Geology and Ground Water of the Savannah River Plant And Vicinity South Carolina

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1841

Prepared in cooperation with the U.S. Atomic Energy Commission

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By GEORGE E. SIPLE

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By GEORGE E. SIPLE

ABSTRACT

The area described in this report covers approximately 2,600 square miles in west-central South Carolina and includes the site of the Savannah River Plant, a major production facility of the U.S. Atomic Energy Commission.

The climate, surface drainage, and land forms of the study area are typical of the southern part of the Atlantic Coastal Plain. Precipitation is normally abundant and fairly evenly distributed throughout the year, and the mean annual temperature is moderately warm (64°F). The major streams that drain the area (the Savannah, Salkehatchie, and Edisto Rivers) have low gradients and flow in a southeasterly direction toward the Atlantic Ocean. Surface features of the area include narrow, flat-bottomed, steep-sided valleys and broad gently rolling interfluvial areas. Those parts of the Coastal Plain included within the report area can be subdivided into the Aiken Plateau, the Congaree Sand Hills, and the Coastal Terraces.

The area is underlain by a sequence of unconsolidated and partly consolidated sediments of Late Cretaceous, Tertiary, and Quaternary age. The unconsolidated sediments were deposited unconformably on a basement of igneous and metamorphic rocks of Precambrian and Paleozoic age and sedimentary rocks of Triassic age. The basement rocks are similar to the granite-diorite complex of the Charlotte Belt, the metamorphosed rocks of the Carolina Slate Belt, and the consolidated sediments of the Newark Group. The unconsolidated sediments strike about N. 60° E. and dip 6–20 feet per mile to the southeast. They form a wedge-shaped mass that increases in thickness toward the southeast to slightly more than 1,200 feet in the vicinity of Allendale, S.C., on the southeast or downdip side of the study area.

The oldest or lowermost unconsolidated sedimentary unit, the Tuscaloosa Formation of Late Cretaceous age, is overlain in the subsurface by beds that are also probably Late Cretaceous in age and that herein are named the Ellenton Formation. The Upper Cretaceous deposits are, in turn, overlain by the McBean Formation and the Congaree(?) Formation of middle Eocene age, the Barnwell Formation of late Eocene age, the Hawthorn Formation of early and middle Miocene age, and by fluvial and marine(?) terrace deposits of Pliocene(?), Pleistocene, and Recent age. In the mapped area, the Congaree(?) Formation includes undifferentiated rocks (mostly Congaree and Barnwell Formations and some Mcbean outliers). (See map explanation.) Structurally, the Upper Cretaceous sediments are overlapped to the northwest by Tertiary deposits. A preliminary geologic map of the general area is included in the report.

The principal aquifer in the area is composed of the beds of medium to coarse sand and gravel contained in the Tuscaloosa and Ellenton Formations. Subordinate aquifers include deposits of sand and limestone of Tertiary and Quaternary age.

The ground water in the principal aquifer occurs under water-table conditions in the outcrop area of the Tuscaloosa Formation in the northern and western parts of the study area, but it is under artesian pressure downdip in the southern and eastern parts of the study area. Contours drawn on the piezometric surface of the water in the principal aquifer indicate that water is recharged to the aquifer mainly by leakage through the overlying Tertiary formations. Likewise, the piezometric contours show that the outcrop area of the Tuscaloosa Formation functions chiefly as an area of discharge. Doubtless, water is also discharged from the aquifer by moving downdip to areas near the coast where the prevailing hydraulic gradient may favor the upward leakage of water through the upper confining beds.

The hydraulic properties of the principal aquifer were determined by a series of pumping tests. The results indicate that the aquifer is highly productive and could supply 15 million gallons per day in the vicinity of the Savannah River Plant without exceeding the available drawdown.

Ground water in the Tertiary and Quaternary sediments occurs under water-table conditions in the outcrop area of the formations and under artesian conditions in the downdip areas. Although some beds in the Tertiary-Quaternary sequence are more permeable than the water-bearing zones in the Tuscaloosa Formation, the overall capacity of the Tertiary and Quaternary sequence to yield water to wells is considerably less than that of the Tuscaloosa and Ellenton Formations. Nevertheless, permeable zones in the Tertiary and Quaternary sequence are moderately productive and supply most of the domestic wells and some of the municipal and industrial wells southeast of the belt of outcrop of the Tuscaloosa Formation.

The water obtained from the geologic formations in the study area is of excellent quality and is acceptable for most uses; however, the water from individual formations tends to have a fairly distinct composition. Characteristically, the water from the Tuscaloosa Formation is very low in dissolved solids—less than 100 ppm (parts per million)—and is soft, slightly acidic, and unlikely to contain objectionable amounts of iron. Water from the Ellenton Formation is a calcium sulfate water and is likely to contain objectionable amounts of iron. Water from the Tertiary limestone is moderately hard (50–100 ppm) and contains objectionable amounts of iron. Finally, water from the Tertiary sands is similar to that from the Tuscaloosa Formation, except that the former is generally more acidic and contains slightly higher concentrations of dissolved solids than the latter.

Calculations of the ultimate drawdown to be expected from the area of the Savannah River Plant from the withdrawal of specified amounts of water from specified wells were made by assuming (1) that the aquifer would be recharged through one or more line sources of recharge and (2) that the aquifer would be recharged by vertical leakage through the upper confining beds. Subsequently, the ultimate drawdown computations were compared with actual measurements of drawdown after 5 or more years of operation of the plant. Inasmuch as the second set of computations compared more favorably with the actual measurements than the first, it was concluded that recharge to the principal aquifer is obtained chiefly by vertical leakage.

The disposal of radioactive wastes has had no serious effect on ground water in the report area.

INTRODUCTION

On January 30, 1951, the U.S. Atomic Energy Commission requested the U.S. Geological Survey to make a geologic and hydrologic study of a large plant site on the South Carolina side of the Savannah River below Augusta, Ga. The major objectives of the study were to determine (1) the character of the earth materials beneath the plant site and (2) the availability and quality of ground water for use in constructing and operating the plant.

Accordingly, an investigation of the Savannah River Plant site was begun in February 1951. Less than a year later, in January 1952, the investigation was expanded to include the area that adjoins the site on the north and northwest. The results of this expanded investigation, extended through December 1960, are contained in this report.

PURPOSE AND SCOPE OF THE INVESTIGATION

The purpose of the investigation was to provide the Atomic Energy Commission with a knowledge of the geohydrologic conditions prevalent in this area, into which would be projected the manmade disturbances connected with the construction and operation of a nuclear processing plant (Savannah River Plant). The effect of this disturbance on the natural environment would also be calculated.

The scope of the investigation was to include (1) the preparation of a geologic map of the area north and northwest of the Savannah River Plant; (2) the compilation and evaluation of the unpublished data concerning the geology, hydrology, ground-water chemistry, and water-level fluctuations that have been obtained in the area; (3) the collection of additional data as needed for analysis of the hydrology of the area; and (4) a determination of the adequacy of the ground-water supply for use by the Savannah River Plant and communities surrounding the plant reservation.

LOCATION OF THE AREA

The area described in this report (fig. 1) includes most of Aiken, all of Barnwell, and the northern part of Allendale Counties, S.C. It is bounded on the southwest by the Savannah River, on the northwest by the Aiken-Edgefield County line, and on the northeast by the North Fork Edisto River. The east boundary of the report area coincides with the east boundaries of Barnwell and Allendale Counties, and the south boundary is represented by lat 33° N. which passes through central Allendale County. The report area, approximately 2,600 square miles, includes the site of the Savannah River Plant, or SRP as it will hereinafter be designated in this report.

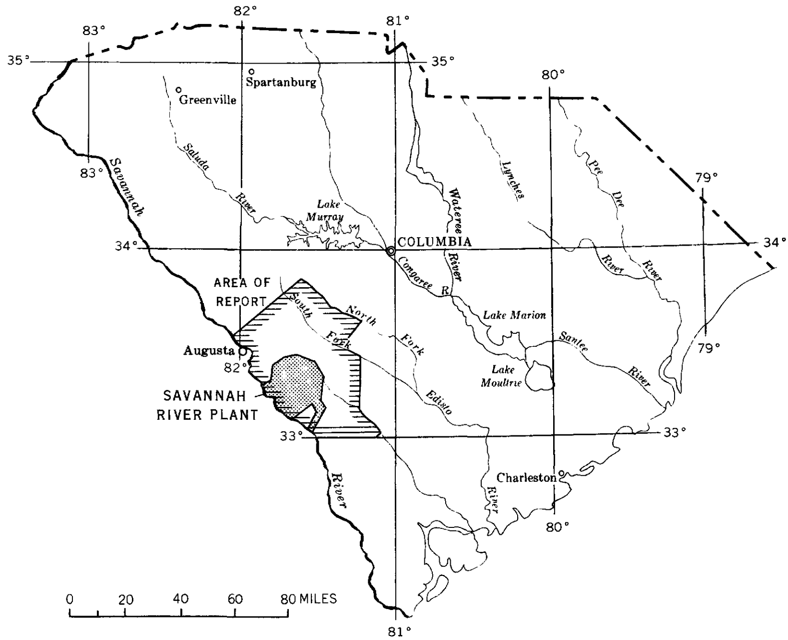

FIGURE 1.—Index map of South Carolina showing location of area studied.

PREVIOUS INVESTIGATIONS

The geology of the report area has been described to some extent in a few earlier reports. In 1848 a report on the geology of South Carolina was published (Tuomey, 1848) in which references were made to certain localities in the report area. In addition, the reports of Dall (1898), Sloan (1908), Veatch and Stephenson (1911), Cooke (1936), Lang (1940), and Siple (1946) contain references to the local geology and stratigraphy or to fossils found in the surficial formations of the report area.

The geology of the contiguous area in Georgia on the west bank of the Savannah River has been described by Veatch and Stephenson (1911), Cooke (1943), Cooke and Shearer (1918), MacNeil (1947), Eargle (1955), and LeGrand and Furcron (1956).

Very little information was available on the occurrence of ground water in the report area prior to the present investigation. General references to the quantity or quality of ground water in the area are included in the reports of Tuomey (1848), Glenn (1905), and Darton (1896). Cooke's (1936) report on the geology of the Coastal Plain of South Carolina included well data and chemical analyses of water samples from 21 wells and springs in Aiken and Barnwell Counties. Geologic and hydrologic data on the deeper wells in Aiken, Barnwell, and Allendale Counties and chemical analyses of water samples from wells and springs within these counties were published in Bulletin 15 of the South Carolina Research, Planning, and Development Board (Siple, 1946).

In connection with the location and construction of the SRP, the U.S. Army Corps of Engineers (1952) issued a report on the geology of the site and the load-bearing characteristics of the soil column.

A discussion of the piezometric surface of the principal sand aquifer (Tuscaloosa Formation) was given by Siple (1960).

PERSONNEL AND ACKNOWLEDGMENTS

This investigation was made under the general supervision of A. N. Sayre, former chief, Ground Water Branch, and C. V. Theis, staff scientist, Water Resources Division, U.S. Geological Survey. Much of the original well-inventory and water-level measurements inside the SRP site were made by R. W. Jones of the Ground Water Branch. Mr. Jones also assisted along with other personnel in the South Carolina district in the preliminary drafting of the illustrations in this report. The water-level data from wells on the Georgia side of the Savannah River were obtained by H. E. LeGrand and S. M. Herrick in connection with their ground-water studies in east Georgia which have been published (LeGrand and Furcron, 1956). H. H. Cooper, Jr., assisted in the analysis and interpretations involved in in estimating the potential yields of wells within the SRP.

The author wishes to express his appreciation to G. H. Giboney and K. E. Herde, of the Atomic Energy Commission, SRP, who provided cooperative assistance during the course of the investigation. G. E. Olsen, project engineer, Corps of Engineers, and his staff at the Ellenton, S.C., office assisted in the collection of data and constructed the elevated recorder shelter for observation well S–411. Several employees of E. I. du Pont de Nemours & Co., the SRP prime contractor, also contributed information on well construction and ground-water pumpage in specific areas. Various local well drillers, municipal water superintendents, and residents of the area provided additional helpful information.

WELL-NUMBERING SYSTEM

Wells that existed in the SRP area before it was acquired by the Atomic Energy Commission were numbered serially by county—that is, AK–21 designated the 21st well inventoried in Aiken County. After the area was acquired by the Commission, all preexisting wells inventoried were designated in consecutive order with the prefix "S". Thus S–215 refers to a domestic or industrial well inside the project area which was scheduled after the acquisition of the area by the

Commission. All other wells drilled subsequently and not otherwise designated are also identified with an "S" prefix. The water-supply wells that were drilled inside the SRP area are numbered serially in the order of drilling. The serial number is suffixed by a capital letter to denote the process area within which the well is located; 45–H represents the 45th water-supply well drilled within the project area, and the well is in the H area. Wells inventoried outside the project area are prefixed by capital letter symbols numbered for the county in which they occur and are numbered consecutively by counties. Well BW–44 is the 44th well inventoried in Barnwell County, and AK–222 is the 222d well inventoried in Aiken County.

Observation wells drilled by the Corps of Engineers and referred to by the Corps as piezometers have numbers prefixed by an uppercase letter which identifies the area within the SRP in which they are located. An exception is the group of wells in and around the F and H areas that have the serial prefix "Z" or "ZW."

Shallow wells drilled at the barricades on the highways leading into the SRP have the suffix "G" placed after the number. Thus, 3G, 6G, and 7G, for example, identify these wells.

The locations of all the wells that were inventoried during the present investigation except the Corps of Engineers' piezometers are shown on plate 1.

CLIMATE

The climate of the report area is typical of the southeastern section of the United States—summers are long and hot and winters are short and wet. According to the records of the U.S. Weather Bureau, the mean annual temperature at Augusta, Ga., on the west edge of the report area is 62.4°F for the 86-year period ending in 1960. It should be noted, however, that the average daily temperature normally ranges from 70.1° to 91.9°F in July, the hottest month, and from 35.6° to 59.2°F in January, the coldest month. Moreover, in the 86 years of observation at Augusta, Ga., the extreme range in temperature was from 3° to 106°F. The temperature data for Augusta, Ga., as compared with similar data for Aiken and Blackville, S.C., is as follows:

Station	Years of record	Number of years of record	Average daily maximum	Average daily minimum	Mean annual
Augusta	1875–1960	86	74.3°F	50.5°F	62.4°F
Aiken	1864–1960	97	74.1°F	52.2°F	63.2°F
Blackville	1884–1960	77	74.5°F	50.6°F	62.6°F

Precipitation in the report area is normally abundant and fairly evenly distributed throughout the year. Nevertheless, it is subject to considerable variation on an annual and monthly basis. Table 1 contains information on the total annual precipitation as recorded at four stations in or near the report area during the 40-year period ending in 1960. According to these data, the lowest annual precipitation in the report area occurred at Aiken, S.C., where 22.38 inches was recorded in 1931. The highest annual precipitation occurred at Augusta, Ga., where 73.82 inches was recorded in 1929.

Normal monthly precipitation at Augusta, Ga., ranges from 2.44 inches in October to 5.21 inches in March. In the period 1921–50, the maximum precipitation recorded in any one month at the Augusta weather station was 14.00 inches; at least a trace of precipitation fell every month.

