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

U.S. GEOLOGICAL SURVEY

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COVER PHOTOGRAPH: Drilling of a test well in Guilford County near the Greensboro-High Point Regional Airport, December 16, 1982. Yield at time of photograph approximately 50 gallons per minute. (Photograph by Charles C. Daniel, U.S. Geological Survey.)

INTERNATIONAL SYSTEM UNITS

The following factors may be used to convert inch-pound units published herein to the International System of Units (SI).

Multiply inch-pound unit	By	To obtain SI unit
Length		
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	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)
	0.003785	cubic meter (m^3)
million gallons (Mgal)	3785	cubic meter (m^3)
Flow		
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.0038	cubic meter per day (m^3/d)
gallon per minute (gal/min)	3.785	liter per minute (L/min)
	0.003785	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]
	0.01242	cubic meter per minute per meter [(m^3/min)/m]

National Geodetic Vertical 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, "mean sea level."

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WATER RESOURCES INVESTIGATIONS REPORT 86-4132

Errata sheet

References were omitted from captions to figures 3 and 6 on pages 7 and 19 respectively. The correct captions are as follows:

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

Figure 6.--Geologic belts, terranes, and some major structural features within the Piedmont and Blue Ridge provinces of North Carolina (From Brown, P.M., and Parker, J.M., III, 1985).

The equation on page 33 is incorrect as shown. The equation should read:

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

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

STATISTICAL ANALYSIS RELATING WELL YIELD TO CONSTRUCTION PRACTICES AND SITING OF WELLS IN THE PIEDMONT AND BLUE RIDGE PROVINCES OF NORTH CAROLINA

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ABSTRACT

A statistical analysis was made of data from more than 6,200 water wells drilled in the fractured crystalline rocks of the Blue Ridge, Piedmont, 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 mi^2, comprising 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 the geologic, topographic, and construction factors associated with high-yield wells.

It is generally held that the crystalline rocks of the Blue Ridge and Piedmont 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 average well drilled in these rocks: 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 underlying the Blue Ridge and Piedmont have the reputation for furnishing only small quantities of ground water. This impression is the outgrowth of drilling large numbers of domestic wells, which do not represent efforts to obtain quantities of water beyond the minimum requirement of 2 to 10 gal/min. About 70 percent of all wells drilled in the Blue Ridge and Piedmont are for domestic supply and most were located and drilled without regard to geology, topography, and optimal construction. There are, however, a significant number of wells that yield a few tens to a few hundreds of gallons per minute. Additional high-yield wells likely could be developed at carefully selected sites throughout the area.

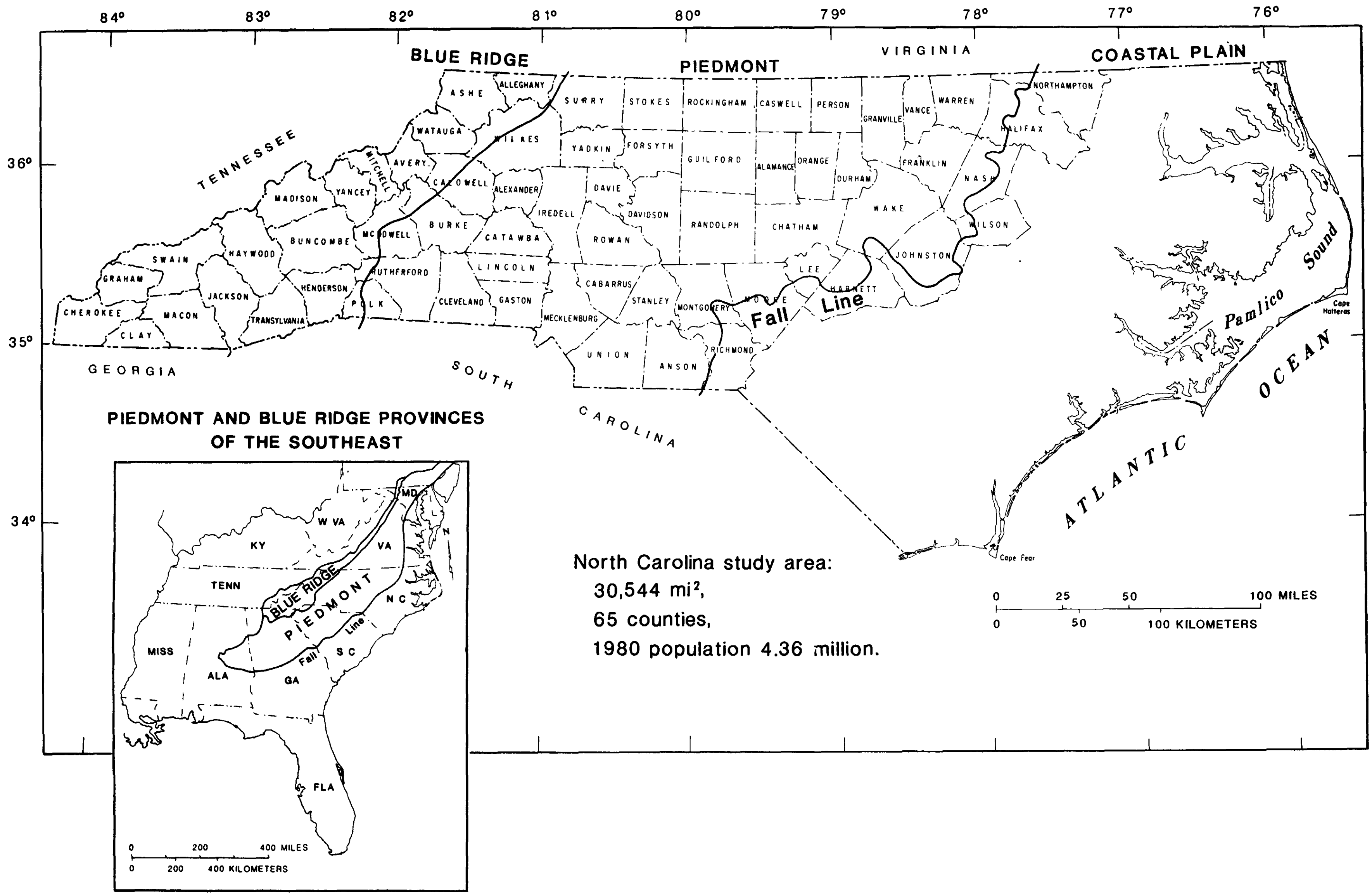


Figure 1.--Area of investigation showing counties and physiographic provinces.

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 five-year study of ground-water resources in the region. This report is part of that study.

Purpose and Scope

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

The statistical analysis was made by using hydrologic, geologic, topographic, and well-construction data obtained from records of more than 6,200 water wells. The wells are in an area including all of the Blue Ridge and Piedmont 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 all of 65 counties in North Carolina, an area of 30,544 mi^2, comprising 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 were selected 21 major rock types, designated herein as hydrogeologic units, of igneous, metaigneous, metasedimentary, metavolcanic, and sedimentary origin considered to have quantifiable hydrogeologic properties.

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.

