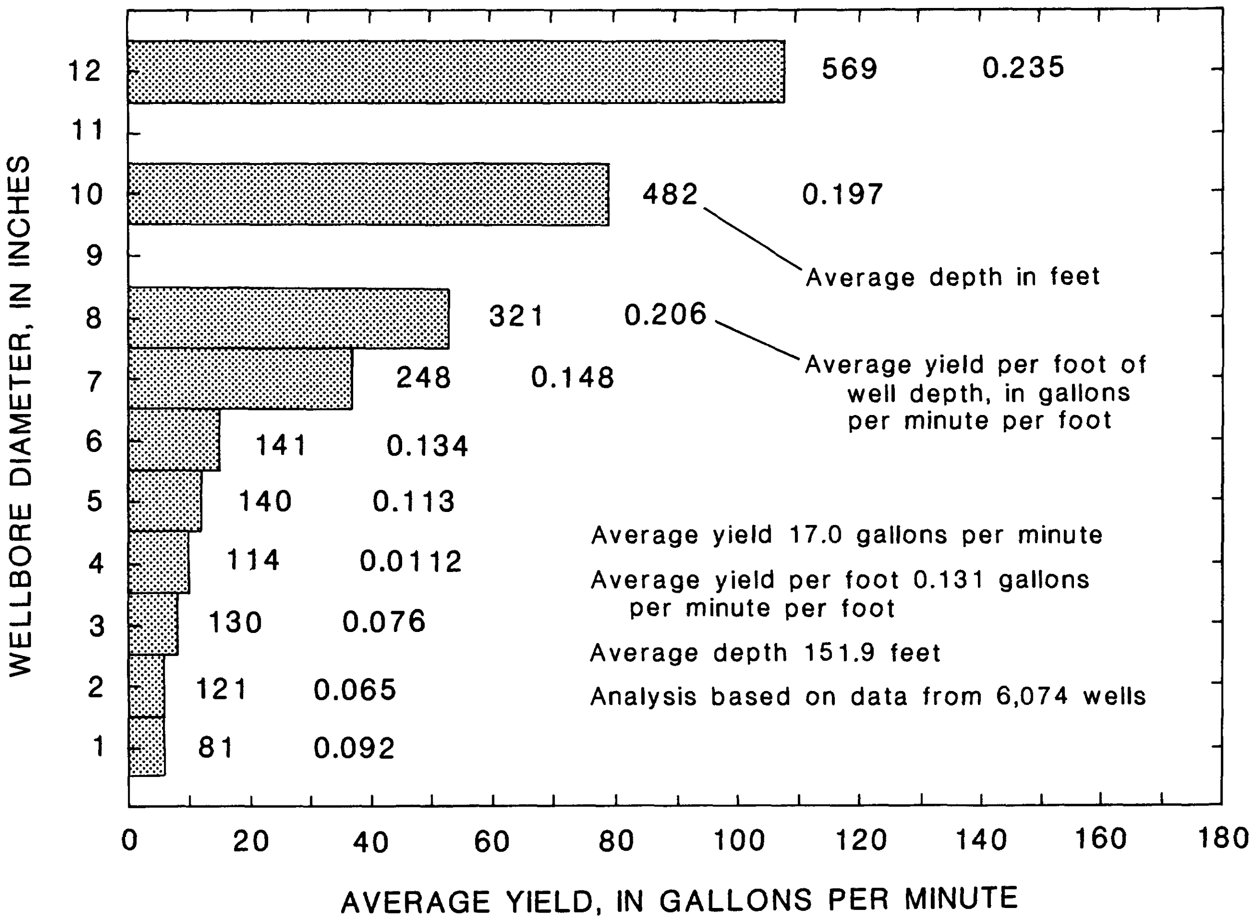


Figure 7. Variation of average yield, average depth, and average yield per foot of well depth with wellbore diameter.

average depth, and average yield per foot of well depth are shown for wells of different diameters. The diameters are subdivided into 1-in. intervals; the actual diameters of the 6,074 wells summarized in figure 7 range from 1.2 in. to 12 in. The significance of figure 7 is the systematic increase in yield and yield per foot that coincides with an increase in depth and diameter.

To better define the nature of the interactions that are indicated in figure 7, least-squares regression analysis was employed. Yield and yield per foot of well depth were treated as dependent variables to be explained in terms of well depth and well diameter with the additional factor of topographic setting to be considered. Including depth and-diameter and interaction terms based on depth and diameter, a total of 20 potential variables were tested in model combinations containing from two to six variables in any one model. The models finally identified as having the best properties and best predictive capabilities contained three variables. Models containing additional variables were only increasingly complex without offering much more in predictive capability. The variance in the model of yield versus depth and diameter was reduced by subsetting the data according to the three topographic groups identified earlier and recomputing the regression coefficients to produce three regression equations of the general form:

$$\text{yield} = a - b\,(\text{depth}) + c\,(\text{depth} \times \text{diameter}) - d\,(\text{depth}^2 \times \text{diameter})$$

where a, b, c, and d are regression coefficients.

The regression equations and contour plots of the trend surfaces defined by these equations are shown in figures 8, 9, and 10. The contour plots are limited to the range of known data. There are no small-diameter wells in the data set deeper than the no-data boundary. The deepest well in the data set is a 6-in. diameter well that is 1,301 ft deep. A number of larger diameter wells in the data set are nearly as deep. The shallowest well is 20 ft deep and 6 in. in diameter.

Information contained in figures 8, 9, and 10 represents several significant new findings regarding drilled wells in the crystalline rocks of the Piedmont and Blue Ridge. The surfaces shown in these illustrations represent the best average fit through yield data that has considerable