From the precipitation departures recorded for Augusta, Ga., in Table 1, and from the reflected changes measured in water levels in wells, the period 1954–58 was characterized as a drought period or one of less than normal rainfall over the greater part of the State.

GEOMORPHOLOGY

SURFACE DRAINAGE

There are three major surface drainage basins in the report area. About two-thirds of the area, including the southwestern parts of Aiken and Barnwell Counties and the western part of Allendale County, is drained by the Savannah River and its local tributaries (pl. 1). The Savannah River, an extended consequent stream, flows southeastward from its point of origin at the junction of the Tugaloo and Seneca Rivers (about 80–90 miles upstream from the report area) to the Atlantic Ocean, a distance of about 200 miles. Throughout its length, the Savannah River constitutes the boundary between Georgia and South Carolina, and it identifies the southwest margin of the report area. Downstream from Augusta, the river, in a stage of early to middle maturity, meanders across a belt 4–5 miles wide. The gradient of the stream is very low, only about 1 foot per mile in the vicinity of the SRP.

The principal tributaries to the Savannah River in the report area, in a downstream direction are: Horse Creek, Holley Creek, Upper Three Runs, Fourmile Creek, Pen Branch, Steel Creek, and Lower Three Runs (pl. 1). All these tributaries flow in a southwesterly direction almost at right angles to the direction of flow of the main river channel, and thus they represent subsequent stream drainage to the principal consequent stream, the Savannah River. The longest tributary, Upper Three Runs, drains most of that part of the SRP in Aiken County.

TABLE 1.—*Precipitation, in inches, at four stations in or near Aiken and Barnwell Counties, S.C.*

[Data for Augusta, Aiken, and Blackville from U.S. Weather Bureau; data for SRP from E. I. du Pont de Nemours & Co.]

Year	Augusta, Ga.		Aiken, S.C.		Blackville, S.C.		SRP	
	Total annual precipitation (inches)	Departure from normal [1] (inches)	Total annual precipitation (inches)	Departure from normal [1] (inches)	Total annual precipitation (inches)	Departure from normal [1] (inches)	Total annual precipitation (inches)	Departure from temporary mean (1951–60)
1921	34.29	−8.88	36.02	−6.48	35.44	−8.02		
1922	49.60	6.43	57.30	14.80	47.60	4.14		
1923	44.14	−.97	42.02	−.48	46.99	3.53		
1924	49.06	5.89	54.31	11.81	52.92	9.46		
1925	34.68	−8.49	34.52	−7.98	33.96	−9.50		
1926	38.78	−4.39	46.04	3.54	52.43	8.97		
1927	38.53	−4.64	35.23	−7.27	42.15	−1.31		
1928	50.80	7.63	63.88	21.38	61.07	17.61		
1929	73.82	30.65	67.11	24.61	50.35	6.89		
1930	39.10	−4.07	32.07	−10.43	46.57	3.11		
1931	28.18	−15.05	22.38	−20.12	28.05	−15.41		
1932	42.47	.90	47.22	4.72	49.42	5.96		
1933	28.05	−15.12	24.65	−17.85	32.45	−11.01		
1934	37.55	−5.62	44.09	1.59	51.83	8.37		
1935	39.04	−4.13	35.77	−6.73	42.96	−.50		
1936	50.89	7.72	55.92	13.42	47.33	3.87		
1937	39.71	−3.46	41.57	−.93	49.66	6.20		
1938	39.74	−3.43	40.27	−2.23	41.30	−2.16		
1939	40.81	−2.36	53.07	10.57	36.33	−7.13		
1940	39.73	−3.44	38.82	−3.68	42.07	−1.39		
1941	39.32	−3.85	46.10	3.60	46.67	3.21		
1942	46.52	3.35	51.00	8.50	42.72	−.74		
1943	39.17	−4.00	38.64	−3.86	40.76	−2.70		
1944	40.27	−2.90	45.07	2.57	44.56	1.10		
1945	39.23	−3.94	45.36	2.86				
1946	35.35	−7.82	44.35	1.85	48.97	5.51		
1947	57.34	14.17	55.39	12.89	50.45	6.99		
1948	58.78	15.61	67.13	24.63				
1949	41.83	−1.34	42.58	.08				
1950	42.11	−1.06						
1951	33.73	−9.44	31.72	−10.78	42.99	−.47	38.79	−4.65
1952	40.09	−3.08	35.13	−7.37	46.19	2.73	46.59	3.15
1953	44.00	1.60	50.35	7.85	48.56	5.10	49.72	6.28
1954	31.53	−11.64	28.63	−13.87	27.85	−15.61	28.80	−14.64
1955	34.05	−9.12	39.10	−3.40	45.40	1.94	40.12	−3.32
1956	32.85	−10.32	45.50	3.00	41.55	−1.91	40.22	−3.22
1957	41.32	−1.85	46.69	4.19	45.13	1.67	48.64	5.20
1958	36.84	−6.33	40.72	−1.78	47.44	3.98	38.34	−5.10
1959	49.47	6.30	60.52	18.02	63.02	19.56	59.75	16.31
1960	45.71	2.54	46.32	3.82	43.38	−0.08	46.82	1.98

[1] Base period, 1921–50.

The report area in northern Aiken and Barnwell Counties is drained by the North and South Forks Edisto River (pl. 1). Like the Savannah River, the North and South Forks Edisto River flow southeastward to the Atlantic Ocean, but unlike the Savannah River, the North and South Forks rise in the Coastal Plain. The flow of the South Fork is considerably enlarged within the report area by Shaw Creek, which carries much of the surface drainage from north-central Aiken County. The water in the North and South Forks Edisto River is locally termed "black" because, like most streams that originate in the Coastal Plain, it is discolored by organic matter. In contrast, streams such as the Savannah River, which rise in the Piedmont or mountain provinces, generally have a red or brown discoloration, due to the presence of colloidal or suspended particles washed in from decomposed crystalline rock.

The report area in southeastern Barnwell County is drained by the headwaters of the Salkehatchie River. The Salkehatchie River also flows southeastward. Water in the Salkehatchie River also is black due to its content of organic matter.

LANDFORMS

Landforms of the report area include those normally present along the inland margin of the Atlantic Coastal Plain, adjacent to the Piedmont province, along with others found normally farther down this plain and closer to the coast. The relatively soft sediments of the Coastal Plain are more easily eroded than the hard crystalline rocks of the adjoining Piedmont. Hence, the general level of the Coastal Plain is lower than that of the Piedmont, and for this reason, the boundary between the two provinces is commonly referred to as the Fall Line. Actually the Fall Line is not a sharp line of contact but a morvan or zone of transition from the typical land forms of one province to those of the other. The position of the Fall Line coincides approximately with the northwest boundary of Aiken County, and therefore with the northwest boundary of the report area. Thus the report area is wholly within the Atlantic Coastal Plain.

The major physiographic divisions of the Coastal Plain within this area are subdivided into the Aiken Plateau, the Congaree Sand Hills, and the Coastal Terraces (fig. 2).

AIKEN PLATEAU

The Aiken Plateau (see Cooke, 1936, p. 9) lies between the Savannah and Congaree Rivers and extends southeastward from the Fall Line (northwest boundary of Aiken County) to the inland margin of the coastal terraces (fig. 2). The surface of the plateau is highly dissected, and is characterized by broad interfluvial areas and relatively narrow steep-sided valleys. The interfluvial areas represent an upland plain that slopes gently to the southeast. Its altitude on the northwest edge is about 650 feet above mean sea level, and the slope to the southeast is about 8 feet per mile. Streams draining the upland have cut steep-sided valleys on the plateau and have left a relief of as much as 300 feet in some areas.

The plateau is underlain by deposits of Eocene, and possibly of Miocene age; it represents a constructional landform of the second order, formed during the later stages of this period.

Although most of the upland area is well drained, poorly drained sinks or depressions are fairly numerous, particularly in those areas underlain by calcareous beds. Many of the smaller depressions repre-

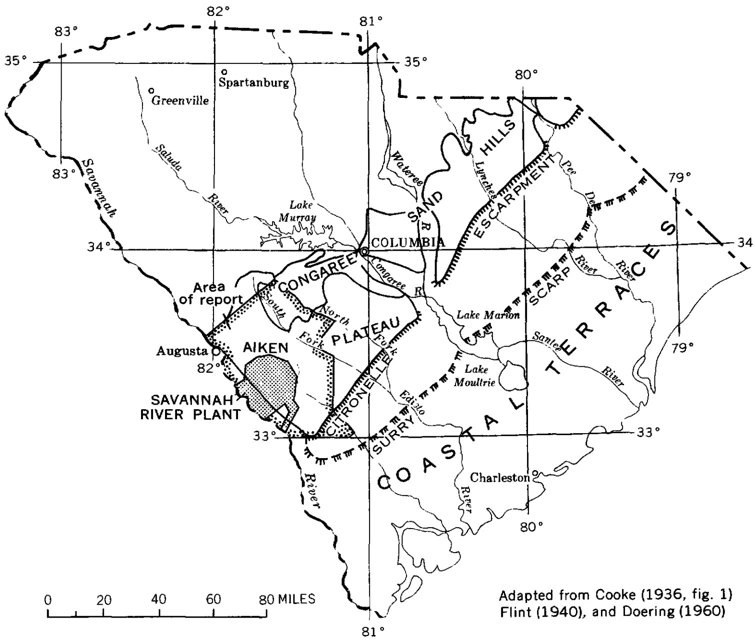

FIGURE 2.—Map of South Carolina showing location of the report area in relation to the physiographic divisions of the Atlantic Coastal Plain.

sent solution depressions or sinks and have an irregular or circular outline, typical of solution sinks formed elsewhere.

Carolina bays.—Whereas many depressions throughout the lower part of the area are of the sinkhole variety, others have the characteristic or identifying features of the "Carolina bay," described from areas farther east on the Coastal Plain (Glenn, 1895; Cooke, 1933, 1954; Melton and Schriever, 1933). These depressions in the report area have a nearly elliptical or ovate shape. Their major axes are alined closer to a north-south direction (N. 14°–N. 18° W.), whereas the axis of the typical Carolina bay as it occurs farther east in Dillon, Marion, and Horry Counties is alined approximately N. 45° W. Moreover, the elliptical outlines of the larger depressions in the report area have been flattened on the north rim and thus have a pear-shaped or triangular perimeter. The major axes of many of the larger bays range from about 2,000 to 4,000 feet in length although that of the large bay in the vicinity of Dunbarton exceeds 6,000 feet. There are only about 12 such bays in the area above the Citronelle Escarpment of Doering (1958, 1960). This escarpment marks the southeast edge of the Aiken Plateau. The smaller bays are much more numerous and have axes ranging from less than 100 feet to several hundred feet in length.

The geometry of the bay structure here deviates somewhat from that described by Cooke (1954, p. 198) for the ideal shape of a precessing eddy in that the ratio of minor axis length to major axis length ranges from about 0.72 to 0.83, whereas the cosine of the latitude (φ) ranges from 0.84 to 0.85. The major axes deviate from true north by an angle (α) that ranges from 14° to 18° and whose cotangent ranges from 4.01 to 3.08. This deviation makes an even wider disparity for this value from that of the ideal shape of the eddy (that is, $\cos \varphi \neq \cot \alpha$). Nevertheless, it appears possible that this particular divergence from an ideal geometric value can be explained by the more detailed analysis of the specific cosmic forces involved. This analysis will not be attempted here, but these forces appear to represent a very plausible explanation for the exterior shape of the bay.

Detailed test borings drilled along the major and minor axes of the typical Carolina bay near the R area, SRP, by the U.S. Army Corps of Engineers indicated (Shockley and others, 1956, p. 115) a collapse structure in the center of the bay caused by solution of calcareous material near the base of the McBean Formation. Beneath the rim of the bay the same calcareous zone was found to be more cavernous than at the center. This fact indicates a less advanced or precollapse stage of solution activity in the tubular calcareous sand at the rim.

In fact, the true Carolina bay as found here or elsewhere on the South Carolina Coastal Plain is restricted to terrane in which the bay structure overlies soluble calcareous deposits. These underlying deposits, identifiable as calcium carbonate mixtures of limestone, marl, calcareous sand, and sandy shell hash of Eocene to Miocene and possibly Pliocene age, are either present now in the subsurface or else are indicated as having been present at some previous time and subsequently removed by solution. The relict calcareous beds are recognized by the nature and structure of the residual material and by the composition of circulating ground waters. Many of the bays, under which the underlying soluble material is now almost completely removed, are in the topographically high areas of the Tertiary overlap, adjacent to the Fall Line. One example is shown on the North Augusta (7½ minute) topographic map near the intersection of U.S. Highway 25 and Interstate Highway 20. The major axis of this bay is alined almost N. 14° W., and the altitude is about 480 feet above mean sea level. On the southern and southeastern boundaries of the report area, Carolina bays overlie the McBean Formation at altitudes as low as 140 feet above mean sea level (on the surface of the Ellenton plain). Intensive development of the Carolina bays begins just south-

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east of the Aiken Plateau Escarpment near Allendale. Between this scarp and the Surry Scarp, near the northwest margin of the Coastal Terraces, extensive limestone deposits of Jackson(?) and Claiborne age (Santee Limestone) occur beneath a thin mantle of younger sand and clay.

Many hypotheses have been advanced for the origin of the typical bay type of undrained depression (Melton and Schriever, 1933; Cooke, 1940, 1954; Johnson, 1942; LeGrand, 1953; Schriever, 1951, 1955). To date, none of the proposed hypotheses appear to satisfy all the conditions surrounding their occurrence. The writer favors a complex or at least dual explanation in which the depression originated with a subsidence following solution of the underlying calcareous material (whether it be limestone, marl, or shell mixed with sand). The significant word here is sand; because as the writer has indicated previously (Siple, 1960b) a large proportion of the bays, particularly those found seaward of the Citronelle or Orangeburg Escarpment, are underlain by late Miocene deposits consisting largely of shell hash and sand. The creation of voids in the subsurface which would ultimately result in subsidence and the formation of a depression at ground level could thus be brought about either by solution of the calcareous material in this subsurface mixture or, in the case of some of the Late Cretaceous deposits, removal of the fine sands, leaving the coarser grains in a bridged or unstable condition. Subsequent readjustment of these grains (by natural or manmade ground-water movement) to a more stable arrangement would then result in a decrease of void space followed by collapsed structures and the formation of a surface depression. The latter condition applies more specifically to those areas in the eastern part of the State on the left flank of the Cape Fear Arch where fine to coarse sands of Late Cretaceous age occur at comparatively shallow depths. The collapse of the overlying beds might be precipitated or advanced by the loading pressure of the transgressing sea and (or) its accompanying pulsating tidal motion. Between this stage and the regression of the sea, or subsequently when the depression is still filled with water, the outline of the bay may have been shaped by a precessing eddy under the impetus of the earth's rotational motion.