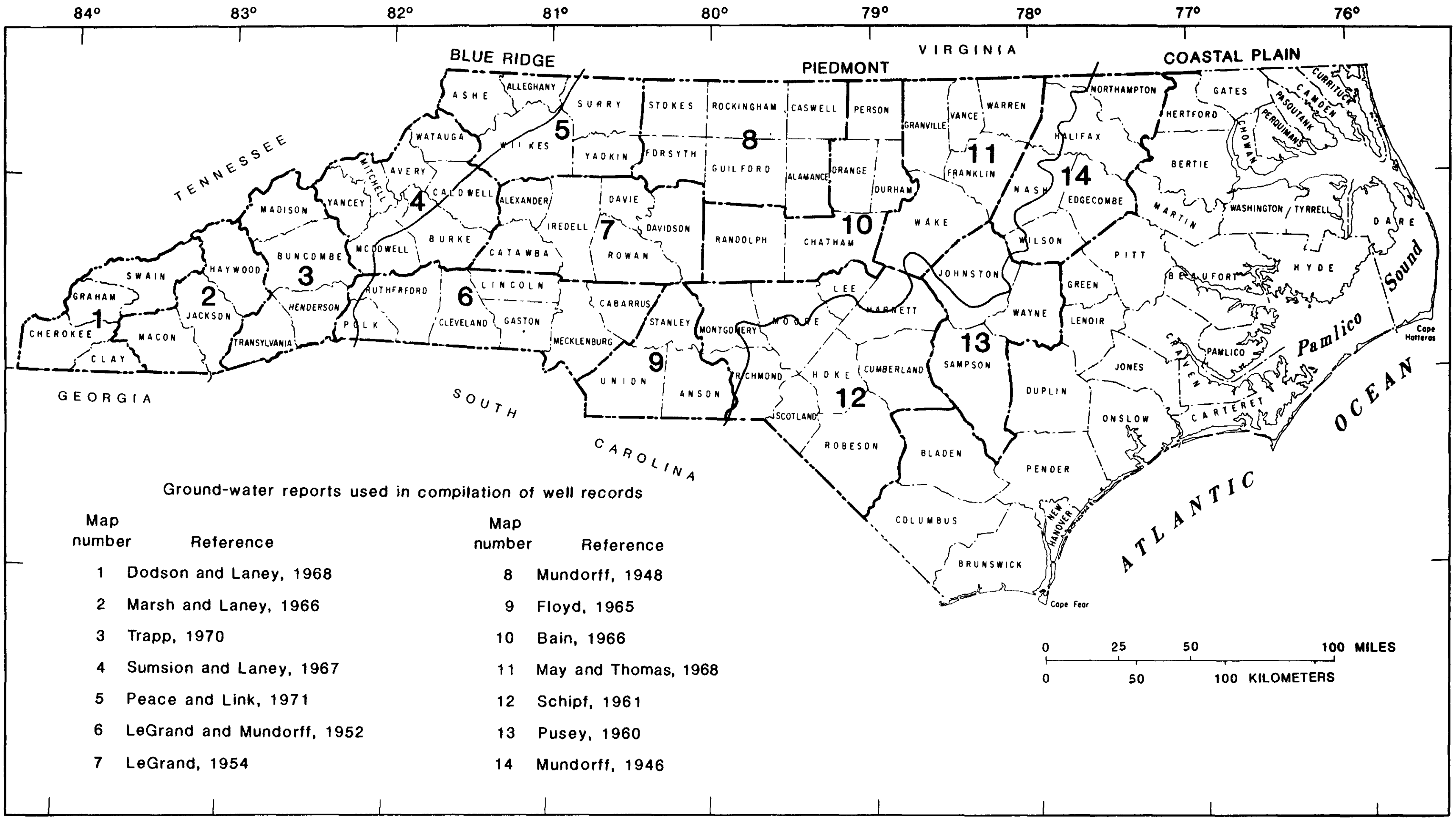
Previous Investigations

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).



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.

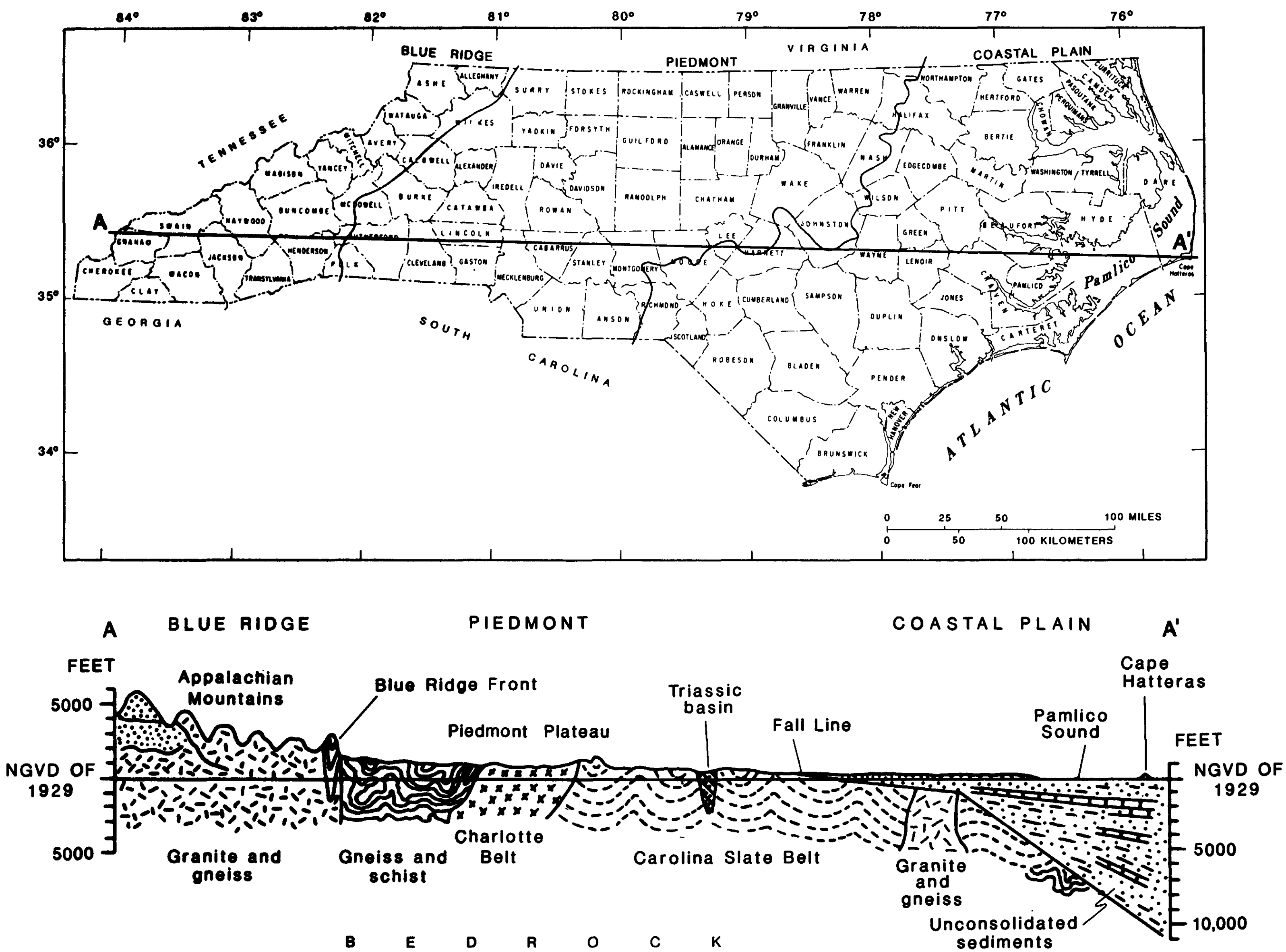


Figure 3.--Physical setting of the ground-water system in North Carolina.

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 cut by numerous small stream valleys. More than 40 peaks are greater than 6,000 feet in altitude and another 82 peaks are between 5,000 and 6,000 feet 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 feet above the Piedmont surface at the North Carolina-Virginia border and reaches a maximum relief of nearly 2,500 feet 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, creating a local topographic relief of 100 to 200 feet between interstream divides and stream bottoms. The Piedmont surface is 300 to 600 feet in altitude along the eastern border and rises gradually to the west to about 1,500 feet 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 feet 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 away 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 predominately 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.

There have been three or more periods of igneous intrusion (Fullagar, 1971) with the emplacement of plutonic bodies ranging in size from batholiths down to dikes, sills, and veins. Most instrusions 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, with the result that permeability is usually greatest parallel to bedding and foliation and zones of fracture concentration, and 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 is overlain by unconsolidated material to depths of more than a hundred feet. 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 nearly everywhere present 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 which 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

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 instrusive	Dark-greenish-gray to black, medium- to coarse-grained instrusive 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.

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
		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 slate belt.
MVI	Metavolcanic, intermediate	Gray to dark-grayish-green tuffs and crystal tuffs generally of andesitic compostion; 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 with 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 terraines.
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.

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
		Metasedimentary Rocks
ARG	Argillite	Fine-grained, thinly-laminated rock with 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 with well developed cleavage; composed primarily of sericite but may contain chlorite; phyllitic zones are common throughout the slate belt and probably represent zones of shearing although displacement of units is usually not recognizable.
QRZ	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.

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
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 redbeds, 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.

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 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.

Using this classification scheme (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.