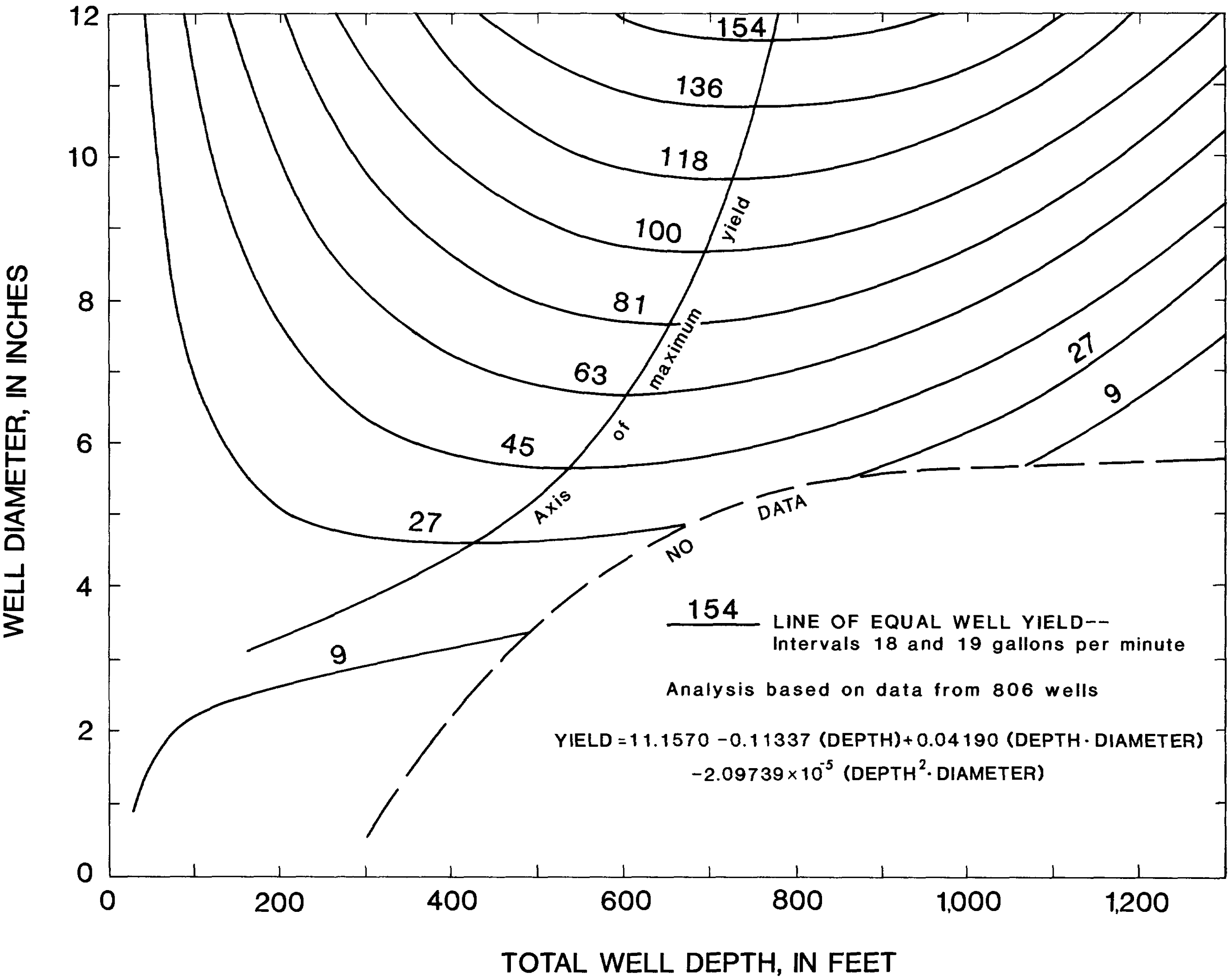


Figure 8. Contour plot of trend surface showing relation between well yield, total well depth, and well diameter for wells that are located in draws and valleys.

variation at any given point. That is, for a point on any of the three contour plots there may be several wells of the same depth and diameter, all having different yields. This is important in interpreting the significance of the axes of the yield surfaces and why the average yield for wells of a given diameter decreases to the right of the yield-surface axes. Take for example, a point on the surface of figure 9 (wells on slopes and flats) representing a well depth of 525 ft and a diameter of 6 in. The predicted average yield at this point, which also is on the yield-surface axis, is 32 gal/min. If a 6-in. well were drilled to this depth and had no water, two things could be done: stop or drill deeper. If drilling were stopped, that zero yield would be averaged with the yields of all other 6-in., 525-ft wells, which would average about 32 gal/min. If the well is drilled deeper and finally obtains water, the yield of that well averaged with other wells of the same depth will be less than at the yield-surface axis. Thus, for a given diameter well, the yield-surface axis represents the depth at which the maximum average yield will be obtained. Beyond the depth indicated by the axis, the chances of obtaining significant amounts, or additionala-mounts, of water decrease rapidly.

This is perhaps better illustrated by figure 11 which is in effect a cross section of figures 8, 9, and 10. The figure is for a narrow range of well diameters, average 6 in., and shows the average yield and yield per foot for wells in intervals of well depth. The large data base of wells having diameters between 5.5 and 6.5 in. provides a sufficient number of wells in each depth interval to give a consistent picture and reduce scatter. A maximum average yield is reached in the interval between 500 and 550 ft (fig. 11), which is the approximate location of the yield-surface axes for 6-in. wells in figures 8, 9, and 10. The likelihood of

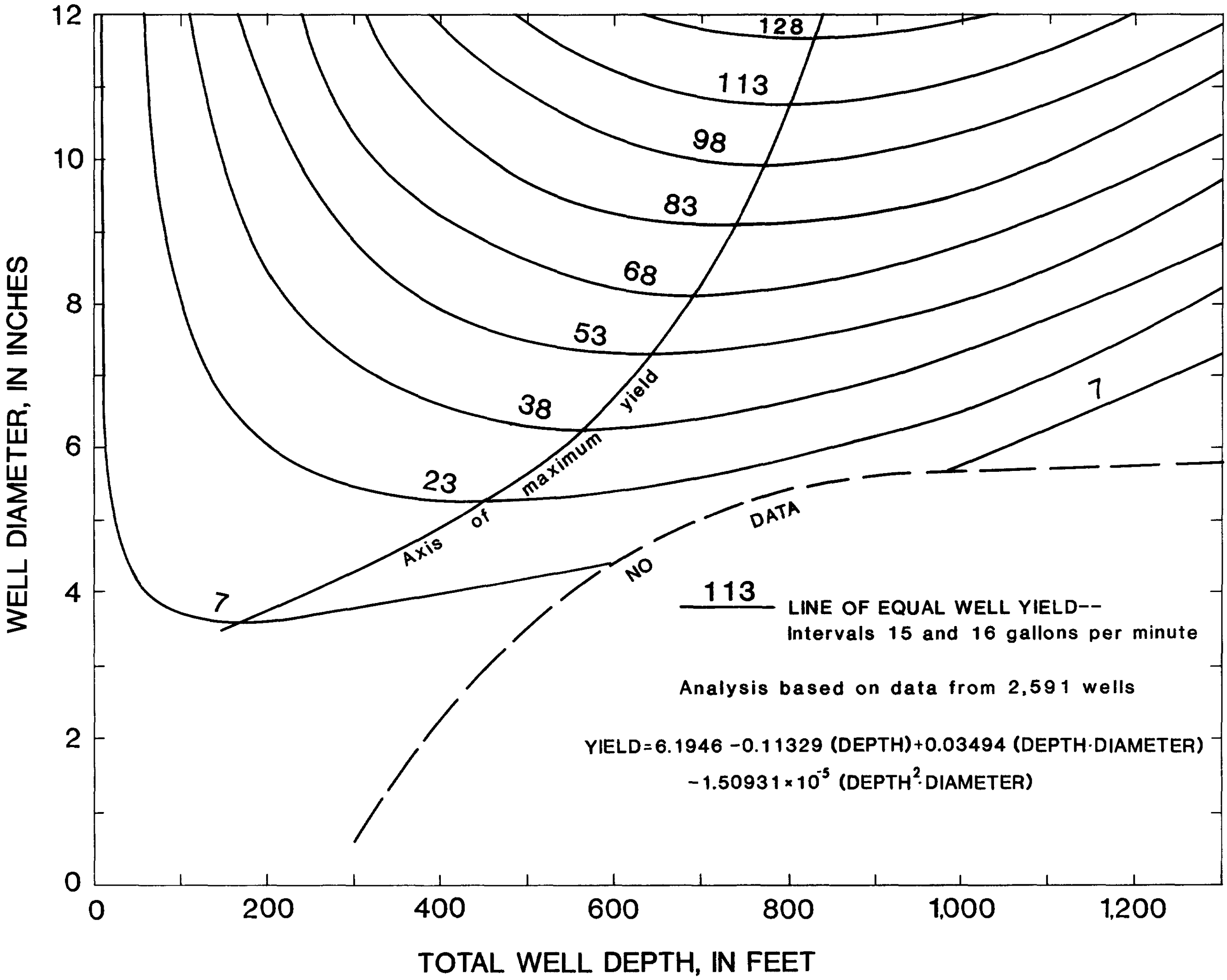


Figure 9. Contour plot of trend surface showing relation between well yield, total well depth, and well diameter for wells that are located on slopes and flats.

obtaining significant additional quantities of water from 6-in. diameter wells decreases rapidly below depths of 550 ft. However, the increase in yield with increasing depth (up to the optimum depth) does not occur in proportion to depth but actually decreases as the ratio to depth.