As yet undescribed is the connection, if any, between these depressions and the presence of bubbling springs, which occur chiefly in the Aiken Plateau area in conjunction with the undrained depressions. Moreover, the bubbling springs are closely related to blowing wells, which occur in the same geologic and geomorphic environment as the undrained depressions, namely on the dissected plateau underlain by Tertiary sediments. Presumably, there is more to the relations among these features than the coincidence of their occurrence in the same area. In all likelihood, the bubbling springs and flowing wells are caused by the entrapment of air in voids within or beneath beds of indurated sandstone or coquina in the sequence of Tertiary sediments.

CONGAREE SAND HILLS

The Congaree Sand Hills adjoin the Aiken Plateau on the north and west and extend northeastward into North Carolina (fig. 2). The sand hills adjoin the coastal terraces on the southeast and are characterized by long gentle slopes and rounded summits. According to Cooke (1936, p. 11), wind action seems to have had considerable effect in shaping the contours of the land in places where the soil consists of loose sand. In South Carolina the typical sandhill topography is interrupted by the valleys of the major streams and their tributaries.

COASTAL TERRACES

The coastal terraces section extends from the outer or shoreward margin of the Aiken Plateau to the Atlantic coast, a distance of 80–90 miles. The section includes the lowland along the Savannah River. As the name implies, terraces—either alluvial or marine—are the characteristic feature of the area. According to Cooke (1936, p. 6), the coastal terraces mark the position of seven former stands of the sea during which waves cut into the headlands and built offshore bars.

The seven coastal terraces and their altitudes are as follows: Pamlico, 25 feet; Talbot, 42 feet; Penholoway, 70 feet; Wicomico, 100 feet; Sunderland, 170 feet; Coharie, 215 feet; and Hazlehurst, 270 feet. The highest four terraces were indicated by Cooke as present in the report area.

Objections have been raised to the designation of the higher (above 100 ft) terraces as marine features of Pleistocene age. The highest Pleistocene shore feature recognized by Flint (1940, p. 772) is the Surry Scarp, or strandline, which he indicated as extending through South Carolina at about 90–100 feet above the present sea level, but which in Georgia occurs at altitudes as high as 160 feet. A terrace toe or scarp beginning at about 100–110 feet altitude is recognizable in the Savannah River flood plain near Ellenton and is possibly equivalent to the Surry strandline. The plain to the northeast is equivalent in altitude to the Sunderland terrace of Cooke (1936, p. 6). Among geologists working in the area, this terrace is referred to locally as the Ellenton plain. The toe of another recognizable terrace occurs at about 160 feet, at the base of the Aiken Plateau, and it is probably equivalent to the Citronelle (or Orangeburg) Escarpment of Doering (1958, 1960) or the Coharie terrace of Cooke (1936, p. 6).

The two scarps (Surry and Orangeburg) are here separated by a very short distance (about 2 miles or less), owing to the deeply embayed estuary of the Savannah River during Pliocene(?)-Pleistocene time. Flint (1940, p. 772) considered the Surry Scarp to be discontinuous where the major streams crossed the Coastal Plain, and he suggested that a fanlike fluvial plain extended through the 90-foot contour in these areas.

ASYMMETRY OF STREAM VALLEYS

Several stream valleys in the area are asymmetric in transverse profile. For example, the Savannah River valley commonly has an escarpment on the southwest side and a gentle slope on the northeast side. Inasmuch as the river flows parallel to the regional dip of the underlying formations, the asymmetric downcutting of the valley by the Savannah River is not the result of rock structure. It might be the result, however, of rotational deflection in conformance with Ferrel's law, (Ferrel, 1859) which states that moving bodies in the Northern Hemisphere are deflected to the right. Similar asymmetric profiles prevail in the valleys of other southeastward-flowing streams including Shaw Creek and, to a lesser exent, the South Fork Edisto River.

The asymmetry of the Savannah River Valley has apparently favored greater development of tributaries on the gently sloping northeast side of the main valley, as for example such large tributaries as Horse Creek, Upper Three Runs, and Lower Three Runs. In these stream valleys the asymmetry might be related to structure, inasmuch as the steep banks occur on the southeast side of the stream and progress in the direction of regional dip. Where the asymmetry is related to structure the stream divides tend to migrate in the direction of dip in accordance with the law of monoclinal shifting (Salisbury, 1898). An example of such a valley is that of the Upper Three Runs, in which the stream flows almost parallel to the strike of the underlying formation and cuts a steep slope on the southeast and a gentle slope on the northwest bank. The formation of this profile is accented by the undersapping, on the downdip side, of a loosely compacted bed of fine sand. A similar profile is found in the valley of Lower Three Runs, but the asymmetry of this valley is probably brought about as much by differential erosion as by structure. The valley of Horse Creek in western Aiken County does not exhibit marked asymmetry. The creek has formed as a subsequent stream in the outcrop area of the Tuscaloosa Formation in a position nearly parallel to the strike.

GROUND-WATER GEOLOGY

Ground water is defined as that part of the water beneath the land surface that is free to move by gravity. It occurs in the zone of saturation, in which all the interconnected openings or pores in the rocks of the earth's crust are filled with water under hydrostatic pressure. The top of the zone of saturation is the water table, except where that surface is formed by impermeable material. The number, size, and shape of the rock openings and the degree of their interconnection determine the amount of water that can be stored in the openings and the effectiveness of any saturated rock material to yield water to wells. A rock material that yields sufficient water to wells to make it an economic source of supply is called an aquifer. Rock formations that are adjacent to but less permeable than aquifers are called confining beds, because they tend to restrict or retard the movement of ground water.

Within the zone of saturation, ground water occurs under either water-table or artesian conditions. Under water-table conditions the ground water is not confined, and the upper surface of the saturated zone is free to rise and fall. Under artesian conditions the ground water is confined between an upper and lower confining bed, and the piezometric surface of the aquifer is above the top of the aquifer. If the artesian reservoir is penetrated by a well, the water rises in the well above the bottom of the upper confining bed. The piezometric surface is an imaginary surface that coincides with the level to which the confined water rises in wells.

The area described in this report is underlain by a sequence of unconsolidated and partly consolidated sediments of Cretaceous, Tertiary, and Quaternary ages. These materials were deposited on an eroded basement of highly indurated igneous and metamorphic rocks of Precambrian(?) and Paleozoic ages and consolidated sedimentary rocks of Triassic age. Table 2 summarizes the stratigraphic and age relations, lithology, and water-bearing character of the geologic formations that occur in the area.

Geology of the report area is shown on plate 1 for parts of Aiken and Barnwell Counties. The map shows the outcrop areas of the individual formations except in the area north of the SRP proper where the Tertiary sediments have not been differentiated because they are thin, lithologically similar, sparsely fossiliferous, and hence difficult to identify as separate stratigraphic units.

The subsurface geology as determined from wells in Aiken and Barnwell Counties is shown in figure 3 and plates 2 and 3. Figure 3 shows the sequence and character of the beds penetrated by well 55–P in the central part of the report area. Plate 2 shows the areal

TABLE 2.—*Stratigraphic units in the vicinity of Aiken and Barnwell Counties, S.C.*

System	Series		Formation	Description and water-bearing characteristics
Quaternary to Tertiary	Recent to Pliocene		Recent alluvium Wicomico Formation; Sunderland Formation; Coharie Formation; Hazlehurst Formation	Alluvial fill and terrace deposits in stream valleys, consisting of tan to gray sand, clay, silt, and gravel; blanket deposits of coarse gravel on higher terraces; of minor importance as aquifers.
Tertiary	Miocene		Hawthorn Formation	Tan, red, and purple sandy clay, interbedded lenses of gravel and numerous clastic dikes. Small to moderate amounts of ground water.
	Eocene	Jackson age	Barnwell Formation	Red, brown, yellow, and buff fine to coarse massive to crossbedded sand and sandy clay. Ground water available in limited quantities, sufficient for domestic use.
		Claiborne age	McBean Formation and Congaree(?) Formation	Yellow-brown to green fine to coarse glauconitic quartz sand, interbedded with green, red, yellow and tan clay, sandy marl or limestone, and lenses of siliceous limestone. Ground-water supply moderate to large; sufficient for varied municipal and industrial use. Quality likely to be harder than other ground water with possibility of a high iron content.
Cretaceous(?)	Upper		Ellenton Formation	Dark-gray to black sandy lignitic micaceous clay containing disseminated crystals of gypsum. Medium- to dark-gray coarse sand and gravel. Yields moderately large to large amounts of water to wells. Water generally moderately high in sulfate and quite high in iron content.
Cretaceous	Upper		Tuscaloosa Formation	Tan, buff, red, and white crossbedded micaceous quartzitic and arkosic sand and gravel, interbedded with red, brown, and purple clay and white kaolin. Large supplies of ground water available with a yield of as much as 2,000 gpm from 8- to 12-inch gravel-pack wells. Water is soft and low in total solids; likely to be corrosive to metals.
Triassic	Upper		Newark(?) Group	Gray, dark-brown, and brick-red sandstone, siltstone, graywacke, and claystone with included sections of fanglomerate or conglomerate containing gray calcareous pebbles. Rocks identified in only one well and areal extent unknown. Water circulates very slowly through well and low yields are typical of this type rock in other areas.
Paleozoic and Precambrian(?)			Basement rock of the Carolina Slate Belt and Charlotte Belt	Granite, gneiss, chlorite-hornblende, and chlorite-tremolite schist, slate, and volcanic rocks. Yields small supplies of ground water. The water in the granitic rocks is generally soft and low in dissolved solids; in mafic rocks it is likely to be harder and more mineralized.

extent and stratigraphic relations of the formations that underlie the report area. Plate 3 shows the geologic structure of the formational units along cross section *A–A′* as shown on plate 1.

Each of the stratigraphic units listed in table 2 is capable of yielding some water to wells because each contains one or more zones that are moderately to highly permeable. The units, parts of units, or combinations of units that are sufficiently permeable to produce adequate supplies of water for municipal and industrial needs constitute the major aquifers in the area. The remaining parts of the stratigraphic sequence constitute the confining beds or aquicludes; they serve to restrict or at best retard the local movement of ground water.

By application of the above reasoning, the stratigraphic sequence given in table 2 can be subdivided into several aquifers and aquicludes. On the following pages of this report, the geologic character and water-bearing properties of the formational units are described in order from oldest to youngest.

BASEMENT ROCKS

CHARACTER AND EXTENT

The basement rock ranges in age from Triassic to Paleozoic to Precambrian(?). The older rocks consist of granitic intrusive rocks and a granite-diorite injection complex generally referred to as the Charlotte Belt (King, 1955). Included also are rocks of the Carolina Slate Belt which comprise metamorphosed sedimentary rocks and associated volcanic rocks such as tuff, rhyolite, andesite, and breccia.

The rocks of the Carolina Slate Belt are coextensive with the eastern part of the Little River Series of Peyton and Cofer (1950), a series of intercalated volcanic and sedimentary rocks exposed along Little River in Georgia. The Triassic rocks include sandstone, siltstone, and graywacke.

The basement rock is exposed beneath the Tuscaloosa Formation in the northern tributaries of Horse Creek and in the northern reaches of Shaw Creek and in Horse Creek (pl. 1). A typical exposure of the weathered schistose rocks is shown in figure 4. Because the altitudes of the separate exposures range from 170 feet in the area north and west of Horse Creek to 460 feet in the northern reaches of Shaw Creek, the exposures of the basement rock in Aiken County appear to be "windows" in the sedimentary cover rather than residual hills or upward protrusions of the basement rock.

At least two periods of granitic intrusion, or granitization, were thought to be represented by the granitic rocks in the Piedmont. The first period of intrusion was considered to have taken place in Precambrian time, and the other in late Paleozoic time. However, the results obtained from radioactive (potassium-argon and uranium-lead) methods of rock dating (Eckelmann and Kulp, 1957; Stose and Stose, 1949) indicate that a large part of the granitic rocks formerly

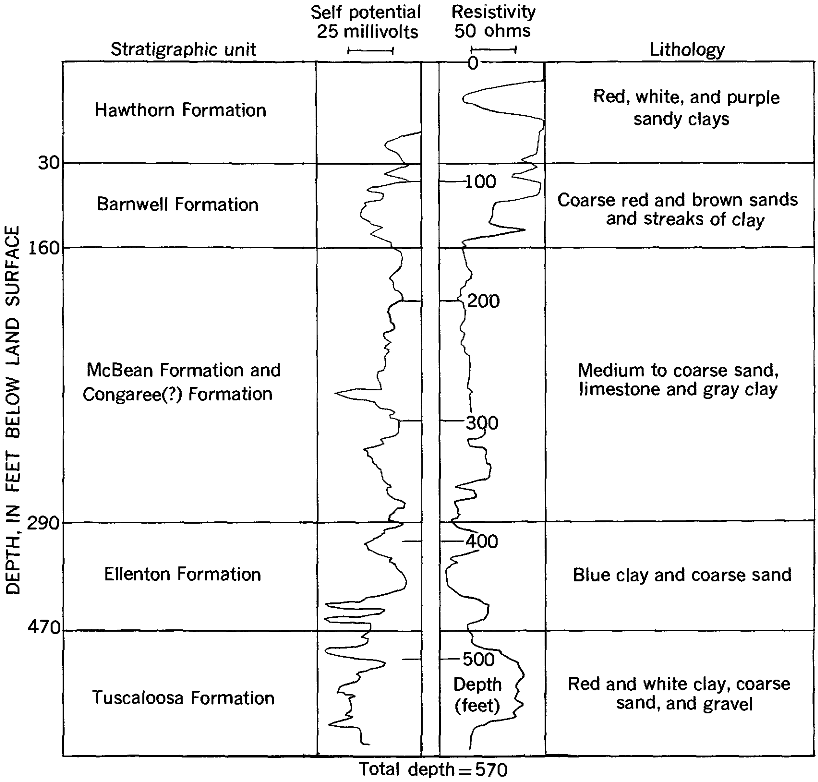

FIGURE 3.—Stratigraphic interpretation of electric and lithologic logs of well 55–P in the Savannah River Plant.

thought to be Precambrian in age (Watson, 1911) are more probably Paleozoic in age.

Well 35–H, near the Aiken-Barnwell County line, was cored into the basement rock, and the surface of the crystalline basement was logged at an altitude of 696 feet below sea level. The rock section cored could be described generally as a dark green to greenish gray fine-grained chlorite-hornblende schist that has numerous healed fractures containing secondary calcite and zeolite. From a core taken at an altitude of 733 feet below sea level, a thin section was prepared and described by Anastasia Van Burkalow for the U.S. Army Engineers (written commun., 1952). Van Burkalow's description is reproduced here to indicate the character of the basement rock at depth.

The ground mass is composed of a very fine-grained mosaic of quartz and slightly turbid feldspar (some grains show plagioclase twinning), tiny grains of epidote, and shreds of chlorite and biotite. The latter are in more or less parallel arrange-

FIGURE 4.—Exposure of weathered quartz-biotite schist in roadcut along county road S–2–23 at Franklin Branch, Aiken County.

ments, but they are not abundant enough to give a very pronounced schistosity. There are scattered black opaque grains, rather large and somewhat corroded in outline, and a few that are much smaller and slightly elongated. In this matrix are numerous large feldspar crystals that have been saussuritized. In some the plagioclase twinning still shows through a cloud of fine needles, with occasional larger crystals of epidote or zoisite. Others have been entirely replaced by a much coarser mosaic of epidote grains, with occasional zoisite. There are a few tiny veins and patches of calcite.