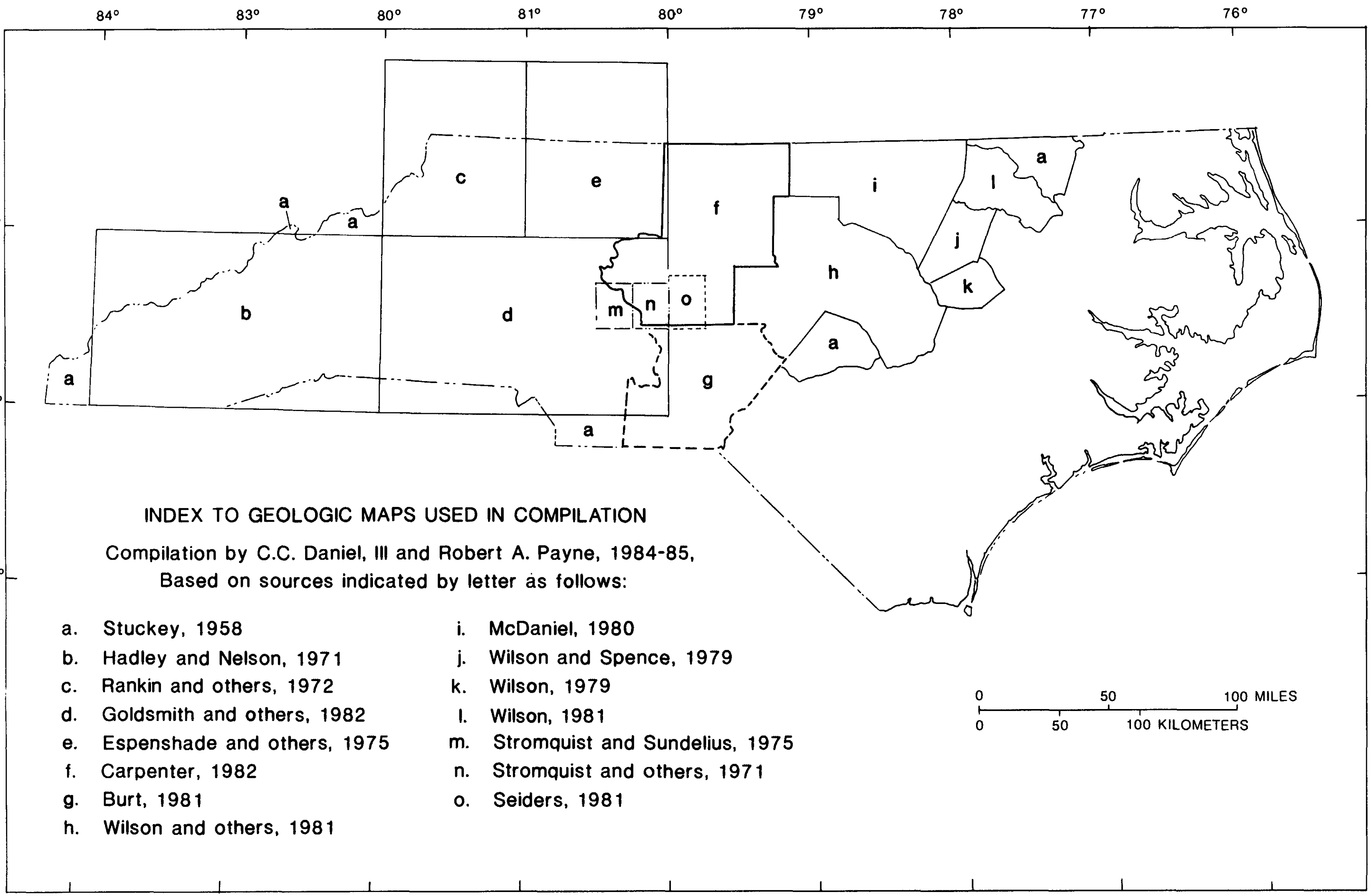


Figure 4.--Areas of geologic maps used in compilation of the hydrogeologic unit map of the Piedmont and Blue Ridge provinces.

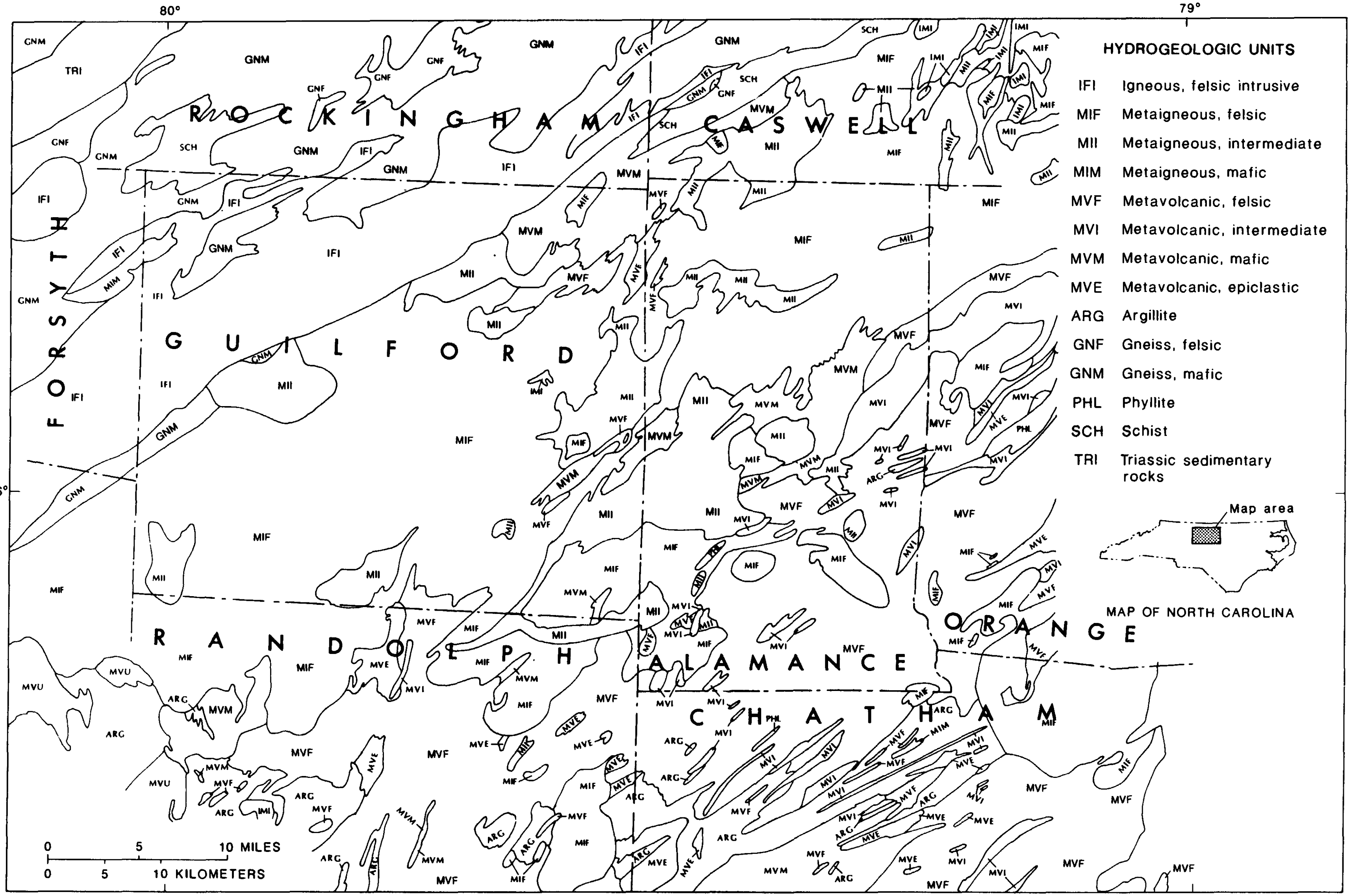


Figure 5.--Hydrogeologic unit map of Guilford and Alamance Counties and vicinity in the north-central Piedmont of North Carolina.