By subsetting the well data by topographic groups, the regression analysis has resulted in three graphs (figures 8, 9, and 10) that at any well depth and diameter retain the relative magnitudes of yields identified in table 4. At any position on the graphs, the average yield for wells in valleys and draws is nearly three times the yield for wells on hills and ridges. The yield for wells on slopes and flats falls in between. Although there are differences in yield, the yield-surface axes of the three contour plots are nearly coincident, suggesting that topography may have little effect on the depth at which the maximum average yield is attained. The real significance lies in the position and shape of the yield-surface axes, which indicate that (1) well yield increases with depth to a much greater depth than previously thought and (2) well yield increases dramatically as well diameter increases. The curvature of the yield-surface axes shows that depth is still a limiting factor, especially at depths greater than 500 to 600 ft as the axes of the yield surfaces rapidly curve away from the depth axes. However, the maximum average yield for 12-in. wells is reached between 700 and 800 ft. This is much deeper than previously thought. Cressler and others (1983) recently described similar large-diameter, deep, high-yield wells from the Piedmont of Georgia. Even the depth at which 6-in. wells reach their maximum average yield (about 500 ft) is 200 ft deeper than is usually recognized in the literature (LeGrand, 1967; Snipes and others, 1983).

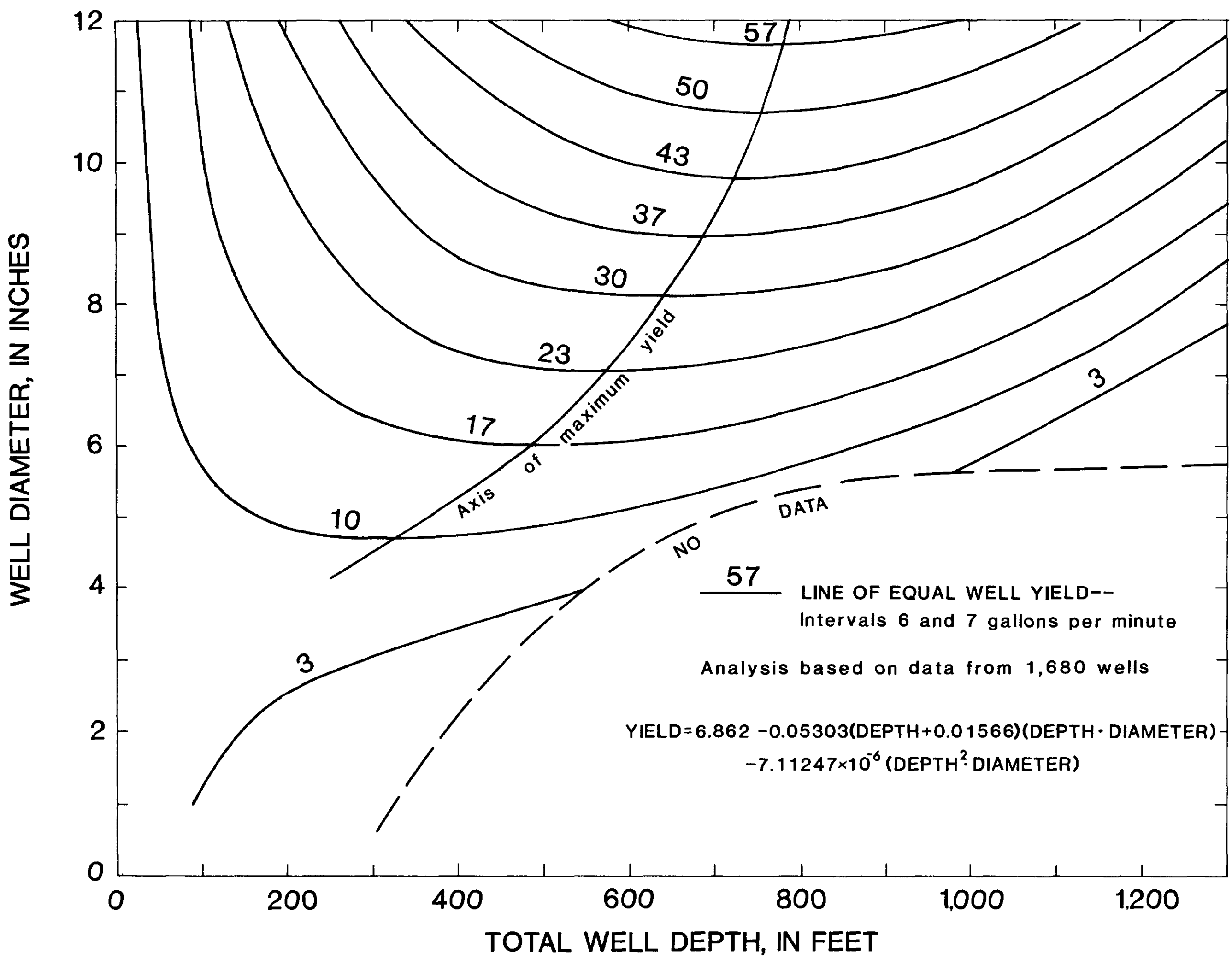


Figure 10. Contour plot of trend surface showing relation between well yield, total well depth, and well diameter for wells that are located on hills and ridges.

Although the regression analysis indicates that average well yields continue to increase at greater depths than previously thought, perhaps the most interesting finding is the dramatic increase in average yield with an increase in well diameter. The effectiveness of increasing well diameter as opposed to drilling to greater depths is illustrated in figure 12, which is the result of a regression analysis of yield per foot versus well depth and diameter. The equation was derived in the same manner described earlier for the yield versus well depth and diameter relations. For a well of a given diameter, the yield per foot of hole is inversely proportional to the depth of the well, indicating that the amount of additional water obtained by drilling deeper is continuously decreasing. For wells of the same depth, however, increases in diameter are directly proportional to increases in yield per foot of well.

