THE HYDROGEOLOGY OF THE COASTAL PLAIN STRATA OF RICHMOND AND NORTHERN BURKE COUNTIES, GEORGIA

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ENVIRONMENTAL PROTECTION DIVISION
GEORGIA GEOLOGIC SURVEY

Information Circular 61

Cover photo: 1983 addition to the Proctor and Gamble Corporation plant located on Old Savannah Road (Georgia Highway 56), Augusta, Richmond County.

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THE HYDROGEOLOGY OF THE COASTAL PLAIN STRATA OF RICHMOND AND NORTHERN BURKE COUNTIES, GEORGIA

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ABSTRACT

Rapid industrialization and urbanization in Richmond and northern Burke Counties, along with growth in the use of ground water for irrigation, have resulted in increasing withdrawals from ground-water sources. Ground-water use in the study area in 1980 was approximately 26.5 Mgal/day, most of which was pumped from the basal Cretaceous aquifer, the lowermost of two aquifers within the Cretaceous Gaillard formation. The upper Cretaceous aquifer is not extensively developed. Likewise, the shallower water-bearing units, including portions of the Huber Formation, the Lisbon Formation, the Barnwell Group, and the Altamaha Formation, are not extensively developed. Well information was adequate to define the hydrogeology of the basal Cretaceous aquifer; however, an evaluation of the hydrogeology of shallower units was not possible due to inadequate well information.

Both the basal and upper Cretaceous aquifers dip to the southeast. The aquifers are separated by a red clay or sandy clay that acts as a confining bed and is inferred to be a weathered surface within the Gaillard formation. Well logs indicate that this confining bed ranges in thickness from 7 to 60 feet thick. Aquifer test analyses indicate that this confining bed is leaky, with vertical hydraulic conductivities ranging from about 9.3×10^{-8} ft/s to 1.6×10^{-6} ft/s. The upper Cretaceous aquifer also is capped by a confining bed that is considered to be a weathered surface. Transmissivities of the basal Cretaceous aquifer range from about 2.6×10^{-2} ft²/s to 2.0×10^{-1} ft²/s.

Potentiometric data indicate that regional ground-water flow in the basal Cretaceous aquifer is generally from west to east. Natural discharge is into the Savannah River as well as into creeks and streams where the aquifer sediments are close to or at land surface. Recharge to the aquifer occurs as direct infiltration in the outcrop area and as leakage through overlying units. Pumping in eastern Richmond County has modified the natural flow system of the basal Cretaceous aquifer. A cone of depression exists immediately west of Bush Field as a result of large-scale industrial and municipal pumping. The potentiometric data also indicate that the basal Cretaceous aquifer is heavily stressed in the eastern industrial complex. As a result, additional ground-water withdrawals might adversely affect overall ground-water availability in this area. Ground-water availability in other parts of the study area is good, particularly in southern Richmond and northern Burke Counties. Yields from the basal Cretaceous aquifer are lower in the northwestern portion of the study area than in other parts of the study area due to the aquifer sediments being thin and shallow. The upper Cretaceous aquifer as well as the permeable portion of the Huber Formation is capable of supporting additional development of the ground-water resource.

Water in the basal Cretaceous aquifer is low in total dissolved solids and is slightly acidic. In some locations, the concentration of iron and manganese exceeds the EPA recommended limit. However, such concentrations do not pose a health risk, but may lead to the staining of fixtures and clothing.

INTRODUCTION

PURPOSE

The Augusta-Richmond County area has experienced rapid growth in both population and industrial capacity in recent years. This growth is expected to continue in the future and will probably include the northern part of Burke County. As such, the demand for water has grown and will continue to grow. Because much of this growth is anticipated to occur in areas where surface-water supplies are not readily available or practical to develop, the ground-water system will supply much of the additional demand.

Preliminary studies have suggested that increases in ground-water withdrawals might create local problems with both ground-water availability and ground-water quality. Therefore, future development should be planned such that any adverse impacts on both the quantity and quality of available ground water will be minimized. In order to adequately plan for this development, the hydrogeology of the area must be understood. This study was planned and executed to satisfy this need. Specific objectives were to:

1. Define and characterize the hydrogeologic units in the study area.
2. Define the geometry of the aquifer systems.
3. Evaluate the direction and rate of ground-water flow.
4. Identify the nature of recharge to the aquifer.
5. Evaluate the effects of aquifer inhomogeneity on hydrogeology.
6. Estimate water use.
7. Evaluate, if possible, how the aquifers in the area are hydrogeologically connected to each other and to rivers and streams.
8. Evaluate ground-water quality.
9. Evaluate general ground-water availability.

SCOPE

The records of more than 100 wells were compiled for this study from a number of sources. Aquifer tests were compiled and, where possible, the data were analyzed. No wells were drilled for this study. Some data deficiencies such as a lack of wells in certain areas, incomplete records on existing wells, and a lack of geophysical and drillers' logs limited the completion of the defined objectives. Nevertheless, for the basal Cretaceous aquifer, which is the most intensively used aquifer in the study area, the objectives of the study were fulfilled.

DESCRIPTION OF THE STUDY AREA

The area of this study is bounded on the northwest by the Fall Line, on the northeast by the Savannah River, on the southwest by Brier Creek, and on the southeast by Brigham's Landing Road (Fig. 1). Brigham's Landing Road is an arbitrarily chosen boundary, and has no hydrogeological significance. Geologically, the Fall Line is considered to be the surface exposure of the contact between the Coastal Plain sediments and the crystalline rocks of the Piedmont (Clark and Zisa, 1976). The Fall Line is a hydrogeologic boundary by virtue of the contrast in permeabilities of the crystalline rocks of the Piedmont relative to the unconsolidated sands and gravels of this area of the Coastal Plain. Both Brier Creek and the Savannah River act as hydrologic sinks. Because Brier Creek is smaller than the Savannah River, it has less effect on the ground-water flow.

The study area lies within the Fall Line Hills and Vidalia Upland Districts of the Coastal Plain Physiographic Province (Clark and Zisa, 1976). The Fall Line Hills District is highly dissected. Slopes are steep except in the floodplains of rivers. Most of Richmond County is within this district. The southern edge of Richmond County and almost all of Burke County are within the Vidalia Upland District. The topography of this area is characterized by moderate dissection and relatively narrow floodplains (Clark and Zisa, 1976).

Major streams in the study area include Brier Creek, McBean Creek, Spirit Creek, and Butler Creek. Brier Creek, which forms the southwestern boundary of the study area, flows into the Savannah River approximately 25 miles southwest of the study area. The other major streams join the Savannah within the study area.

Augusta is the only large city in the study area. In 1980, the population of Augusta was 47,532; however, there are many more people living in adjacent unincorporated areas. The total population of Richmond County in 1980 was 181,629 (U.S. Bureau of the Census, 1982). Census figures for Richmond County from 1930 to 1980 (Fig. 2) show the population growth in this area.

Industries are concentrated in Richmond County along the Savannah River and paralleling highways and rail lines. These industries manufacture a wide range of products including textiles, paper products, lumber, fertilizer, structural bricks, refractory ceramics, and a number of chemicals used in agriculture, textiles, and paper processing. Many of these industries use large quantities of water in their manufacturing process. Future industrial development appears likely due to the availability of large tracts of land, the abundant labor force, good transportation facilities (rail, air, road and river) and an abundant water supply. As a result, there is a potential for increased demand for ground water and a corresponding increase in the potential for ground-water contamination.

In the southern part of the study area, agriculture is the primary land use. Although the topography of the area is not conducive to the very large scale irrigation equipment that is popular in other areas where fields are large and flat, new equipment specifically designed for smaller, irregularly shaped fields is being developed. As a result, water use for irrigation is expected to increase.

The climate of the study area is characterized by warm, humid summers and mild winters. Monthly mean high temperatures at Bush Field, southeast of Augusta, range from 91°F in July to 58°F in December and January. Monthly mean low temperatures range from 39°F in December and January to 72°F in July (Michael Baker, Jr., Inc., 1979, p. 27).

Although climatological data indicate that the study area is within a relatively dry part of the state, precipitation is still plentiful. Mean annual precipitation at Bush Field is approximately 44.6

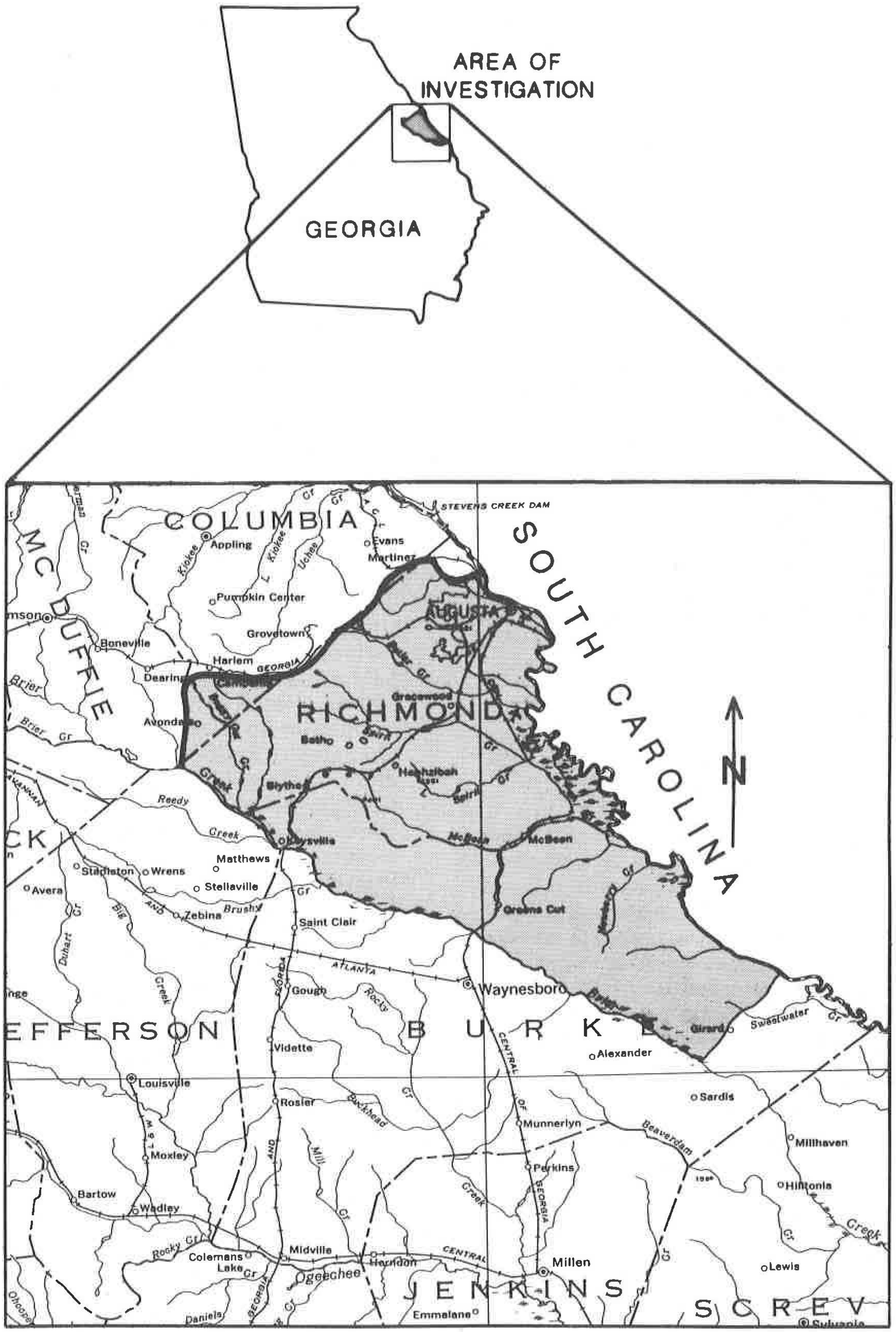

Figure 1. Location of the study area.

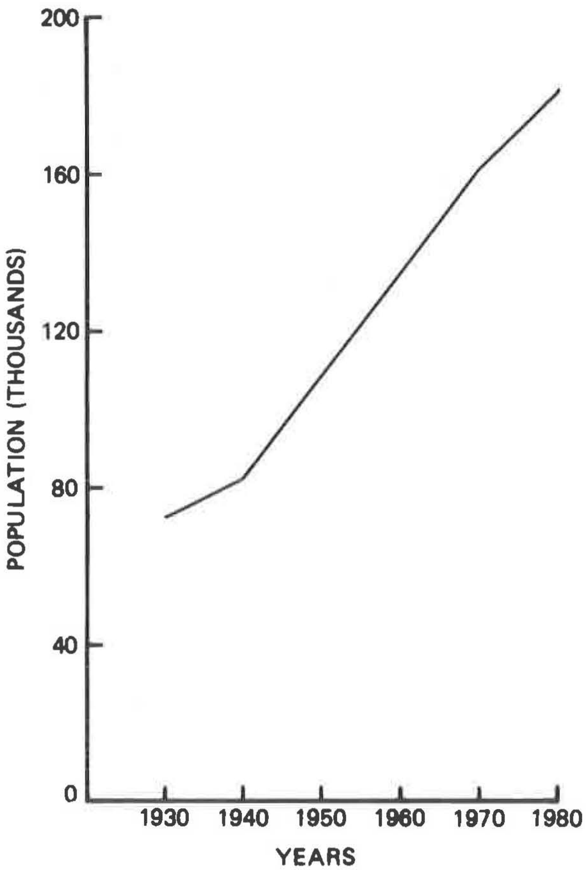

Figure 2. Population of Richmond County from 1930 to 1980. Data from the U.S. Bureau of the Census (1982).

inches per year based on 89 years of records (Michael Baker, Jr., Inc., 1979, pg. 27). Figure 3 indicates that precipitation is greatest in July and August, a period which coincides with peak thunderstorm activity. Precipitation is lowest in October and November. Although as much as 14 inches of snowfall have been recorded, snowfall is not a significant part of the total precipitation, and averages less than an inch per year.

PREVIOUS INVESTIGATIONS

A number of geologic and hydrogeologic investigations have been conducted in areas that include or adjoin the area of this study. Most of these studies were regional in scope. In 1898, McCallie reported on the artesian wells in south Georgia, including Richmond and Burke Counties. Ladd (1898) inventoried the clays of Georgia. Sloan (1904, 1907) reported on the geology and clay deposits of South Carolina. Veatch (1909) investigated the clay deposits of Georgia. Later, Veatch and Stephenson (1911) made a preliminary report of the geology of

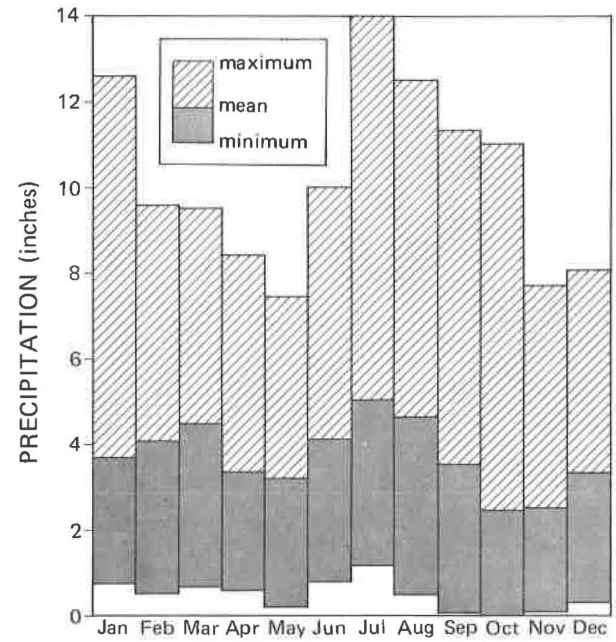

Figure 3. Mean and extreme monthly precipitation at Bush Field, Augusta. Data from Michael Baker, Jr., Inc. (1979).

Georgia's Coastal Plain. Cooke studied the Coastal Plain of South Carolina (1936) and Georgia (1943). LaMoreaux (1946a, 1946b) studied the geology and hydrogeology of east-central Georgia. Eargle (1955) mapped the Cretaceous rocks and reported on their stratigraphy. LeGrand and Furcron (1956) reported on the geology and hydrogeology of central-east Georgia, including the area of this investigation. Hurst and others (1966) inventoried the mineral resources of the central Savannah River area. Prowell and others (1975) documented the Belair Fault in western Richmond County. Huddlestun and Hetrick (1978, 1979) revised the stratigraphy of the updip Jacksonian sediments. Faye and Prowell (1982) examined the hydrology of eastern Georgia and western South Carolina for the effects of possible faulting. Vincent (1982) reported on the hydrogeology of the Jacksonian-age aquifer in eastern Georgia.

WELL NUMBERING SYSTEM

Wells used in the preparation of this report were assigned arbitrary numbers. Plate 1 indicates the locations of the wells referred to in this report. Appendix A lists these wells in numerical order along with the owner's name, the owner's well number for the well, latitude, longitude, and the type of data available. The locations of wells that were still in existence were field checked. A number of wells (and core holes) were plugged or otherwise abandoned.

ACKNOWLEDGEMENTS

I would like to express my appreciation to the many individuals representing industries, municipalities, and other government agencies, as well as private citizens who have enabled me to conduct this study by supplying information and allowing access to their wells. Without their cooperation, this study would not have been possible.

I would like to thank Donald Hudson of Proctor and Gamble and William Martin of Virginia Supply and Well Co. for their cooperation in allowing me to collect data during the testing of the Proctor and Gamble well. I thank Harry Blanchard of the U.S. Geological Survey for providing equipment for the Proctor and Gamble aquifer test as well as information on the location and access to wells in the study area. Robert E. Faye of the U.S. Geological Survey provided unpublished data that otherwise would have been unobtainable, in addition to discussions on the framework and character of the aquifer. His review of the manuscript in various stages resulted in a much improved document. Mr. Faye's input is greatly appreciated. Without the help of all of these people, this study would have been much more difficult to complete.

STRATIGRAPHY

GENERAL

Figure 4 is a stratigraphic column of Coastal Plain units within the study area, and is modified from Huddlestun's (1981) correlation chart of Coastal Plain sediments. A brief description of each unit is included below. Some of the units included here are currently informal with respect to the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). Capitalized rank designations indicate formal units, for example: Barnwell Group, Huber Formation, and Irwinton Sand Member. Uncapitalized rank designations indicate informal units, for example: Oconee group, and Gaillard formation.

"BASEMENT" COMPLEX

The "basement" complex in the study area is a subsurface extension of the crystalline rocks of the Piedmont Province. These rocks are very complex metavolcanics which locally have been intruded by granite. Rock types noted include gneisses and schists of varying mineralogy, granite, phyllite and slate. Detailed studies of these rocks have been conducted, but are not pertinent to this investigation. Useful references relative to the "basement" complex include Snoke (1978) and Bramlett and others (1982).

UNDIFFERENTIATED TRIASSIC-JURASSIC ROCKS

Red to greyish-brown siltstones, sandstones and breccias underlie the Coastal Plain strata in the southern part of the study area. Faye and Prowell (1982, p. 11) note that these rocks are probably of Triassic to Early Jurassic age. Marine and Siple (1974) present evidence to indicate that these rocks are fanglomerates that fill an elongate basin that runs southwest from South Carolina into Georgia. Marine and Siple (1974) named the basin after the former town of Dunbarton, now a part of the Savannah River Plant. They suggest that the Dunbarton Basin is correlative with the Newark Supergroup, and postulate that the Dunbarton Basin formed due to normal faulting of the crystalline rocks that are exposed north of the Fall Line.

COASTAL PLAIN SEDIMENTS

Oconee Group

In the area of study, the Oconee group includes the Huber Formation and Gaillard formation. The Oconee group as used in this report is roughly equivalent to the "Tuscaloosa Formation" as used by a number of authors, including Cooke (1936), LeGrand and Furcron (1956), and Siple (1967). The formal definition of the Oconee group is in review by Huddlestun. Although the Huber and Gaillard are of different ages, they are similar lithologically. The Oconee group typically contains cross-bedded sands and gravels interbedded with sandy clays. The sand and gravel is commonly comprised of quartz with lesser quantities of feldspar. The sands and gravels contain some clay. Large flakes of mica are common.

The kaolin that is mined at a number of locations near the Fall Line in Georgia and South Carolina is from the Oconee group. These commercial-grade kaolin deposits, however, are not representative of the clays of the Oconee group as a whole in that Oconee group clays are typically sandy.