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 in some degrees 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 comprise 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

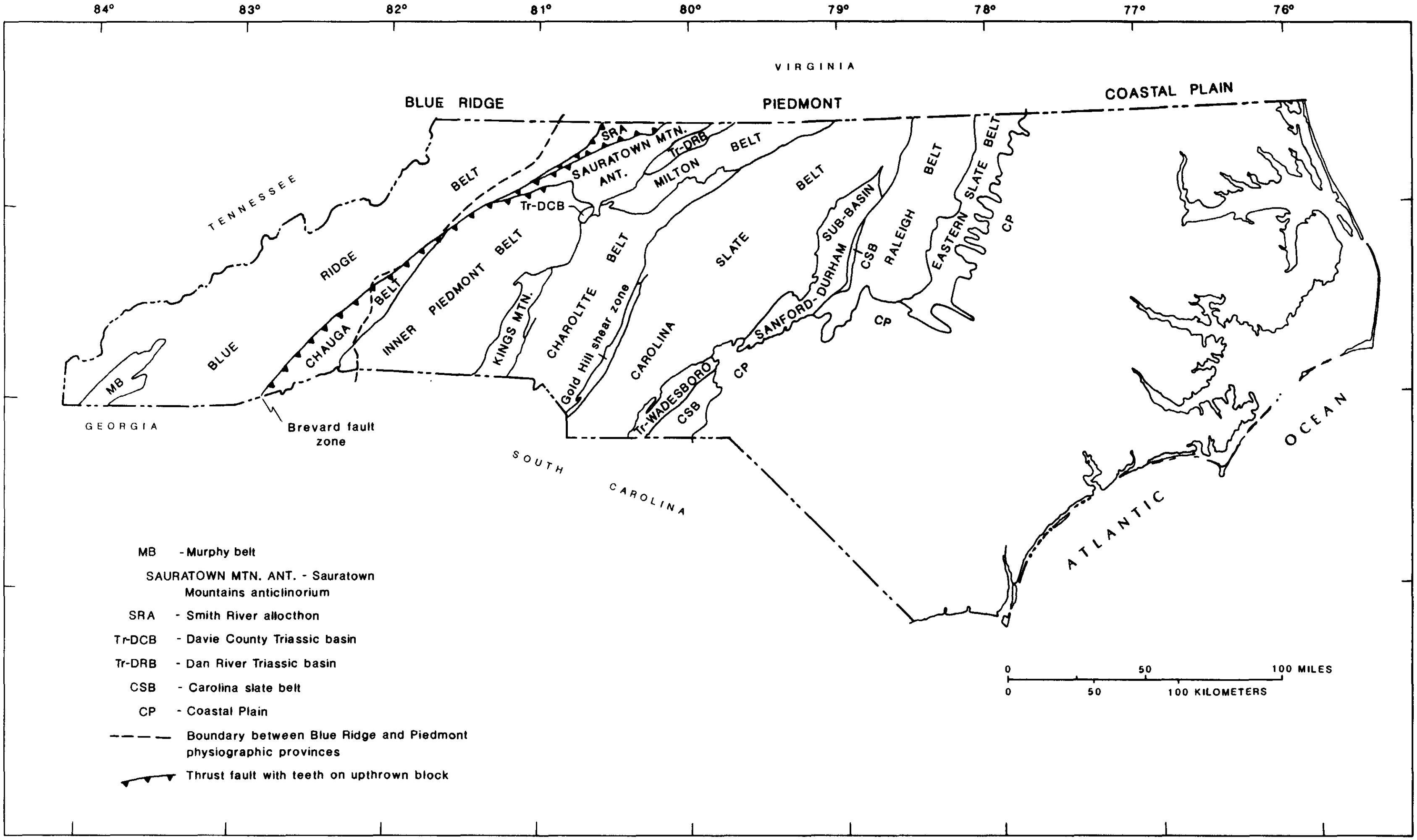


Figure 6.--Geologic belts, terranes, and some major structural features within the Piedmont and Blue Ridge provinces of North Carolina.

Table 2.--Geologic belts and terranes of the Blue Ridge, Piedmont, and Coastal Plain provinces of North Carolina

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 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 allocthon	SR	Blue Ridge belt on northeast and Sauratown Mountains anticlinorium on southeast	GNF
Sauratown Mountains anticlinorium	SA	Smith River allocthon 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

Table 2.--Geologic belts and terranes of the Blue Ridge, Piedmont, and Coastal Plain provinces of North Carolina--Continued

Belt or terrane	Letter designation	Boundaries	Dominant hydrogeologic units
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

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

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

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, 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 which is 600 feet deep and is cased to the bottom of the hole. No other well has more than 300 feet of casing and only 157 wells, or 2.5 percent, are cased to within the bottom 5 feet of the well.

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

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 overlayed on maps of the hydrogeologic units and geologic belts in order 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 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 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. Using a combination of the new maps and the published descriptions, each well in the data base subsequently was assigned to one 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 least number of data entries, being reported for slightly more than one-half of the wells. The second smallest number of entries was for casing depth, with less than two-thirds of the well records having 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, with the final computation based on no more than, and commonly fewer observations than the smallest number of variable entries.

Statistical Procedures

The data were statistically analyzed using programs developed by the SAS Institute[1/] (SAS Institute, Inc., 1982a) and available on the U.S. Geological Survey computer system in Reston, Virginia. 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 which 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.

[1/] Use of firm and trade names in this report is for identification pruposes only and does not constitute endorsement by the U.S. Geological Survey.

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 which best explain the variation in the data. Those variables which repeatedly appeared in the models offering the highest r-square were further tested 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 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 per-comparison 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 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 which was similar to the results from Tukey's procedure. Because of the properties of Tukey's procedure, the nature of the data 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 mean and median values of these characteristics are shown for wells in each of six topographic settings. The topographic settings are arranged in order of 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.

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

Well characteristic	Topographic setting						All wells					Number of wells
	Draw	Valley	Slope	Flat	Hill	Ridge	Average	First Quartile	Median	Third Quartile	Ninth Dectile	
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.

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 feet 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 feet 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 foot 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 17 to 25 feet 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 indicates 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 which 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 was the same for wells in draws and 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 valley 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 which 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.

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	2,685	71.7	293
Median casing (feet)	43	55	60	53.5	698	45	46	41	44	2,685	63	293
Average saturated thickness of 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.

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 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 feet 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 inches in diameter or larger, whereas 20 percent of the commercial-industrial and 26 percent of the public-supply wells were 8 inches 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, and a definite relation between topographic group and several well characteristics, including yield, as well as an apparent cultural bias in the siting and construction of wells related to the intended use of the well.

It is possible that the relation of well yield to rock type, which has been described by many past authors, also could be distorted by cultural bias in siting and construction. For example, in the upper Cape Fear River

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

Use of well	Percentages of wells according to use in selected topographic settings						Statistical summary of well characteristics according to use					
	Draw	Valley	Slope	Flat	Hill	Ridge	Average yield (gal/min)	Average yield/foot (gal/min)/ft	Average depth (feet)	Average casing (feet)	Average water level (feet)	Number of wells
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

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 system. 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, average depth, and average yield per foot of well depth are shown for wells of different diameters. The diameters are subdivided into 1-inch intervals; the actual diameters of the 6,074 wells summarized in figure 7 range from 1.2 inches to 12 inches. 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 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:

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

where a, b, and c are regression coefficients.