The upper surface of the basement (pre-Cretaceous) rock has been eroded, tilted to the southeast, and buried. The configuration of the buried surface is shown by generalized contours on plate 4.

The general plane of the surface strikes north 62° east and dips to the southeast at approximately 36 feet per mile, according to the values of strike and dip that are plotted in figure 5.

The values given in figure 5 were calculated by the three-point method from altitudes of the basement-rock surface as determined from wells in eastern Georgia and western South Carolina and from seismic data in the vicinity of Ellenton, S.C. The spread or range of calculated values reflects, in part, the unevenness of the basement surface; hence, observations taken over more widely separated points tend to yield more consistent values of strike and dip. Other factors that probably affect the range of calculations of dip and strike by the three-point method include (1) the difference between the estimated and actual well altitudes, (2) the accuracy of reported well data, and (3) the thickness of saprolite buried beneath the Coastal Plain sediments.

The relief of the basement surface, as indicated by the well data, is perhaps as much as 150 feet (pl. 4). This relief is taken as evidence that peneplanation was incomplete prior to the deposition of the overlying sediments.

During the course of this investigation two reversed seismic reflection profiles were made within the SRP area by the University of Wisconsin (Woollard and others, 1957, p. 23). The first profile was made in Aiken County near Greenland, about 1 mile from well 35–H. The results indicated that the average altitude of the basement-rock surface between the two ends of the profile was 565 feet below sea

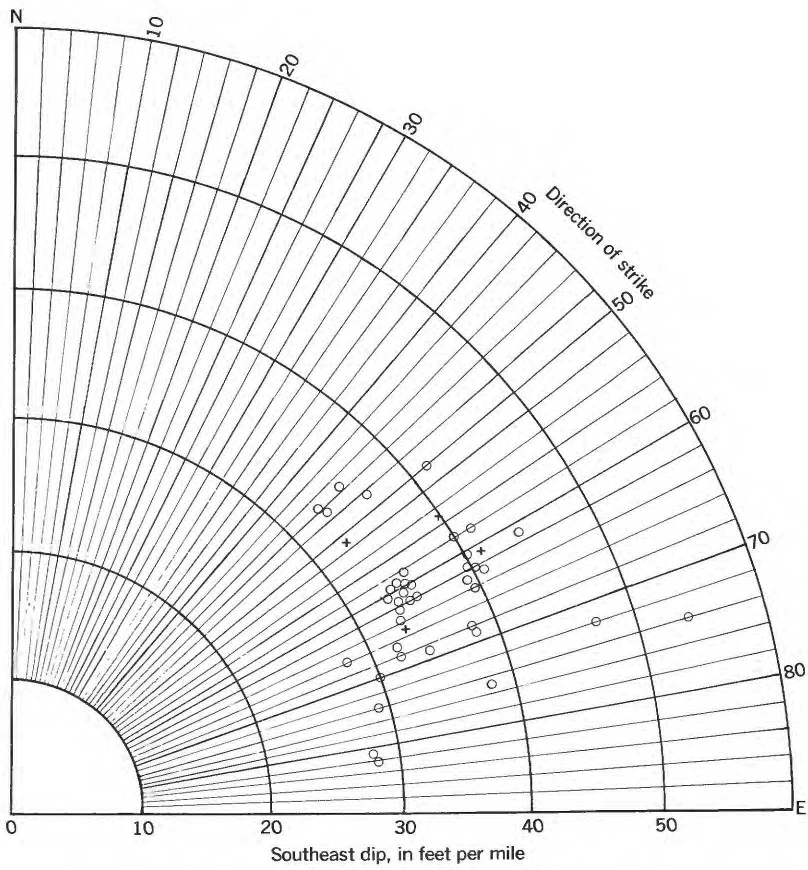

FIGURE 5.—Values of strike and dip on surface of basement rock. Single three-point value shown by a circle, group values by a plus sign.

level. This figure deviates from the data obtained in well 35–H, which indicated a basement altitude of −696 feet; however, the dip of the rock surface (between the well and the seismic profile) probably accounts for as much as 36 feet of the 131-foot difference in basement altitudes. The thickness of the buried saprolite in this location probably is 30–50 feet.

Subsequent to the investigation here reported, a series of test wells was drilled at the SRP in connection with a feasibility study of storing high-level radioactive wastes in the buried crystalline rock. One of this series, well DRB–3, within about 1 mile of well 35–H, penetrated the sediments and saprolite and bottomed in the crystalline rock. On the basis of the lithologic and geophysical logs available for this well, the writer estimated that the surface of the buried saprolite was penetrated at an approximate altitude of −599 feet. This altitude would appear to show a close agreement between the well data and the reflection data for the altitudes of the top of the weathered rock. However, the seismic velocities recorded for the basement rock as a result of the seismic traverse probably cannot be attributed to the sediment-saprolite boundary, in spite of the fact that the saprolite represents a transitional zone (increasing in density with depth) rather than a sharp boundary and that velocities recorded for the buried crystalline rock in other parts of the Atlantic Coastal Plain indicate, in most places, a higher altitude for the rock interface than that logged as the top of the rock in nearby wells.

The second profile was made in Barnwell County near Steel Creek, and the results indicated an average altitude for the basement-rock surface there as 997 feet below sea level. The average figure was obtained from the two altitudes determined for the west and east ends of the profile, −923 feet and −1,045 feet, respectively. The well data at this site as indicated by test well P–5–R (drilled in the later program described above and approximately 2 miles northeast of the profile) shows the altitude of the pre-Cretaceous surface to be −1,044 feet. Inasmuch as P–5–R is closer to the east end of the profile and on the strike, there would appear to be a very close agreement between the seismic and well data if the altitude taken from the well data is that of the top of the indurated rock rather than that of the saprolite. The rock slope between the two profiles (a distance of about 11 miles) was calculated at 29 feet per mile. This slope is in nominal agreement with the value for regional dip as calculated from well data (figure 5).

Additional information about the basement rocks was interpreted from the seismic data. The seimsic velocity of the basement rock, as recorded at Greenland, was 19,500 fps (feet per second). Velocities of this magnitude are commonly associated with such rocks as the chlorite-hornblende schist which was cored in well 35–H. At Steel Creek the seismic velocity of the basement rock was recorded as 15,850 fps. This velocity is lower than those generally obtained from rocks characteristic of the Piedmont, which generally have a range of from 16,000 to 19,000 fps. The velocity at Steel Creek, 15,850 fps, approaches those generally associated with Triassic sediments (less than 16,000 fps); however, most of the velocities obtained in Triassic rocks fall within a lower range of 10,400–14,000 fps (Bonini and Woollard, 1960, p. 304). In addition, velocities as low as 15,900 fps have been obtained from at least two areas in the Piedmont underlain by gneissic and volcanic rocks (Woollard and others, 1957, p. 20).

TRIASSIC ROCKS

Test hole P–5–R, drilled near the Steel Creek spread, bottomed in a pre-Cretaceous basement, which was interpreted as Triassic in age on the basis of its lithologic characteristics supplemented by magnetic anamolies. This interpretation corroborates the lower velocities obtained in the seismic traverse. A 12-foot core obtained from a 14-foot interval at the bottom of the hole (1,299–1,313 ft.) consisted of brick-red siltstone and claystone with included dark-gray calcareous pebbles. This lithology is characteristic of the fanglomeratic or conglomeratic facies of the Newark Group of Late Triassic age. The extent of these buried Triassic rocks is not known in this area, but other Triassic basins in adjoining areas trend in a northeast-southwest direction, and it is highly probable that these are elongated in a similar manner. An airborne magnetometer survey made in this area in 1958 by the U.S. Geological Survey indicates that the Triassic basin is associated with a correlated area of low gamma intensity extending approximately 9 miles to the northwest of well P–5–R.

A preliminary estimate of the dimensions of the Triassic basin is given on plate 4. This estimate shows the basin to be correlative with a belt of low-gamma intensity extending across the lower part of the SRP area in a direction approximately N. 63° E., paralleling the regional strike of the crystalline rocks. The boundaries are inferred from the steep gradients in magnetic intensity shown in the regional aeromagnetic map (Petty and others, 1965). The southeast boundary shows a differential of more than 500 gammas across about 3 miles, whereas the northwest boundary is less steep and more indefinite.

The area of low magnetic intensity associated here with the Triassic basin, extends about 25 miles to the northeast, but to the southwest, on the Georgia side, it appears to terminate rather abruptly within about 5 miles of the Savannah River.

WATER-BEARING PROPERTIES

Although the basement rock differs greatly with respect to its origin, its water-bearing properties are fairly similar. All the rocks are hard, dense, and massive, and, in their natural state, they are practically impervious to water. Nonetheless, some water is stored in secondary openings in the rocks, such as those formed by fissures and joints and other fracture openings. Secondary openings are those that were developed by processes that affected the rocks after they had been formed. For this reason, meager to fair supplies of water are generally obtained from wells tapping the basement rock. Four such wells for which records are available have yields that range from 2 to 100 gpm (gallons per minute) and that average 47 gpm. Doubtless, the average yield would be less than 47 gpm, perhaps as low as 5–10 gpm, if a representative sample of well yields and a representative number of well failures were included in the sampling.

The permeability of the Triassic rocks is not known, but it presumably approximates that of the crystalline rock, depending in part on degree of fracturing. A yield of 0.5 gpd (gallons per day) was measured from one well drilled. Low yields are characteristic of crystalline rocks in other areas.

COASTAL-PLAIN SEDIMENTS

The Coastal-Plain sediments range in age from Late Cretaceous to Recent and are composed of a wedge-shaped block of stratified gravel, sand, silt, clay, and limestone. This mass thickens in South Carolina from less than 1 foot along the Fall Line or landward margin of the Coastal Plain to more than 4,000 feet along the Atlantic coast near the mouth of the Savannah River. The oldest or lowermost beds forming the base of the wedge rest directly upon the basement complex and appear at the surface along the landward margin of the Coastal Plain immediately adjacent to the Fall Line. The structural dip of the lowermost beds is seaward, following the slope of the basement-rock surface (pl. 4). In general, each successively younger formation appears at the surface in a belt that lies seaward of the belt of outcrop of its predecessor, and each successively younger formation dips more gently than its predecessor. Although a general or regional dip to the southeast is attributed to these beds, it is nevertheless recognized that several deviations or ambiguities which exist where the beds dip and thicken in a different direction indicate that one or more stages of deposition took place in basins not alined in a unidirectional southeastern direction.

The sequence of beds indicates that the coastal-plain sediments are separable into the Cretaceous, Tertiary, and Quaternary Systems.

CRETACEOUS SYSTEM

The Cretaceous System is represented by the nonmarine Tuscaloosa Formation and the marine or estuarine Ellenton Formation.

TUSCALOOSA FORMATION

The Tuscaloosa Formation was named by Smith and Johnson (1887, p. 98) for exposures of light-colored irregularly bedded nonmarine sediments near Tuscaloosa, Ala. Subsequently, the name was applied to equivalent strata in Georgia by Spencer (1890) and in South Carolina by Cooke (1936, p. 17) who correlated Sloan's Hamburg and Middendorf beds (Sloan, 1908) with the Tuscaloosa of Georgia.

GEOLOGIC CHARACTER

The Tuscaloosa Formation consists mainly of fluvial and estuarine deposits of crossbedded sand and gravel intercalated with lenses of variegated silt and clay. As shown by the fence diagram (pl. 2), the Tuscaloosa rests directly upon the basement rock and dips to the southeast following the slope of the bedrock floor. The Tuscaloosa is overlain conformably by the Ellenton Formation, but near the Fall Line it is overlain unconformably by sediments of Tertiary and Quaternary age.

No faunal remains have been found in the Tuscaloosa Formation in the report area; however, Berry (1914) described 17 species of fossil plants from a locality in the vicinity of Langley in Aiken County and 41 species from a locality near Middendorf in Chesterfield County. Of the 41 species found near Middendorf, 23 are known to occur in the Raritan and Magothy Formations of New Jersey and Maryland and in the Tuscaloosa Formation of Alabama.

In a restudy of these floras, Dorf (1952) concluded that the plant-bearing beds of the Middendorf locality were of the same age as the flora of the Black Creek Formation (of Late Cretaceous age) of North Carolina. Although Dorf's evidence is not conclusive, his correlation suggests that the Middendorf beds are representative of sediments of post-Tuscaloosa age, equivalent perhaps to strata of Eutaw and Taylor age on the Atlantic and Gulf Coastal Plains.

The Tuscaloosa Formation crops out in a belt that is 10–30 miles wide and extends northeastward across South Carolina from Augusta, Ga., to the North Carolina State line. It is exposed in the report area in the lower parts of the valleys of Horse Creek, Shaw Creek, South Fork Edisto River, Holley Creek, and Town Creek (pl. 1). On the upper slopes of these valleys, the Tuscaloosa is covered by Tertiary and Quaternary deposits that, in places, completely transgress the outcrop area of the Tuscaloosa and rest directly upon the crystalline rocks of the Piedmont. Southeast of the belt of outcrop, the Tuscaloosa Formation is completely covered by younger sediments and occurs at progressively greater depths in the subsurface in the direction of the Atlantic Ocean.

The altitude of the top of the Tuscaloosa Formation in the area of this report is shown by means of contours on plate 5. As shown by the contours (pl. 5), the average strike of the formation is N. 65° E., and the dip is to the southeast. The average rate of dip between the +500-foot contour and the +250-foot contour is approximately 15 feet per mile, whereas the rate of dip between the +250-foot contour and the −200-foot contour is approximately 30 feet per mile. Significantly, the lesser rate of dip occurs near the Fall Line where the surface of the Tuscaloosa was probably beveled by the transgressing sea that sorted and deposited the Tertiary sediments.

The thickness of the Tuscaloosa Formation ranges from a featheredge along the Fall Line in the northwestern part of the area of this report to approximately 600 feet in the vicinity of Upper Three Runs in the south-central part of the area. Southeast of Upper Three Runs the thickness of the formation is fairly constant.

In the report area the Tuscaloosa Formation consists of light-gray to white, tan, and buff crossbedded quartzitic to arkosic coarse sand and gravel intercalated with lenses of white, pink, red, brown, and purple silt and clay. Individual beds of coarse and fine sediment are intermixed in no regular sequence and grade laterally into one another or pinch out within comparatively short distances. Ferruginous sandstone concretions are commonly found in nodular or lenticular shapes at the contact of a permeable bed above a less permeable bed, and siderite nodules are scattered throughout some of the silt and clay strata. In addition, numerous lenses of kaolin ranging from 2 to 40 feet in thickness are present in the Tuscaloosa; these are particularly abundant a few miles southeast of the Fall Line.

The predominant rock-forming minerals of the coarse-grained deposits are quartz, partially altered feldspar, and mica. The grains of quartz are angular to subrounded, have a clear to greasy luster, and commonly contain internal fractures and inclusions of rutile grains. Though less abundant than quartz, grains of feldspar are conspicuous in most exposures of the Tuscaloosa not only in the report area but also in other parts of the State. Most of the mica in the sand is colorless muscovite, but some of it may be bleached biotite.