Gaillard Formation. The lower part of the Oconee group in the study area is the Gaillard formation. A formal proposal for the term Gaillard formation is in preparation by Huddlestun and Chowns. The proposed type locality is the pit of the Atlanta Sand and Gravel Company near the town of Gaillard in Crawford County. In the northern part of the study area the Gaillard overlies the crystalline rocks of the Piedmont. In the southern part of the study area it overlies the undifferentiated Triassic rocks. It, in turn, is overlain by the Huber Formation. The Gaillard formation-Huber Formation contact marks the Cretaceous-Tertiary unconformity. A minor unconformity is inferred to exist within the Gaillard formation. An oxidized zone noted on many drillers'

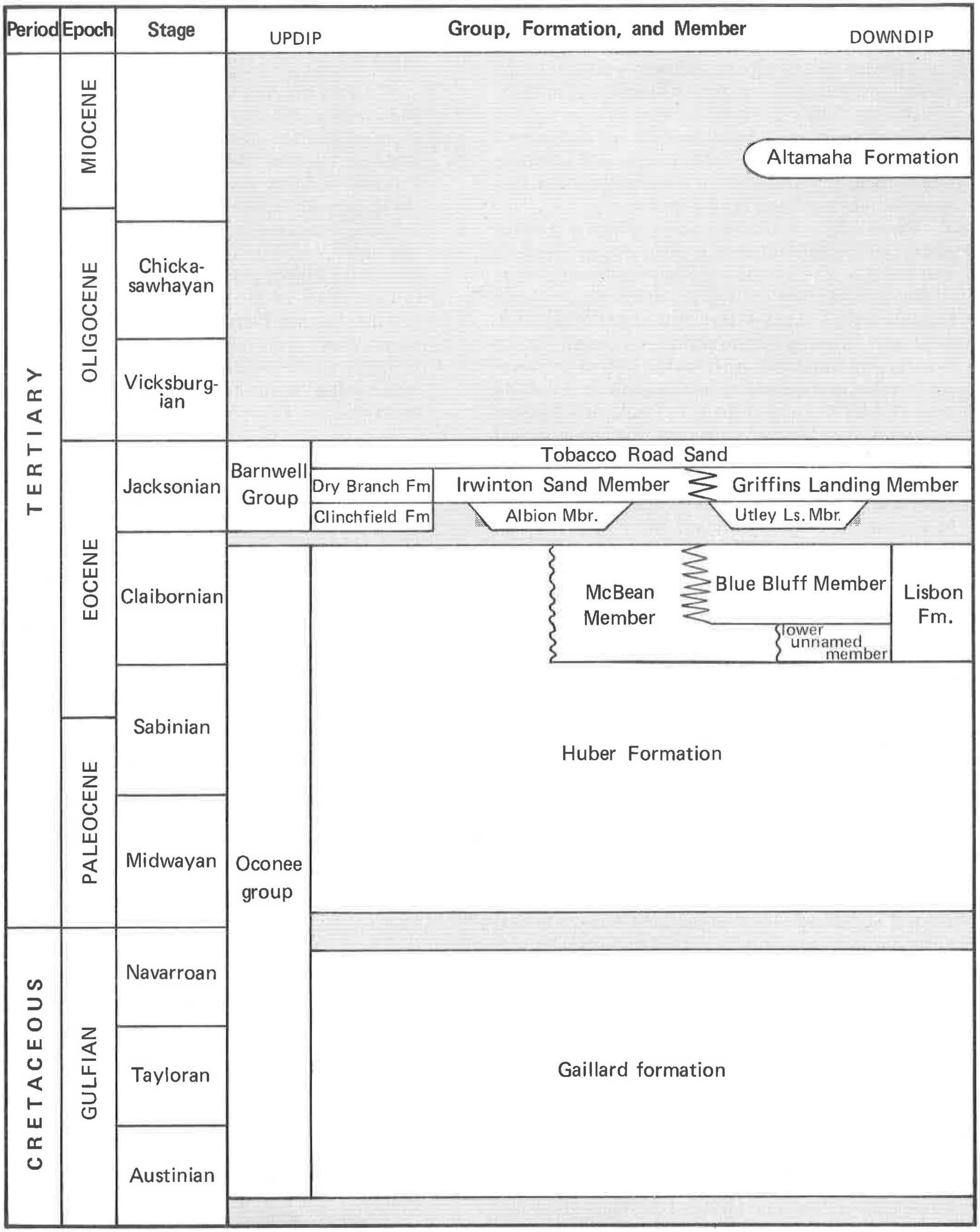

Figure 4. Stratigraphic column of Coastal Plain sediments in Richmond and northern Burke Counties. Modified from Huddlestun (1981). Shaded areas indicate time not represented by sediments.

logs as a red clay or sandy clay marks both the unconformity at the top of the Gaillard and the inferred unconformity within the unit. In some locations, the oxidized zone is not present due to erosion prior to the deposition of the overlying sediments. The Tertiary-Cretaceous contact is exposed at a cut on the south side of Dixon Airline Road approximately 0.4 mile east of Highway 56 (4000 feet west-northwest of well 77). At this exposure, the red clay is approximately 20-feet thick at both ends; however, it pinches out and is absent in the middle of the exposure. Figure 5 is a photograph of the eastern side of this exposure. The clay is a moderate-red color in outcrop and contains moderate quantities of silt and small quantities of sand. Because of weathering of the exposure, bedding is indistinct. At locations where the upper oxidized zone is missing, the contact between the Gaillard formation and the Huber Formation is difficult to distinguish due to the similar lithologies of the two units.

The Gaillard formation is composed of alternating beds of clay, sand, and gravel. The sandy parts of the formation are poorly sorted and contain very coarse to fine sand with gravel, interspersed clay, and flakes of muscovite mica. Quartz and feldspar are the dominant sand components. The sands and gravels of the Gaillard formation are typically crossbedded. Figure 6 is a photograph of a typical exposure of the sand and gravel of the Gaillard formation at the exposure noted above. Kaolinite is the dominant clay mineral in the Gaillard formation. Clay beds within the unit range from very pure, commercial-grade kaolin, to sandy and silty micaceous clays. The environment of deposition of the Gaillard formation is thought to be fluvial (Siple 1967, p. 26-28) based upon the lack of marine fossils, the poor sorting of the sands and gravels, the irregular thickness of individual beds, the sedimentary structures (particularly crossbedding) and the presence of gradational changes from clay to sand in short distances within an individual bed. A late Cretaceous age for the Gaillard formation is now generally accepted. A more specific age for the unit has not been satisfactorily established due to the sparseness of fossils and the resulting lack of paleontological study. The inferred weathered zone within the formation suggests that the unit was deposited during at least two intervals of time.

Faye and Prowell (1982, p. 12-15) refer to the Gaillard formation of this report as the Middendorf and "Black Creek(?)" formations. They state that "a zone of oxidation and weathering marks the Middendorf-Black Creek Contact" (p. 15). This zone of weathering is believed to be the same as the weathered surface previously noted within the Gaillard formation. Therefore, the lower part of the Gaillard is probably equivalent to their Middendorf, whereas the upper part is probably equivalent to their "Black Creek(?)" formation.

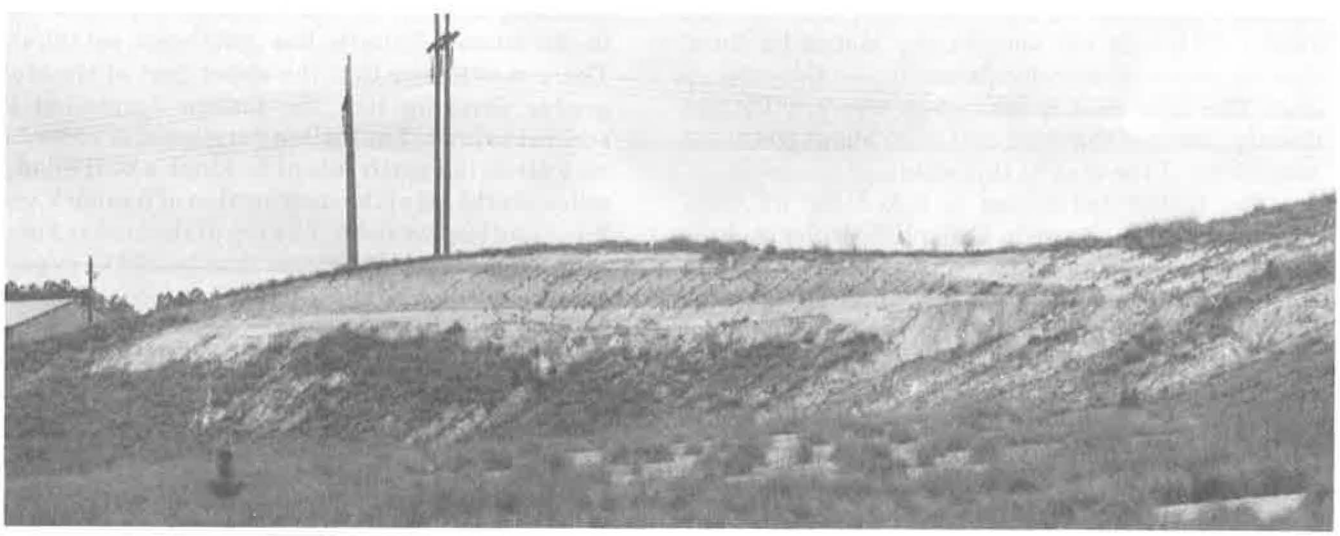

Figure 5. Photograph of the Tertiary-Cretaceous contact exposed along Dixon Airline Road, Richmond County. Note the weathered zone at the top of the Cretaceous pinching out to the right.

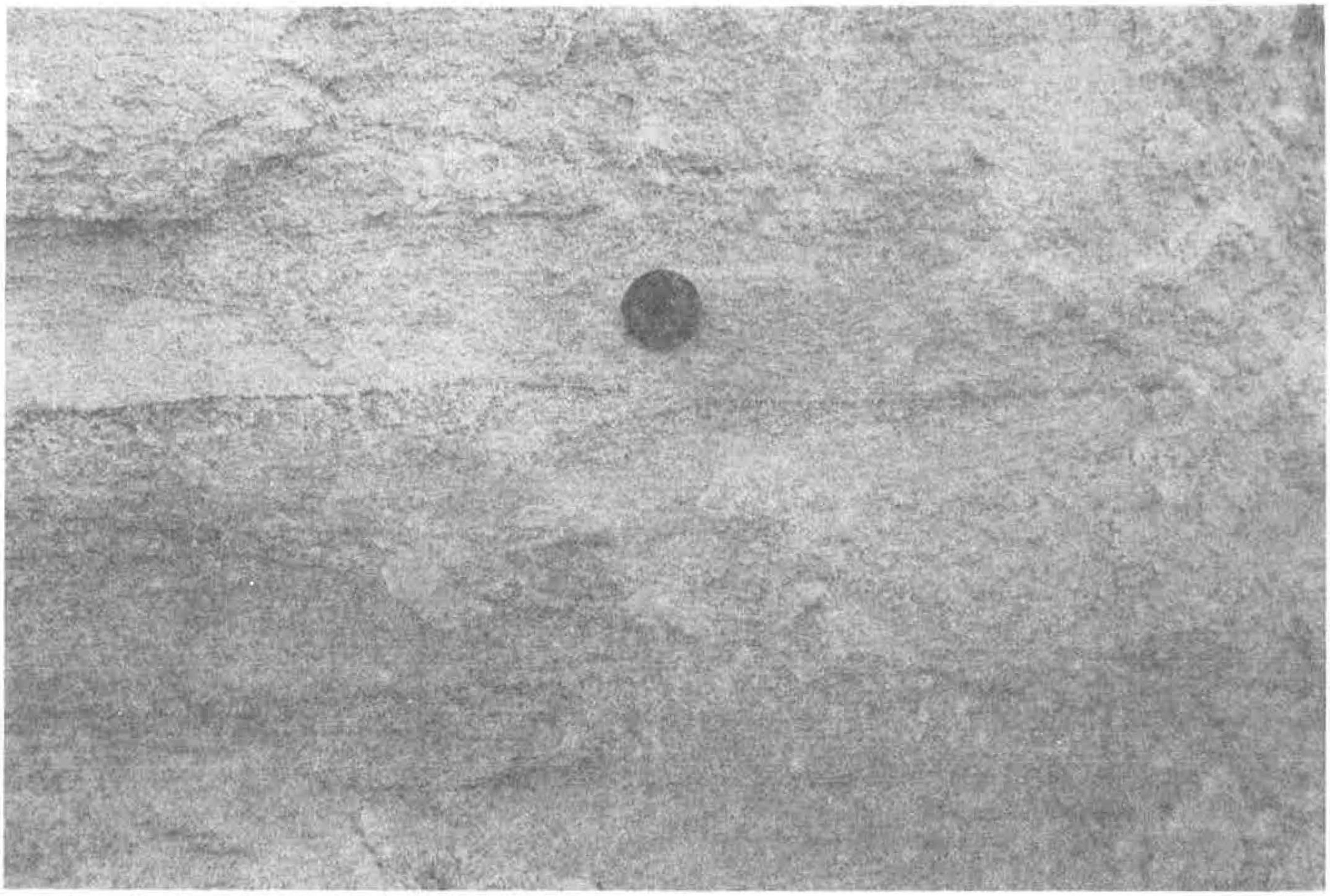

Figure 6. Photograph of typical Gaillard formation sediments. The lens cap is 2½ inches in diameter.

Huber Formation. The upper unit of the Oconee group is the Huber Formation, which Buie (1978) defined to include all pre-Jacksonian age Tertiary strata. Although not specifically stated by Buie, this definition is intended primarily for the outcrop area. The type area is located in western Twiggs County, north of the town of Huber, about 100 miles southwest of the area of this study.

The Huber Formation is noted for its commercial-grade kaolin beds. Other lithologies include sandy clays, coarse sands, and gravels. In many localities, the sand and gravel contain appreciable amounts of interspersed clay. Buie (1978, p. 3) noted that Huber Formation lithologies are typical of nearshore deposition. Evidence for this includes the variety of lithologies and the presence of *Ophiomorpha nodosa*.

The Huber Formation was once considered to be Cretaceous in age, probably due to its lithologic similarity with the Upper Cretaceous sediments underlying it. The Huber Formation is typically slightly finer grained and better sorted than the Gaillard formation. Paleontological evidence indicates that the Huber contains beds of both Paleocene and Eocene age (Buie, 1978). The precise age(s) (Midwayan, Sabinian, or Claibornian) of the Huber in Richmond County has not been established. There is evidence that the upper part of the Huber grades downdip into the Lisbon Formation (described below). The Lisbon Formation is absent in a clay pit on the north side of Bennock's Mill Road, 1½ miles southeast of the intersection of Bennock's Mill Road and Highway 56. The top of the Huber Formation at this location is higher than would be expected by projecting the dip of this surface from wells farther downdip (where the Lisbon Formation is present). If the Huber Formation does grade into the Lisbon (another possibility being that the Lisbon abruptly pinches out), then the uppermost part of the Huber is Claibornian in age.

Lisbon Formation

The Lisbon Formation overlies the Oconee group in the downdip part of the study area. Smith (1907) named the Lisbon Formation for Claiborne-age deposits in Clarke County, Alabama, and MacNeil

(1947a, 1947b) extended the term into Georgia. The Lisbon Formation, as used in this report, includes the McBean and Blue Bluff members, and an unnamed lower member. Within the study area, the unnamed lower member of the Lisbon Formation is a non-calcareous sand which becomes calcareous downdip and eventually grades into limestone (Huddlestun, personal commun.). The driller's log of well 146 describes the unit as a very dense, clayey, fine to medium sand with few clay seams. At Plant Vogtle, 27 miles south-southeast of Augusta, Bechtel (1982) describes the lower member as an unconsolidated, well-sorted, fine- to medium-grained quartz sand containing little, if any, clay.

The Blue Bluff member of the Lisbon Formation occurs primarily in the subsurface. The type locality is on the Savannah River at Blue Bluff, adjacent to the plant Vogtle site in Burke County (Huddlestun, in review). The Blue Bluff member is dominated by clay and calcite.

Although the sand content is generally low, it is an important constituent in some areas. Huddlestun (in review) describes the characteristic lithology as a "fine-grained, thinly bedded to laminated, silty to finely sandy, very calcareous clay to very argillaceous limestone."

The McBean member is known to occur only in the vicinity of McBean Creek and at Shell Bluff on the Savannah River in northern Burke County. This usage is quite restricted from previous investigations and follows the usage of Huddlestun (1981, 1982, in review). In this restricted usage, the McBean member is a sandy, massively bedded limestone. Carbonate content ranges from 70 to 87 percent (Brantley, 1916). The lateral extent of the McBean member is not well defined due to a lack of well information in northern Burke County. The McBean member grades laterally into the Blue Bluff member. Surface exposures are known only at Shell Bluff and along McBean Creek.

Barnwell Group

The Jacksonian-age Barnwell Group contains three formations: the Clinchfield Formation, the Dry Branch Formation, and the Tobacco Road Sand. Huddlestun and Hetrick (1979) raised the Barnwell to the group rank. The inferred environment of deposition is nearshore to marginal marine.

Clinchfield Formation. The lowermost formation of the Barnwell Group is the Clinchfield Formation, named by Pickering in 1970. Within the area of this study, the Clinchfield Formation is represented by the Albion Member and the Utley Limestone Member. Carver (1972) defined the Albion Member for spiculite deposits exposed in Richmond and Glascock Counties, most notably at the Albion mine west of Hephzibah. The Albion Member is present only locally, possibly due to its being deposited only in low areas in a terrain of moderate relief (Huddlestun and Hetrick, 1979).

Huddlestun and Hetrick (1979, p. 16, 17) named the Utley Limestone Member for limestone beds exposed at Utley's Cave on the Plant Vogtle site. Within the study area, the Utley Limestone occurs only locally. The unit has not been identified north of Hancock Landing, on the Savannah River in Burke County.

Dry Branch Formation. The Dry Branch Formation was named by Huddlestun and Hetrick (1979). The unit consists of three interfingering members: the Twiggs Clay Member, the Irwinton Sand Member and the Griffins Landing Member.

The Twiggs Clay Member is a green to dark-grey silty clay which weathers to a shaley rubble. Within the area of this study, the Twiggs Clay occurs only as lenses.

The Irwinton Sand Member is a well-sorted, fine- to medium-grained quartz sand. Well-developed horizontal- and cross-bedded sands are common. The Irwinton commonly contains small clasts of Twiggs Clay.

Huddlestun and Hetrick (1979) named and described the Griffins Landing Member for sediments exposed along the Savannah River at Griffins Landing in Burke County. Within the area of this study, the Griffins Landing is primarily a calcareous sand, although clay beds and lenses and thin limestone beds are common. The most obvious characteristics of the Griffins Landing Member is the local abundance of the oyster shell *Crassostrea gigantissima*. The oyster shells are most commonly associated with clay beds and lenses which resemble those of the Twiggs Clay Member.

Tobacco Road Sand. The Tobacco Road Sand was named and described by Huddlestun and Hetrick (1978) for sediments exposed along Morgan Road, north of Tobacco Road in Richmond County. The typical Tobacco Road Sand is thoroughly bioturbated, with burrows of *Ophiomorpha nodosa* common. Sand ranges from fine grained and well sorted to coarse grained, even pebbly, and poorly sorted (Huddlestun and Hetrick, 1979). The concentrations of flat pebbles common at the base of the unit are attributed to a beach deposit by LaMoreaux (1946b, p. 63, 64). In their definition of the deposit, Huddlestun and Hetrick (1978) suggest a beach to sound or lagoon environment of deposition for the Tobacco Road Sand.

Altamaha Formation

The Altamaha Formation was originally named by Dall and Harris (1892), and is being reintroduced by Huddlestun (in review) as part of the Hawthorne Group. The type locality is at Upper Sister Bluff on the Altamaha River in Appling County. The Altamaha Formation occurs on hill tops in the southern part of the study area and is a sandy clay lacking primary sedimentary structures. In outcrop the unit is mottled due to weathering. Huddlestun (in review) suggests an early Miocene age for the Altamaha in Screven and Burke Counties whereas in the type area the age is thought to be middle Miocene.

Alluvium

Alluvium deposits in the study area occur along the Savannah River and along major creeks. The alluvial sediments range in size from sand and gravel to clay and sandy clay. Sedimentation patterns are complex. Clay beds within the alluvium commonly pinch out. The deeper sediments are generally coarser and more uniform. The base of the alluvium is difficult to distinguish where it overlies the Gaillard formation due to the similar lithologies. The lack of a weathered surface at the top of the Gaillard formation compounds the problem in many areas. In the logs of wells 71 and 106 (see Appendix B), the contact is inferred to exist where the color of the sediments changes from brown to white.