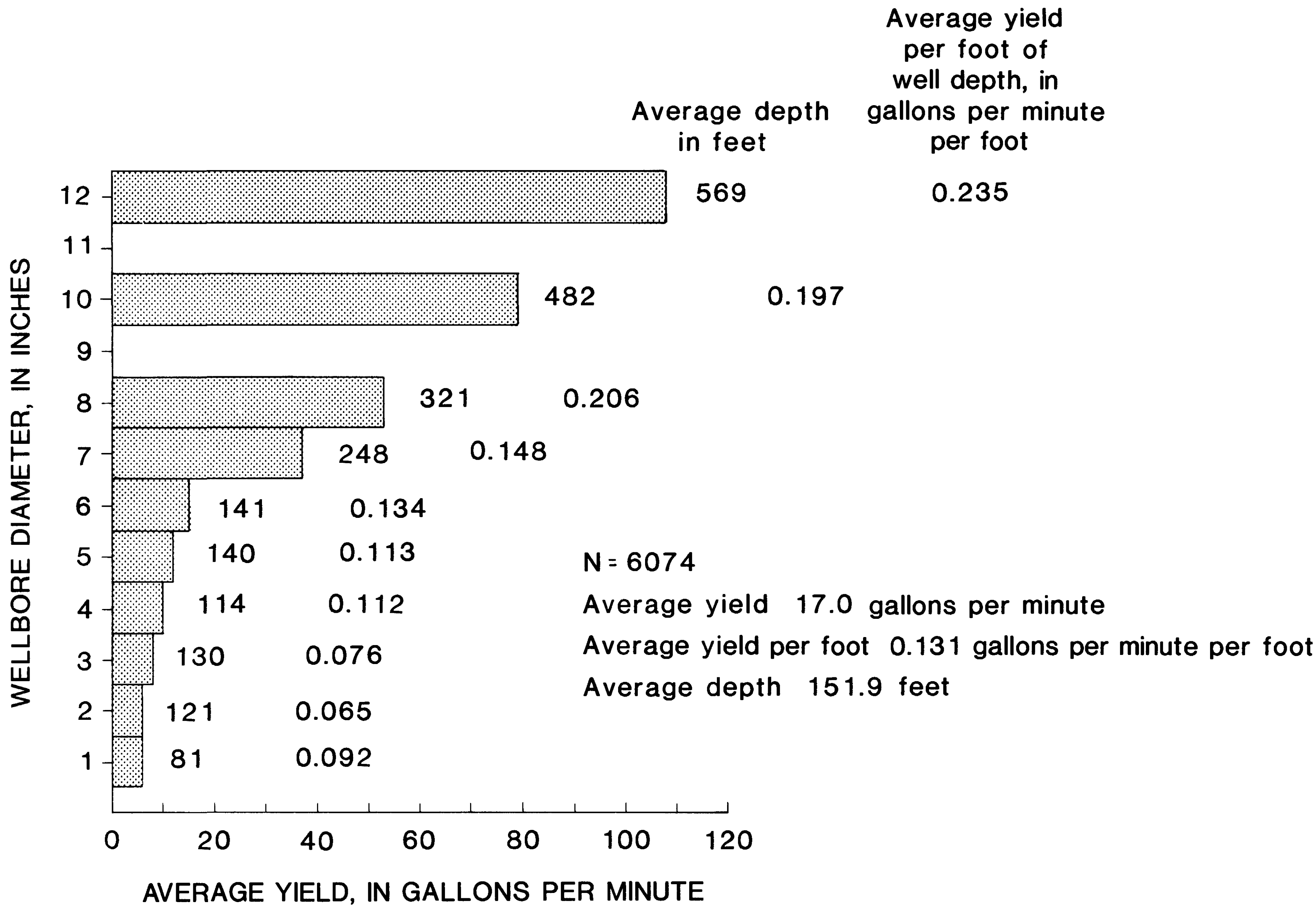


Figure 7.--Variation of average yield, average depth, and average yield per foot of well depth with wellbore diameter.

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-inch diameter well that is 1,301 feet deep. A number of larger diameter wells in the data set are nearly as deep. The shallowest well is 20 feet deep and 6 inches 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 variation at any given point. That is, for a point on either of the three contour plots there may be several wells of the same depth and diameter, all with 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 feet and a diameter of 6 inches. The predicted average yield at this point, which also is on the yield-surface axis, is 32 gal/min. If a 6-inch 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-inch, 525-foot wells, which will 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 additional amounts, 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 inches, and shows the average yield and yield per foot for wells in intervals of well depth. The large data base of wells

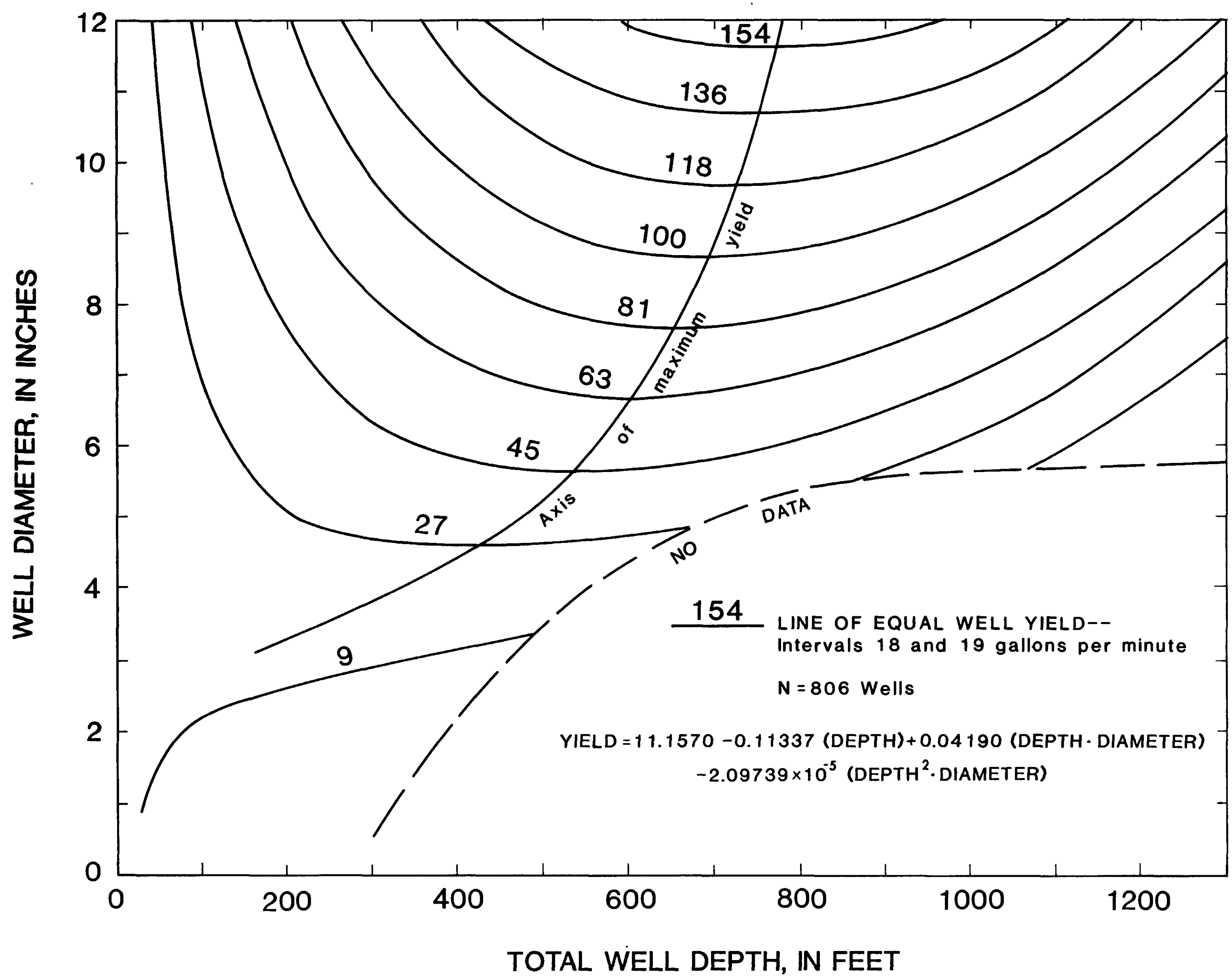


Figure 8.--Contour plot of trend surface showing relation between well yield, total well depth, and well diameter for wells located in draws and valleys.