Heavy minerals identified in the Tuscaloosa include ilmenite, tourmaline, rutile, zircon, monazite, and garnet. A gamma-ray log of well AK–183 shows a zone of comparatively high radioactivity opposite the upper beds of the Tuscaloosa Formation at an altitude of 169–232 feet above sea level. This zone of higher gamma radiation is interpreted as an indication of a comparatively high percentage of monazite in the sand strata.

Typical crossbedded sand and gravel of the Tuscaloosa Formation are illustrated in figure 6. Typical exposures of the silt and clay strata of the Tuscaloosa Formation are shown in figure 7. Although the beds of laminated clay are considered here as part of the Tuscaloosa Formation, they may conceivably represent a thin wedge of Tertiary sediments that rest unconformably upon the Tuscaloosa.

The coarsely reworked nature of some deposits, whose stratigraphic position is concordant with part of the Tuscaloosa Formation, is shown in figure 8. These deposits, however, occur as a surficial mantle almost exclusively within the basin of the Savannah River near the Fall Line. For this reason they are believed to represent material that was reworked in post-Tuscaloosa time by the ancestral Savannah River drainage system.

The composition and the irregularity of the sediments of the Tuscaloosa Formation suggest derivation from the disintegrated and partially weathered crystalline rocks of the nearby Piedmont and deposition in a fluvial or nonmarine environment. Hence, it is

FIGURE 6.—Crossbedded white micaceous clayey sand of the Tuscaloosa Formation exposed in a bluff 0.8 mile east of Graniteville along county road S-2-33.

FIGURE 7.—White kaolinitic clay of the Tuscaloosa Formation exposed beneath red sandy clay of the Tertiary Barnwell Formation 0.8 mile east of Graniteville along county road S–2–33.

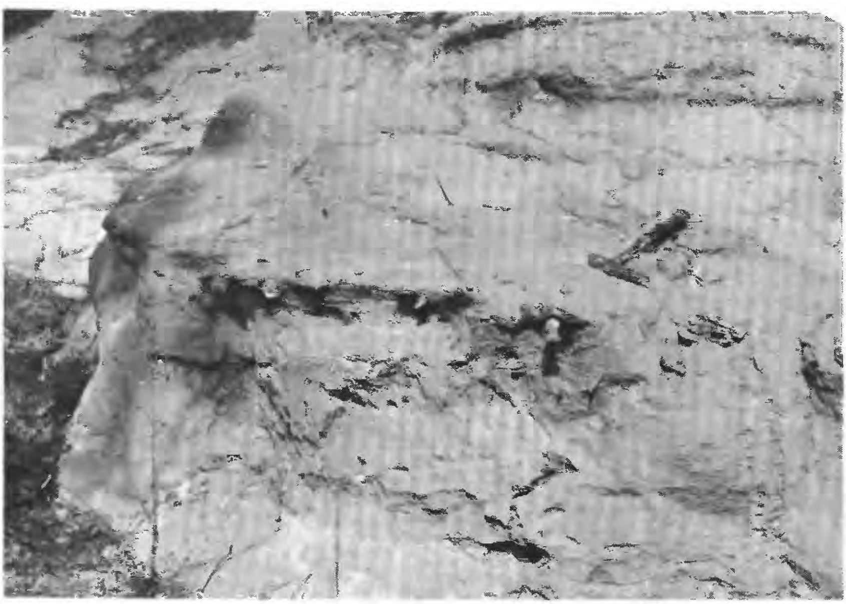

FIGURE 8.—Pliocene or Pleistocene deposits derived from the Tuscaloosa Formation, exposed on the north side of U.S. Highway 1.

243–540 O—67——3

assumed that the Tuscaloosa Formation was deposited by sediment-laden streams that eroded and drained the Piedmont in Late Cretaceous time. Conceivably, the Tuscaloosa sediments accumulated as a series of coalescing deltas that bordered the shoreline of the Late Cretaceous sea.

The beveling of the Tuscaloosa Formation in the area of Tertiary overlap was preceded by (1) a gradual seaward tilting of the bedding planes, which either established or increased the dip of the formation toward the southeast, and (2) a period of erosion. The tilting action probably occurred during latest Cretaceous time while the Peedee Formation was being deposited beneath the Cretaceous sea, which lay farther to the southeast. The period of erosion, on the other hand, probably occurred coincident with the deposition of the earliest Tertiary sediments (Paleocene) and ended with inundation as a result of the westward migration of the Tertiary sea.

ELLENTON FORMATION

The dark lignitic clay and associated coarse sand that occur in the subsurface of the report area above the Tuscaloosa Formation and beneath the formations of Eocene age constitute a separate and distinct lithologic unit. Therefore, it is proposed to give this unit a formal rock-stratigraphic name. The name Ellenton Formation has been selected because the unit is traceable and typically occurs in the subsurface in the vicinity of Ellenton, a small town within the SRP area near the junction of the Savannah River and the Aiken-Barnwell County line.

GEOLOGIC CHARACTER

The Ellenton Formation consists of a dark-gray to black sandy lignitic micaceous clay interbedded with medium to coarse quartz sand. Some of the quartz grains contain inclusions of pyrite, others are rutilated. Much of the free pyrite appears to be decomposed. Authigenic gypsum crystals are commonly distributed throughout the formation. Generally, the upper part of the formation contains a gray silty to sandy micaceous lignitic clay with which the gypsum is commonly associated. In some wells the clay zone may be overlain by coarse quartz sand.

The lower part of the Ellenton consists generally of clayey quartz sand of medium to coarse texture, which in some areas becomes very coarse and gravelly. The quartz grains are bluish gray. Lignite and decomposed pyrite or marcasite fragments, muscovite, and aggregates of kaolinite or other very soft minerals are fairly common.

The Ellenton Formation probably is unconformable with the underlying Tuscaloosa Formation and the overlying Tertiary sediments.

The lower contact is characterized by a change in color of the clay and a change in the composition of the sand. The dark-gray to black clay of the Ellenton is readily distinguishable from the variegated clay of the Tuscaloosa. Likewise, the quartzose sand of the Ellenton can generally be differentiated from the arkosic sand of the Tuscaloosa. The upper contact is also characterized by a change in the color of the clay above and below the contact. In drilling, the color of the sediments characteristically changes from the red, tan, or mustard-yellow of the basal sand and clay of the Tertiary System to the dark-gray to black of the silty to sandy clay of the Ellenton Formation.

The type-locality well for the Ellenton Formation is well 52–C which is 4 miles northeast of the town of Ellenton and 7¾ miles southeast of Jackson, Aiken County, S.C. (See well—location map.) The Ellenton Formation was penetrated in the type well at a depth of 310–370 feet. The appropriate part of the descriptive log of the type well is given here to provide a detailed description of the type section of the Ellenton Formation.

Description of the type section for the Ellenton Formation in well 52–C

[Owner: U.S. Atomic Energy Commission. Driller: Layne-Atlantic Co., Savannah, Ga. Date completed: June 5, 1952. Surface altitude: 290 feet]

Description	*Thickness*	*Depth*
Tertiary System:		
McBean Formation:		
Sand, tan to pale-yellow; 70 percent of sample medium to coarse grained; subangular to subrounded quartz grains. Dark minerals more common than in units above. Soft white mineral with basal cleavage (talc or kaolinite?) and muscovite flakes present	5	295
Sand, colorless to medium gray; 75 percent of sample coarse to very coarse. Subangular to subrounded quartz grains. Dark minerals common. Muscovite present. Some of dark minerals phosphatic; some highly magnetic. Talcose or kaolinite grains fairly common	15	310
Cretaceous(?) System:		
Ellenton Formation:		
Clay, bluish-gray, micaceous, lignitic, sandy; muscovite common to abundant; altered pyrite or marcasite fairly common. Subangular to subrounded fine to medium quartz grains. Trace of chlorite. Interval from 325–335 ft predominantly clay	25	335
Sand, coarse, clayey, micaceous, lignitic; subangular milky quartz; dark-gray clay; minor percentage shows conchoidal fractures. Heavy minerals in rare to trace amounts—may be contamination	10	345
Sand, same as above except for appearance of colorless acicular crystals of gypsum (selenite) in the dark-gray clay. Other gypsiferous forms noted include satin spar. Some of the lignite replaced by pyrite or marcasite; 55 percent of sand coarse to very coarse. Laboratory determination of permeability indicates 66 gpd (Meinzer's units)	20	365
Sand, white to gray, clayey and silty, micaceous and lignitic. Subangular fine to coarse quartz. Driller logged interval as clay	5	370

Description of the type section for the Ellenton Formation in well 52-C—Continued

Description	*Thickness*	*Depth*
Tertiary System—Continued		
Tuscaloosa Formation:		
Sand, tan to yellow, clayey, micaceous, kaolinitic; contains scattered red ferruginous sand nodules	15	385

The presence of the Ellenton Formation is indicated by the cuttings from several wells in the SRP area in addition to the type well, 52–C. Wells that are screened wholly or partly in the Ellenton include 21–F, 25–P, 27–R, 28–L, 29–L, 30–P, 33–K, 54–R, and 55–P. Other wells from which the drill cuttings indicate the presence of the Ellenton Formation include S–315, 411, 414, 424, and XM–16 (a test well). In addition, the characteristic dark-gray clay containing crystals of gypsum in a stratigraphic position equivalent to the Ellenton occurs in wells as far south and east as central Allendale County and as far north as Salley in northern Aiken County. Although the Ellenton Formation is probably stratigraphically equivalent to the Black Creek Formation, crystals of gypsum have not been recognized in the typical dark-gray clay of the Black Creek Formation in the northeastern part of the South Carolina Coastal Plain.

The thickness of the Ellenton Formation in the type locality is 60 feet, and its thickness increases from 0 feet along the northwest boundary of the SRP area to approximately 100 feet in western Allendale County.

No faunal remains, either macrofaunal or microfaunal, have been recovered from the Ellenton; however, some poorly preserved and very small leaf prints were discovered in the cuttings of dark-gray clay from the type well. Owing to the lack of faunal evidence, a definite age assignment is not possible. Nonetheless, the tentative age assignment of the Ellenton is Late Cretaceous. This assignment is based on the similarity of the lithology and stratigraphic position of the Ellenton with other formations of Late Cretaceous age in other parts of the coastal plain. Specifically, the lithology of the Ellenton is similar in many respects to that of the Black Creek or Peedee Formations of Late Cretaceous age in the subsurface several miles east of the SRP area and to the Blufftown Formation of Late Cretaceous age in western Georgia. The Ellenton Formation might possibly represent the upper part of the Tuscaloosa Formation, but the lithology of the Ellenton is radically different from that of the typical Tuscaloosa. An exception to the preceding statement may be the exposure of lignitic clay at Cheraw in Chesterfield County, S.C., that has been included in the Tuscaloosa Formation (Siple and others, 1956).

The Ellenton Formation also resembles, but less definitely, the Midway Group of Paleocene age. Such a correlation should not be overlooked because sediments of Paleocene age have not been recognized generally in South Carolina. On the other hand, the Paleocene age of the Ellenton seems less likely when it is noted that the dark clay included in the Black Mingo Formation of Eocene (Wilcox) age in South Carolina is lithologically similar to that of the Midway Group in the gulf coastal area. Moreover, C. W. Cooke (oral commun., 1952) indicated there was as much faunal evidence in the Black Mingo Formation for a Midway (Paleocene) age as for a Wilcox (Eocene) age.

An X-ray analysis of samples from the Ellenton Formation (made by the U.S. Geol. Survey) indicated only 1.7 percent of the total sample contained amorphous and (or) opaline silica as contrasted with more than 30 percent found in clay of the Black Mingo Formation.

WATER-BEARING PROPERTIES OF THE CRETACEOUS SEDIMENTS

Although the Tuscaloosa Formation can be differentiated from the Ellenton Formation, the permeable or water-bearing zones within the two formations are not completely separated by an intervening confining bed. Therefore, ground water is free to move from one formation into the other through points or areas of mutual hydraulic connection. For this reason the permeable zones in the Tuscaloosa and Ellenton Formations are considered to constitute a single aquifer or exhibit hydraulic continuity over a large part of the area.

A few wells within the SRP are screened in the Ellenton Formation. More specifically, the screens in these wells are set opposite beds of coarse sand at the top and at the bottom of the formation in the type area. Although these sands are sufficiently permeable to yield water to wells, they probably do not have as large a capacity to yield water as the permeable materials in the underlying Tuscaloosa Formation.

The Cretaceous sediments are used extensively as a source of water in the SRP as well as in other parts of Aiken, Barnwell, and Allendale Counties. The water is obtained from highly permeable deposits of medium to coarse sand and gravel. In general, the permeable deposits occur as irregular masses intercalated with nearly impervious beds of silt and clay. Although the Cretaceous sediments are not uniformly permeable throughout their vertical and horizontal extent, they do constitute the principal source of ground water in the report area. For this reason, the aquifer formed by the Cretaceous sediments is referred to as the principal aquifer. However, it is also recognized that within the Tuscaloosa Formation, there are beds or lenses of clay which in some areas might be sufficiently extensive as to separate the water bearing sands into two or more aquifers.

CAPACITY TO STORE AND TRANSMIT WATER

An aquifer functions both as a reservoir and as a conduit. The capacity of an aquifer to function as a reservoir can be expressed in terms of a dimensionless fraction, the coefficient of storage, which is defined by the U.S. Geological Survey as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The capacity of an aquifer to function as a conduit is measured in terms of its coefficient of transmissibility, which is defined by Theis (1935) as the quantity of water in gallons per day that will pass through a 1-foot strip of the aquifer extending the full height of the aquifer under a unit hydraulic gradient.

Coefficients of storage and transmissibility were determined for the Cretaceous and Tertiary sediments from the results of a series of pumping tests. Most of the tests were made on wells within the SRP proper by E. I. du Pont de Nemours & Co. and the Layne-Atlantic Co., but two tests were made on wells outside the SRP by the U.S. Geological Survey. The data from all the tests were analyzed by using either the Theis (1935) nonequilibrium method or the Cooper and Jacob (1946) straight-line method. As indicated by Wenzel (1942), both of these methods of analyzing pumping-test data are based on several simplifying assumptions: namely, (1) that the water-bearing formation is homogeneous and isotropic, (2) that the formation has an indefinite areal extent, (3) that the pumped well is screened opposite the entire thickness of the aquifer, (4) that the coefficient of transmissibility is constant at all places and at all times, and (5) that the withdrawn water from the aquifer is released instantaneously from storage in the aquifer.

The Theis nonequilibrium and the Cooper-Jacob straight line formulas were used to analyze the data from the tests in which measurements were obtained in one or more observation wells. The Theis recovery formula was used to analyze the data from the tests in which measurements were obtained only in the pumped well. Detailed descriptions of the computation procedures for those formulas are given by Brown (1953), and samples of the computations for each of the two types of tests are given in figures 9 and 10.