STRUCTURE

REGIONAL DIP

The geologic units of interest in this study dip and thicken to the southeast, creating a wedge of sediments. Figure 7 shows a cross-sectional view of the study area running from north-northwest to south-southeast. This cross section is simplified in that the formations are not subdivided, and control points are widely spaced. The location of the undifferentiated Triassic deposits in Figure 7 is based on information from Marine and Siple (1974) and Faye and Prowell (1982).

The base of the Gaillard formation dips to the south-southeast at approximately 38 ft/mi. This rate agrees with the values given by LeGrand and Furcron (1956, p. 12) and by Siple (167, p. 19). The rate of dip is not constant, as indicated in Figure 7. The dip at the top of the Gaillard formation (the top of the Cretaceous) is approximately 23 ft/mi. The Gaillard thickens rapidly to the south-southeast. At well 119, the Gaillard formation is approximately 427-feet thick. The apparent dip at the top of the Huber Formation is approximately 16 ft/mi. between well 118 and well 92. Because these wells are nearly perpendicular to the regional strike, the true dip should not be significantly different. The maximum thickness of the Huber Formation in the study area, based on drillers' logs, is 155 feet at well 92.

The apparent dip at the top of the Lisbon Formation between well 118 and well 92 is about 10 ft/mi. The thickness of the Lisbon ranges from 174 feet at well 92 to 61 feet at well 118. The Lisbon Formation is absent at outcrops along Bennock Mill Road, approximately 2 miles north of well 118, indicating that the Lisbon either pinches out or grades into the Huber Formation.

FAULTING

The Belair Fault zone runs from northeast to southwest along the northwestern edge of the study area (see Plate 1). It was first noticed in a clay pit wall by O'Connor (O'Connor and Prowell, 1976) and has subsequently been traced by mapping, drilling and trenching. The fault zone is comprised of a series of en echelon, reverse faults in which the southeastern block has moved upward relative to the northwestern block. Movement of up to 100 feet on the top of the basement has been noted in the northern part of the fault zone (O'Connor and Prowell, 1976, p. 24). However, at the southern end of the fault zone, vertical separation on this horizon was only 15 feet, which O'Connor and Prowell considered to be the limit of resolution due to relief on the unconformity.

Faye and Prowell (1982) reported data suggestive of faulting in the southern part of the area of this study. They proposed the existence of two faults that displace at least the base of the Cretaceous, and estimated their locations. The Millet Fault was postulated to exist along a northeast-southwest trend that falls along Brigham's Landing Road, the southeastern margin of the area for this study. The second postulated fault, the Statesboro Fault, parallels the Millet Fault and lies to the southeast of the study area. The Georgia Power Company, builders of Plant Vogtle, a nuclear-powered generating facility, retained the Bechtel Corporation to assess whether the postulated faults exist. Based on the results of a number of test borings across the trace of the postulated fault, on seismic profiling and on other methods of investigation, the Bechtel report concluded that there was no capable fault in the vicinity of the postulated Millet Fault (Bechtel Corp., 1982, p. iii).

HYDROGEOLOGIC UNITS

INTRODUCTION

The boundaries of geologic and hydrogeologic units often do not coincide, which is the case in Richmond and northern Burke Counties. For example, the Gaillard formation contains two permeable zones and two confining zones that are laterally extensive within the study area. Neverthe-

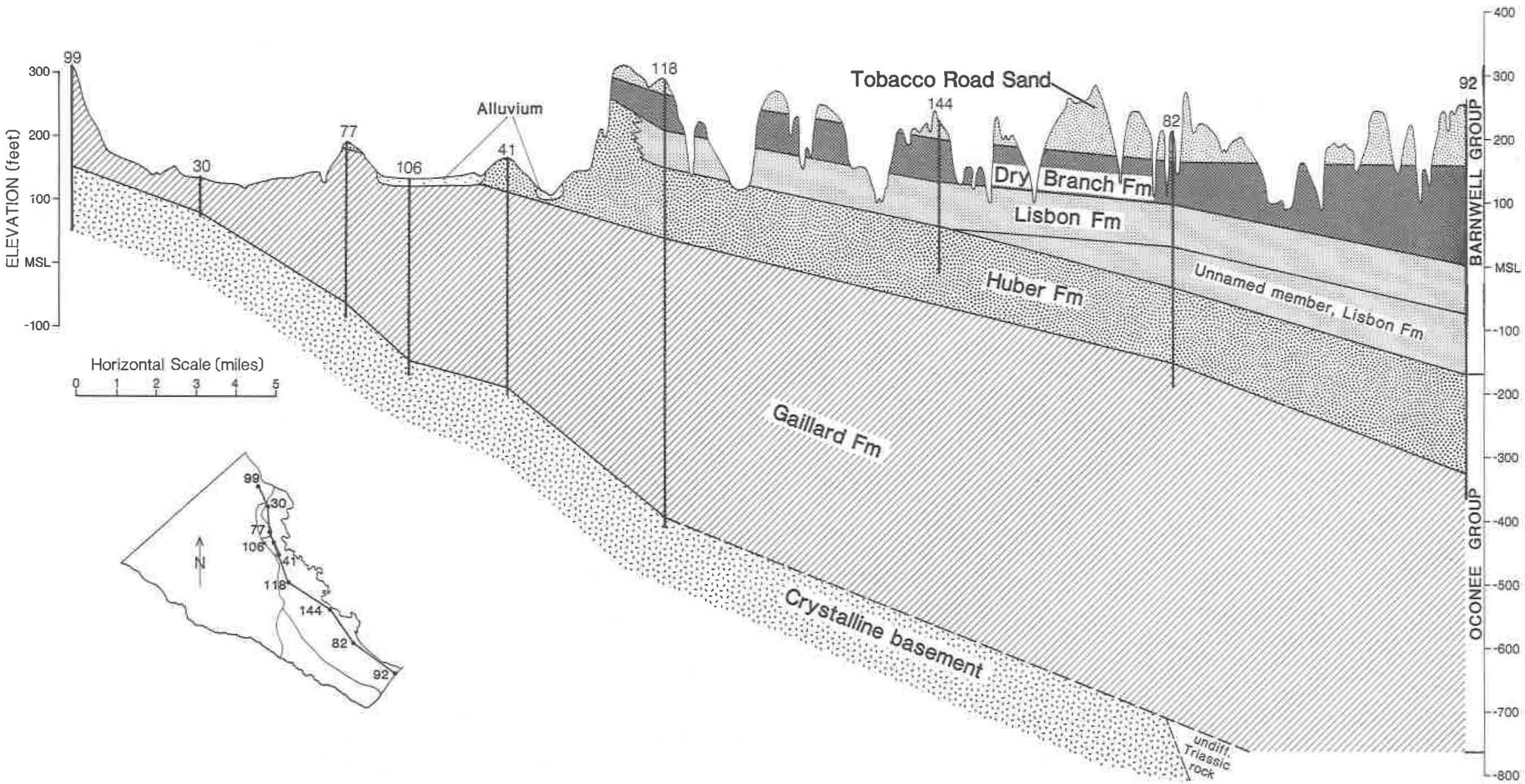

Figure 7. Geologic cross section. Location of Triassic rock based on Marine and Siple (1974) and Faye and Prowell (1982).

less, the aquifers within Coastal Plain sediments are discussed in the context of the geologic units for ease of understanding.

GAILLARD FORMATION

Introduction

Previous investigators have considered the Cretaceous sediments to contain a single aquifer (often including the Huber Formation within the Cretaceous). On a regional scale, considering the Cretaceous to be a single aquifer may not result in any problems. However, at the scale of this investigation it is impossible to understand the hydrogeology of the area without recognizing that two distinct flow systems exist within the Gaillard formation. As will be discussed later, the confining bed separating the basal Cretaceous aquifer from the upper Cretaceous aquifer appears to be less distinct in the western part of the study area than in the east. Therefore, the use of these hydrogeologic units beyond the limits of this study may not be appropriate.

Basal Cretaceous Aquifer

Sediments of the Upper Cretaceous Gaillard formation contain two aquifers. These two aquifers are the primary source for ground water in the study area. The lower aquifer within the Gaillard formation is herein called the basal Cretaceous aquifer. In most locations where the aquifer is utilized, the base of the aquifer is the top of the saprolite overlying the crystalline "basement." Several well logs (wells 41, 102, and 118 for example) indicate that at some locations, the aquifer lies directly on unweathered rock, suggesting that the saprolite was eroded prior to the deposition of the aquifer, that it never formed, or that it was present but not detected by the person making the log. In several locations, well 106 for example, a clay bed that may be of Cretaceous age underlies the aquifer. Farther downdip in Burke County, the basal Cretaceous aquifer overlies the Triassic "basement," although few wells are deep enough to encounter the Triassic due to the availability of water from the upper Cretaceous aquifer and the high costs associated with deep drilling.

The basal Cretaceous aquifer is confined at the top by a red clay or sandy clay. This clay is interpreted to be a weathered surface that developed during a pause in the deposition of the Gaillard formation due to its red color, and the wide range of thicknesses known for this bed even within a small area. Faye and Prowell (1982, Fig. 3) report this clay at the top of their unit UK_2. They also report a slightly younger age for the overlying unit UK_3. Faye and Prowell's findings support the interpretation that the red clay is a weathered surface.

Upper Cretaceous Aquifer

The top of the red clay bed noted in the previous section marks the base of the second and upper aquifer within the Gaillard formation, herein called the upper Cretaceous aquifer. This aquifer is confined at the top by the red clay located at the top of the Gaillard formation. This red clay, like the red clay that separates the two aquifers, is interpreted to be a weathered surface. The upper clay is generally thicker than the clay between the aquifers; however, the thicknesses of both clay beds vary widely, probably due to erosion just prior to the deposition of the overlying unit.

Within both the basal and upper Cretaceous aquifers, other clay beds have been noted, particularly in downdip areas. The presence of these clay beds illustrates the fact that many permeable zones of varying interconnection could be delineated within the Gaillard formation, given enough detailed information. The two Cretaceous aquifers delineated in this report are probably interconnected to some degree; however, they are individually traceable throughout the study area.

HUBER FORMATION

Sediments of the Huber Formation are only tapped by wells in the southern part of the study area due to the limited thickness of permeable sediments in updip areas and the availability of water from the Cretaceous aquifers. The Huber's thick beds of clay and sandy clay reduce the permeable thickness of the formation significantly. The basal portion of the formation, however, would produce a moderate yield. Within the study area, the Huber is rarely used for wells of high capacity.

LISBON FORMATION

The fine- to medium-grained, moderately to well-sorted sands of the unnamed lower member of the Lisbon Formation are sufficiently permeable to supply water for domestic wells. Within the study area, the permeable thickness of the unnamed lower member is generally less than 50 feet, limiting the usefulness for larger capacity wells. The Blue Bluff member would not be expected to yield significant quantities of water. The McBean member could provide small to moderate quantities of water.

BARNWELL GROUP

The hydrogeologic character of the Barnwell Group is quite variable within the study area. The tendency of the Clinchfield Formation to occur only in local areas precludes its use as a regional aquifer. In addition, the Albion Member of the Clinchfield is not sufficiently permeable to be considered an aquifer. The Twiggs Clay and Griffins Landing Members of the Dry Branch Formation are relatively impermeable when compared to the well-sorted sands of the Irwinton Sand Member. The Irwinton Sand Member is sufficiently permeable to supply water for domestic use. The Tobacco Road Sand is relatively permeable; however, its saturated thickness is small compared to deeper aquifers. Therefore, use of the Tobacco Road Sand as a water-bearing unit is limited to domestic use within the study area.

ALTAMAHA FORMATION

Because the Altamaha Formation consists of sandy clays, the unit has a low hydraulic conductivity. Within the study area, sediments of the Altamaha Formation cannot supply large quantities of water. Although there are no high capacity wells tapping the unit, there are shallow, dug or bored wells that are limited to the tops of hills where the unit occurs. These types of wells can be developed in the Altamaha because of their large diameter and high storage capacity.

ALLUVIUM

The lower part of the Savannah River alluvium is highly permeable and in the northernmost part of the study area is hydraulically connected to the basal Cretaceous aquifer. In the vicinity of the Olin plant (wells 42 and 71) and the Bush Field well field (wells 101-106), drillers' logs indicate that the alluvium is at least indirectly connected to the upper Cretaceous aquifer. The alluvium contains a number of permeable zones separated by clay-rich beds. The degree of interconnection of the permeable zones has not been established. No production wells directly tap the alluvium.

AQUIFER GEOMETRY

Plate 2 is a cross section running approximately perpendicular to dip through the area of greatest well concentration. Although the cross section was constructed primarily using drillers' logs, geophysical logs were used to help clarify ambiguities. The cross section indicates that both the basal and upper Cretaceous aquifers dip gently to the southeast. Appendix B contains the drillers' logs used to construct Plate 2.

Figure 8 is a structure-contour map showing the altitude at the base of the basal Cretaceous aquifer. The base of the aquifer shows some relief, as indicated by the bending of the 0, -150 and -400 foot contours. Considering that the base of the basal Cretaceous aquifer is probably an old erosional surface, it is likely that there is more relief on this surface than is depicted in Figure 8 due to the generalizing effect of the wide well spacing. The dip of the base of the aquifer increases between the Continental Forest well (41) and the Kimberly Clark wells (117-120). This is readily apparent on the cross section, and is also indicated in Figure 8 by the tighter spacing of the -200, -250, -300, -350, and -400 foot contours. For well 99, (indicated by an open circle on Figure 8), a reliable altitude at the base of the basal Cretaceous aquifer was not available; therefore, the top of the "basement" complex was assumed to be the base of the aquifer.

As noted earlier, the Belair Fault Zone is known to cut the base of the Cretaceous sediments in the northwestern part of the study area. (Prowell and others, 1975; O'Connor and Prowell, 1976; and Prowell and O'Connor, 1978). The structure-contour map in Figure 8 indicates a 17-foot difference in the elevation of the base of the basal Cretaceous aquifer at wells 112 and 113, core holes drilled as a part of the Belair fault study on opposite sides of the fault. The effects of the fault on the hydrologic units could not be evaluated due to the sparseness of well data in the area.

Figure 9 is a structure-contour map of the top of the basal Cretaceous aquifer. Like the base of the aquifer, the top dips to the southeast. Northwest of the Continental Forest well (41), the dip of the top of the aquifer is approximately 25 ft/mi. Southeast of the Continental Forest well, the dip increases to approximately 60 ft/mi. Another area where the top of the aquifer dips more steeply, approximately 65 ft/mi, is west of Hephzibah. These dips are unusually high for the study area.

Plate 2 illustrates that the thickness of the basal Cretaceous aquifer varies considerably. The aquifer thickens from 30 feet at well 51 at the Babcock and Wilcox plant, just south of Augusta, to 141 feet at well 71 at the Olin Corporation plant, south of Bush Field, a distance of 7 miles. South of the Olin plant, the thickness of the basal aquifer decreases at a rate of approximately 15 ft/mi, largely as a result of the increased dip of the top of the aquifer.

Figure 10 is an isopach map of the basal Cretaceous aquifer. Although well density is low west of the industrial complex, it appears that the axis of the thickest part of the aquifer trends from the Olin complex toward Hephzibah. The anomalously large aquifer thicknesses reported for wells 9 and 10 are not totally representative of the basal Cretaceous aquifer. Much of the Gaillard formation (including the clay beds that are used to define the limits of the aquifer) has been eroded by the

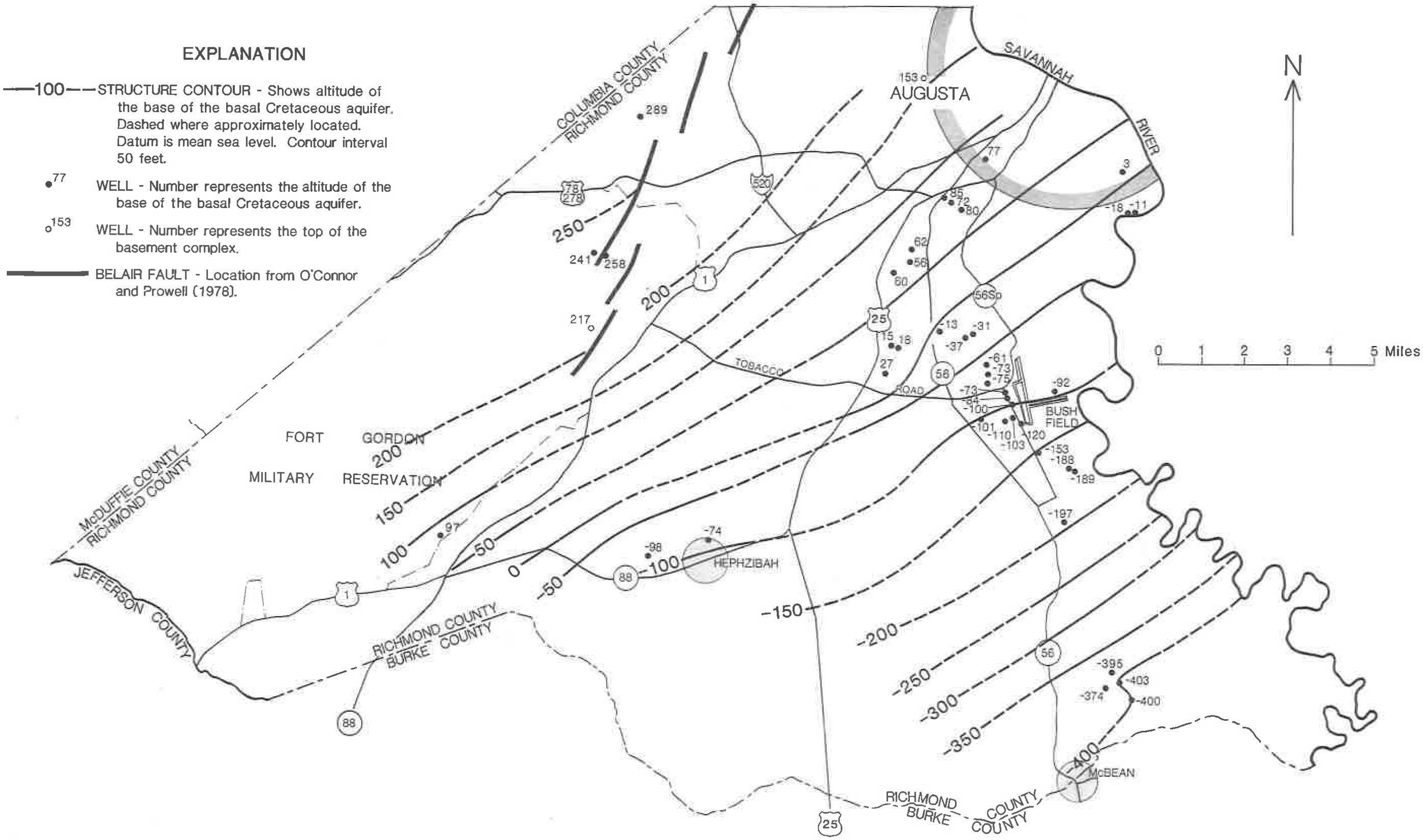

Figure 8. Structure-contour map of the base of the basal Cretaceous aquifer.