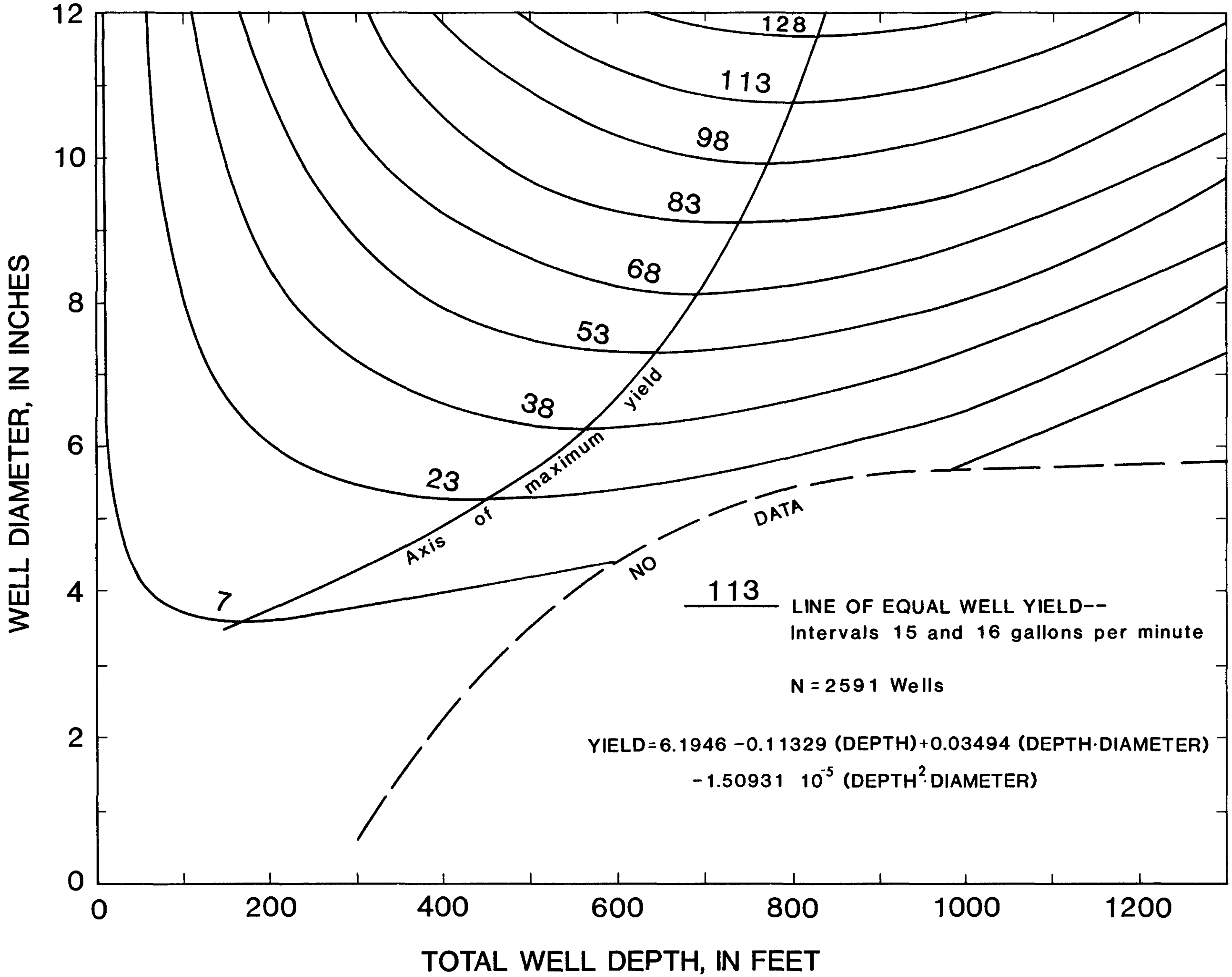


Figure 9.--Contour plot of trend surface showing relation between well yield, total well depth, and well diameter for wells located on slopes and flats.

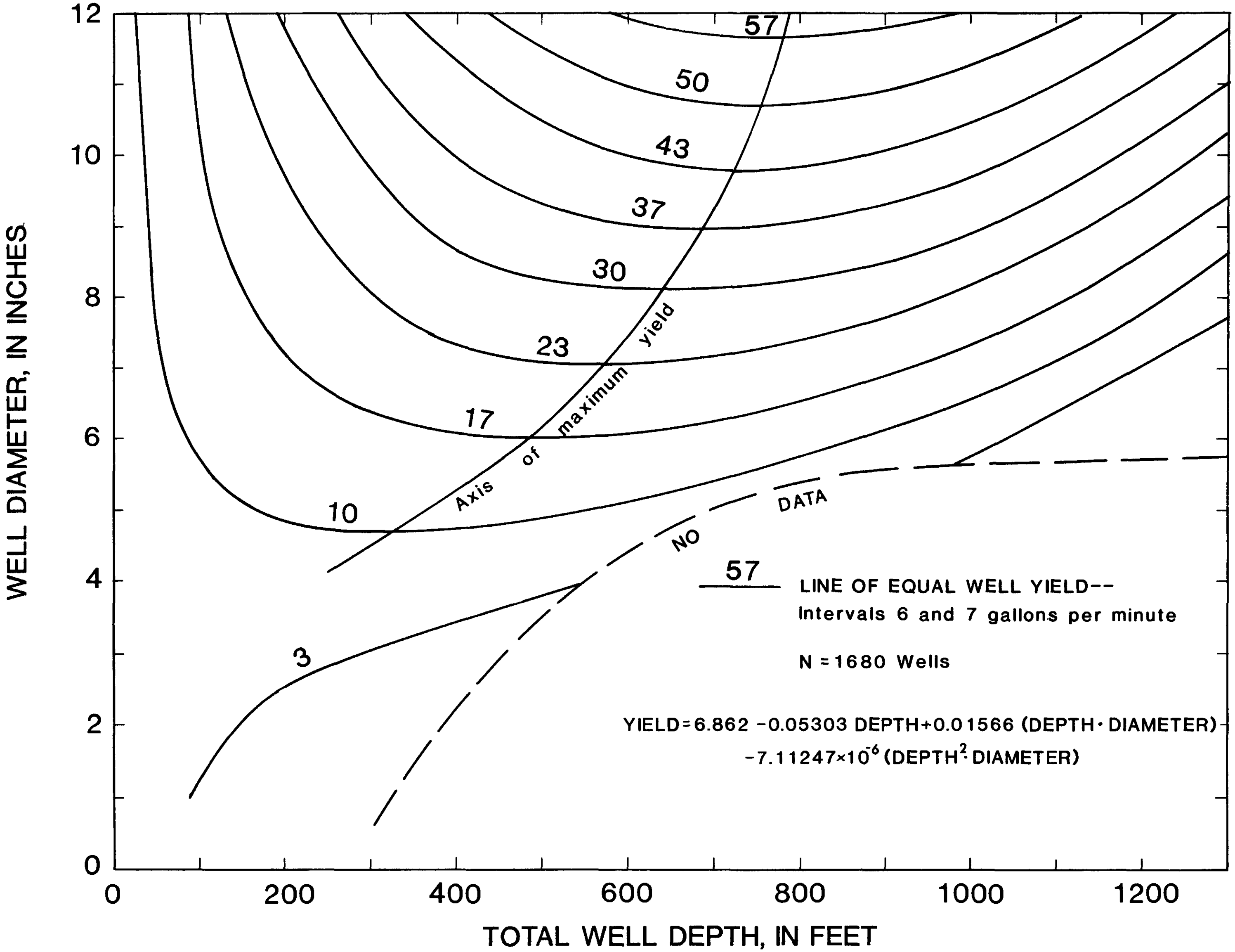


Figure 10.--Contour plot of trend surface showing relation between well yield, total well depth, and well diameter for wells located on hills and ridges.