Well Yields by Hydrogeologic Unit

Well yields were matched to rock types to determine the relative yields of the different hydrogeologic units. The yield data were simultaneously sorted by topographic group to compare the relative importance of hydrogeologic unit versus topography as a consideration in selecting sites for wells. The results of these computations to compare yield, hydrogeologic unit, and topography are presented in table 7. Because yield is strongly influenced by well depth and diameter, which can lead to cultural bias favoring one hydrogeologic unit over another, a series of calculations was performed to remove the variation in well yield attributed to differences in depth and diameter. By using the equations (figs. 8, 9, and 10) relating well yield to depth and diameter for the three major topographic groups, the well yields were adjusted to an average 154-ft depth and

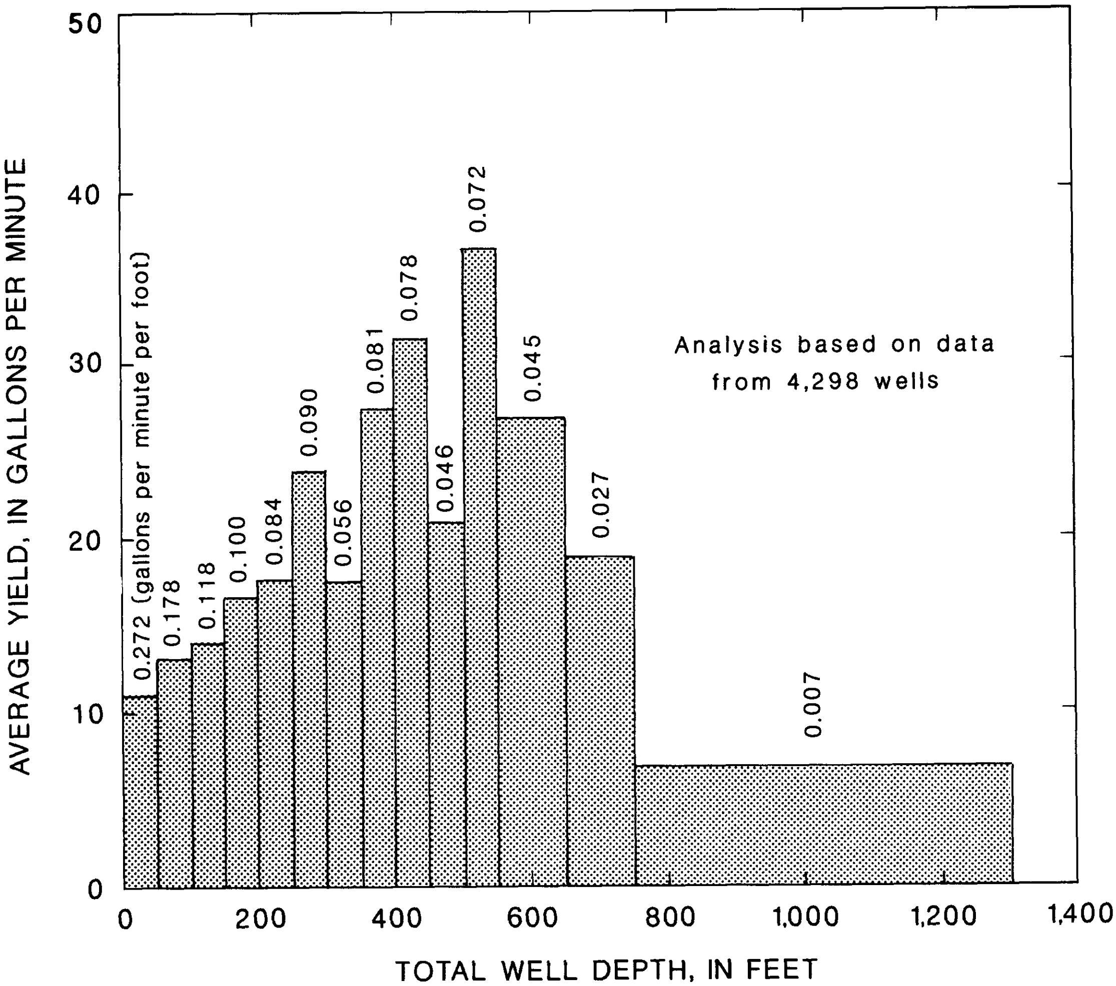


Figure 11. Variation of average yield and yield per foot of well depth with depth for wells having diameters between 5.5 and 6.5 in.

6-in. diameter, the average of all wells in the data set. Because the influence of topography on well sites in the Coastal Plain is uncertain, the yields of wells in the Coastal Plain category were adjusted by using a regression equation that was computed for the entire data set and disregards topographic setting. It is nearly the same as the equation for wells on slopes and flats. The hydrogeologic units III (intermediate composition igneous intrusives), MBL (marble), and SLT (slate) each had fewer than 15 observations having the necessary data (depth, diameter, yield, topography) to adjust the yields. Statistics for these hydrogeologic units, therefore, are not given, although the yields were included in the summary statistics.

A regression of adjusted yields on hydrogeologic units is shown in figure 13. The average yields range from 23.6 gal/min for SCH (schist) to 11.6 gal/min for TRI (sedimentary rocks of Triassic age). The average difference in yield between adjacent hydrogeologic units in the regression is only 0.6 gal/min. However, owing to the effect of the large number of wells in the analysis, the hydrogeologic unit can be used as a statistically reliable estimator (0.99 confidence level) of average well yield.

Analysis-of-variance tests were also used to determine whether any hydrogeologic units were significantly different from other hydrogeologic units in terms of yield. Because the average yields of all hydrogeologic units are not very different and the range of yields within units is very large, only those units toward opposite ends of the distribution are statistically different (0.95 confidence level) as indicated by the inequalities in figure 13.

Three groups of hydrogeologic units stand out in figure 13. The metavolcanic units and ARG (argillite) form a group at the low end of the graph with only TRI (sedimentary rocks of Triassic age) having a lower average yield. Midway in the range of yields are the igneous units. At average or slightly above average yields are the metaigneous units and QTZ (quartzite). The Piedmont crystalline