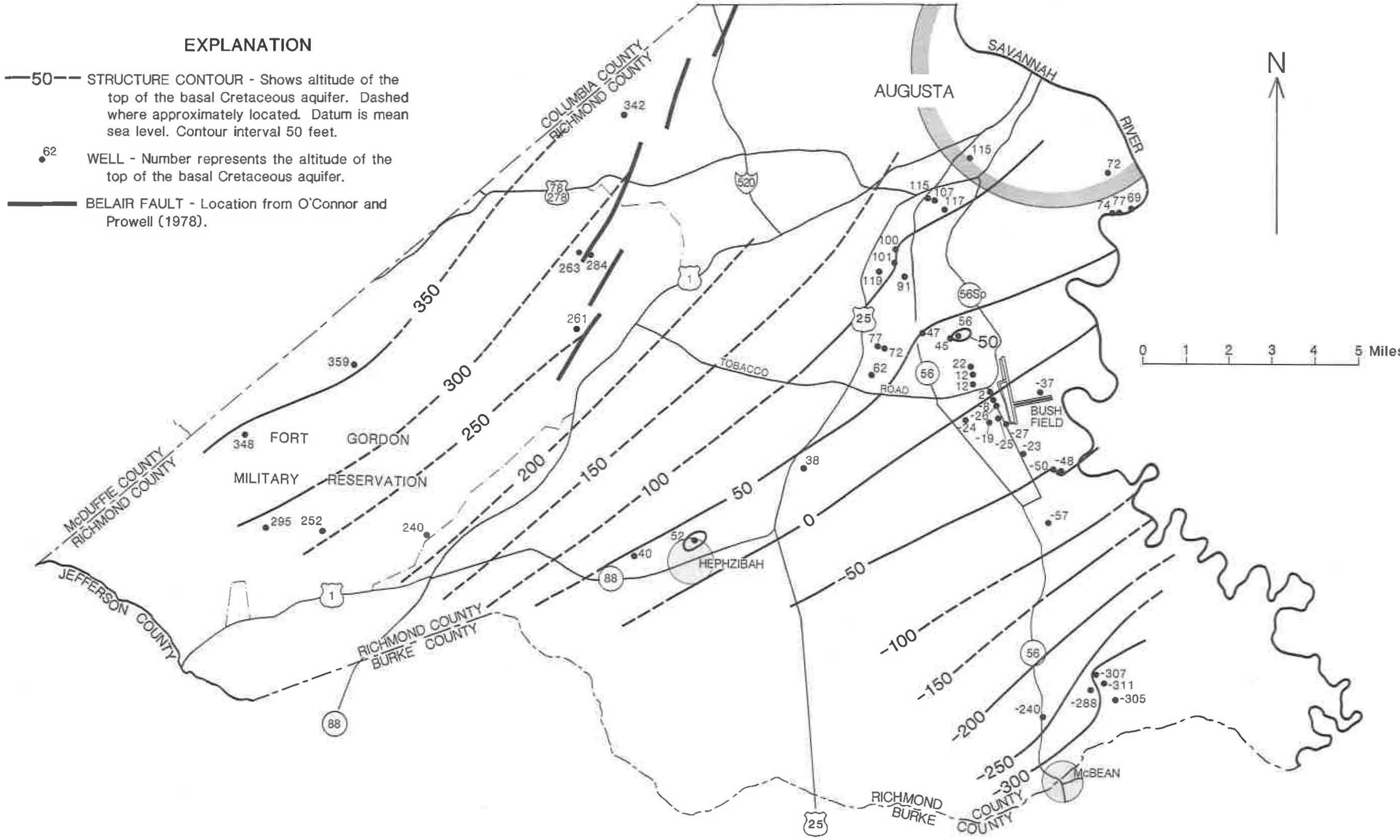

Figure 9. Structure-contour map of the top of the basal Cretaceous aquifer.

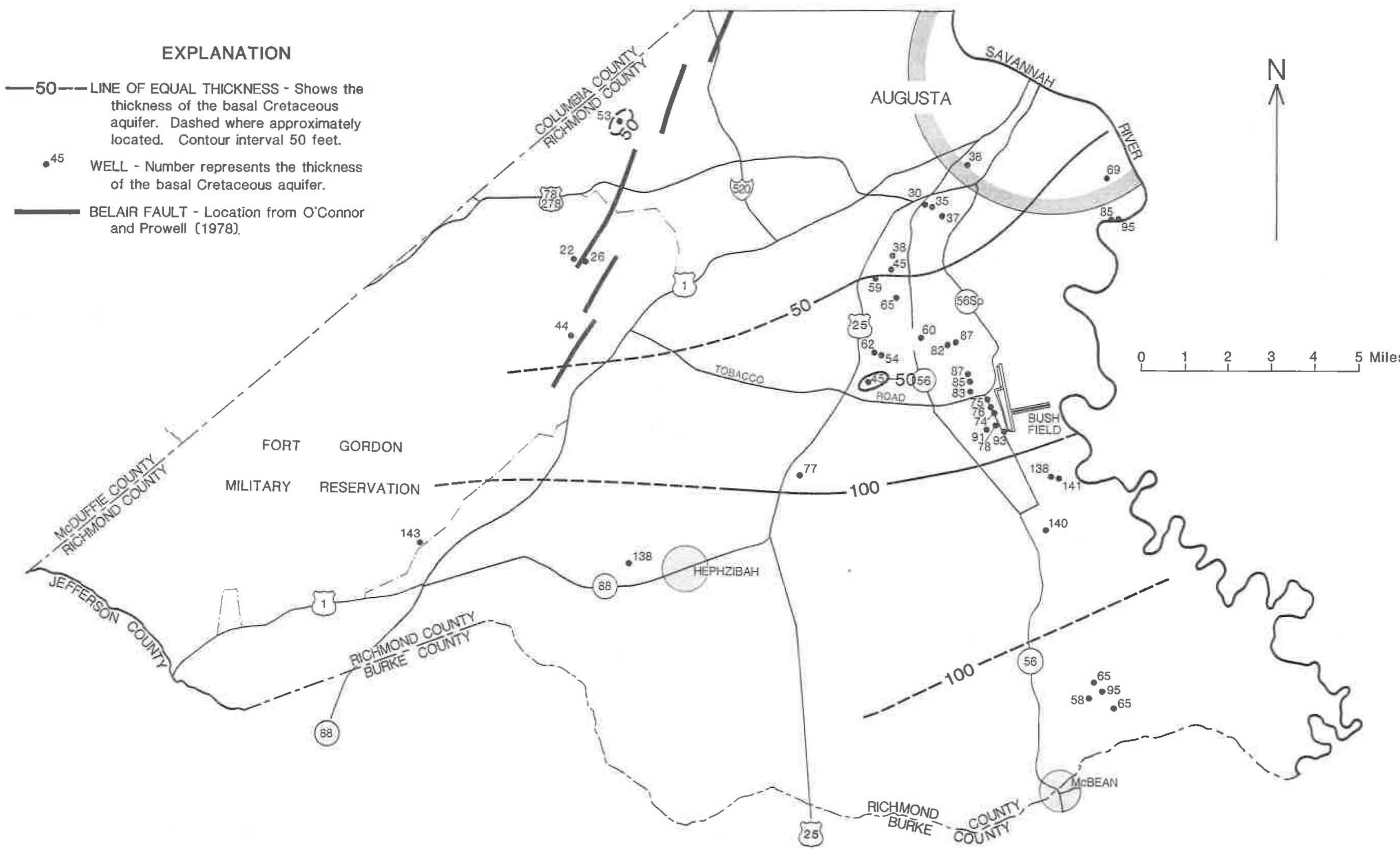

Figure 10. Isopach map of the basal Cretaceous aquifer.

Savannah River, which subsequently deposited alluvium above it. Thus, the aquifer in this location may be comprised of both Cretaceous and Recent sediments.

Well density is greatest in the eastern portion of Richmond County and decreases rapidly to both the west and south. The drillers' logs of many of the wells in western Richmond County indicate a permeable strata at the base of the well. Because it is unusual to cease drilling within a permeable strata, the author believes that in some of these wells, either the "basement" complex or a confining bed was encountered at the end of drilling, but was not noted on the driller's log.

The clay beds that separate the aquifers are of particular interest hydrologically in that they inhibit the vertical movement of water. The degree of hydraulic separation is dependent upon the vertical hydraulic conductivity and the thickness of the clay beds which vary widely, even over a short distance. The red clay that separates the basal and upper Cretaceous aquifers is less distinctive on the electric logs of wells in western Richmond County than on the electric logs of wells in the industrial district. For example, on the electric log of the Albion mine well (32), the red clay noted on the driller's log is one of several intervals of uniformly low resistivity in that part of the log, whereas the confining zone between the basal and upper Cretaceous aquifers is quite distinct on the electric logs of wells 41 and 102 (See Plate 2). This may indicate that the effectiveness of the confining bed between these aquifers diminishes to the west. If this is the case, it is possible that in the western part of Richmond County, the basal and upper Cretaceous aquifers are in closer hydraulic connection and may act as a single aquifer system. Nevertheless, for this report the basal and upper Cretaceous aquifers in western Richmond County are delineated as separate aquifers.

The known thickness of the clay bed between the Cretaceous aquifers ranges from 60 feet at well 39 to 7 feet at well 122. The thickness of the clay bed at the top of the Gaillard formation ranges from 110 feet at well 72 to 10 feet at well 77. Although there are no documented instances of the clay beds being absent in the subsurface, the wide range of thicknesses suggests that windows may occur in the clay beds.

Figure 11 is a structure-contour map of the base of the upper Cretaceous aquifer. The southeastward dip and the abrupt increase in the magnitude of dip south of the Continental Forest well (well 41) generally coincide with the dip patterns of the top and bottom of the basal Cretaceous aquifer.

Figure 12 depicts the altitude of the top of the upper Cretaceous aquifer. In the northeastern portion of the study area, elevations of the top of the upper Cretaceous aquifer do not correspond to the regional dip, suggesting that the top of the upper Cretaceous aquifer has been eroded. Like the basal aquifer at wells 9 and 10, the upper Cretaceous aquifer is in direct contact with permeable alluvial sediments in the area of Bush Field. Relief on the top of the upper Cretaceous aquifer is significant. This is particularly evident at the town of Hephzibah, where drillers' logs of wells 1200 feet apart indicate a difference of 57 feet in the elevation of the top of the upper aquifer, and north of McBean, where a 38-foot difference is indicated by the electric logs of wells 1700 feet apart.

Core logs (well numbers 112 and 113) indicate a 25-foot difference in the altitude at the bottom of the upper Cretaceous aquifer across the Belair fault. A difference of 24 feet is indicated on the top of the aquifer.

AQUIFER PARAMETERS

Transmissivity, storativity and hydraulic conductivity are parameters that describe the flow characteristics of an aquifer. The transmissivity of an aquifer is defined as the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient. Thus, the transmissivity (T) of an aquifer is a measure of the ability of an aquifer to transmit water and is given in square feet per second (ft^2/s). The hydraulic conductivity (K) is the volume of water that will flow through a unit area of material in one unit of time under a unit hydraulic gradient and is expressed in feet per second (ft/s). Thus, for an aquifer with a uniform hydraulic conductivity, the transmissivity is the hydraulic conductivity multiplied by the thickness of the aquifer. The storativity (S) of an aquifer, also known as the storage coefficient, is a measure of the ability of the material to store water. It is defined as the volume of water released from a column of aquifer of unit area for a unit decline in the head, and is dimensionless.

The most common method of measuring the hydrogeologic parameters of an aquifer (T, K and S) is through an aquifer test. A description of aquifer test methods along with a discussion of analysis techniques and assumption can be found in most ground-water texts, for example, Freeze and Cherry (1979, p. 314-355). The aquifer test data available for this report were analyzed using the Jacob method. More sophisticated analysis techniques were used on the data from the Proctor and Gamble and the Gracewood State Hospital aquifer tests. Table 1 lists the aquifer parameters obtained from analysis of the aquifer test data. All of the values in Table 1 are for the basal Cretaceous aquifer except for wells

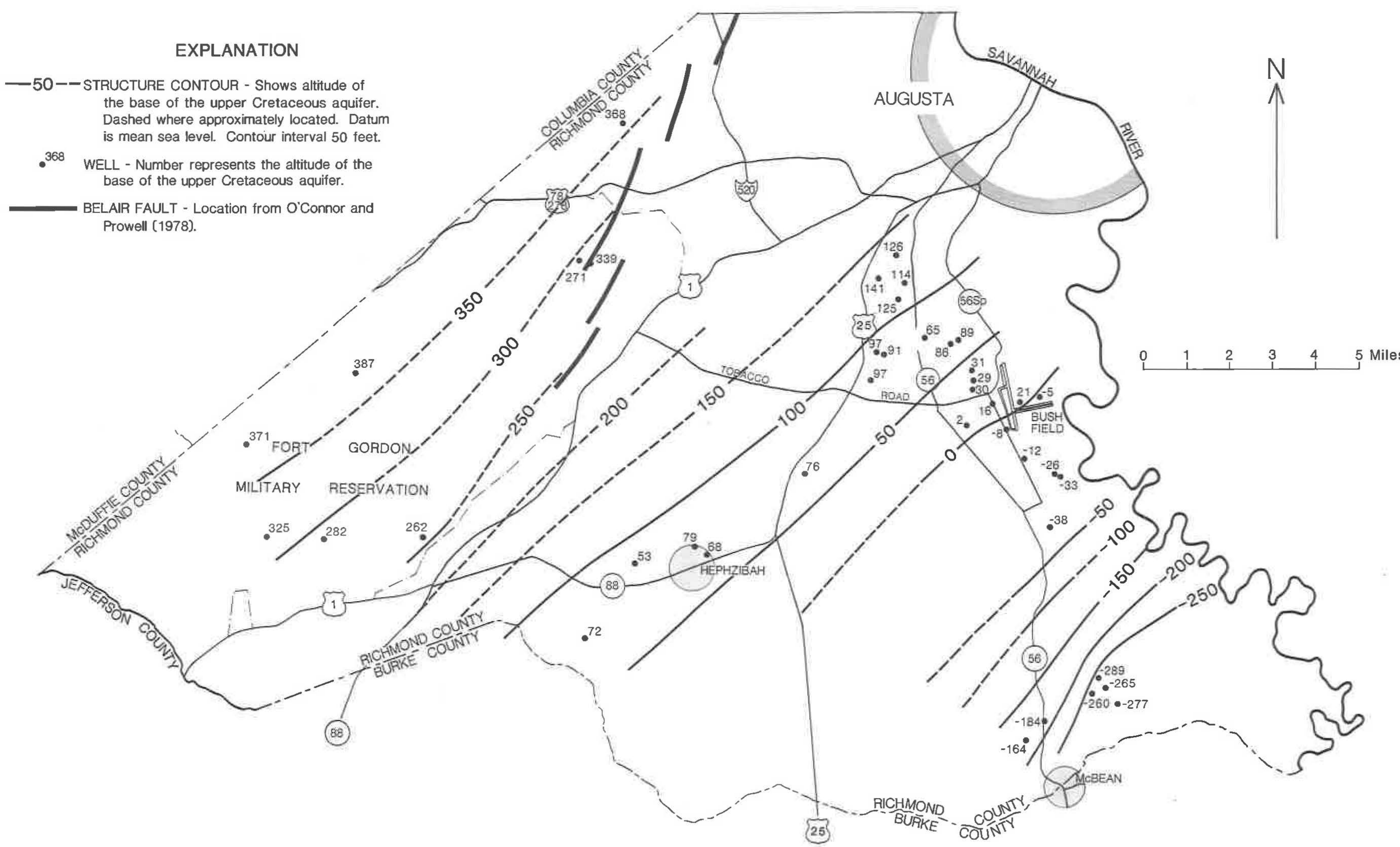

Figure 11. Structure-contour map of the base of the upper Cretaceous aquifer.

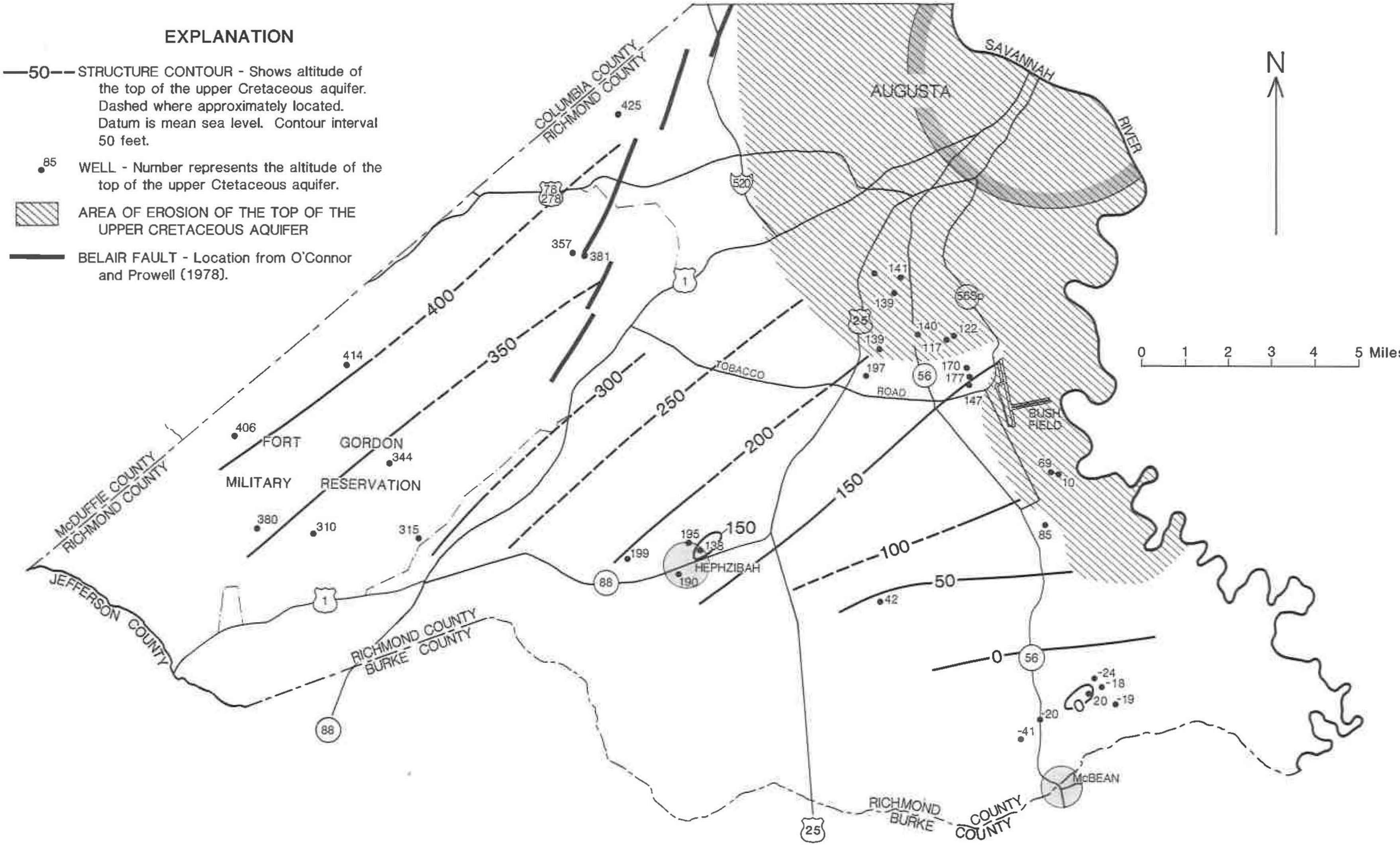

Figure 12. Structure-contour map of the top of the upper Cretaceous aquifer.

Table 1. Hydrogeologic parameters determined from aquifer test analyses.

Well #	Owner	Date	Length (hrs)	Method	T(ft²/s)	K(ft/s)	S	Source
16	Columbia Nitrogen	7-28-75	72	J	*$3.7x10^{-2}$		$6x10^{-2}$	Nuzman (1974)
38	Monsanto	7-31-74	8	J	$9.4x10^{-2}$	$1.1x10^{-3}$		Layne-Atlantic
44	Richmond County	not available	7½	J	$8.3x10^{-2}$	$1.8x10^{-3}$		GGS Data Files
45	Richmond County	not available	4½	J	*$2.0x10^{-1}$	$3.4x10^{-3}$		GGS Data Files
46	Richmond County	not available	6	J	$1.0x10^{-1}$	$1.4x10^{-3}$		GGS Data Files
47	Richmond County	not available	4	J	*$1.3x10^{-1}$	$3.7x10^{-3}$		GGS Data Files
48	Richmond County	not available		J	*$8.0x10^{-2}$	$1.5x10^{-3}$		GGS Data Files
49	Richmond County	not available	4	J	$5.5x10^{-2}$			GGS Data Files
58	Gracewood School and State Hospital							
	r=100	8-25-65	24	S	$3.9x10^{-2}$	$8.7x10^{-4}$	$5.0x10^{-5}$	
	r=400	8-25-65	24	S	$4.9x10^{-2}$	$1.1x10^{-3}$	$7.5x10^{-5}$	
	r=100	8-25-65	24	J	$4.1x10^{-2}$	$9.1x10^{-4}$	$5.4x10^{-5}$	
	r=400	8-25-65	24	J	$5.5x10^{-2}$	$1.2x10^{-3}$	$7.5x10^{-5}$	
	r=100	8-26-65	48	J	$8.1x10^{-2}$	$1.8x10^{-3}$		
	r=400	8-26-65	48	J	$9.4x10^{-2}$	$2.1x10^{-3}$		
71	Olin	7-30-70	8	J	*$2.6x10^{-2}$	$4.7x10^{-4}$		Layne-Atlantic
117	Kimberly-Clark	not available	4	R	*$3.5x10^{-2}$			Sirrine (1980)
118	Kimberly-Clark	not available	8	J,T,R	*$4.3x10^{-2}$	$3.0x10^{-4}$	$3.2x10^{-4}$	Sirrine (1980)
118	Kimberly-Clark	6-10-80	72	J,T,R,D	*$5.9x10^{-2}$	$4.1x10^{-4}$	$5.5x10^{-4}$	Sirrine (1980)
119	Kimberly-Clark	not available	4	R	*$4.4x10^{-2}$			Sirrine (1980)
120	Kimberly-Clark	not available	4	R	*$6.5x10^{-2}$			Sirrine (1980)
135	Proctor & Gamble	8-17-83	24	HJ	*$3.5x10^{-2}$	$6.8x10^{-4}$	$2.2x10^{-4}$	GGS Data Files

*Average Value Methods — J - Jacob, R - Recovery, S - Simulation, T - Theis, D - Distance Drawdown, HJ -Hantush-Jacob

117-120, which are for both the basal and upper Cretaceous aquifers. Storativity values are listed for aquifer tests in which drawdowns were measured in an observation well. The parameters listed for wells 16, 117, 118, 119, and 120 are from published sources. Table 1 also lists the method of analysis as well as the source of the data for each aquifer test.