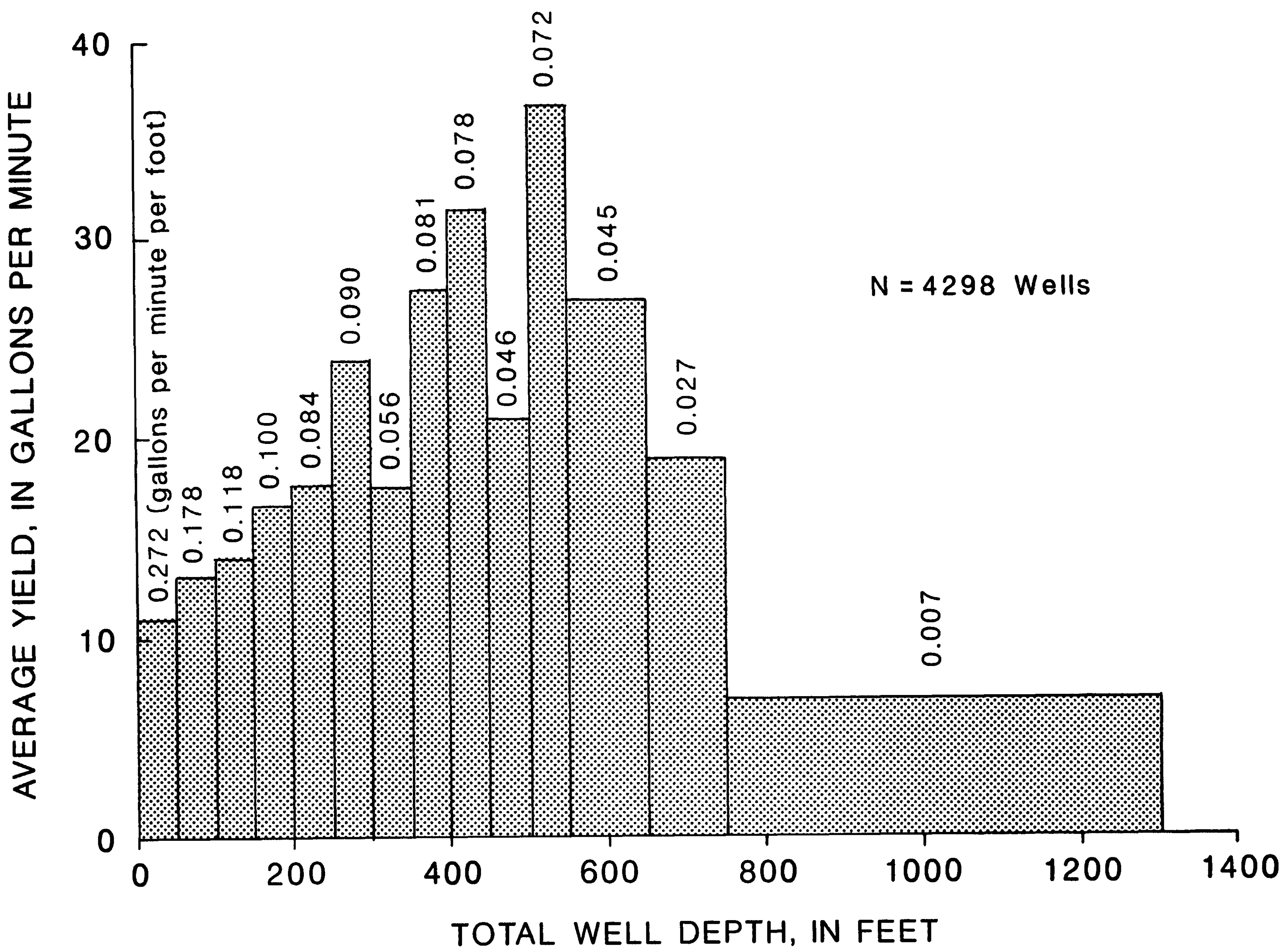


Figure 11.--Variation of average yield and yield per foot of well depth with depth for wells having diameters between 5.5 and 6.5 inches.

having diameters between 5.5 and 6.5 inches 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 feet (fig. 11), which is the approximate location of the yield-surface axes for 6-inch wells in figures 8, 9, and 10. The likelihood of obtaining significant additional quantities of water from 6-inch diameter wells decreases rapidly below depths of 550 feet. 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 retains 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 feet as the axes of the yield surfaces rapidly curve away from the depth axes. However, the maximum average yield for 12-inch wells is reached between 700 and 800 feet. 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-inch wells reach their maximum average yield (about 500 feet) is 200 feet deeper than is usually recognized in the literature (LeGrand, 1967; Snipes and others, 1983).

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 could 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. 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-foot depth and 6-inch 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 with the necessary data (depth, diameter, yield, topography) to adjust the yields. Statistics for these hydrogeologic units,

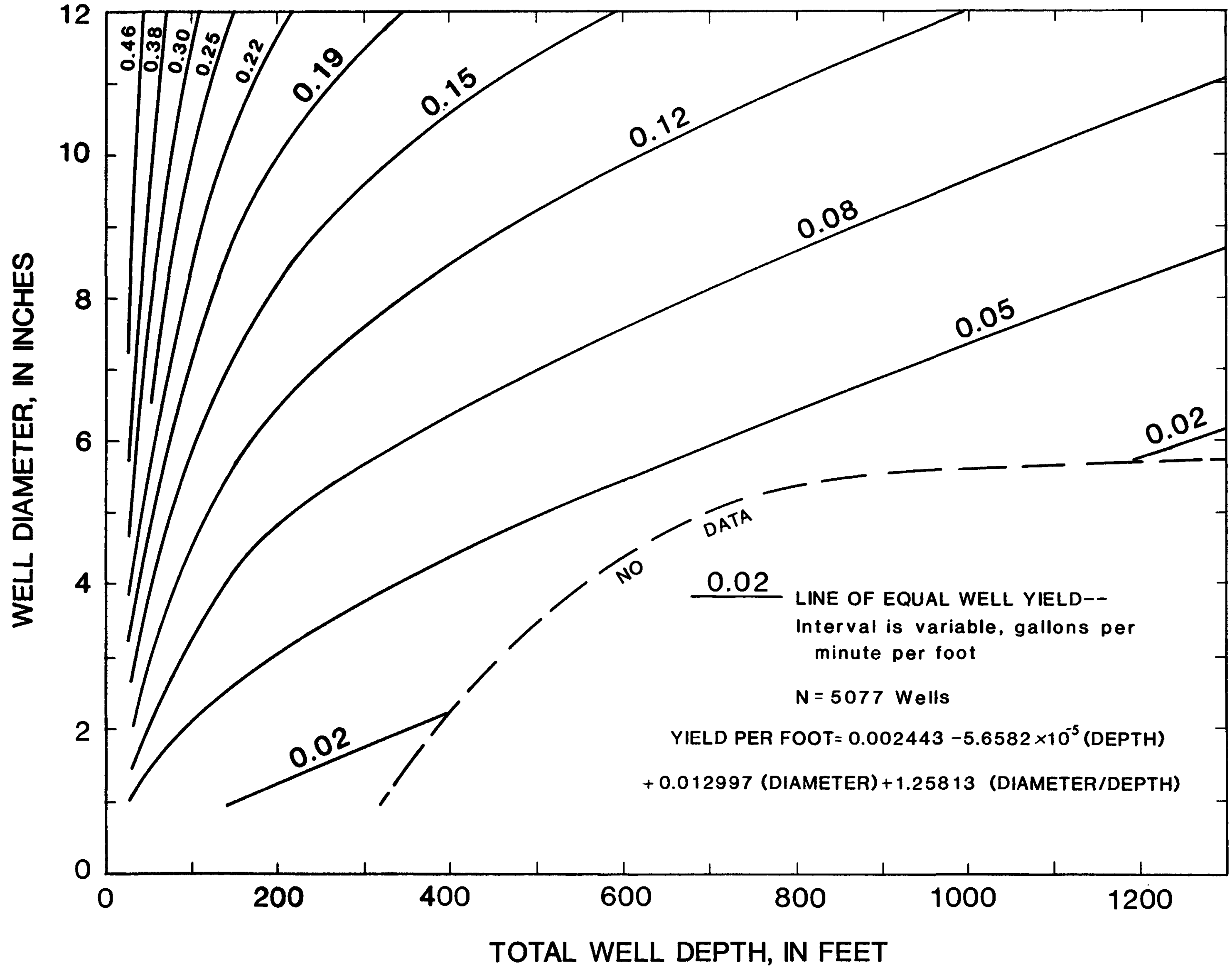


Figure 12.--Contour plot of trend surface showing relation between yield per foot of well depth, total well depth, and well diameter.

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 inches in diameter and 154 feet deep.]

Hydrogeologic unit	Mean yield by topographic group			Yield of all wells					
	Draws and valleys	Slopes and flats	Hills and ridges	Average	First quartile	Median	Third quartile	Ninth dectile	Number of wells
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

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 inches in diameter and 154 feet deep.]--Continued

Hydrogeologic unit	Mean yield by topographic group			Yield of all wells					
	Draws and valleys	Slopes and flats	Hills and ridges	Average	First quartile	Median	Third quartile	Ninth decile	Number of wells
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	23.6	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.