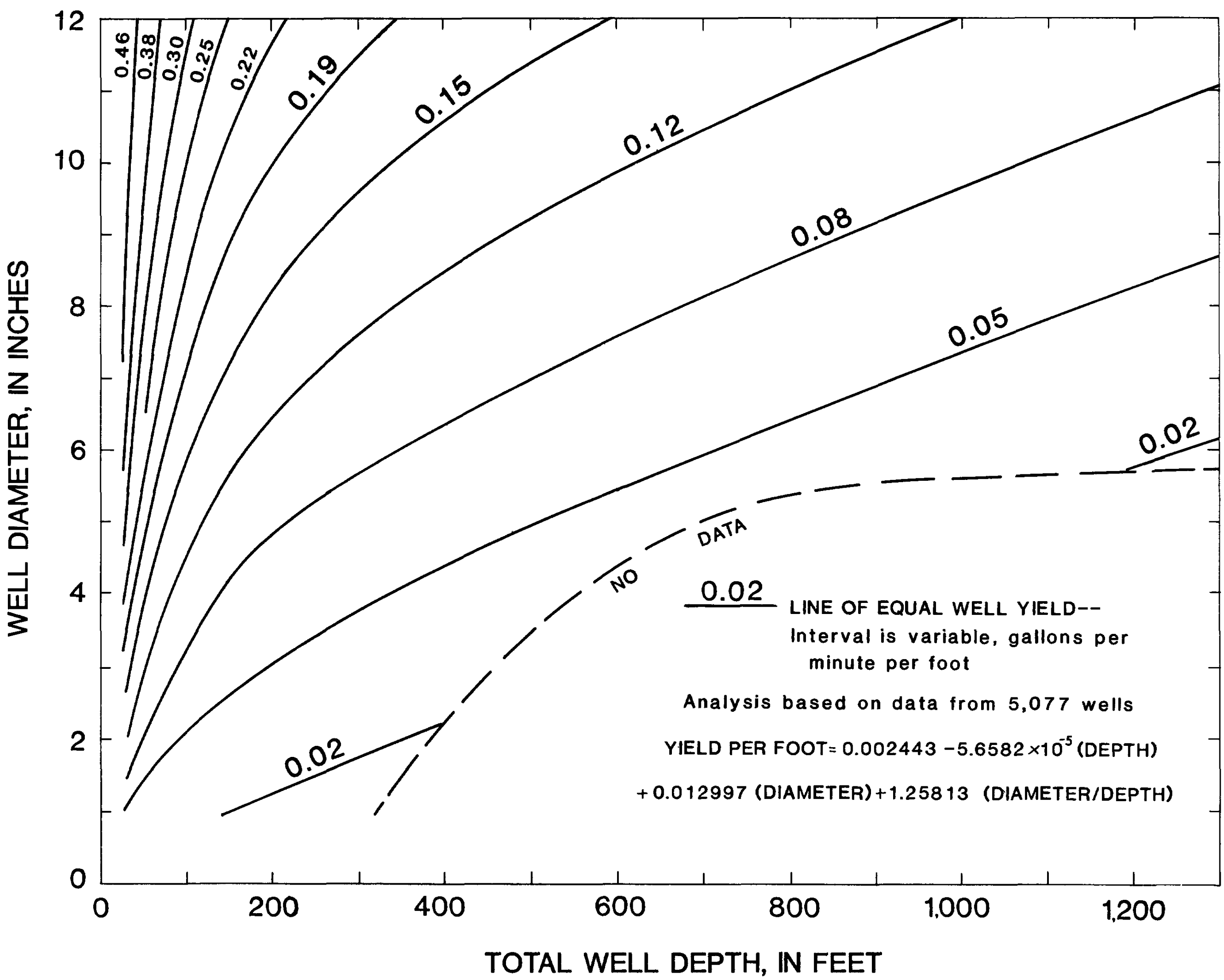


Figure 12. Contour plot of trend surface showing relation between yield per foot of well depth, total well depth, and well diameter.

rocks underlying the Coastal Plain have the second highest average yield regardless of differences in crystalline rock composition. The high yield of these wells is attributed to the greater saturated thickness of overburden, which at an average 47.7 ft is 1.8 times thicker than the 26.8-ft average for the rest of the study area based on 2,391 observations, including wells for which topographic information was not available.

Well Yields by Geologic Belts and Terranes

Comparison of well yields from the various geologic belts and terranes generally reflects the average yield of the predominant hydrogeologic unit(s). The yield data that were used for this comparison also were corrected to an average 154-ft depth and 6-in. diameter. A regression analysis of well yields in the various belts is shown in figure 14. The average difference in yield between belts is 0.9 gal/min. Average yield varies from a low of about 11.5 gal/min for the Smith River allochthon (SR) and Triassic basins (TR) to a high of about 25.5 gal/min for the Murphy (MU). Analysis of variance tests found that the average yield of belts at the upper and lower ends of the data are significantly different. The inequalities significant at the 0.95 confidence level are also shown in figure 14.

The belts having the highest yields, the Murphy (MU), Blue Ridge (BR), Chauga (CA), and Inner Piedmont (IP), are dominated by medium to high rank metasedimentary rocks, mafic gneisses, schists, and quartzites, and they include smaller areas of metaigneous rocks, all of which have above average yields. The Charlotte belt (CH), which is characterized by igneous rocks intruded into country rocks of metavolcanic and metaigneous origin (Fullagar, 1971), and the Carolina slate belt (CS), which is dominated

Table 7. Relation of well yields to hydrogeologic unit and topography

[Yield data are adjusted to account for differences in yield due to differences in well depth and diameter. The average well is 6 in. in diameter and 154 ft deep. The hydrogeologic units are described in table 1; gal/min, gallons per minute]

Hydrogeologic unit	Mean yield by topographic group (gal/min)			Yield of all wells (gal/min)					Number of wells
	Draws and valleys	Slopes and flats	Hills and ridges	Average	First quartile	Median	Third quartile	Ninth decile	
ARG	26.8	16.3	12.5	14.6	7.0	11.5	17.0	27.0	319
CPL[1]	---	---	---	21.7	9.1	14.5	21.8	37.2	419
GNF	28.3	16.6	11.5	17.4	6.4	12.3	22.3	35.9	741
GNM	33.5	19.6	12.3	19.9	6.5	12.5	23.4	40.7	1,129
IFI	24.8	17.8	12.6	17.7	8.1	15.8	23.4	34.4	412
III[2]	---	---	---	---	---	---	---	---	7
IMI[2]	---	24.4	12.1	17.8	4.7	14.0	19.9	44.0	29
MBL[2]	---	---	---	---	---	---	---	---	3
MIF	27.6	20.5	12.4	19.1	7.8	14.0	22.5	35.6	791
MII	22.1	20.6	13.3	18.4	8.8	16.0	23.3	36.2	284
MIM	26.0	21.6	12.5	19.7	10.2	16.9	28.9	36.7	85
MVE[2]	---	16.6	11.9	16.9	7.5	11.8	16.0	25.0	95
MVF	19.0	15.1	9.5	13.0	6.2	11.2	17.8	25.9	280
MVI[2]	---	17.1	15.5	16.8	9.2	13.4	23.6	35.2	43
MVM[2]	---	17.8	7.2	11.9	4.6	7.9	17.4	24.6	63
MVU	27.1	23.4	10.9	20.2	8.1	14.8	24.5	41.2	141
PHL	22.9	21.5	13.6	20.3	9.9	14.5	25.4	44.2	127
QTZ[2]	20.6	16.8	---	18.6	4.8	15.2	29.4	46.5	65
SCH	43.3	20.8	11.4	33.6	7.8	15.3	27.5	43.6	199
SLT[2]	---	---	---	---	---	---	---	---	2
TRI	19.0	12.2	8.5	11.6	4.7	9.0	14.5	25.5	269
All types	28.7	19.0	11.8	18.2	7.9	13.1	22.0	35.5	5,503

[1]Topography of bedrock surface cannot be determined. Influence of topography on well yield in CPL area is unknown.

[2]Statistics for categories having less than 15 observations are not given.

by metavolcanic rocks (Butler and Ragland, 1969), both are belts having low average yields.

The areas containing sedimentary rocks, the Triassic basins (TR) and the western edge of the Coastal Plain (CP), are far apart in average yield, with the Triassic basins having the next-to-lowest yield and the Coastal Plain the third highest.