Time-drawdown measurements from two observation wells from an aquifer test of the basal Cretaceous aquifer (well 58) at the Gracewood State Hospital were analyzed using the Hantush-Jacob equations. These equations consider vertical leakage through one or more confining beds. Figure 13 is a conceptual diagram indicating the geometry and flow paths associated with the Theis, Hantush-Jacob and modified Hantush equations. The conceptual diagram for the Theis equation, Figure 13a, indicates that water that flows to the well is derived solely from storage within the aquifer. The conceptual diagram for the Hantush-Jacob equation, Figure 13b, indicates that water that flows to the well is derived not only from storage in the aquifer, but also from flow through a semi-confining bed. The modified Hantush equations are similar, but also account for the release of water from storage in the semi-confining bed (Fig. 13c).

The lack of drawdown measurements in the first 10 minutes of the test and the resulting flatness of the time-drawdown curves discouraged the use of the type-curve fit method of analysis. Instead, a method described by Warner and Yow (1980) was used to solve for drawdown in a semi-confined aquifer by a single, fully penetrating well. Inputs necessary for the method are the pumping rate, the distance from the pumping well to the point of observation, the time since pumping began, estimates of the transmissivity and storativity of the aquifer, an estimate of the vertical hydraulic conductivity of the confining bed(s), and the thickness of the confining bed(s). Known parameters were the time-drawdown measurements, the discharge rate, and the thickness of the confining bed (from the driller's log). The analysis for this study assumes leakage only from above. Drawdowns calculated using the Warner and Yow procedure and estimates of the unknown parameters, were compared to the measured drawdowns. By varying the estimates of the unknown parameters,it was possible to obtain a close fit between the measured and calculated drawdowns (Fig. 14). Table 2 lists the drawdowns plotted in Figure 14.

In addition to providing an estimate of the hydrogeologic properties of the basal Cretaceous aquifer, the analysis of the pump test at the Gracewood State Hospital indicates that there is vertical leakage through the confining bed. The estimated vertical hydraulic conductivity of the confining bed is 9.3×10^{-8} ft/s. Vertical leakage is an important feature of the ground-water flow system, resulting in drawdowns in the basal Cretaceous aquifer that are smaller and less extensive than in a totally confined aquifer.

The analysis of an aquifer test conducted at the Proctor and Gamble Manufacturing Company plant near Highway 56 and Marvin Griffin Road (well 130) also indicated that vertical leakage to the basal Cretaceous aquifer occurred during the test. Table 3 lists the drawdowns measured during the test. Figure 15 shows the time-drawdown plot along with the best fit from a family of type curves based on the Hantush-Jacob equations (Lohman, 1972, Plate 3). The Hantush-Jacob method (Hantush and Jacob, 1955) solves for the aquifer's transmissivity and storativity as well as the vertical hydraulic conductivity of the confining bed. The method assumes vertical leakage without a release of water from storage in the confining bed (Reed, 1980). The observed data deviate from the type curve after 120 minutes of pumping. This greater than expected drawdown could be the result of a number of factors, including interference from nearby pumping wells, minor lateral changes in the thickness or character of the hydrogeologic units, boundary effects, and/or the release of water from storage in the confining bed.

Hantush (1960) modified the leaky aquifer theory to account for release of water from storage in the confining bed. Analysis of the aquifer test data using this modified theory (Reed, 1980, p. 25) yields values for the transmissivity and the storativity of the aquifer that differ only slightly from the values obtained from the Hantush-Jacob analysis. Figure 16 shows the field data with the appropriate superimposed type curve (Lohman, 1972, Plate 4). Reed (1980, p. 26) cautions that these curves are only valid for very early data. Therefore, the deviation of the type curve from the later data is not of concern.

An alternative method of analysis of the Gracewood State Hospital and Proctor and Gamble aquifer test data is the Theis non-equilibrium method. Two major assumptions of the Theis method are that the confining beds do not leak and that steady state is never reached. Analysis of the drawdown data from the observation well at a radius of 400 feet using the Theis method indicates a transmissivity of 9.07×10^{-2} ft^2/s and a storativity of 1.3×10^{-5}. The Theis analysis of the data from the observation well at a radius of 100 feet indicates a similar value for the transmissivity but a storativity of 5.7×10^{-8}, which is unreasonable. It should be noted that steady state

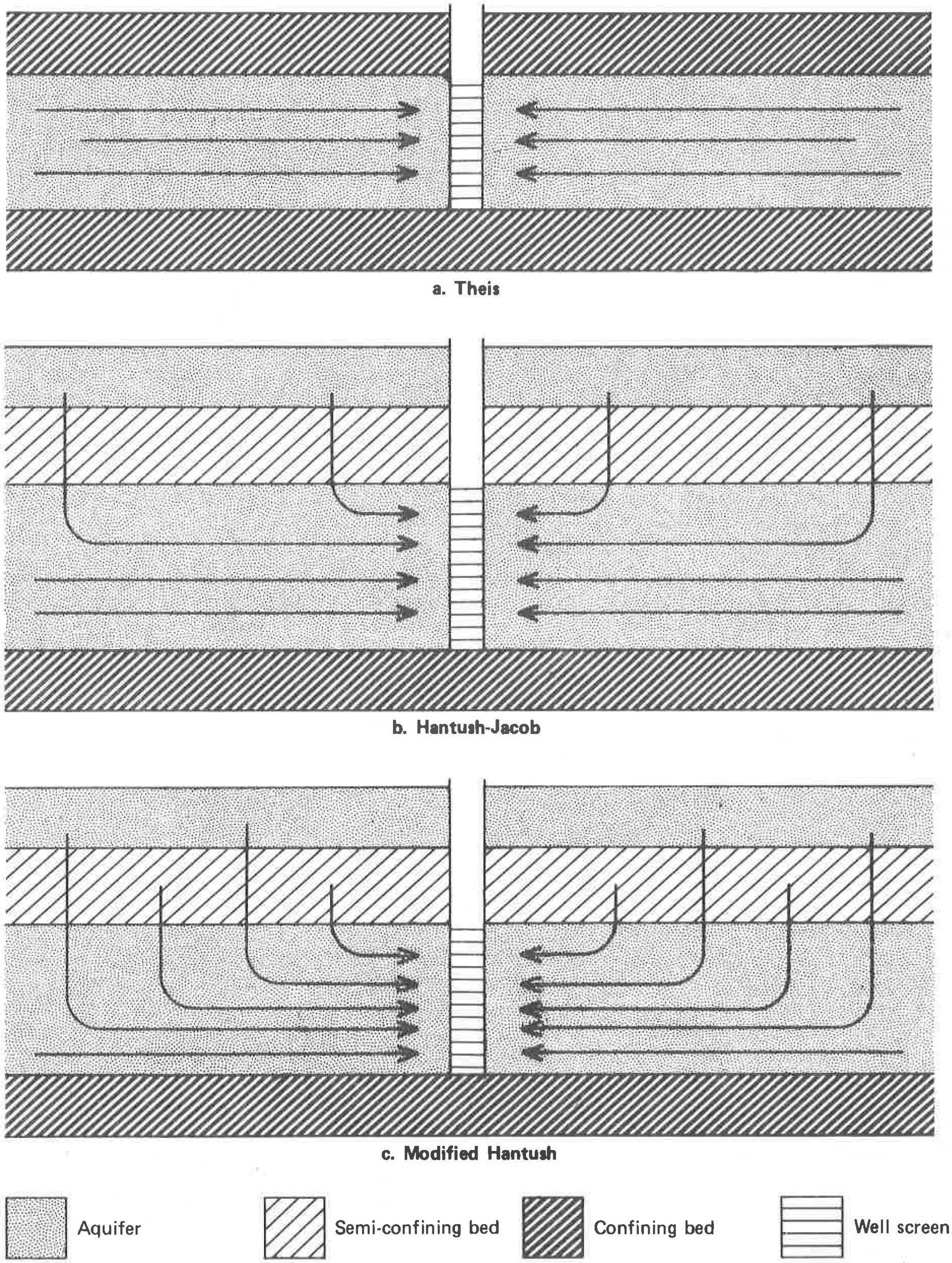

Figure 13. Geometry and flow paths associated with the Theis, Hantush-Jacob, and modified Hantush equations (a, b, and c respectively).

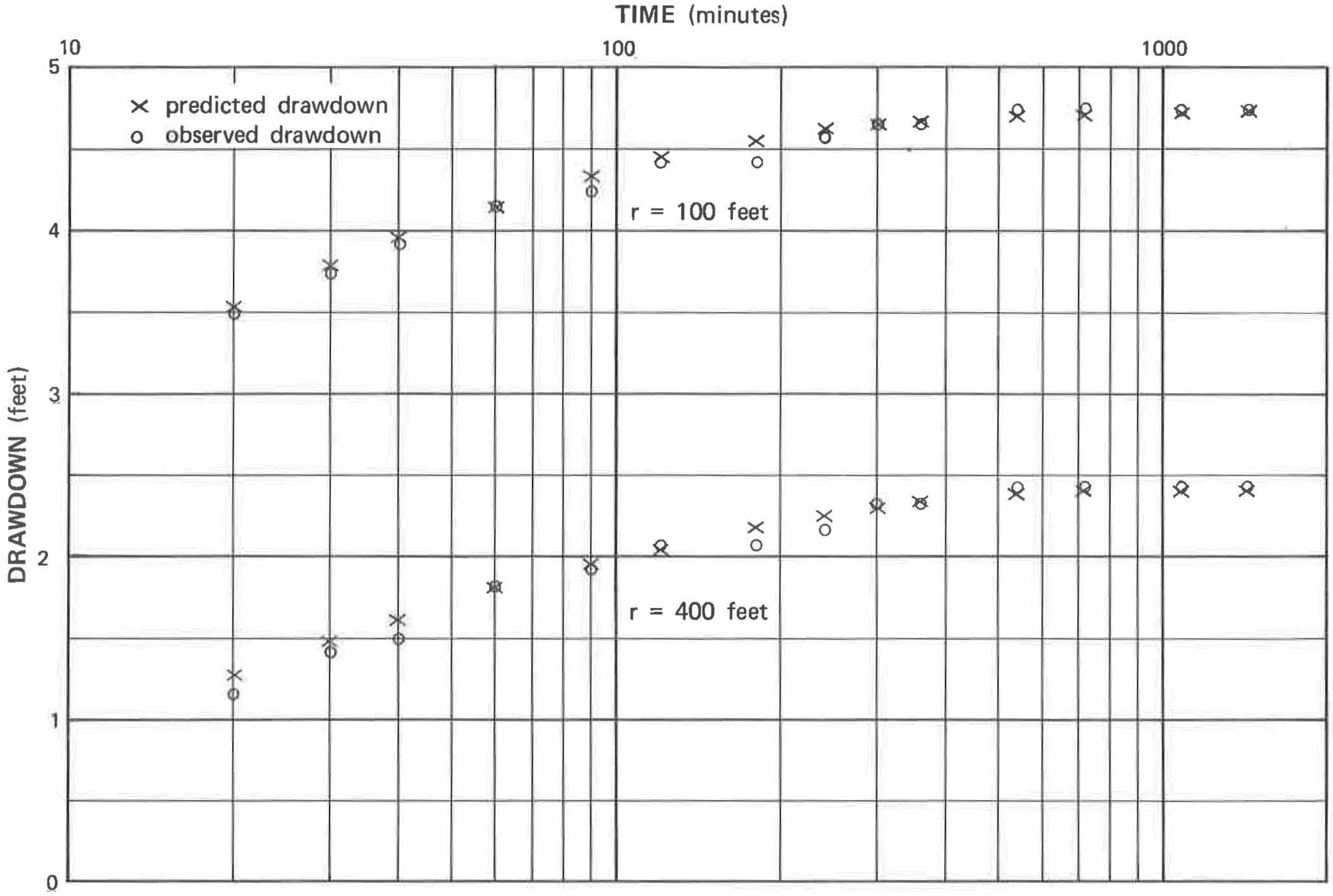

Figure 14. Comparison of calculated and observed drawdowns for the aquifer test at the Gracewood State Hospital, Richmond County, August 25, 1965. Predicted drawdowns are based on Warner and Yow (1980).

Table 2. Calculated and observed drawdowns for the aquifer test at Gracewood State Hospital, Richmond County.

Elapsed Time (in hours)	Drawdown at 100 Feet (in feet) Measured	Calculated	Drawdown at 400 Feet (in feet) Measured	Calculated
0.33	3.50	3.54	1.17	1.29
0.5	3.75	3.79	1.42	1.49
0.67	3.92	3.95	1.50	1.62
1.0	4.17	4.16	1.83	1.80
1.5	4.25	4.34	1.92	1.96
2.0	4.42	4.45	2.08	2.07
3.0	4.42	4.57	2.08	2.19
4.0	4.58	4.63	2.17	2.26
5.0	4.67	4.66	2.33	2.31
6.0	4.67	4.68	2.33	2.34
9.0	4.75	4.71	2.42	2.38
12.0	4.75	4.71	2.42	2.40
18.0	4.75	4.72	2.42	2.40
24.0	4.75	4.72	2.42	2.41

Parameters

Pump Discharge	Q (gal/min)	150	150
Distance to observation well	r (feet)	100	400
Transmissivity	T (ft^2/s)	3.94×10^{-2}	4.92×10^{-2}
Vertical hydraulic conductivity of confining bed	Kc (ft/s)	9.26×10^{-8}	9.26×10^{-8}
Thickness of confining bed	bc (ft)	20	20
Storativity	S	5×10^{-5}	7.5×10^{-5}

Table 3. **Drawdowns observed during the aquifer test at the Proctor and Gamble Plant, Richmond, County.**

Elapsed Time (Minutes)	Drawdown in Pumping Well (feet)	Drawdown in Observation Well (r=300 feet) (feet)
1	60	0.11
2	69	0.54
3	76	1.10
4	78	1.54
5	80	1.96
6	80	2.31
7	82	2.57
8	82	2.87
9	82	3.10
10	83	3.31
12	-	3.64
14	-	3.99
15	85	-
16	-	4.26
18	-	4.50
20	85	-
21	-	4.82
25	85	5.15
30	86	5.48
35	87	5.74
40	88	5.98
45	89	6.15
50	90	6.33
55	90	6.44
60	90	6.54
65	90	6.68
70	90	-
71	-	6.81
75	90	6.90
80	90	6.99
85	90	7.05
90	90	7.12
105	90	7.31
120	90	7.47
135	90	7.58
150	90	7.73
165	90	7.84
180	90	7.87
210	90	8.01
240	90	8.12
270	90	8.21
300	90	8.32
360	90	8.49
420	90	8.62
480	90	8.75
540	90	8.80
600	90	8.84
660	90	8.83
720	90	8.93
780	90	9.06
840	90	9.18
900	90	9.21
960	90	9.26
1020	90	9.34
1080	90	9.40
1140	90	9.40
1200	90	9.41
1260	90	9.43
1320	90	9.47
1380	90	9.48
1440	90	9.52

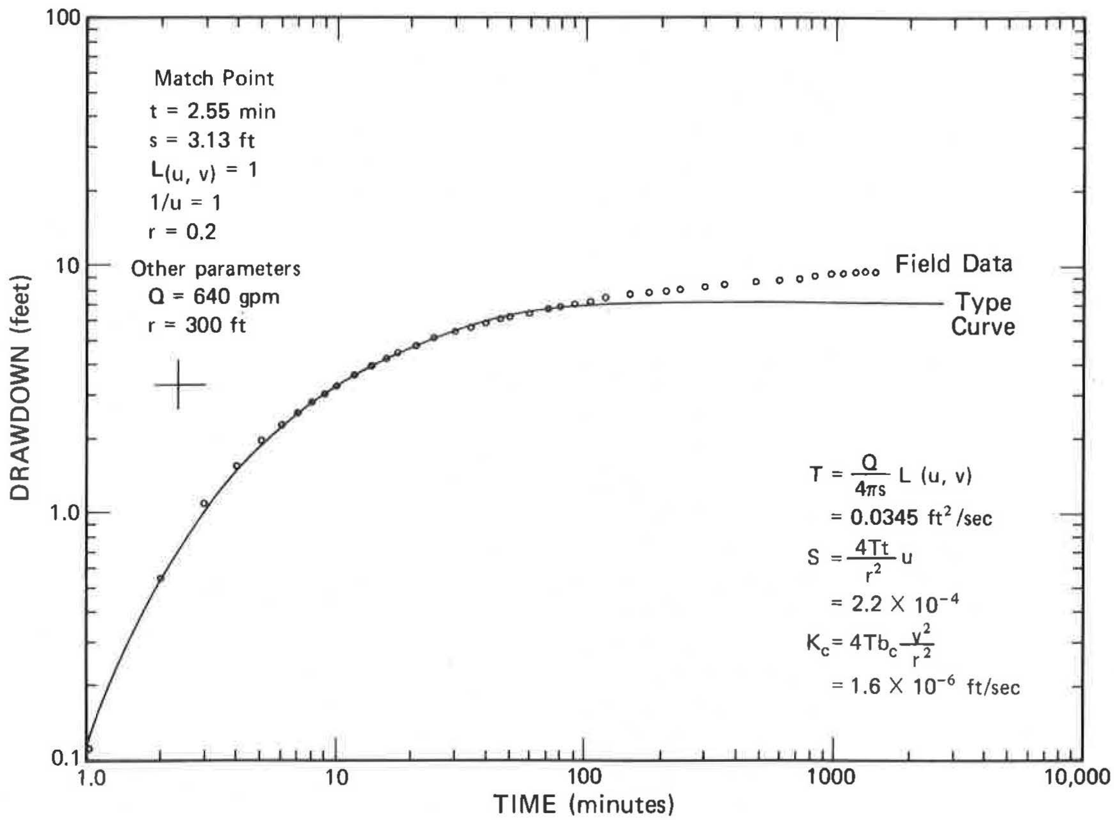

Figure 15. Hantush-Jacob type-curve fit for the aquifer test at the Proctor and Gamble plant, Richmond County, August 17, 1983. Type curve from Lohman (1972, plate 3).

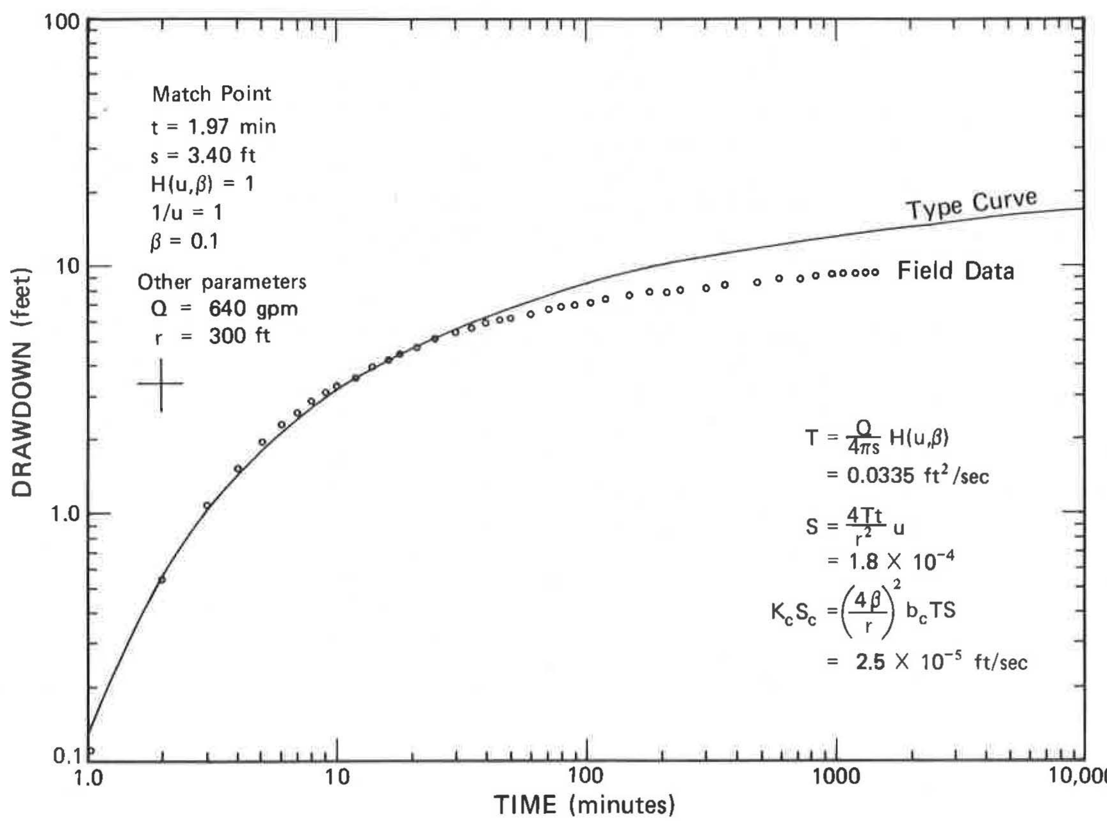

Figure 16. Modified Hantush type-curve fit for the aquifer test at the Proctor and Gamble plant, Richmond County, August 17, 1983. Type curve from Lohman (1972, plate 4).

was reached in both observation wells after 7 hours of pumping, violating an assumption of the Theis method. A Theis analysis of the data from the Proctor and Gamble aquifer test indicates a transmissivity of 8.48×10^{-2} ft²/s and a storativity of 8.9×10^{-5}. The fit of the Proctor and Gamble data to the Hantush-Jacob curve (Fig. 15) was much closer than the fit to the Theis curve.