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 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 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 feet is 1.8 times thicker than the 26.8-foot 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

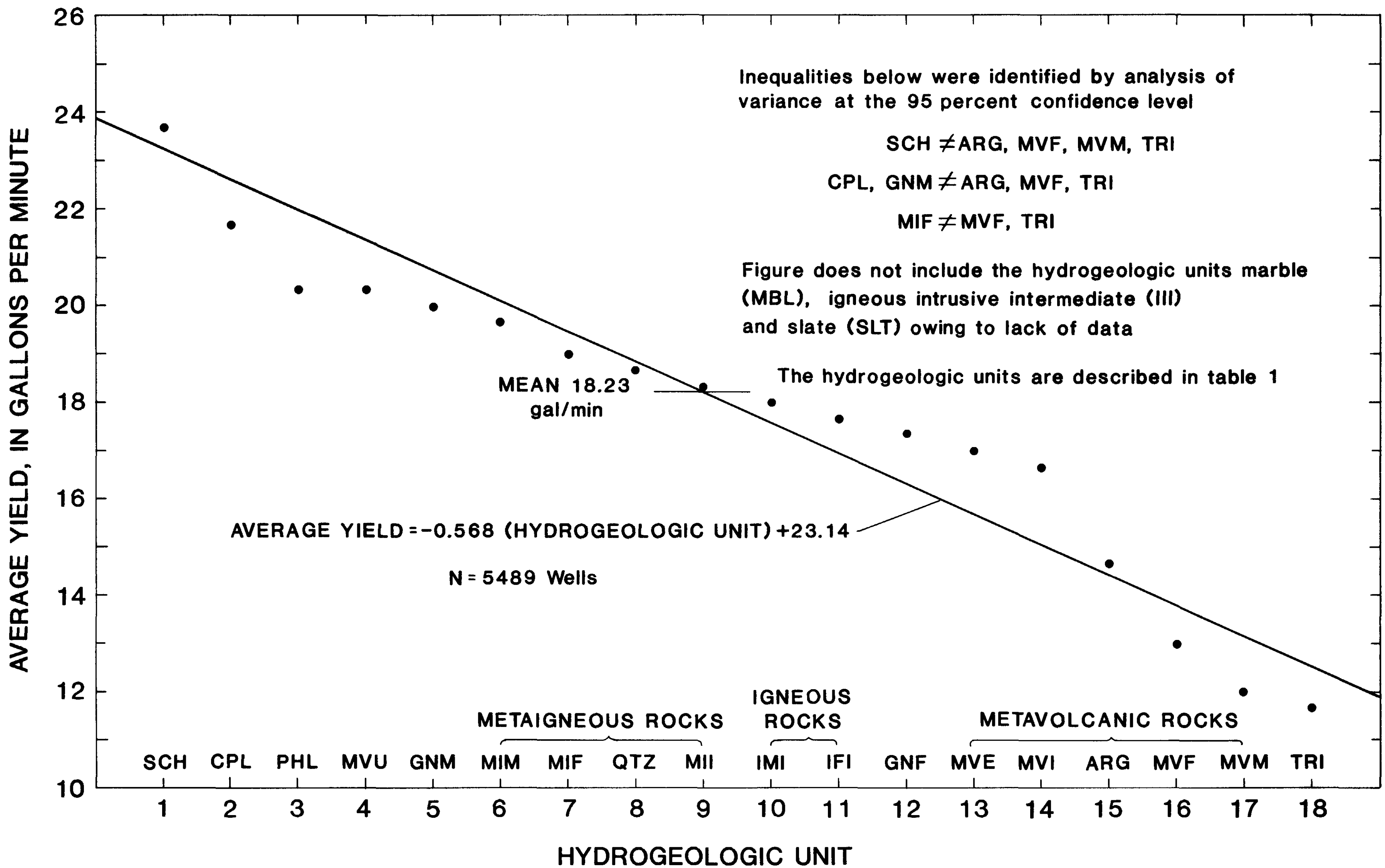


Figure 13.--Average yield of wells of average construction in the hydrogeologic units of the Piedmont and Blue Ridge provinces of North Carolina.

unit(s). The yield data used for this comparison also were corrected to an average 154-foot depth and 6-inch 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 allocthon (SR) and Triassic basins (TR) to a high of about 23 gal/min for the Blue Ridge belt (BR). 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 with the highest yields, the Blue Ridge (BR), Chauga (CA), and Inner Piedmont (IP), are dominated by high rank metasedimentary rocks, mafic gneisses, schists, and quartzites, and 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 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 in the crystalline rocks of the Blue Ridge, Piedmont, and the western edge of the Coastal Plain where crystalline rocks underlie sediments at shallow depths. This analysis was made to identify factors 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.

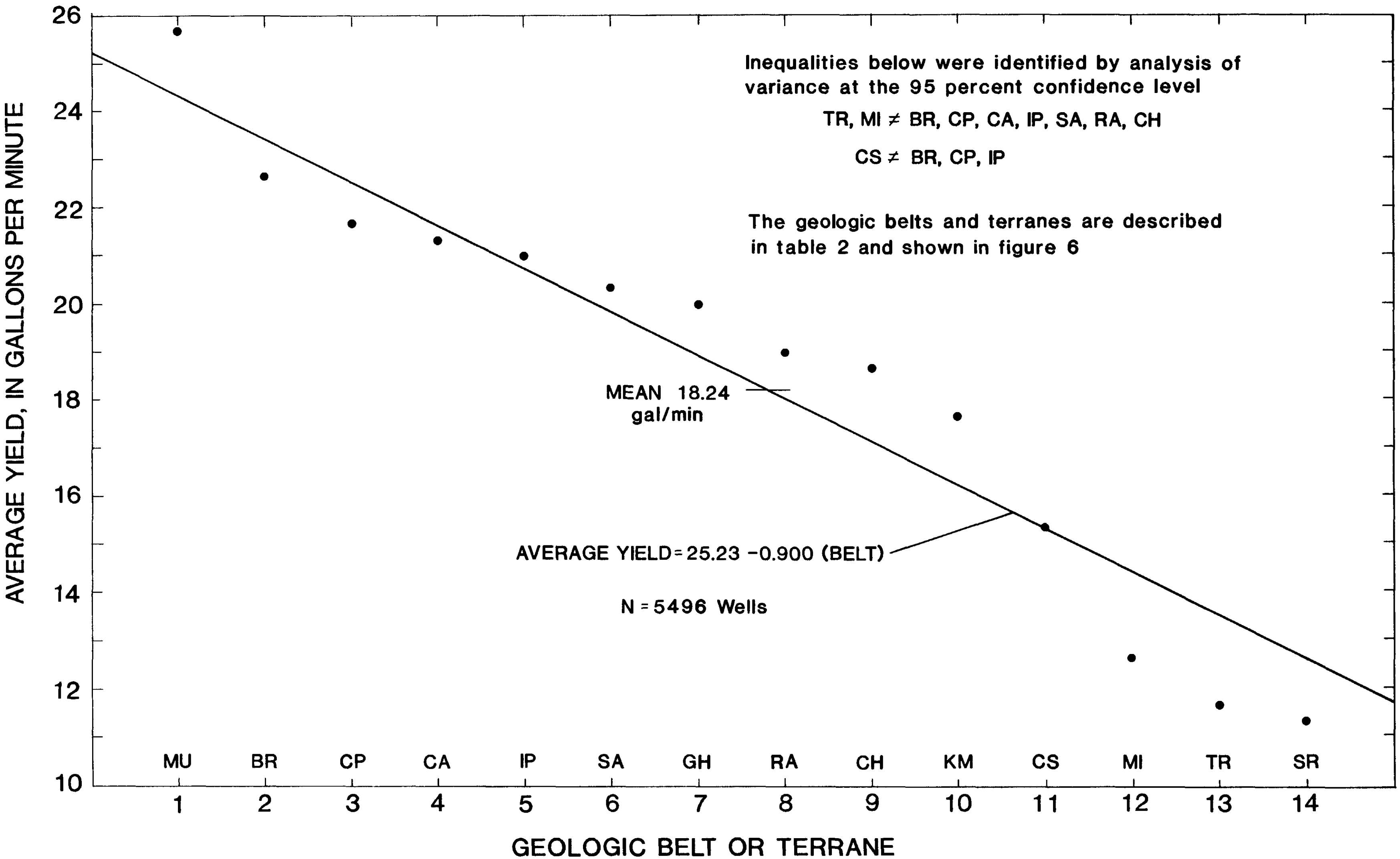


Figure 14.--Average yield of wells of average construction in the geologic belts and terranes of the Piedmont and Blue Ridge provinces of North Carolina.

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 feet) under hills and ridges and greatest (about 34 feet) 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 9 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 feet, the public-supply and commercial-industrial wells about 225 feet. Fewer than 2 percent of the domestic wells were 8 inches in diameter or larger, whereas nearly 25 percent of the public-supply and commercial-industrial wells were 8 inches or larger.

Selecting the most favorable hydrogeologic unit or geologic belt alone can improve the chance of increasing the yield of the average 6-inch diameter, 154-foot deep well from about 11 to 12 gal/min to about 23 to 24 gal/min, about a two-fold 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 feet. As a result, the drilling of many wells has been arbitrarily stopped when the depth of 300 feet 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-inch diameter wells located in draws or valleys reaches a maximum of about 45 gal/min at depths of 500 to 525 feet; the average yield of 12-inch diameter wells located in draws or valleys reaches a maximum of about 150 gal/min at depths of 700 to 800 feet.

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.

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