The results of the pumping tests made inside and outside the SRP proper are summarized in table 3. As indicated by the data, the highest values for the coefficients of transmissibility and storage were obtained from pumping tests in the F and H areas. In these areas the coefficient of transmissibility ranged from 105,000 gpd per ft to 400,000 gpd per ft and the coefficient of storage from 0.0002 to 0.0008. In the M area the coefficient of transmissibility ranged from 33,500 gpd per ft to 147,000 gpd per ft and the coefficient of storage was 0.0003.

The variations in the results obtained from different tests in any one area may be attributed to the effects of partial well penetration, settings of well screens, well construction and development, and other

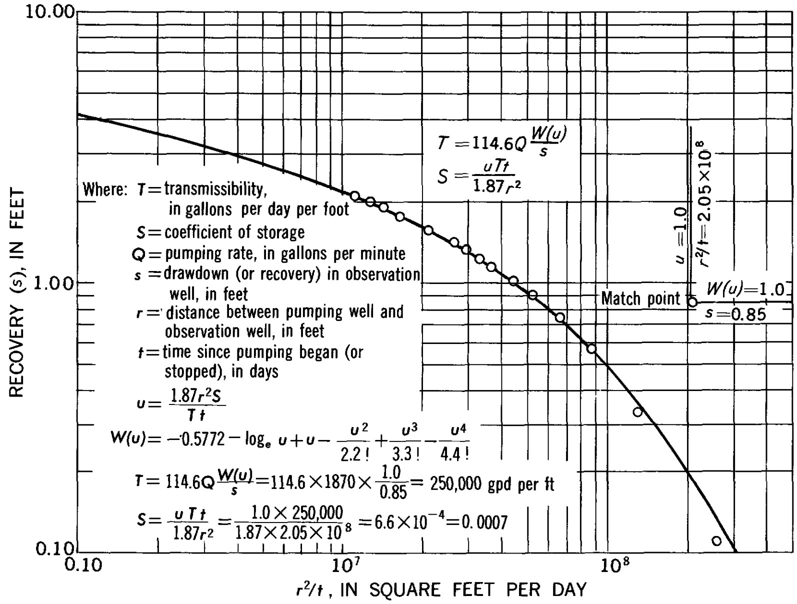

FIGURE 9.—Recovery of water level in well 24–F after pumping well 21–F.

TABLE 3.—*Summary of pumping-test data for the principal aquifer*

Well pumped	Well observed	Date of test	Area	Pumping rate (gpm)	Average effective sand thickness (feet)	Transmissibility (gpd per ft)	Permeability coefficient (gpd per sq ft)	Storage coefficient
35–H	35–H	5– 8–52	H	1,350	273	196,000	720	----------
35–H	35–H (45, 48)	5– 8–52	H	1,530	273	290,000 (400,000)	1,060 1,465	0.0002
35–H	35–H	1– 3–52	H	560	273	198,000	725	----------
43–H	43–H	2–23–52	H	560	277	204,000	736	----------
44–H	44–H	3–17–52	H	570	239	375,000	1,569	----------
48–H	48–H	5– 6–52	H	600	260	198,000	762	----------
24–F	21–F	9–29–51	F	600	237	215,000	907	.0008
21–F	24–F	11–16–51	F	1,870	237	252,000	1,065	.0007
24–F	24–F	9–29–51	F	610	237	253,000	1,063	----------
37–F	37–F	2–29–52	F	589	213	178,000	836	----------
49–F	49–F	4–28–52	F	562	267	105,000	393	----------
31–M	4–M, 20–M	1–19–52	M	1,500	181	147,000	812	.0003
20–M	31–M	1–31–52	M	1,500	----------	90,000	----------	.0003
15–M	15–M	4–23–51	M	450	160	33,500	209	----------
25–P	105–P	8– 3–52	P	370	219	46,000	210	.0004
25–P	25–P	9–20–51	P	540	219	63,500	290	----------
30–P	30–P	11– 3–51	P	540	144	52,000	361	----------
27–R	105–R	8–10–52	R	440	103	90,000	874	.0004
27–R	27–R	10– 9–51	R	560	----------	90,000	----------	----------
51–C	51–C	5–26–52	C	589	----------	95,000	----------	----------
52–C	52–C	6–16–52	C	567	136	140,000	1,029	----------
33–K	33–K	12–31–51	K	578	154	109,000	708	----------
29–L	29–L	11–28–51	L	525	124	71,000	573	----------
AK–266	AK–266	3–10–53	Aiken	383	138	95,000	690	----------
BW–44	BW–44	9–10–52	Williston.	530	255	120,000	470	----------

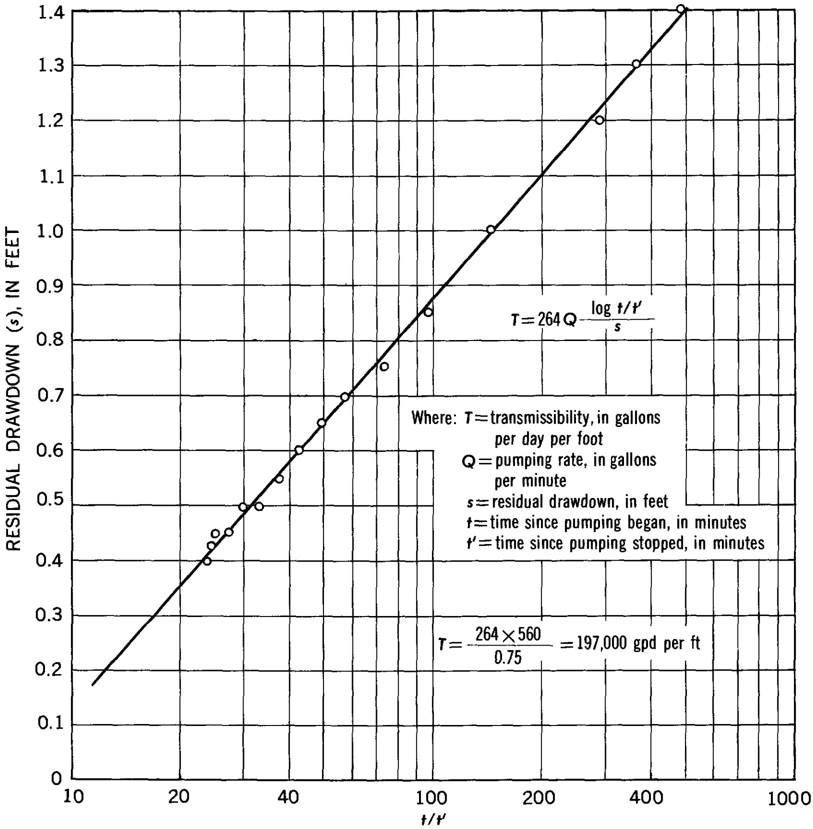

FIGURE 10.—Recovery of water level in pumped well 43–H.

factors. The fact that some wells were not screened throughout the aquifer affected the calculated transmissibility. The partial screening of a supply well is fully warranted, but the effect of partial penetration tends to vitiate the results of a pumping test. Computations based on drawdowns in observation wells close to the partly screened pumped well tend to give a figure for transmissibility that is either too high or too low—depending upon the position of the screen in the observation wells with respect to that in the pumped well and upon the distance between the observation wells and the pumped wells in relation to the effective thickness of the water-yielding zone.

Well 25–P is screened both in the Tuscaloosa and in the Ellenton Formation, but the average transmissibility as calculated from the recovery data amounts to less than that characteristic of the Tuscaloosa.

The results of the pumping tests indicate that in the L and P areas the transmissibility is lower than in the F, H, and M areas, where continuous pumping from the aquifer is planned. Furthermore, in those areas where continual use of the ground water is contemplated, the transmissibility can be conservatively estimated at 200,000 gpd per ft.

PERMEABILITY

The hydrologic term "permeability" is used frequently and forms a basis of comparing one aquifer with another, or one part of an aquifer with another part. The coefficient of permeability is defined (Wenzel, 1942, p. 7) as the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at a temperature of 60°. The field coefficient of permeability is measured at the prevailing temperature and is equivalent to the transmissibility divided by the effective thickness of the aquifer.

Table 3 lists the field coefficients of permeability for some of the wells for which the coefficients of transmissibility were computed. The permeability coefficients were determined by dividing the coefficient of transmissibility for a given well by the total thickness of the permeable beds of sand or gravel that were penetrated and screened by the well. As shown in table 3, the coefficients of permeability range from 210 gpd per sq ft in area P to 1,569 gpd per sq ft in area H. One of the reasons for the observed differences in permeability is the differences from place to place in the grain-size distribution of the sediments in the aquifer. For comparison purposes the grain-size distribution of some disturbed samples from the Tuscaloosa Formation is presented in figure 11. The permeabilities of disturbed sand samples from the Tuscaloosa Formation, as determined in the laboratory, ranged from 150 to 7,000 gpd per sq ft.

Determinations of the coefficient of permeability were made on several samples of sand from the Tuscaloosa Formation in the U.S. Geological Survey Hydrologic Laboratory at Denver.

These coefficients are listed below with the comparative value of permeability as determined from a pumping test in the same or nearby well.

Inasmuch as the laboratory measurements were made on disturbed samples, these permeabilities are considered less accurate than the permeabilities obtained from the pumping tests. In addition, the permeability obtained from the pumping-test data is an average of all the sands in the aquifer system tapped by the well, whereas the permeability measured in the laboratory pertains only to one small segment of the system.

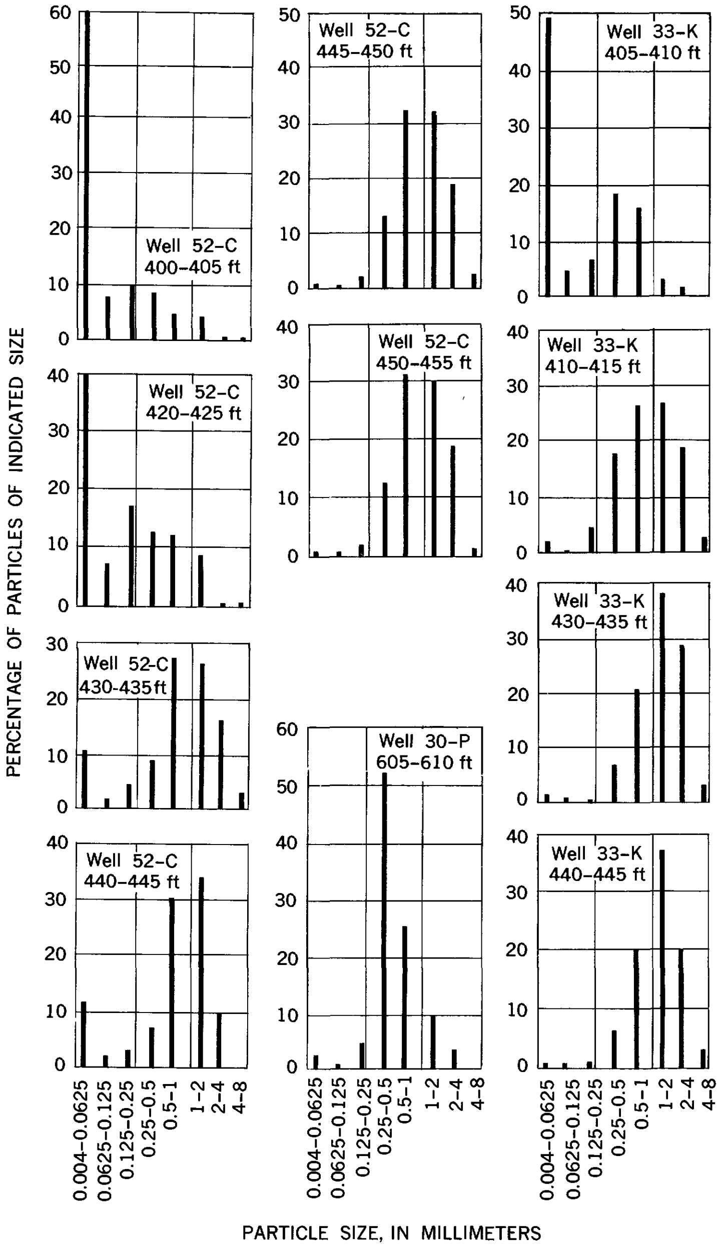

FIGURE 11.—Particle-size distribution of selected intervals in the principal sand aquifer of the Tuscaloosa Formation.

Coefficient of permeability (gpd per sq ft)

Well no. or area	*Interval (feet)*	*As determined in laboratory*	*As calculated from pumping test*
33-K	450–455	300	708
52-C	445–450	150	1, 029
20-M	570–585	2, 100	
	585–620	570	812
	630–695	530	
35-H	325–330	4, 700	
	385–390	600	1, 569
	855–860	1, 000	
45-H	765–770	860	
	855–860	7, 000	1, 569
	885–890	1, 600	

DIRECTION OF WATER MOVEMENT

Ground water moves from areas of recharge or high head to areas of discharge or low head. An artesian aquifer such as the Tuscaloosa Formation is recharged (1) by direct infiltration of precipitation in the outcrop area of the aquifer, (2) by accretion from water percolating downward through the formations overlying the aquifer, and to a much lesser extent, (3) by the infiltration of water from surface streams in the outcrop area of the aquifer under conditions of flood flows or where streams cross a semipermeable clay bed perched above the water table. On the other hand, an artesian aquifer is discharged by water moving downgradient and emerging (1) as upward leakage into overlying beds, (2) as outflow from subaqueous exposures of the aquifer, such as are presumed to occur on the edge of the Continental Shelf, or (3) as withdrawal from wells.

Generally, the direction of movement of ground water in an artesian aquifer can be determined from a piezometric contour map of the aquifer because the "highs" on the piezometric surface represent areas of recharge and the "lows" represent areas of discharge. A piezometric contour map of the principal artesian aquifer in the report area is represented by the isopiestic lines, shown on plate 6. The piezometric surface shown by the isopiestic lines is an imaginary surface every point of which coincides with the October 1954 static water level in a network of wells ending in the principal artesian aquifer. As some of the data used in the construction of the piezometric map are reported depths to water, the map may not be accurate in all details, but the control is considered sufficiently adequate to indicate the major features of the piezometric surface.

The "highs" on the piezometric surface represent areas of recharge to the principal artesian system. These are indicated on plate 6 as (1) just south of Horse Creek basin and immediately east of the

Savannah River basin, and (2) east to southeast of the city of Aiken. The same areas are also topographically high areas where the artesian system is covered by Tertiary sediments. It is evident, therefore, that water must move downward in these areas through the Tertiary sediments and into the artesian system.

In addition the piezometric contours suggest that in the outcrop areas of the Tuscaloosa Formation ground water is discharged rather than recharged. Some recharge doubtless occurs in the interfluves of the outcrop area, but discharge occurs along the streams. Thus, little, if any, water moves down the dip from the outcrop area. Moreover, there is a depression in the piezometric surface along the Savannah River downstream from Augusta and along lower Horse Creek. This depression indicates that the principal aquifer is discharging a considerable quantity of water into Horse Creek and into the Savannah River. In the northern part of this depression, where the river crosses the outcrop of the Tuscaloosa, ground water discharges into the river very readily. Near the south end of the depression the confining clay above the Tuscaloosa appears to have been breached by erosion during Pleistocene time, and the resultant erosional scar appears to have been filled with permeable material. The permeable fill doubtless permits water from the artesian system to move upward and to discharge into the river.