As estimated by the Hantush-Jacob method, the value of the vertical hydraulic conductivity in the confining bed at Proctor and Gamble was 1.6×10^{-6} ft/s, which is over an order of magnitude greater than that estimated at Gracewood Hospital. Although this is a large difference, it is not unreasonable considering the erosional nature of the confining bed and the wide range of values known in natural materials. Another factor which may contribute to the large difference is a clay bed reported in the driller's log of the Gracewood State Hospital well used for the aquifer test (well 58). This clay bed, described as a white chalky clay with some sand, lies beneath the red clay used to define the top of the basal Cretaceous aquifer, but is not noted in the driller's log of well 34, 500 feet to the east. The electric log of well 58 indicates that this clay bed has a lower resistivity than the red clay. This may indicate that, in the immediate vicinity of well 58, the aquifer is more fully confined than in other areas.

The transmissivity values determined from the Gracewood aquifer test and the Proctor and Gamble aquifer test are comparable to other values from within the study area. Computed transmissivity values for the basal Cretaceous aquifer throughout the study area range from 2.0×10^{-1} ft²/s to 2.6×10^{-3} ft²/s, and average 6.9×10^{-2} ft²/s. Although the Kimberly Clark wells are screened in both aquifers, and are thus open to a larger thickness of permeable material, the transmissivities are below the average for the study area. Similarly, the hydraulic conductivity values that were obtained for the Kimberly-Clark production well (well 118) are significantly lower than the hydraulic conductivities determined at other wells in the study area. The only exception to this is the hydraulic conductivity from the analysis of pumping data from Olin's potable well (well 71), which is only slightly higher than that from well 118. The hydraulic conductivity of a 10-foot section of the basal Cretaceous aquifer in well 118 was reported by Sirrine (1980, p. 8, Stratum 2) to be 1.6×10^{-3} ft/s, which suggests that the basal Cretaceous aquifer may become less permeable downdip. Because of the low number of aquifer tests conducted in the study area and the clustering of these few tests into localized areas, it is not possible to reliably indicate trends in aquifer parameters.

Hydraulic conductivity values from wells in the basal Cretaceous aquifer range from about 3.7×10^{-3} to 4.7×10^{-4} ft/s. Siple (1967, table 3) reported hydraulic conductivities in the range of 2.4×10^{-3} to 3.2×10^{-4} ft/s for the Cretaceous aquifer (both the basal and upper Cretaceous aquifers of this report) in adjacent areas of South Carolina which are in general agreement with those measured for this study. Corresponding transmissivity values reported by Siple (1967, table 3) range from 6.2×10^{-1} to 5.2×10^{-2} ft²/s, which are somewhat higher than the values measured for this study.

The specific capacity of a well is defined as the well discharge divided by the corresponding drawdown, and is expressed as gallons per minute per foot of drawdown (gal/min/ft). The specific capacity of a well is dependent not only on the material which comprises the aquifer, but also on the well efficiency and the time since pumping began. Therefore, it is not as useful a tool in estimating the hydrologic properties of an aquifer as transmissivity, hydraulic conductivity, and storativity. However, because many drillers routinely record the specific capacity of new wells, specific capacity data are usually more numerous than standard aquifer test data.

Figure 17 is a map showing the areal distribution of specific capacity and transmissivity values. The specific capacity values have a wide range even for nearby wells. This is particularly evident at the Babcock and Wilcox plant where well 30 has a specific capacity of 38 gal/min/ft compared to 7.9 gal/min/ft for well 27, which is less than 1600 feet away. The difference in specific capacities is probably due to differences in the efficiencies of the wells. The Richmond County Water System's Peach Orchard Road wells (wells 44-48) have consistently high specific capacities. Although this could be attributed to the high efficiency screen installed in the wells, the higher than normal transmissivities indicated by aquifer tests would be expected to be a contributing factor. The lowest specific capacities are probably due to the use of slotted PVC screen, which typically is inefficient, as well as the reduced thickness of the aquifer in this area. Figure 16 indicates that south of wells 44-48, specific capacities and transmissivities are generally lower. However, the scarcity and scatter of values limits the identification of trends.

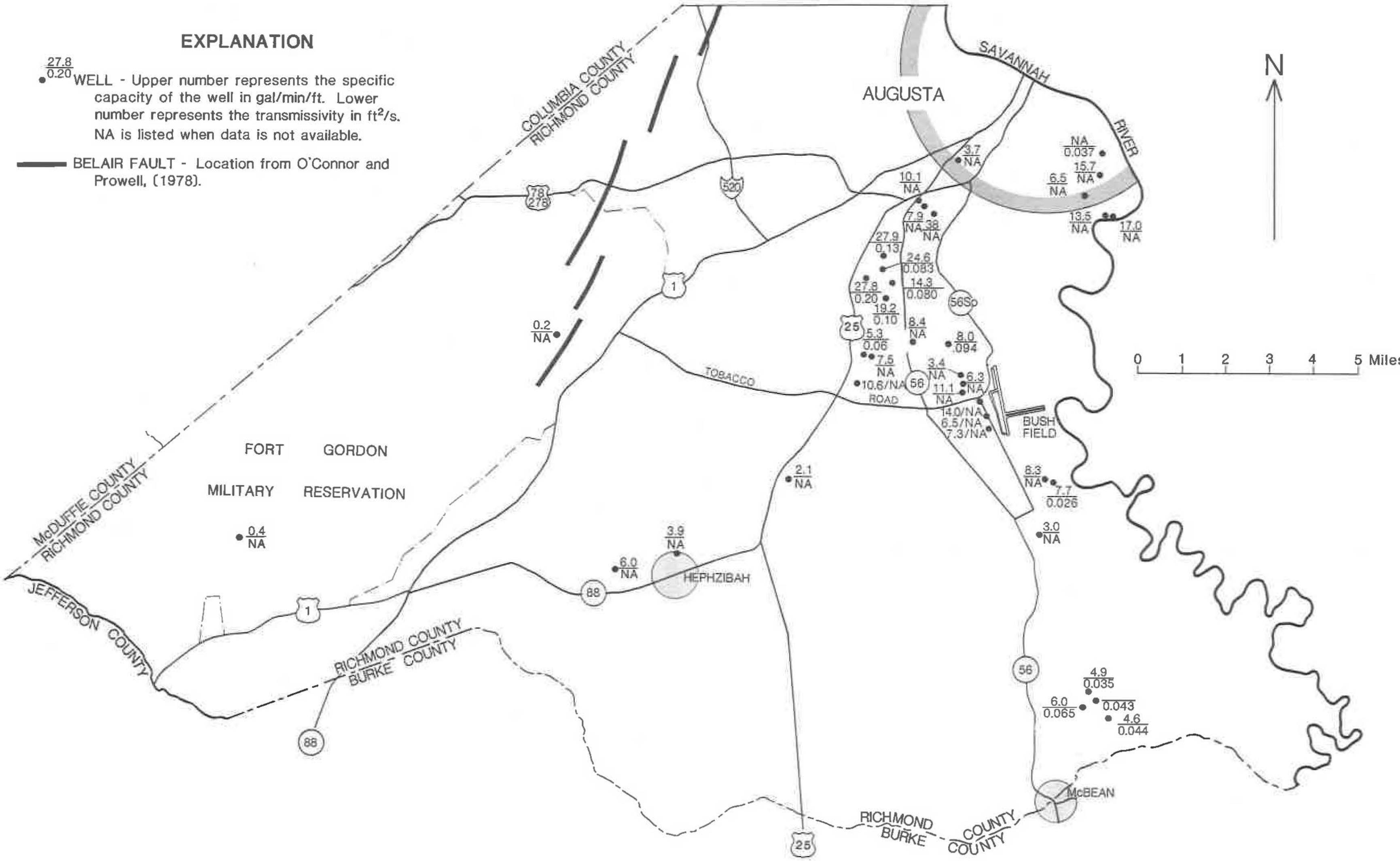

Figure 17. Map of specific capacity and transmissivity values.

GROUND-WATER FLOW

Ground water flows from areas of high potential energy to areas of low potential energy. The water table represents the potential energy of ground water in an unconfined aquifer. In a confined aquifer, the potentiometric head represents the potential energy. The potentiometric head is the level to which water will rise in a tightly cased well. For the purpose of this report the potentiometric head is assumed to be the static water level in a properly constructed well. The potentiometric surface of an aquifer represents the potentiometric head at all points in that aquifer.

Figure 18 is a map showing the potentiometric surface of the basal Cretaceous aquifer. Ground water generally flows from the western part of the study area toward the east (down the potentiometric gradient). Recharge to the basal Cretaceous aquifer is concentrated in the western part of the study area. Natural recharge occurs as infiltration of precipitation directly into the sediments that comprise the aquifer or as downward leakage through overlying units. The aquifer test data presented earlier indicate that recharge to the basal Cretaceous aquifer is induced through overlying confining beds during pumping.

In the northwestern part of the study area, the basal Cretaceous aquifer is at or near the surface. As a result, the aquifer is hydraulically connected to local streams. Although the streams can recharge the aquifer while at high stage, the local streams are usually an area of discharge from the aquifer. As a result, in the area where the basal Cretaceous aquifer is at or near the surface, the potentiometric surface of the aquifer is thought to be a subdued expression of the land surface. This is indicated in Figure 18 by the irregular shape of the potentiometric contours in the northwestern part of the study area. Toward the southeast, the basal Cretaceous aquifer is more deeply buried and the effects of the streams on the ground-water flow are reduced.

Most of the natural discharge from the basal Cretaceous aquifer is into the Savannah River. The effect of the Savannah River on ground-water flow is indicated in Figure 18 by the large area of ground-water flow toward the river. LeGrand and Pettyjohn (1981) discuss the effect of the Savannah River on ground-water flow in this area. In their discussion they considered all of the Cretaceous sediments to be a single aquifer. Their discussion was based on a potentiometric map by Siple (1960) which included a number of wells screened within sands now known to be within the Huber Formation. Large-scale ground-water withdrawals in eastern Richmond County have altered the natural ground-water flow pattern. A large cone of depression is indicated on Figure 18 at the Richmond County Bush Field well field (wells 101-106). A smaller cone of depression exists at the Olin Corporation plant (well 71). In this area, flow toward the Savannah River has been disrupted. It is possible that in this area, pumpage has caused the Savannah River to recharge the basal Cretaceous aquifer. Although data are not adequate to define a cone of depression, the potentiometric map indicates that pumping at Richmond County's Peach Orchard Road well field (wells 44-48) has also modified ground-water flow.

The effects of the Belair Fault zone on the hydrogeology and ground-water flow are not known. Assessing the effects of the fault would be difficult, requiring a canvassing of domestic wells. Faye (personal commun.) suggests that the flowing wells reported on page 99 of LeGrand and Furcron (1956) flow because the basal Cretaceous aquifer is truncated by the Belair Fault, which runs to the east of these wells. The Lassiter well of LeGrand and Furcron (1956, p. 99; number 5 and well 140 on Plate 1) still flows, indicating that in the area around the Lassiter well, water levels have not declined appreciably since the mid 1950's.

Records of long-term water-level fluctuations offer valuable insight into the effects of ground-water withdrawals on an aquifer. Only one well in the study area is equipped with a water-level recorder. This well, near McBean (well 60), taps the upper Cretaceous aquifer. The monthly mean water level has not varied more than 2 feet since the installation of the recorder in June, 1979. This lack of fluctuation may be the result of the limited use of the upper Cretaceous aquifer. This record of water-level fluctuations without the effects of large-scale pumping may be an important tool in assessing the impact of future development of this aquifer.

The lack of a continuous, long-term record of water levels in the basal Cretaceous aquifer in the study area makes it difficult to assess the effects of the current withdrawals. Records of static water levels reported to the Water Resources Management Branch of the Georgia Environmental Protection Division by permitted users, as well as periodic water-level measurements made by U.S. Geological Survey and Georgia Geologic Survey personnel, do not indicate a consistent, county-wide trend of declining water levels.

Comparison of the May, 1983, water-level measurements used in the construction of Figure 18 with the static water levels recorded when the wells were drilled provides an estimate of the net water level change. However, these comparisons can be misleading in a number of ways. For instance,

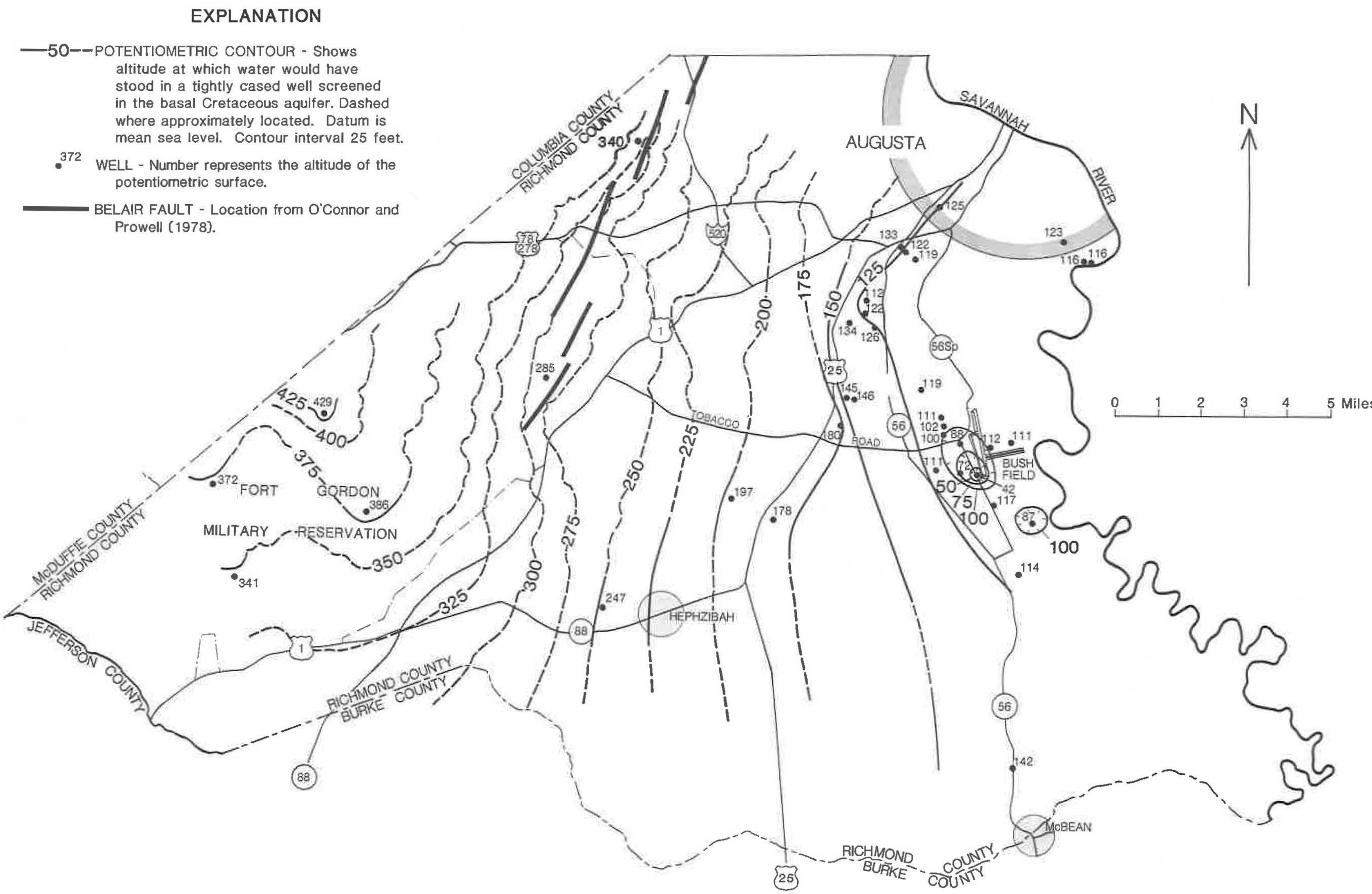

Figure 18. Potentiometric map of the basal Cretaceous aquifer, May 1983.

because the wells in the study area were drilled over a period of many years, the original static water levels for nearby wells may be widely different. For example, the static water level for well 58 was 8 feet when the well was drilled in June, 1953, whereas the static water level for well 34, about 500 feet away, was 20 feet when the well was drilled in June, 1974. The water levels in wells 32, 74 and 75, near Hephzibah, have declined over 15 feet between the time that they were drilled (April, 1967, October, 1972, and April, 1974, respectively) and May, 1983. In November, 1982, the water level in the Albion mine well (well 32) was at approximately the same level it was when the well was drilled in April, 1967. However, between November, 1982, and May, 1983, the water level in this well dropped 16 feet. It is not known whether this decline is a normal seasonal fluctuation for this area.

In general, water levels have declined in the industrial district. The axis of this decline in water levels runs from the Olin plant (well 42) to the Peach Orchard Road well field (wells 44-48). The greatest declines have occurred in the vicinity of the airport well field (including Transco Textiles, wells 77-79). In this area, a water-level decline of over 30 feet has been noted. A water-level decline of over 20 feet has been documented between August, 1964, and May, 1983, at the Olin plant (well 42). Water level declines north-northwest of the Bush Field -Transco area are generally smaller. At the Peach Orchard Road well field, water levels have declined approximately 25 feet.

GROUND-WATER AVAILABILITY

Ground water is available in at least moderate amounts throughout the study area. The lowest reported yield was 13 gal/min for well 80 at Mirror Lake on the Fort Gordon reservation. This low yield is probably a function of the use of an inefficient PVC screen, the thinness of the permeable zone in the updip area, and the lack of necessity for larger quantities. Several wells reported yields of 800 gal/min or more.

Most of the high capacity wells in the study area tap the basal Cretaceous aquifer. Use of the upper Cretaceous aquifer becomes more feasible downdip due to the increased construction costs for basal Cretaceous aquifer wells, the general thickening of the upper aquifer, and the thinning of the basal Cretaceous aquifer. Few wells tap the upper Cretaceous aquifer at this time. However, as the Augusta area expands, use of water from the upper Cretaceous aquifer for industrial and municipal uses will increase.

Wells yielding several hundred gallons per minute or more can be developed within the basal Cretaceous aquifer in all areas except the northwest portion of the study area, where the aquifer is very shallow, and downdip from Continental Forest, where the basal Cretaceous aquifer thins. The aquifer test data suggest that in the downdip areas, the basal Cretaceous aquifer becomes less permeable in addition to thinning. However, in the downdip areas, the upper Cretaceous aquifer can also be tapped to increase the well yield. Because of the length of screen necessary to produce high capacities, these wells are expensive. Aquifer test data indicate that the transmissivity would still be low, even with the great thickness of permeable material being tapped.

The potentiometric data in Figure 18 indicate that in the area of large industrial and municipal withdrawals along the eastern portion of Richmond County, the basal Cretaceous aquifer is heavily stressed. Major new withdrawals in this area would further stress the aquifer, resulting in greater water-level declines. Problems that may result from declining water levels include reduced yields, higher pumping costs and possible damage to wells and pumps. In central and southern Richmond County and in the northern part of Burke County, the ground-water system is not heavily stressed, and as a result, ground water is readily available in this area.