SUMMARY AND CONCLUSIONS

A statistical analysis was made of data from more than 6,200 wells drilled into the crystalline rocks of the Blue Ridge, the Piedmont, and the western edge of the Coastal Plain where crystalline rocks underlie sediments at shallow depths. This analysis was made to identify factors that are associated with high-yield wells. The data were classified according to geologic belts, hydrogeologic units composed of similar rock types,topographic setting, total and saturated thickness of regolith, water level, casing depth, yield, total depth, well diameter, and water use.

Six topographic settings were combined into three groups based on well yields: hills and ridges, slopes and flats, and draws and valleys. Wells on hills and ridges had the lowest yields (averaging about 10 gal/min); wells in draws and valleys, the greatest (averaging about 30 gal/min). Regolith thickness was about the same regardless of topographic group, but saturated thickness was least (about 19 ft) under hills and ridges and greatest (about 34 ft) under draws and valleys. Average yields in the geologic belts and hydrogeologic units ranged from about 11 to 25 gal/min. There was considerable scatter in yields in all geologic belts and hydrogeologic units. Of 14 geologic belts, 10 were statistically different on the basis of well yield, as were 8 of 21 hydrogeologic units.

About 70 percent of the wells were drilled for domestic use and, on the average, yielded about 11 gal/min; 80 percent of these wells were located on hills and ridges. The 30 percent of the wells drilled for public supply and commercial-industrial supply yielded about 30 gal/min on the average; about 50 percent of these wells were located in draws and valleys. The domestic wells had an average depth of about 125 ft; the public-supply and commercial-industrial wells, about 225 ft. Fewer than 2 percent of the domestic wells were 8 in. in diameter or larger, whereas nearly 25 percent of the public-supply and commercial-industrial wells were 8 in. or larger.

Selecting the most favorable hydrogeologic unit or geologic belt alone can improve the chance of increasing the yield of the average 6-in. diameter, 154-ft deep well from

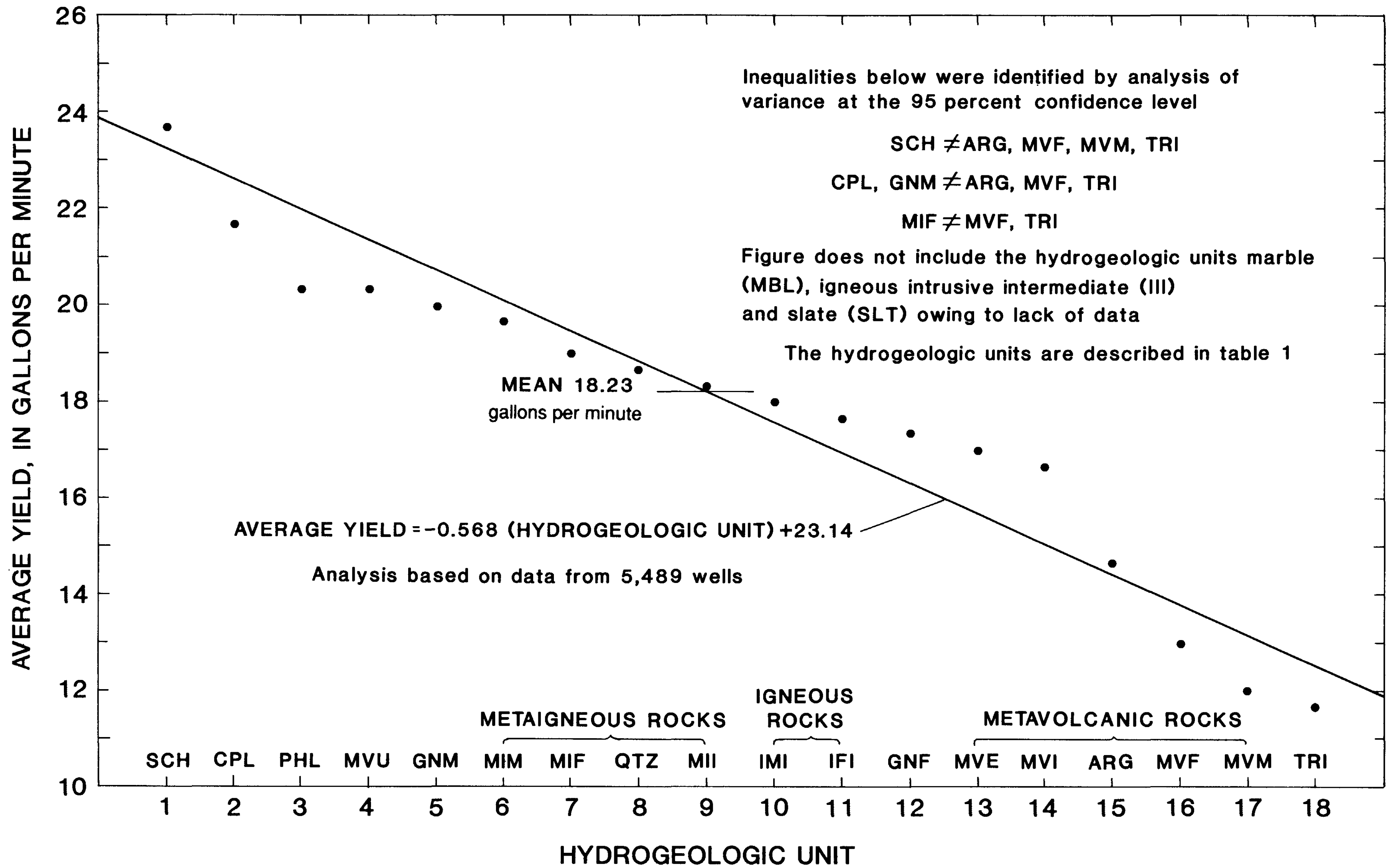


Figure 13. Average yield of wells of average construction in the hydrogeologic units of the Piedmont and Blue Ridge provinces of North Carolina.