Another significant factor with respect to the piezometric map as shown on plate 6 is its continuing contemporaneity. Thus whereas the original data used in the preparation of the map was obtained during 1954, several of these data were rechecked in 1960 and 1963 and found to reflect substantially the same distribution of piezometric contours, except for a somewhat higher state in some wells, reflecting the recovery from the 1954–58 drought. This contemporaneity function of the map is attributed to the fact that the fairly high permeability of the sand, together with the relatively small increases in ground water withdrawal over the entire area, tend to affect the natural equilibrium condition of the aquifer only by a relatively insignificant amount as far as the gross features of the map are concerned.

RATE OF WATER MOVEMENT

The coefficient of permeability and the hydraulic gradient may be used to calculate roughly the velocity of ground-water movement. Thus, the contours shown on plate 6 indicate that the water in the principal sand aquifer is moving generally west to southwest toward the Savannah River and southeast toward the Atlantic coast. The steepest gradients are indicated for the area between Aiken and the mouth of Horse Creek, where the head differential amounts to approximately 15 feet per mile. More gentle gradients of less than 7 feet per mile are shown extending southeast from the vicinity of Aiken. In the central part of the SRP area, the natural gradient of the piezometric surface is indicated as about 4–5 feet per mile in a south to southwest direction. The permeability of the principal aquifer in this vicinity (H area) might be assumed from table 4 to approximate 1,000 gpd per sq ft. If the porosity is assumed to be approximately 30 percent, then from the basic Darcy law, the ground-water velocity in this area can be computed as follows:

$$V = \frac{PI}{395p} \qquad (1)$$

where

V=velocity, in feet per day;
P=permeability, in gallons per day per square foot;
I=hydraulic gradient, in feet per mile;
p=porosity, in percent.

Thus, with a gradient of 4 feet per mile, a permeability of 1,000 gpd per sq ft, and a porosity of 30 percent, the velocity is calculated to be about one-third foot per day or about 125 feet per year. If the porosity is assumed to be less than 30 percent, for example 20 percent, the rate of movement would then be about one-half foot per day or 185 feet per year.

NATURAL DISCHARGE

The natural discharge of ground-water reservoirs is equivalent to the base flow of surface streams draining the area of outcrop of the reservoir. Those streams draining areas underlain by permeable sediments such as the Tuscaloosa Formation have but a small deviation between low-water flow and mean flow. Conversely, those streams draining areas underlain by crystalline rock or less permeable coastal-plain sediments show large differences between low and mean discharge. Likewise, the runoff or discharge per square mile of drainage area, in inches, is less for those streams draining areas that are underlain by permeable sediments of the Coastal Plain than for those streams draining areas that are underlain by the less permeable formations of the Piedmont.

To obtain estimates of the amount of ground water being discharged from the Tuscaloosa Formation, a series of base-flow measurements were made by the U.S. Geological Survey on each of five streams that were selected by the writer as being representative of those draining the outcrop area of the Tuscaloosa Formation. In addition, base-flow data were compiled from the records obtained at the regular gaging station on the South Fork Edisto River near Montmorenci. The points at which miscellaneous discharge measurements were made are indicated in figure 12 and a summary of the measurements is shown in table 4. The measurements obtained at all stations during November 1952, and those obtained at some stations during September 1954, apparently represented base flows more nearly than others.

The lowest discharge measurement on the five streams was obtained from Little Horse Creek near Vaucluse—10.2 cfs (cubic feet per second)—and the highest measurement was obtained from Shaw Creek near Montmorenci—72.4 cfs. The highest average discharge

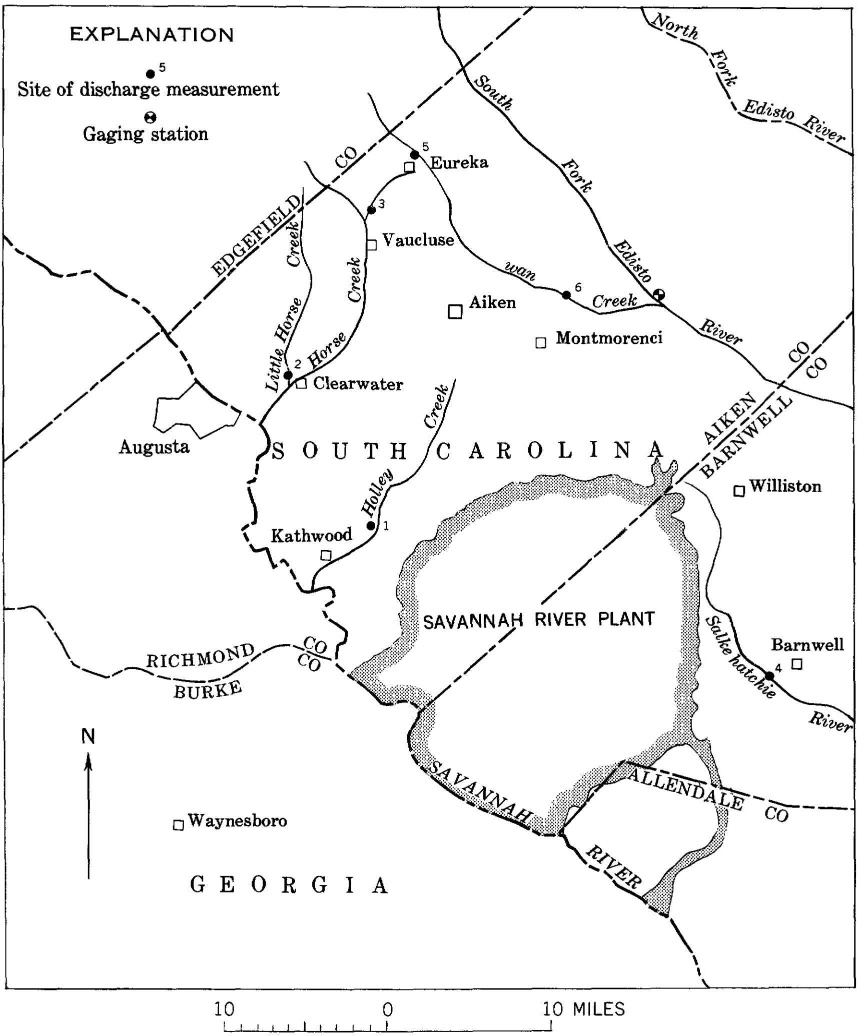

FIGURE 12.—Location of miscellaneous stream-discharge measurements.

TABLE 4.—*Miscellaneous discharge measurements of streams in the outcrop area of the Tuscaloosa Formation*

Stream	Drainage area (sq mi)	Discharge, in cfs, on date indicated														Average discharge	Minimum discharge per sq mi
		6-9-52	6-10-52	11-5-52	11-6-52	12-17-52	12-18-52	11-4-53	11-5-53	7-30-54	9-10-54	9-28-54	11-10-55	11-14-55	11-21-55		
Holley Creek near Kathwood	[1] 87	------	68.8	------	65.8	------	72.0	------	63.4	------	------	------	81.7	------	------	70.3	0.729
Little Horse Creek near Clearwater	41	------	57.0	------	32.3	33.4	------	25.8	------	------	------	------	------	------	------	37.1	.629
Little Horse Creek near Vaucluse	10.5	11.6	------	10.2	------	10.4	------	11.3	------	------	------	------	------	------	------	10.9	.971
Salkehatchie River near Barnwell	64.6	------	20.2	------	29.8	------	33.8	------	25.9	------	------	------	------	------	------	27.4	.313
Shaw Creek at Eureka	[1] 38	21.9	------	20.3	------	23.7	------	20.1	------	17.1	------	10.8	------	------	17.8	18.8	.284
Shaw Creek near Montmorenci	103	57.4	------	55.6	------	72.4	------	61.4	------	42.9	27.2	------	------	46.2	------	51.9	.264
South Fork Edisto River near Montmorenci [2]	198	134	------	126	------	142	------	------	125	101	53	81	107	131	125	120.3	.267

[1] Approximate. [2] Mean daily discharge taken from rating curve.

during the period of measurements was obtained at Holley Creek near Kathwood where the discharge averaged 70.3 cfs or 0.803 cfs per sq mi of drainage area. Holley Creek flows through the south-central part of the Augusta quadrangle, and the areal geology indicates that most of the base flow is supplied by ground water from the Tuscaloosa Formation.

The mean daily discharges at the gaging station on South Fork Edisto River near Montmorenci (a mile upstream from Shaw Creek), recorded for the same days that the miscellaneous discharge measurements were obtained, averaged 120.3 cfs and the minimum discharge represented 0.268 cfs per sq mi of drainage area. As may be noted from figure 13, this amount of discharge occurs at the station for more than 99.99 percent of the record of measurement. Thus, in general, it can be assumed conservatively that the miscellaneous discharge measurements obtained at a coincident time on streams in the vicinity of this station represented flows that could be expected at least 90 percent of the time. Figure 13 also shows that for 99.9 percent of the time the discharge at Montmorenci is 0.34 cfs or more per square mile of drainage area. Therefore this quantity, equivalent

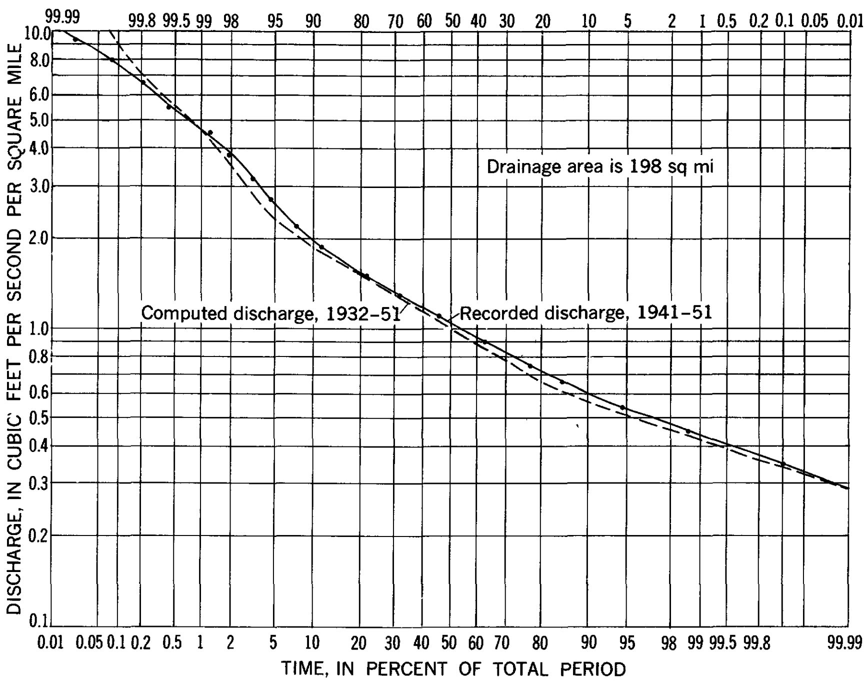

FIGURE 13.—Duration curves of daily flow, South Fork Edisto River near Montmorenci.

to 43.5 mgd (million gallons per day), may be considered as the minimum amount of potential recharge to the Tuscaloosa Formation from the South Fork Edisto River basin.

From the few data so far collected and computed, it appears that the ground water now being discharged as base flow in surface-water streams is considerably in excess of that required to balance the proposed ground-water withdrawals form the Tuscaloosa Formation for the operation of the SRP.

TERTIARY SYSTEM

McBEAN FORMATION AND CONGAREE(?) FORMATION

GEOLOGIC CHARACTER

The McBean Formation and the Congaree(?) Formation as defined in this report represent equivalents of the Claiborne Group of middle Eocene age of the Gulf Coastal Plain. The McBean Formation was named originally by Veatch and Stephenson (1911, p. 237) from the type locality at the town of McBean, Ga., and at McBean Creek, a tributary of the Savannah River. Cooke (1936, p. 55) considered part of Tuomey's (1848) Buhrstone Formation and Sloan's (1908) Warley Hill phase as partly equivalent to the McBean. As thus interpreted, the McBean included all the sediments of Claiborne age in South Carolina. Cooke and MacNeil (1952. p. 24) restricted the McBean to the sequence of deposits of late middle Claiborne age in South Carolina and thereby made the McBean Formation equivalent to the Cook Mountain Formation in Mississippi. Thus the McBean, as restricted, may be considered an offshore facies of the Santee Limestone in the subsurface southeast of the SRP area. This unit is probably correlative with the calcareous zone in the middle of the Claiborne section beneath the SRP and with the deposits of marl or limestone cropping out on the Savannah River along the strike.

The remaining older parts of the deposits of Claiborne age were raised to formational rank by Cooke and MacNeil (1952) and named the Congaree (early Claiborne) and Warley Hill (early middle Claiborne) Formations. The youngest deposit of Claiborne age in the State was designated the Castle Hayne Limestone; it represents equivalent units of Gosport age in adjacent States. No recognizable beds of this formation were found in the report area.

The correlation of middle and lower Claiborne formations in South Carolina as described by Cooke and MacNeil (1952) and a generalized standard section of the Atlantic and Gulf Coastal Plains are shown in figure 14. As may be noted in the figure, the Warley Hill Marl is considered representative of the lower part of deposits of middle Claiborne age; the Buhrstone (renamed the Congaree Formation) is correlated with the Tallahatta Formation; and the McBean is restricted to

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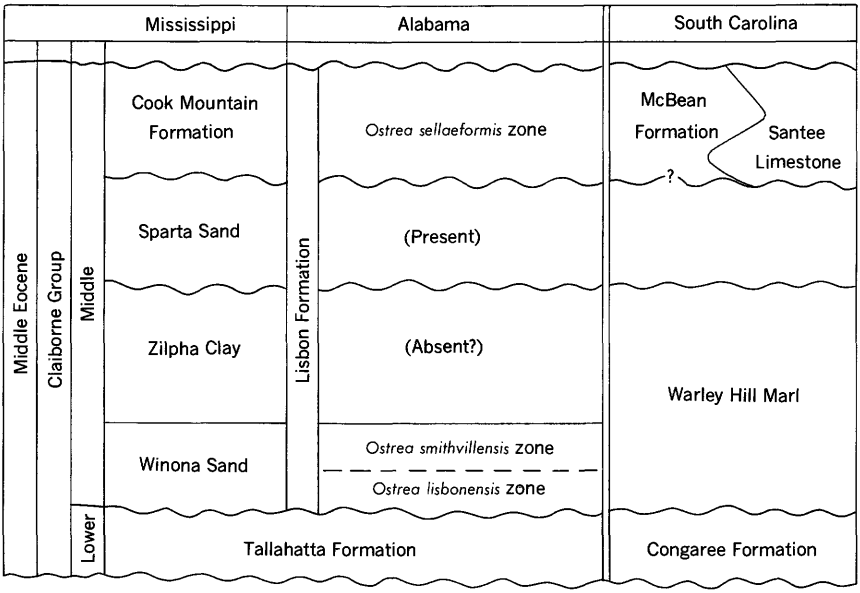


FIGURE 14.—Correlation chart for formations of early to middle Claiborne age in South Carolina. (Modified from Cooke and MacNeil, 1952.)

the uppermost part of the Claiborne Group—the *Ostrea sellaeformis* zone of the type section in Alabama.