In the northwestern part of the study area, the ground-water availability is not well known because of a relative lack of wells with complete information. Well records of wells 127, 128,and 129 indicate that yields of approximately 40 gal/min can be obtained in this area. With proper construction and development, higher yielding wells might be possible. The potential yields in this area are lower than in other parts of the study area due to the thinness of the permeable zones.

Leakage through the confining bed overlying the basal Cretaceous aquifer reduces the drawdown in the aquifer as well as reducing the radius of influence. As a result, wells can pump more water while producing the same drawdown. In addition, well spacing can be reduced. Therefore, vertical leakage is an important source of the water being pumped in the study area. As water use grows, so will the amount of leakage from the upper Cretaceous aquifer and even the Savannah River.

WATER QUALITY

The quality of ground water within the Cretaceous sediments in the study area is generally good. Table 4 contains the results of 25 water-quality analyses from 23 wells in the study area. Of these 23 wells, 15 are open to the basal Cretaceous aquifer only, 7 are open to both the basal and upper

Table 4 — Chemical analyses of water from wells tapping the basal and upper Cretaceous aquifers, Richmond County.

Well Number	Name or Owner	Source	Aquifer	Date	pH	Dissolved Solids (mg/l)	Calcium (Ca) (mg/l)	Magnesium (Mg) (mg/l)	Sodium (Na) (mg/l)	Potassium (K) (mg/l)	Iron (Fe) (mg/l)	Bicarbonate (HCO_3) (mg/l)	Chloride (Cl) (mg/l)	Sulfate (SO_4) (mg/l)	Silica (SiO_4) (mg/l)
Drinking Water Standards						**500**					**0.3**		**250**	**250**	
8	Nipro 15	3	b	6-12-75	4.3		0.6	0.2	2.3	0.4	0.04	5			
37	Monsanto 1	3	b	3-17-76	5.7				5.4			14	0.2		0.8
41	Continental Forest	2	b&u	3-30-59	5.8	20	1.6	0			0.2	3.7	5	0	
41	Continental Forest	3	b&u	10-17-60	7.1	112	1	0.4	37	0.2		95	3	2.4	11
46	Richmond County 14	3	b	6-17-70	5.7	20	0.1	0.4	1.6	0.6	0.02	2	1.5	0	7.7
47	Richmond County 10	3	b	6-17-68	5.7	18	0.4	0.4	0.1	0.5		1	1.8	0	7.5
73	Hephzibah 3	3	b&u	6-17-75	4.7		0.3	0.2	1.1	0.3	0.56	3	1.4	2	16
75	Pine Hill 2	1	b&u	4-5-74	5.6	17	0.8	0	0.5		0.1	4	2.1	.0	4.2
76	Pine Hill 3	1	u	9-7-77	5.4	40	0.2	0.3	0.7			3.7	4	1.2	15
77	Transco 1	2	b	2-13-73	7.2	16	0.4	0.2	0.5			1.2	0.1	1.7	5.6
78	Transco 2	2	b	2-13-74	4.0	10	0	0.1	0.5				4.3	0	4.7
79	Transco 3	2	b	3-21-74	6.7	13	1.4	0.9	0.5			0.6	2.1	0	4.5
101	Richmond County 101	1	b	6-20-77	6.2	14	0.1	0.1	0.5			3.7	1	0	9
102	Richmond County 102	1	b	6-15-77	5.9	25	0.1	0.1	0.5			3.7	1	0	9.5
103	Richmond County 103	1	b	7-6-77	5.7	50	0.1	0.1	1.5			2.4	1	0	9
104	Richmond County 104	1	b	8-11-77	6.4	20	0.1	0.1	0.5			2.4	2	0	13
117	Kimberly Clark	4	b&u	4-9-80	6.3	88	56	4	9.4	1.2	1.2	61	4	9.5	15
118	Kimberly Clark	4	b&u	6-4-80	6.4	94	60	2	4	1.4	0.76	61	1.4	9.4	18
118	Kimberly Clark	4	b&u	6-30-80	6.1	95	49	2	4	1.6	0.7	48	2	10	16
119	Kimberly Clark	4	b&u	5-4-80	6.4	91	47	5	4	2		53	4	9	12
120	Kimberly Clark	4	b&u	5-30-80	6.4	127	68	7	14	2		72	13	11	15
131	Richmond County OW1	1	b	12-16-81	5.2	21			1		0.05	3.8	3	2	
132	Richmond County OW2	1	b	12-15-81	3.8	24			1.2			6.1	7	3	
133	Richmond County OW3	1	b	1-6-82	4.8	20			1.5		0.1	2.4	5	1	
134	Richmond County OW4	1	b	1-7-82	5.0	10			1		0.05	2.4	5.1	1	

Source Code:
1. Virginia Well and Supply Co. Records
2. Water Resources Management Branch Files
3. U.S Geological Survey Watstore File
4. Sirrine (1980)

Aquifer Code:
b — basal Cretaceous aquifer
u — upper Cretaceous aquifer
b&u — basal and upper Cretaceous aquifers

Cretaceous aquifers and 1 is open to the upper Cretaceous aquifer only, as indicated in Table 4.

The pH of the water is low, ranging from 3.8 at well 132 to 7.4 at well 101. The mean pH value is approximately 5.8. The low pH values are probably due to the abundance of carbon dioxide dissolved in the water. The water is corrosive and over time could damage wells, pumps, and plumbing if left untreated. Common treatments are aeration and the addition of lime or lye to neutralize the pH. In many instances, the additives are introduced in the well to reduce corrosion of the well screen.

The total dissolved solids (TDS) of the samples range from 10 to 127 milligrams per litre (mg/l). However, the distribution of TDS values is bimodal with all values falling into the 10 to 50 mg/l or 88-127 mg/l ranges. Total dissolved solids of samples from the basal Cretaceous aquifer ranged from 10 to 50 mg/l. Total dissolved solids in multi-aquifer wells ranged from 12 to 137 mg/l. Sirrine (1980) sampled discrete zones of well 118. However, the total dissolved solids of the sample from the basal Cretaceous aquifer was not significantly lower than the TDS of the composite samples. In all cases the TDS was lower than the U.S. Environmental Protection Agency drinking water limit (500 mg/l).

In some locations the concentrations of iron and manganese exceed the recommended Environmental Protection Agency drinking water limits. The iron and manganese in the water does not pose a health risk, but may lead to the staining of clothes and fixtures and clogging of plumbing by precipitates (Freeze and Cherry, 1979, pg. 386).

As in many areas, the potential for ground-water contamination exists. Contamination of the basal Cretaceous aquifer should be a concern due to the leaky confining bed at the top of the aquifer as well as the close proximity to the recharge area. Possible sources of contamination include leachate from landfills, material leaking from above- or below-ground storage tanks (for example, gasoline), industrial wastes, and agricultural chemicals. Because of the permeable nature of most soils, contaminants could reach the water table.

WATER USE

Water is used in the study area for irrigation, industrial and municipal supply, and domestic use. Although it is impossible to measure the precise amount of water used in the study area, it is possible to compile a reasonable estimate. The data for the water use estimates presented in this report were compiled by the Georgia Water-Use Project (a Georgia Geologic Survey-U.S. Geological Survey cooperative project). The data range from site-specific usage reports filed by permitted users to area-based figures obtained by multiplying the average use by the number of users. Examples of area-based use figures are rural domestic, rural livestock, and irrigation. Non-agricultural users withdrawing over 100,000 gallons per day (gal/d) from either surface- or ground-water sources must obtain a withdrawal permit from the Georgia Environmental Protection Division. In addition they must report actual monthly water use.

The average water use in the study area in 1980 was approximately 100.1 million gallons per day (Mgal/d). Surface-water sources contributed 73.6 Mgal/d, or 74 percent of this total, whereas ground-water use averaged 26.5 Mgal/d. Figure 19 is a graph of water use by month for 1980. Water use peaked in August, averaging 112.8 Mgal/d. This estimate of peak monthly use is probably low due to the fact that area-based water-use estimates, including irrigation, were averaged over the entire year, when in reality, these uses are highly seasonal. On any given day the actual water use could be much greater or much less.

Most of the water used within the study area is for industrial purposes, including paper production, textile printing, and refractory brick manufacturing. Industries account for 53 percent of the water withdrawals within the study area, as indicated in Figure 20. However, they actually use a greater percentage, as a number of industries rely on municipal systems to supply some of their water, either on a continuous basis, for peak flows, or for

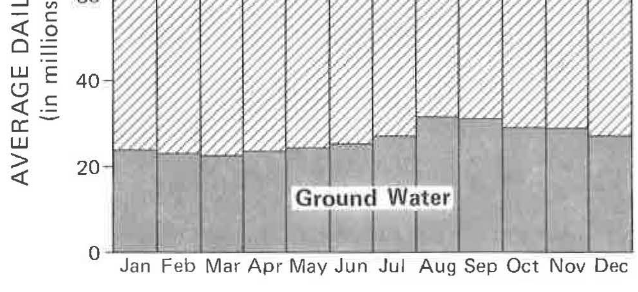

Figure 19. Water use by month, 1980. Data from the Georgia Water-Use Data Collection Program.

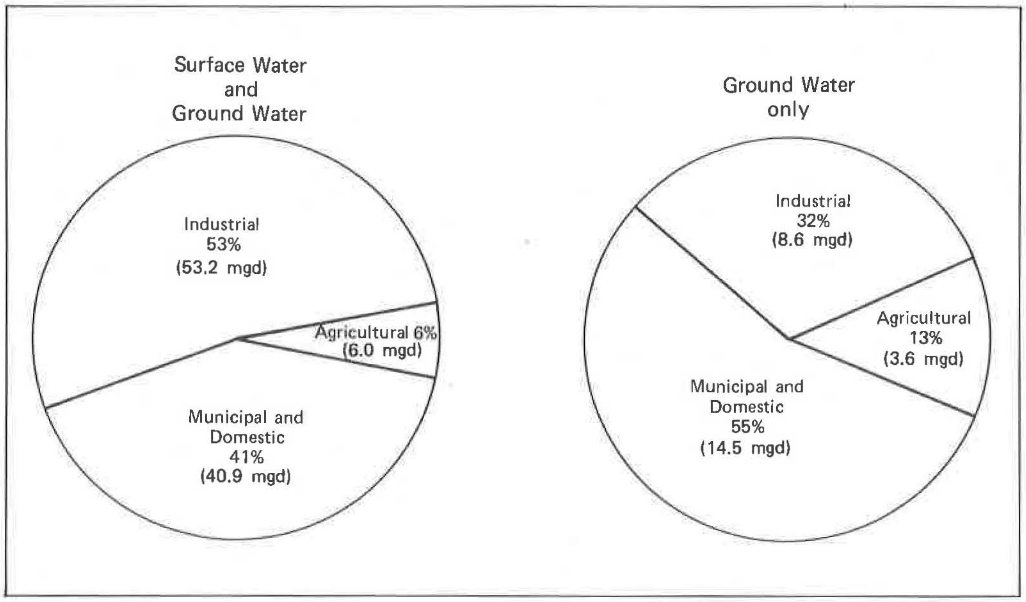

Figure 20. Water use by category, 1980. Data from the Georgia Water-Use Data Collection Program.

emergency use. Ground-water withdrawals are concentrated in the industrialized areas of eastern Richmond County.

In 1980, municipal systems and domestic supplies withdrew 41 percent of the water used within the study area. These withdrawals were dominated by the City of Augusta Water System and the Richmond County Water System. Smaller systems serve the Gracewood State Hospital, Fort Gordon, the city of Hephzibah, the city of Blythe, the town of Girard, and the Oak Ridge community. The city of Augusta obtains water from the Savannah River, and Fort Gordon withdraws from Butler Creek. The other municipal systems rely on ground water.

Although water-use estimates for other years are unavailable, water use in the study area is generally on the increase, as evidenced by the number of users requesting increases in water-use permits. Another indication of increasing water use is the increased number of irrigation systems in the study area. Figure 21 shows the total permitted ground-water withdrawals within the study area from 1975 to 1983. The actual withdrawals are lower because some users do not use their total permitted capacity. Permitted withdrawals increased from 1975 to 1981. The drop in 1982 is a result of Nipro, Inc. switching from ground water to surface water when their need for process water exceeded the capacity of the aquifer in that area. Nipro's wells (including 9, 10, 13, 20, and 24 on Plate 1) were located along the Savannah River, and were generally shallow; as a result, much of the ground water was induced flow from the Savannah River (Nuzman, 1974). The data for 1983 is the total permitted withdrawals as of July 1983 plus a pending request for an increase.

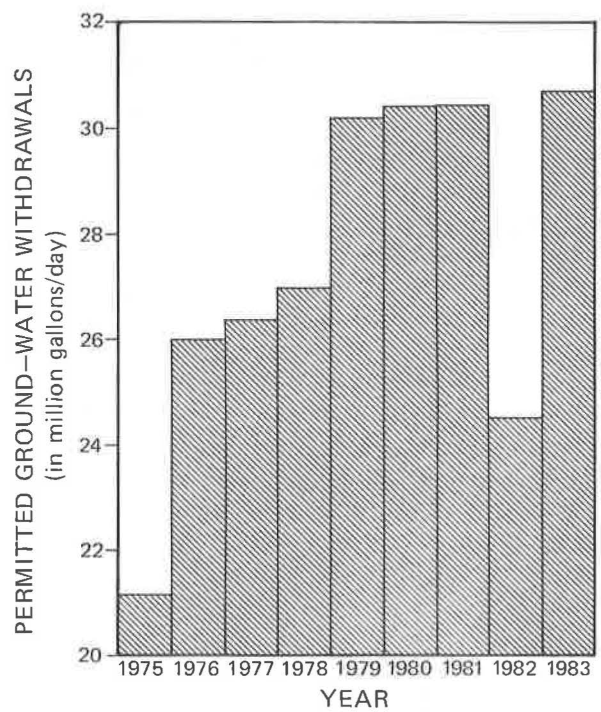

Figure 21. Permitted ground-water withdrawals in the study area from 1975 to 1983. Figure for 1983 includes permitted amount plus a pending request for an increase.

Another indication of increasing water use is the increased number of irrigation systems in the study area. Figure 22 is a graph showing the increase in the number of irrigation systems in Richmond and Burke Counties. Although this includes areas outside the study area, it is indicative of the increase in the amount of water used for irrigation in the study area.

Although the general trend is toward greater water use, there are fluctuations in water use. Some industries found it necessary to slow production in 1981 and 1982 due to the recessed economy; as a result they used less water. In addition, economic factors delayed projects that would have resulted in greater water use.

Future ground-water use is likely to grow as a result of continuing population growth, expansion of existing industries, establishment of new industries, and continuing growth in the use of irrigation. For example, the Richmond County Water System has projected a demand of 20 Mgal/d in 1995 (Robert Pierce, written commun). In 1980 the county's pumpage averaged 10.3 Mgal/d.

At least 72 percent of the ground water used within the study area is taken from the basal Cretaceous aquifer (the 72 percent figure assumes that the basal Cretaceous aquifer supplies none of the estimated 7.1 Mgal/d area-based water use). Plant Vogtle and the town of Blythe withdraw from the upper Cretaceous aquifer. Hephzibah's wells tap both the basal and upper Cretaceous aquifers. All other permitted users tap the basal Cretaceous aquifer.

The estimate of water use for agricultural purposes for 1980 probably was outdated soon afterward due to the increase in the use of irrigation in the study area. In 1982 the Georgia Legislature enacted legislation (House Bills 1109 and 1110) that requires farmers using more than 100,000 gal/d for irrigation to report their use (no permit is required). Farmers may report the number of hours the system was in use, along with information on the capacity of the system instead of the actual number of gallons pumped per month. Preliminary reports did not include use figures (the first set of reports covered only the Fall 1982 season), but information was received for 7 systems within the study area. Subsequent reports should provide more useful information.

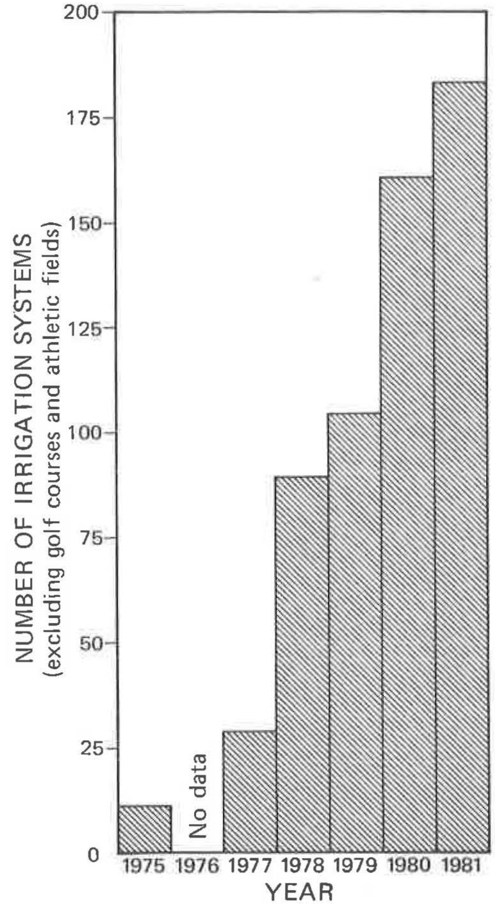

Figure 22. Number of irrigation systems in Burke and Richmond Counties from 1975 to 1981. Data from the Cooperative Extension Service.

CONCLUSIONS

The basal Cretaceous aquifer, the lower of two aquifers within the Gaillard formation, is the main source of ground water in the study area. The aquifer lies at the base of the Coastal Plain sediments, overlying the crystalline rocks of the Piedmont in updip areas and Triassic rocks of the Dunbarton Basin in downdip areas. The basal Cretaceous aquifer is overlain by a clay bed that is thought to be a weathered zone within the Gaillard formation.

The second aquifer within the Gaillard formation is the upper Cretaceous aquifer. It overlies the clay bed that caps the basal Cretaceous aquifer and underlies the clay that marks the weathered zone at the top of the Gaillard formation. Both the basal and upper Cretaceous aquifers are composed of sand and gravel with minor amounts of interspersed clay.

The regional dip in the study area is to the southeast. The basal Cretaceous aquifer thickens downdip to a maximum of approximately 150 feet. Farther downdip the aquifer thins somewhat. Available data indicate that the upper Cretaceous aquifer thickens downdip. Throughout much of the study area, the upper Cretaceous aquifer is either exposed at the surface or is hydraulically connected to alluvial deposits.

In 1980, ground-water use in the study area was approximately 26.5 Mgal/d. Most of this withdrawal was taken from the basal Cretaceous aquifer in the eastern industrial area of Richmond County.

Aquifer test data indicate that transmissivities range from about $2.6x10^{-2}$ ft^2/s to $2.0x10^{-1}$ ft^2/s in the basal Cretaceous aquifer. In addition, tests at the Gracewood State Hospital and at Proctor and Gamble indicate that the basal Cretaceous aquifer receives leakage through the overlying confining bed during pumping. Without this vertical leakage, the concentrated, large-scale pumping in the eastern industrial area would result in larger drawdowns than have been noted. The limited aquifer test data suggest that the aquifer becomes less permeable downdip; however, more data would be necessary to confirm this trend.

Potentiometric data indicate that regional ground-water flow is from west to east. Recharge to the aquifer is from direct infiltration and from seepage through overlying units. Under natural conditions, the basal Cretaceous aquifer discharges into the Savannah River. However, the concentrated pumpage in the industrial district has disrupted this flow pattern. A cone of depression has developed around the Richmond County airport well field. A smaller cone of depression has formed at the Olin plant. Water-level declines have been noted in the industrial areas of Richmond County. However, throughout most of Richmond County, no long-term water-level decline has been documented.

Ground water from the basal and upper Cretaceous aquifers is acidic. The acidity is due to dissolved carbon dioxide. In many water systems the water is treated with lime or lye to neutralize the pH and to make the water less corrosive. In some locations iron and manganese are above the EPA drinking water limits and present a problem with staining of clothes.

Large quantities of ground water are available throughout most of the study area. Well yields in the northwestern part of the study area are lower than in other areas due to the thinness of the aquifer. The basal Cretaceous aquifer is stressed in the industrial area of eastern Richmond County. There has been little development of the upper Cretaceous aquifer in southern Richmond County and northern Burke County. Overlying units within the study area yield smaller quantities of water, and as a result are seldom used as a source of ground water.