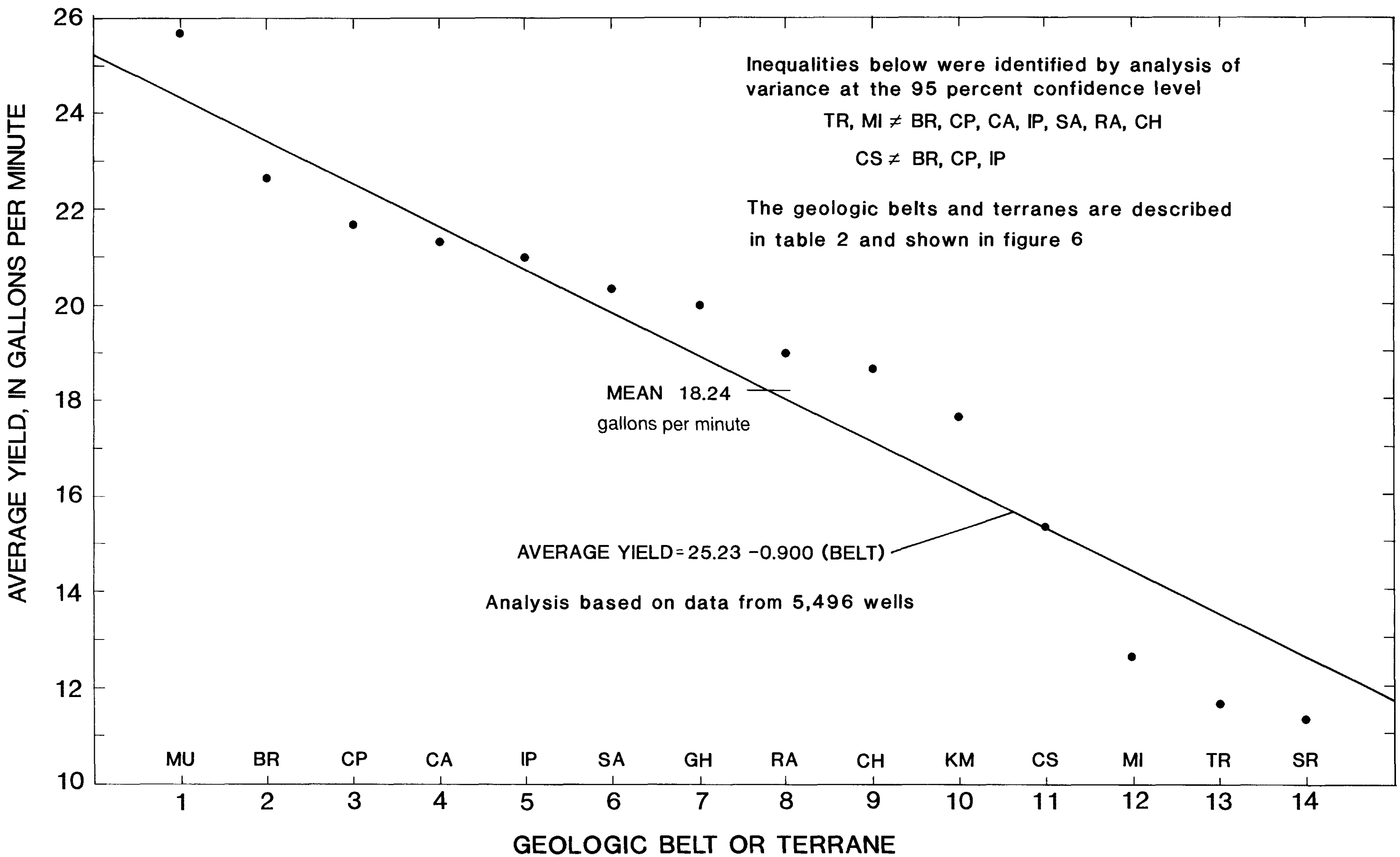


Figure 14. Average yield of wells of average construction in the geologic belts and terranes of the Piedmont and Blue Ridge provinces of North Carolina.

about 11 to 12 gal/min to about 24 to 25 gal/min, about a twofold increase. Considering topography alone, the average well on hills and ridges can be expected to average less than 12 gal/min, whereas wells in draws and valleys can be expected to average about 29 gal/min, an increase of 2.4 times. When the factors of hydrogeologic unit or geologic belt are considered in combination with topographic setting, the range in yields is even greater. Wells in draws and valleys in the most productive units average five times more yield than wells on hills and ridges in the least productive units.

The statistical analysis supported some concepts and criteria for well-site selection, such as the siting of a well with regard to topography. More importantly, however, the analysis indicates that some previously held concepts may be in error. First and foremost is the generally held concept that the crystalline rocks yield only small amounts of water to wells. The analysis showed that this concept may be due to cultural bias. Most wells drilled in these rocks are small diameter, are located primarily on hills and ridges—the poorest possible sites for wells—and are drilled only to depths where sufficient water for a domestic supply is obtained. In the same theme, well diameter has not been considered to have much effect on yield—a large-diameter well was considered a storage tank. Statistical analysis shows, however, that for a given depth the yield of a well is directly proportional to the well diameter. The larger the diameter the greater the yield.

Well construction in crystalline rocks has long been based on the concept of a well intersecting near vertical open fractures and joints that, because of lithostatic pressure, pinch out at depths of about 300 ft. As a result, the drilling of many wells has been arbitrarily stopped when the depth of 300 ft was reached. The average well, whether domestic or commercial-industrial, is not even that deep. The analysis indicates that very few wells have been drilled deep enough to test the full potential of the sites. For example, the average yield of 6-in. diameter wells located in draws or valleys reaches a maximum of about 45 gal/min at depths of 500 to 525 ft; the average yield of 12-in. diameter wells located in draws or valleys reaches a maximum of about 150 gal/min at depths of 700 to 800 ft.

Whatever the hydrogeologic unit or topographic location, the chances of obtaining high yields are enhanced by increasing the depth and diameter of the well to a much greater extent than previously thought.

REFERENCES

Bain, G.L., 1966, Geology and ground-water resources of the Durham area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 7, 147 p.

Brown, P.M., and Parker, J.M., III, compilers, 1985, Geologic map of North Carolina: North Carolina Department of Natural Resources and Community Development, 1 sheet, scale 1:500,000.

Burt, E.R., 1981, Geologic map of Region H, North Carolina: North Carolina Geological Survey, Open-File Map no. NCGS 81–4, scale 1:125,000.

Butler, J.R., and Ragland, P.C., 1969, A petrochemical survey of plutonic intrusions in the Piedmont, southeastern Appalachians, U.S.A.: Contributions to Mineralogy and Petrology, v. 24, p. 164–190.

Carpenter, P.A., III, 1982, Geologic map of Region G, North Carolina: North Carolina Department of Natural Resources and Community Development, Geological Survey Section, Regional Geology Series 2, scale 1:125,000.

Cedarstrom, D.J., 1972, Evaluation of yields of wells in consolidated rocks, Virginia to Maine: U.S. Geological Survey Water-Supply Paper 2021, 38 p.

Conrad, S.G., Carpenter, P.A., III, and Wilson, W.F., 1975, Physiography, geology and mineral resources, *in* Clay, J.W., Orr, D.M., and Stuart, A.W., eds., North Carolina atlas, portrait of a changing southern State: Chapel Hill, North Carolina, University of North Carolina Press, p. 112–127.

Cressler, C.W., Thurmond, C.J., and Hester, W.G., 1983, Ground water in the greater Atlanta region: Georgia Department of Natural Resources Environmental Protection Division, Georgia Geologic Survey Information Circular 63, 144 p.

Daniel, C.C., III, and Sharpless, N.B., 1983, Ground-water supply potential and procedures for well-site selection in the upper Cape Fear River basin, North Carolina: North Carolina Department of Natural Resources and Community Development, 73 p.

Dodson, C.L., and Laney, R.L., 1968, Geology and ground-water resources of the Murphy area, North Carolina: North Carolina Department of Water and Air Resources Ground-Water Bulletin 13, 113 p.

Eder, B.K., Davis, J.M., and Robinson, P.J., 1983, Variations in monthly precipitation over North Carolina: University of North Carolina Water Resources Research Institute Report no. 185, 50 p.