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APPENDIX A

List of Wells

Well No.	Owner/s No.	GGS No.	Latitude	Longitude	Quad	Data Available
8	Nipro Corp. #15		33°26′06″	81°55′00″	Augusta, East	L,C
9	Nipro Corp. #16		33°25′52″	81°55′31″	Augusta, East	L,C
10	Nipro Corp. #17		33°25′53″	81°55′39″	Augusta, East	L,C
13	Columbia Nitrogen #3		33°26′42″	81°55′48″	Augusta, East	L,C
16	Columbia Nitrogen #10		33°26′49″	81°55′52″	Augusta, East	L,C
17	Archer Daniels Midland[1]		33°26′58″	81°59′09″	Augusta, East	L,C
20	Nipro Corp. #8		33°26′16″	81°56′07″	Augusta, East	L,C
24	Nipro Corp. #13		33°25′56″	81°55′11″	Augusta, East	L,C
27	Babcock & Wilcox #3		33°26′06″	81°59′59″	Augusta, East	L,C
29	Babcock & Wilcox #7		33°26′01″	81°59′52″	Augusta, East	L,C
30	Babcock & Wilcox #8		33°25′57″	81°59′45″	Augusta, East	L,C
32	Babcock & Wilcox Mine		33°18′54″	82°07′08″	Hephzibah	L,C,E
34	Gracewood State Hospital #3		33°23′09″	82°01′13″	Augusta, West	L,C
37	Monsanto #1		33°23′22″	81°59′33″	Augusta, East	L,C
38	Monsanto #2	3156	33°23′25″	81°59′20″	Augusta, East	L,C
39	Oak Ridge Water System		33°17′26″	82°08′23″	Blythe	L
40	McBean #3		33°15′44″	81°57′18″	Mechanic Hill	L,C
41	Continental Forest	585	33°19′41″	81°57′12″	Mechanic Hill	L,C,E
42	Olin Potable		33°20′40″	81°56′55″	Mechanic Hill	L,C,E
44	Richmond County #11		33°24′48″	82°00′52″	Augusta, West	L,C
45	Richmond County #12		33°24′38″	81°01′18″	Augusta, West	L,C
46	Richmond County #14		33°24′15″	82°00′48″	Augusta, West	L,C
47	Richmond County #10		33°25′05″	82°00′54″	Augusta, West	L,C
48	Richmond County #13		33°24′34″	82°00′39″	Augusta, West	L,C
51	Babcock and Wilcox #6		33°26′09″	82°00′05″	Augusta, West	L,C
52	Hephzibah #1	526	33°18′38″	82°05′56″	Hephzibah	L,C
57	Gracewood State Hospital #1		33°22′36″	82°01′30″	Augusta, West	L,C
58	Gracewood State Hospital #2		33°23′10″	82°01′18″	Augusta, West	L,C,E
60	McBean #2		33°15′25″	81°57′47″	Mechanic Hill	L
64	Blythe		33°17′30″	82°12′08″	Blythe	L,C
71	Olin Reductone		33°20′44″	81°57′03″	Mechanic Hill	L,C
72	Hephzibah #2	1075	33°19′05″	82°05′29″	Hephzibah	L,C
73	Hephzibah #3		33°19′09″	82°05′41″	Hephzibah	L,C
74	Pine Hill #1[2]		33°20′43″	82°03′08″	Hephzibah	L,C
75	Pine Hill #2[2]		33°21′06″	82°04′11″	Hephzibah	L,C
76	Pine Hill #3[2]		33°18′05″	82°01′10″	Hephzibah	L,C
77	Transco #1		33°22′46″	81°59′08″	Augusta, East	L,C
78	Transco #2		33°22′32″	81°59′00″	Augusta, East	L,C
79	Transco #3		33°22′21″	81°59′01″	Mechanic Hill	L,C
80	Fort Gordon-Mirror Lake	3430	33°23′30″	82°08′31″	Grovetown	L,C
81	Fort Gordon-Bldg. 456	3429	33°19′40″	82°16′08″	Avondale	L,C
82	Georgia Power		33°08′56″	81°46′22″	Shell Bluff Landing	L
83	Fort Gordon-Kaolin test		33°20′26″	82°15′29″	Avondale	L
84	Fort Gordon #1		38°22′44″	82°13′50″	Grovetown	L,C
86	Georgia Power MU 6		33°08′46″	81°45′52″	Shell Bluff Landing	L
92	Georgia Power VG 2		33°05′09″	81°40′32″	Girard	L,E,N,C
94	Georgia Power VG 4		33°05′29″	81°41′38″	Girard	L,E,N,C
97	Georgia Power VG 7		33°05′55″	81°42′29″	Girard	L,E,N,C
99	Hotel Bon Aire	309	33°28′33″	82°00′36″	Augusta, West	L

List of Wells (Continued)

Well No.	Owner/s No.	GGS No.	Latitude	Longitude	Quad	Data Available
101	Richmond County #101		33°22'15"	81°58'35"	Mechanic Hill	L,E,C
102	Richmond County #102		33°22'08"	81°58'31"	Mechanic Hill	L,E,C
103	Richmond County #103		33°21'59"	81°58'26"	Mechanic Hill	L,E,C
104	Richmond County #104		33°21'45"	81°58'24"	Mechanic Hill	L,E,C
105	Richmond County #105		33°21'41"	81°58'35"	Mechanic Hill	L,C
106	Richmond County #106		33°21'38"	81°58'13"	Mechanic Hill	L,C
112	GGS Core	3180	33°24'56"	82°08'13"	Grovetown	L,E
113	GGS Core	3181	33°25'02"	82°08'30"	Grovetown	L,E
114	GGS Core	3182	33°27'12"	82°06'34"	Augusta, West	L,E
115	GGS Core	3183	33°27'45"	82°07'25"	Augusta, West	L,E
116	GGS Core	3184	33°19'22"	82°12'06"	Blythe	L,E
117	Kimberly-Clark OW#1	3446	33°16'36"	81°56'04"	Mechanic Hill	L,E,N,C
118	Kimberly-Clark test well		33°16'30"	81°55'54"	Mechanic Hill	L,E,N,C
119	Kimberly-Clark OW#3		33°16'07"	81°55'32"	Mechanic Hill	E,N,C
120	Kimberly-Clark OW#2		33°16'19"	81°56'09"	Mechanic Hill	E,N,C
122	Olin-test boring T2		33°20'28"	81°57'26"	Mechanic Hill	L,E,N
127	Fort Gordon #2		33°21'20"	82°17'00"	Avondale	L,C
128	Fort Gordon #3		33°20'45"	82°12'48"	Blythe	L,C
129	Fort Gordon #4		33°19'25"	82°14'38"	Blythe	L,C
130	Proctor and Gamble #2	3531	33°23'22"	82°00'04"	Augusta, West	L,E,C
131	Richmond County OW#1		33°21'44"	81°59'12"	Mechanic Hill	E,N
132	Richmond County OW#2		33°20'49"	81°57'41"	Mechanic Hill	E,N
133	Richmond County OW#3		33°22'12"	81°57'54"	Mechanic Hill	E,N
134	Richmond County OW#4		33°22'18"	81°57'17"	Mechanic Hill	E,N
135	Proctor and Gamble OW#1		33°23'22"	82°00'02"	Augusta, West	L,C
140	Lassiter[3]		33°28'15"	82°06'22"	Augusta, West	3
144	Georgia Power test boring		33°13'07"	81°49'59"	Shell Bluff Landing	L
146	Georgia Power test boring		33°13'03"	81°49'56"	Shell Bluff Landing	L

Data Available Code:
C — Construction Data
E — Electric Log
L — Lithologic Log
N — Nuclear Log

Notes:
1. Well formerly known as Buckeye Cellulose #1.
2. Pine Hill wells are now owned by Richmond County.
3. Information from LeGrand and Furcron (1956, p. 99).

APPENDIX B

Drillers' logs of wells used in the hydrologic cross section (Plate 2).

Well 17 **Buckeye Cellulose (now Archer Daniels Midland)**

DEPTH	LITHOLOGY
0 - 9	Sandy clay
9 - 15	Red sandy clay
15 - 33	Coarse sand and gravel
33 - 36	Gravel and sand
36 - 38	Hard gravel
38 - 53	Medium coarse white sand
53 - 67	Hard sandy yellow clay
67 - 81	Soft sandy yellow clay

Well 25 **Babcock and Wilcox #1**

DEPTH	LITHOLOGY
0 - 20	Interbedded sand and clay
20 - 35	Fine sand
35 - 68	Firm sand with gravel at base
68 - 68	Clay

Well 29 **Babcock and Wilcox #7**

DEPTH	LITHOLOGY
0 - 4	Top soil
4 - 9	Sand and clay
9 - 12	Hard white clay
12 - 22	Medium and fine sand with streaks of clay
22 - 25	Coarse white sand
25 - 32	Gravel
32 - 42	Coarse sand and gravel
42 - 48	Coarse and medium brown sand
48 - 52	Medium and fine brown sand with streaks of clay
52 - 63	Medium and fine brown sand
63 - 72	Yellow and brown clay

Well 48 **Richmond County #13**

DEPTH	LITHOLOGY
0 - 2	Top soil
2 - 5	Brown sandy clay
5 - 14	Mixed sandy clay
14 - 16	White sand and clay
16 - 18	Brown sand and gravel
18 - 22	Mixed clay
22 - 30	Sand and gravel with streaks of clay
30 - 35	Medium white sand and mixed clay
35 - 42	Medium white sand with streaks of clay

Well 48 **Richmond County #13** — continued

42 - 49	Coarse white sand with streaks of clay
49 - 52	Mixed clay
52 - 62	Blue sandy clay
62 - 72	Mixed clay
72 - 93	Brown sand with rock and gravel
93 - 102	Coarse white sand and gravel with streaks of clay
102 - 106	Coarse white sand with streaks of clay
106 - 112	Coarse sand with streaks of hard clay
112 - 119	Coarse white sand and gravel with streaks of clay
119 - 122	Medium white sand
122 - 126	Brown and white coarse sand and gravel

Well 130 **Proctor and Gamble #2**

DEPTH	LITHOLOGY
0 - 1	Fill
1 - 3	Soil
3 - 14	Red clay
14 - 18	Clay with a layer of white sand
18 - 28	White sand
28 - 30	White clay with a streak of sand
30 - 32	Pink clay
32 - 41	White sand
41 - 42	Tight clay
42 - 58	Brown sand with a layer of clay
58 - 71	Brown sand and gravel
71 - 79	Medium tight clay
79 - 95	Medium coarse white sand
95 - 122	Medium tight red clay
122 - 173	Medium coarse sand and gravel
173 - 211	Yellow clay
211 - 230	Yellow clay with a layer of rock
230 - 240	Green weathered rock

Well 77 **Transco #1**

DEPTH	LITHOLOGY
0 - 1	Soil
1 - 10	Yellow clay
10 - 16	Red clay
16 - 20	Yellow sandy clay
20 - 25	Coarse brown sand
25 - 27	White clay
27 - 35	Brown sand with layers of clay
35 - 62	White clay with layers of white sand
62 - 71	White sand with layers of clay

Well 77	Transco #1 — continued
71 - 96	White clay
96 - 109	Coarse white sand and gravel
109 - 117	White clay with layers of sand
117 - 125	Soft white sandy clay
125 - 133	Light clay
133 - 159	Coarse sand and gravel with layers of clay
159 - 168	Tight clay
168 - 202	Soft sandy clay
202 - 219	Brown sandy clay
219 - 251	Coarse sand
251 - 277	Blue clay with layers of rock

Well 79	Transco #3
DEPTH	LITHOLOGY
0 - 1	Soil
1 - 33	Brown sandy clay
33 - 54	Brown sand with layers of white clay
54 - 68	Soft clay
68 - 76	Tight white clay
76 - 98	Soft clay with layers of sand
98 - 103	Fine brown sand
103 - 117	Clay with layers of brown sand
117 - 126	Tight clay
126 - 136	Medium clay with layers of sand
136 - 140	Tight clay
140 - 150	Coarse sand with layers of clay
150 - 168	Tight clay
168 - 195	Coarse sand and gravel
195 - 197	Tight clay
197 - 216	Medium coarse sand with layers of clay
216 - 222	Soft clay with layers of sand
222 - 234	Tight clay
234 - 255	Medium coarse sand
255 - 271	Tight clay and rock

Well 102	Richmond County #102
DEPTH	LITHOLOGY
0 - 1	Top soil
1 - 8	Gray clay
8 - 10	Yellow clay
10 - 18	White and yellow mixed clay
18 - 44	Red sandy clay
44 - 50	Tight red clay
50 - 69	Soft white sandy clay
69 - 84	Tight white clay with streaks of gravel
84 - 96	Soft white sandy clay
96 - 104	Tight clay with streaks of soft sandy clay
104 - 116	Medium coarse sand
116 - 120	Soft sand with streaks of clay
120 - 122	Streaks of sand
122 - 140	Tight red clay with streaks of rock
140 - 146	Soft sandy clay
146 - 168	Loose medium coarse sand

Well 102	Richmond County #102 — continued
168 - 196	Loose coarse sand and gravel
196 - 198	Rock
198 - 222	Coarse sand and gravel
222 - 240	Soft rock with streaks of clay

Well 106	Richmond County #106
DEPTH	LITHOLOGY
0 - 3	Fill
3 - 4	Top soil
4 - 10	Gray clay
10 - 30	Gray sand with streaks of white clay
30 - 68	Coarse brown sand and gravel
68 - 98	Coarse white sand with streaks of clay
98 - 107	Tight white clay
107 - 140	White clay with streaks of sand
140 - 159	Tight red clay
159 - 202	Coarse sand and gravel
202 - 208	Tight white clay
208 - 218	Coarse sand and gravel
218 - 227	Tight white clay with streaks of sand
227 - 252	Coarse sand and gravel
252 - 283	Tight white clay
283 - 306	Tight blue clay and rock

Well 71	Olin Reductone
DEPTH	LITHOLOGY
0 - 1	Top soil
1 - 8	Mixed clay
8 - 10	Coarse brown sand and gravel
10 - 12	Coarse white sand and gravel
12 - 38	Coarse brown and white sand and gravel with streaks of clay
38 - 43	Coarse white sand and gravel with very little clay
43 - 63	Coarse brown and white sand and gravel with very little clay
63 - 106	Coarse and medium white sand with streaks of gray clay
106 - 151	Clay with little white sand
151 - 158	Coarse white sand with very little clay
158 - 182	Mixed clay with little sand
182 - 204	Coarse white sand and gravel with streaks of clay
204 - 219	Mixed clay
219 - 251	Coarse white sand and gravel with streaks of clay
251 - 265	Gray clay with streaks of coarse white sand and gravel
265 - 303	Coarse white sand and gravel with streaks of clay
303 - 314	Coarse white sand, gravel and rock with very little clay
314 - 320	Coarse white sand and gravel with little rock and clay
320	Rock

Well 41 **Continental Forest**

DEPTH	LITHOLOGY
0 - 10	White sandy clay
10 - 20	White clay and sand
20 - 30	White sandy clay
30 - 40	Yellow sandy clay
40 - 50	Clay and sand
50 - 70	Red clay
70 - 80	Mixed clay
80 - 110	White sand and gravel
110 - 160	White sand and gravel with streaks of clay
160 - 170	Coarse white sand
170 - 180	Coarse sand with streaks of clay
180 - 203	Medium coarse sand
203 - 222	Red clay
222 - 242	Coarse sand with little clay
242 - 303	White sandy clay
303 - 324	Mixed clay with streaks of sand
324 - 362	Sandy white clay
362 - 370	Very hard rock

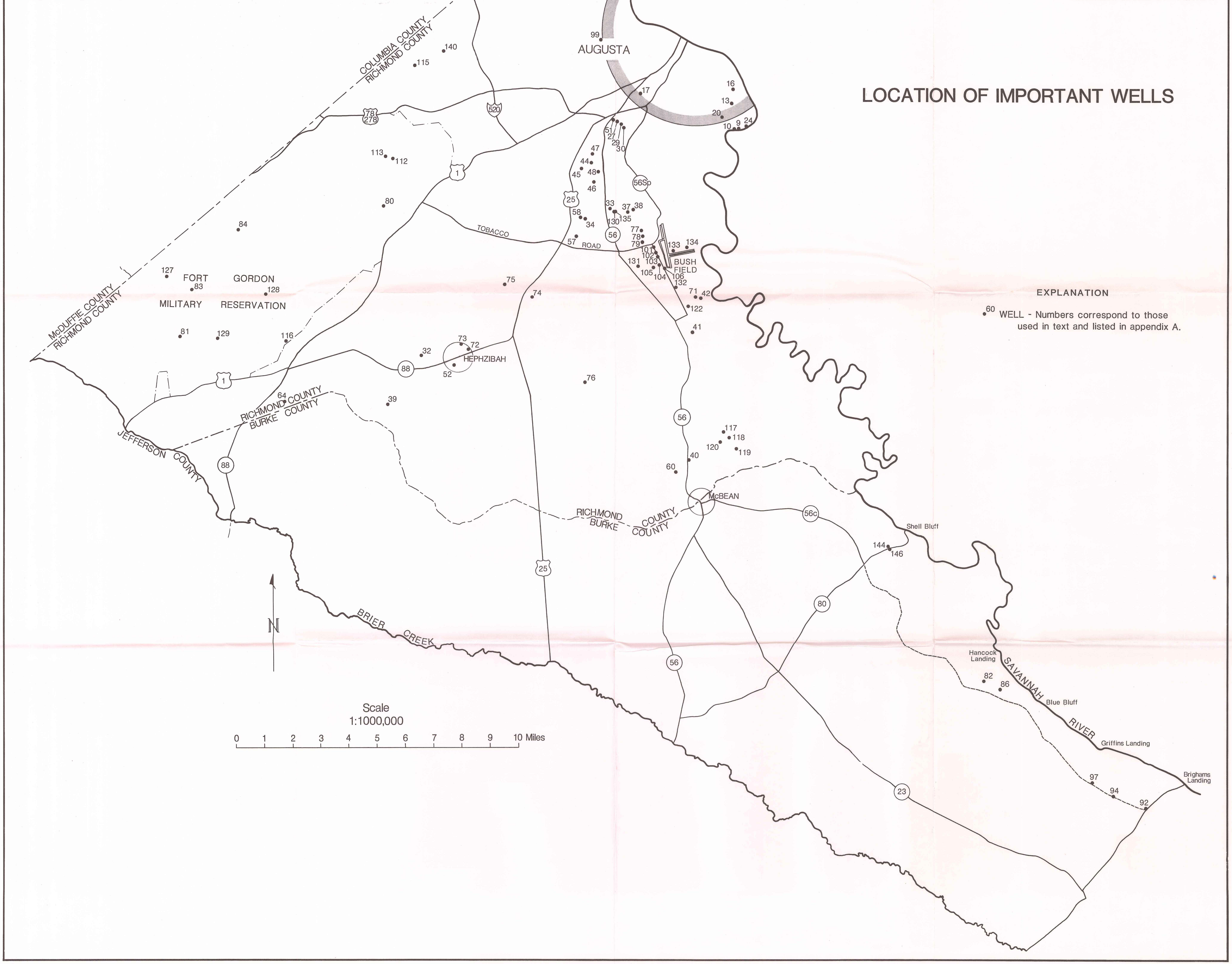
Well 118 **Kimberly Clark Production Well**

DEPTH	LITHOLOGY
0 - 5	Tan sandy clay
5 - 10	Red sandy clay
10 - 22	Red and yellow sandy clay
22 - 40	Tan sand with some clay
40 - 41	Tough sandy clay
41 - 79	Soft yellow clay
79 - 100	Hard sandy clay with streaks of gray sandstone and some shells

Well 118 **Kimberly Clark Production Well — continued**

100 - 140	Softer sandy clay with streaks of gray sandstone and some shells
140 - 162	Tough clay
162 - 184	Sand and soft white clay
184 - 190	Hard black clay
190 - 192	Hard rough rock
192 - 250	Soft gray clay with some sand
250 - 305	Tough red sandy clay
305 - 325	Softer red sandy clay
325 - 350	Soft clay with coarse to fine sand and streaks of white clay
350 - 452	Very soft coarse to fine sand with streaks of clay
452 - 458	Tough clay
458 - 520	Tough white clay with streaks of sand
520 - 555	Soft pink clayey sand with streaks of white clay
555 - 568	Tough white sandy clay
568 - 580	Sand with soft red clay
580 - 581	Soft rock
581 - 595	Tough red sandy clay
595 - 615	Softer sand with red clay streaks
615 - 630	Soft coarse to fine sand
630 - 638	Hard red sandy clay
638 - 642	Hard rock with streaks of clay
642 - 660	Soft red sandy clay
660 - 690	Soft sand and gravel
690 - 692	Rock
692 - 700	Tough rock and sandy clay
700 - 705	Very hard rock

LOCATION OF IMPORTANT WELLS



HYDROGEOLOGIC CROSS SECTION