Espenshade, G.H., Rankin, D.W., Shaw, K.W., and Neuman, R.B., 1975, Geologic map of the east half of the Winston-Salem quadrangle, North Carolina-Virginia: U.S. Geological Survey Miscellaneous Investigations Series Map I–709–B, scale 1:250,000.

Fenneman, N.M., 1938, Physiography of Eastern United States: New York, McGraw-Hill, 714 p.

Floyd, E.O., 1965, Geology and ground-water resources of the Monroe area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 5, 109 p.

Fullagar, P.D., 1971, Age and origin of plutonic intrusions in the Piedmont of the southeastern Appalachians: Geological Society of America Bulletin, v. 82, p. 2845–2862.

Goldsmith, Richard, Milton, D.J., and Horton, J.W., Jr., 1982, Simplified preliminary geologic map of the Charlotte 1° × 2° quadrangle, North Carolina and South Carolina: U.S. Geological Survey Open-File Report 82–56, scale 1:250,000.

Hadley, J.B., and Nelson, A.E., 1971, Geologic map of the Knoxville quadrangle, North Carolina, Tennessee, and South

Carolina: U.S. Geological Survey Miscellaneous Investigations Series Map I–654, scale 1:250,000.

Heath, M.S., and Coffield, H.I., III, 1970, Cases and materials on ground water law—with particular reference to the law of North Carolina: Chapel Hill, North Carolina, University of North Carolina Institute of Government, 72 p.

Heath, R.C., 1980, Basic elements of ground-water hydrology with reference to conditions in North Carolina: U.S. Geological Survey Water-Resources Investigations Open-File Report 80–44, 86 p.

LeGrand, H.E., 1954, Geology and ground water in the Statesville area, North Carolina: North Carolina Department of Conservation and Development Bulletin 68, 68 p.

———1967, Ground water of the Piedmont and Blue Ridge provinces in the southeastern States: U.S. Geological Survey Circular 538, 11 p.

LeGrand, H.E., and Mundorff, M.J., 1952, Geology and ground water in the Charlotte area, North Carolina: North Carolina Department of Conservation and Development Bulletin 63, 88 p.

Marsh, O.T., and Laney, R.L., 1966, Reconnaissance of the ground-water resources in the Waynesville area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 8, 131 p.

May, V.J., and Thomas, J.D., 1968, Geology and ground-water resources in the Raleigh area, North Carolina: North Carolina Department of Water and Air Resources Ground-Water Bulletin 15, 135 p.

McDaniel, R.D., 1980, Geologic map of Region K, North Carolina: North Carolina Geological Survey, Open-File Map no. NCGS 80–2, scale 1:125,000.

Mundorff, M.J., 1946, Ground water in the Halifax area, North Carolina: North Carolina Department of Conservation and Development Bulletin 51, 76 p.

———1948, Geology and ground water in the Greensboro area, North Carolina: North Carolina Department of Conservation and Development Bulletin 55, 108 p.

Peace, R.R., Jr., and Link, D.R., 1971, Geology and ground-water resources of northwestern North Carolina: North Carolina Department of Water and Air Resources Ground-Water Bulletin 19, 135 p.

Pusey, R.D., 1960, Geology and ground water in the Goldsboro area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 2, 77 p.

Ragland, P.C., Hatcher, R.D., Jr., and Whittington, David, 1983, Juxtaposed Mesozoic diabase dike sets from the Carolinas: A preliminary assessment: Geology, July 1983, v. 11, p. 394–399.

Rankin, D.W., Espenshade, G.H., and Neuman, R.B., 1972, Geologic map of the west half of the Winston-Salem quadrangle, North Carolina, Virginia, and Tennessee: U.S. Geological Survey Miscellaneous Investigations Series Map I–709–A, scale 1:125,000.

Reinemund, J.A., 1955, Geology of the Deep River coal field, North Carolina: U.S. Geological Survey Professional Paper no. 246, 159 p.

SAS Institute Inc., 1982a, SAS user's guide: basics, 1982 edition: Cary, North Carolina, SAS Institute, Inc., 923 p.

———1982b, SAS user's guide: statistics, 1982 edition: Cary, North Carolina, SAS Institute, Inc., 584 p.

Schipf, R.G., 1961, Geology and ground-water resources of the Fayetteville area: North Carolina Department of Water Resources Ground-Water Bulletin 3, 99 p.

Seiders, V.M., 1981, Geologic map of the Asheboro, North Carolina, and adjacent areas: U.S. Geological Survey Miscellaneous Investigations Series Map I–1314, scale 1:62,500.

Snipes, D.S., Padgett, G.S., Hughes, W.S., and Springston, G.E., 1983, Ground-water quantity and quality in fracture zones in Abbeville County, South Carolina: Clemson, South Carolina, Clemson University Water Resources Research Institute Technical Report no. 102, 54 p.

Steel, R.G.D., and Torrie, J.H., 1960, Principles and procedures of statistics, with special reference to the biological sciences: New York, McGraw-Hill, 481 p.

Stromquist, A.A., Choquette, P.W., and Sundelius, H.W., 1971, Geologic map of the Denton quadrangle, central North Carolina: U.S. Geological Survey Geologic Quadrangle Map GQ–872, scale 1:62,500.

Stromquist, A.A., and Sundelius, H.W., 1975, Interpretive geologic map of the bedrock showing radioactivity, and aeromagnetic map of the Salisbury, Southmont, Rockwell, and Gold Hill quadrangles, Rowan and Davidson Counties, North Carolina: U.S. Geological Survey Miscellaneous Investigations Series Map I–888 (sheet 1 of 2), scale 1:48,000.

Stuckey, J.L., 1958, Geologic map of North Carolina: Raleigh, North Carolina, North Carolina Department of Conservation and Development, Division of Mineral Resources, scale 1:500,000.

Sumsion, C.T., and Laney, R.L., 1967, Geology and ground-water resources of the Morganton area: North Carolina Department of Water Resources Ground-Water Bulletin 12, 119 p.

Trapp, Henry, Jr., 1970, Geology and ground-water resources of the Asheville area, North Carolina: North Carolina Department of Water and Air Resources Ground-Water Bulletin 16, 127 p.

Weigand, P.W., and Ragland, P.C., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contributions to Minerology and Petrology, v. 29, p. 195–214.

Wilson, W.F., 1979, Geology of Wilson County, North Carolina: North Carolina Department of Natural Resources and Community Development, Division of Land Resources, Geological Survey Section, Open-File Map NCGS 79–2, scale 1:125,000.

———1981, Geology of Halifax County, North Carolina: North Carolina Geological Survey, Open-File Map NCGS 81–3, scale 1:125,000.

Wilson, W.F., Carpenter, P.A., III, and Parker, J.M., III, 1981, Geologic map of Region J, North Carolina, *in* A guide for North Carolina mineral resource development and land use planning: North Carolina Department of Natural Resources and Community Development, Geological Survey Section, Regional Geology Series 1, scale 1:125,000.

Wilson, W.F., and Spence, W.H., 1979, Geology of Nash County, North Carolina: North Carolina Department of Natural Resources and Community Development, Division of Land Resources, Geological Survey Section, Open-File Map NCGS 79–3, scale 1:125,000.