The name "Congaree" was first used by Sloan (1908, p. 455) as his Congaree phase, underlying the Warley Hill phase and overlying the Black Mingo phase. Exposures along the western scarp of the Congaree River were regarded as typical. In Georgia, Veatch and Stephenson (1911, p. 238) designated the Congaree Clay as the basal member of the McBean Formation, the oldest Claiborne unit recognized at that time. As indicated above, the Congaree was raised to formational rank by Cooke and MacNeil (1952, p. 22) and considered equivalent to the Tallahatta Formation of Alabama, Georgia, and Mississippi. At its new type locality, half a mile east of Creston in Calhoun County, S.C., on State Highway 33, the unit consists of well to poorly sorted sand, fuller's earth, brittle siltstone, and light-gray to green shale alternating with thin-bedded fine-grained sandstone which contains the two guide fossils, *Anodontia? Augustana* Gardner, and *Ostrea johnsoni* Aldrich. Elsewhere in Lexington and Calhoun Counties the unit includes tan, white, and reddish-brown crossbedded sand, very similar to that in the McBean Formation.

Some exposures in the report area suggest a possible correlation with the Warley Hill Marl, but these occurrences are spotty and discontinuous. Glauconitic sand similar to that generally associated with the

Warley Hill Marl appears in the well cuttings from several wells in the SRP area, but it is found rarely or questionably in surface exposures.

Whereas a complete subdivision of the Claiborne Group (fig.14) may be warranted in a detailed interpretation of the stratigraphic section in areas downdip or farther to the east, such a subdivision appears less warranted in the report area where the shoreward facies of each subdivided unit grades into a comparatively thin zone and the criteria for distinguishing them becomes doubtful. In view of this difference and because the rocks of Claiborne age within the report area appear to function principally as one or two water-bearing zones, the deposits of Claiborne age are grouped together for convenience as the McBean Formation generally and more specfically as the McBean Formation for the upper part and the Congaree(?) Formation for the lower part. On plate 1, the full section of deposits of Claiborne age is represented as the McBean Formation, and similarly the data on pumping tests refer to the McBean Formation for convenience but include all sand of Claiborne age. Thus, except where specified as the restricted McBean Formation, or differentiated in the illustration, the McBean may be interpreted to include both units.

The deposits of Claiborne age strike about N. 60° E. and dip about 8–9 feet per mile toward the south or southeast. Their thickness ranges from 0 in the northwestern part of the area to about 250 feet in the southeastern part near the Allendale County line. They overlie the Ellenton Formation in the area southeast of Upper Three Runs and overlap, unconformably, the Tuscaloosa Formation in the northern part of Aiken County and southern Edgefield County.

The deposits of Claiborne age include (1) fine to medium sand (the grains being generally clear, transparent, and highly polished); (2) green glauconitic marl and clayey sand; (3) laminated beds of red, brown, yellow, and ochre colored semiplastic to nonplastic clay (generally of the montmorillonite group but in part koalinitic); (4) impure beds of soft fossiliferous limestone or marl; (5) lenses of silicified limestone and a fossiliferous indurated tan to gray sandy marl (fig. 15).

The claystone cropping out north of New Holland Crossroads, at an altitude of 470–475 feet mean sea level, contains molds of the following pelecypods and gastropods, which, although indicative of a Claiborne age, are not restricted to either the lower or middle Claiborne: *Turritella mcbeanensis* Bowles (Cooke and MacNeil, 1952, p. 23), *Venericardia* (Venicor) sp., *Plastomiltha* sp., cf. *P. claibornensis* (Conrad), and *Turritella* sp. All but the first of this group were identified by Druid Wilson (written commun., Nov. 1961).

FIGURE 15.—Fossiliferous claystone of Claiborne age exposed on west side of State Highway 39, 2.3 miles north of New Holland.

A pisolitic clay zone, similar to that occurring in the Gulf Coastal Plain and indicative of the base of the Claiborne deposits in that province, is also present at the base of the Claiborne in South Carolina (fig. 16).

The McBean Formation (restricted) is exposed in the valleys of Upper Three Runs, Holley Creek, Town Creek, Tims Branch, Tinker Creek, Lower Three Runs, and in scattered localities in the central to northern parts of Aiken County.

Most of the sand and sandy clay of northern Aiken County are considered herein as correlative with similar reddish-brown sand and clay of the Congaree(?) Formation that occur beneath the calcareous zone in the subsurface of southern Aiken County and also as surface exposures in Lexington, Calhoun, and Orangeburg Counties to the east. A Claiborne age for most of these beds is indicated by the presence of pisolitic clay referred to above and illustrated in figure 16.

Exposures of the typical Tallahatta-like clay of the Congaree Formation have not been recognized in northern Aiken County. An exception may be the hackly gray to green clay cropping out at an altitude of about 455 feet in a small tributary of Shaw Creek, about 6 miles N. 20° E. of Aiken. Here the clay appears to underlie a thin bed of indurated shell rock or coquina that is probably strati-

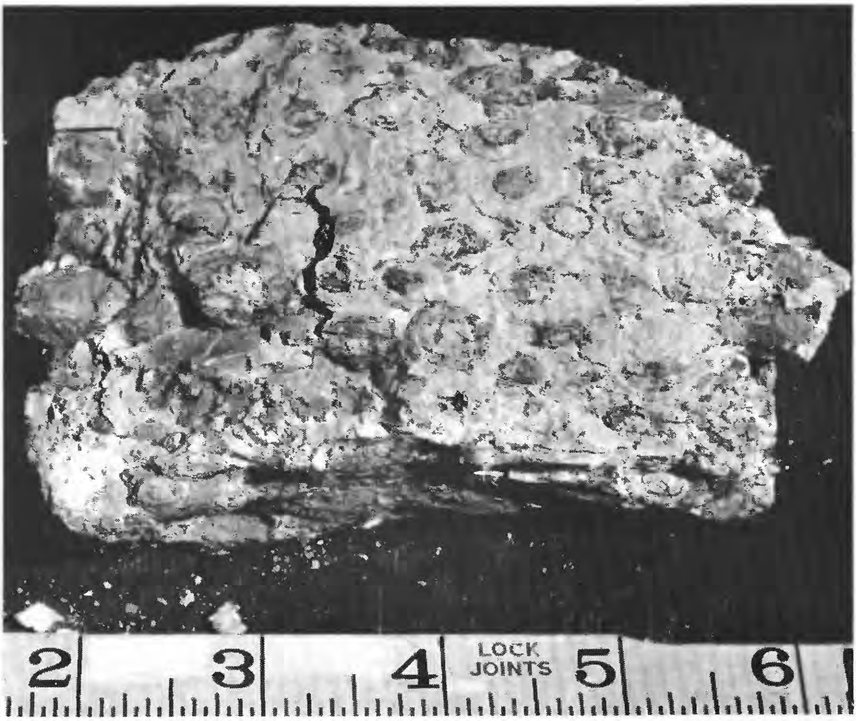


FIGURE 16.—Pisolitic clay from base of rocks of Claiborne(?) age, Bell Kaolin Co. pit (×0.7).

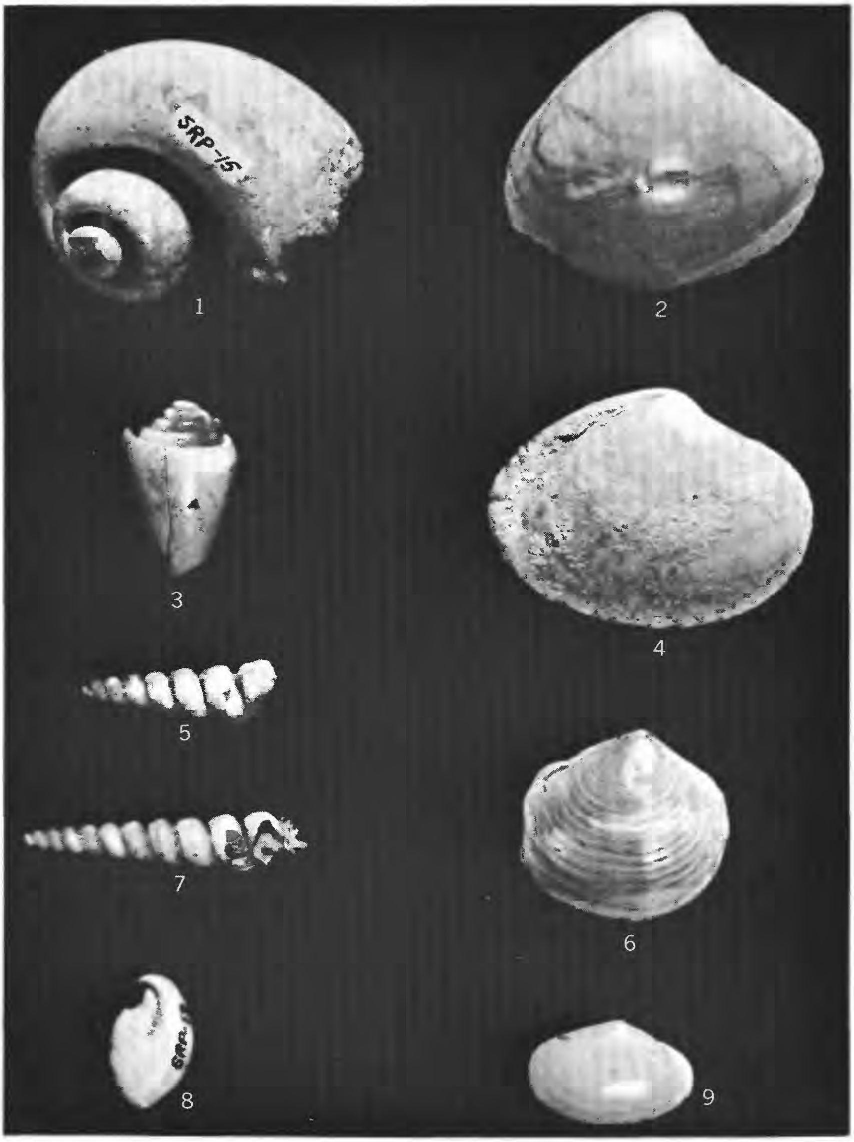
graphically accordant with similar beds exposed at the mouth of Upper Three Runs and on the south side of Montmorenci. The position of the hackly gray clay just above the Tuscaloosa Formation and its "fuller's earth" appearance lend some plausibility to its inclusion in the Black Mingo Formation of early Eocene or Wilcox age. However, if this clay is of Wilcox age, then it represents a singular occurrence of the older Eocene bed in this part of the State.

One exposure of greenish-gray clay similar to the Congaree clay was noted near the junction of Upper Three Runs with Tinker Creek. This particular occurrence could not be traced very far down dip although some wells penetrated thin (0–2 ft) beds of a dark-gray clay in the lower part of the formation.

From the approximate vicinity of Upper Three Runs and Tinker Creek and extending to the southeast, a bed of silty to sandy marl of varying thickness (but generally less than 50 ft) occurs in the subsurface at about a hundred feet above mean sea level. This marl is interpreted tentatively as the dividing bed between the younger McBean Formation and the older Congaree(?) Formation, but a persistent green clay positioned above the marl may also represent this contact. The marl is probably equivalent to the silicified limestone, coquina, and buhrstone exposed near Montmorenci and to similar rock near the mouth of Upper Three Runs. Stratigraphically and lithologically it is also probably equivalent to exposures found in central Lexington County, about 30 miles to the northeast.

The McBean Formation (as restricted) is considered the shoreward facies of the Santee Limestone. In this area, then, the calcareous zone at the base of the restricted McBean Formation may represent a tongue of the Santee Limestone (middle Eocene), or if the entire Claiborne section is represented by the McBean Formation, the Santee is interfingering with the sand and clay beds of the McBean. This bed of marl (or in part, limestone) has evidently been subjected to subsurface solution that caused subsidence of the overlying beds. This subsidence is indicated on the surface topography in the form of sinks, although not all areas underlain by the calcareous zone have sinks on the surface. Indication of subsurface solution was also discovered in the drilling of wells in this area. In many of the wells penetrating this zone, the drill dropped through cavernous or loosely compacted sections. Owing to the presence of these cavities formed by this subsurface solution, large volumes of cement grout were required to stabilize the subsurface support for heavy buildings constructed on the surface.

Fossil mollusks in the McBean Formation include gastropods and pelecypods that are most abundant in the zones which were once calcareous but have subsequently been silicified. The megafossils shown in figure 17 were collected from exposures on the southeast side of Upper Three Runs and Tinker Creek 7–10 miles northeast of Ellenton. These beds consist typically of light-tan to mustard colored fine to medium quartz sand, sandy clay, and claystone. Identification of the original specimens was made by Julia Gardner of the U.S. Geological Survey. Additional specimens from this and nearby localities were identified by the writer. The bed containing the fossils is stratigraphically higher in the Claiborne section than the Congaree and is more typical of the upper part of the deposits of the Claiborne section. The inclusion of *Pteropsis lapidosa* Conrad, the index fossil of the McBean Formation (restricted), correlates it rather definitely with this part of the Claiborne section. A similar faunal suite is present in the calcareous deposits cropping out at river level along the west bank of the Savannah River south of Shell Bluff. This suite includes, in addition to the *P. lapidosa*, specimens of *Ostrea sellaeformis* and *Venericardia planicosta*.



1. *Ampullina dumblei* (Hellprin)
2. *Spisula* sp. cf. *S. praetenuis* Conrad
3. *Conus* sp. cf. *C. sauridens* Conrad
4. *Spisula* sp.

5, 7. *Turritella nasuta* Gabb
6. *Pteropsis lapidosa*
8. *Crepidula* sp.
9. *Tellina* sp. cf. *T. papyrina* Conrad

FIGURE 17.—Representative gastropods and pelecypods from the McBean Formation. All specimens × 0.93.

The McBean Formation is the only deposit in this area from which an appreciable number of microfauna were recovered. Ruth Todd of the U.S. Geological Survey identified the following species of Foraminifera from the interval 33.7 to 33.8 feet, in test hole DU–7 (in the D area) and classified the assemblage as Claiborne in age; the age determination was based on the *Discorbis georgiana:*

Nonion advenum (Cushman)
Discorbis cocoaensis (Cushman and Garrett)?
Discorbis georgiana (Cushman and Herrick)

Additional microfauna including several species of Ostracoda were obtained from test wells AK–02 and AK–03 which were drilled in the central part of the Talatha quadrangle between Upper Three Runs and Tinker Creek. Several Ostracoda were obtained from a sand and shell bed at an altitude of approximately 180 feet in well AK–02 and from an underlying dark-gray clay at an approximate altitude of 150 feet in well AK–03. They were tentatively identified by P. M. Brown (written commun., 1961) as Eocene in age.

The Ostracoda obtained from well AK–02 at a depth of 34–57 feet were identified as:

Haplocytheridea montgomeryensis (Howe and Chambers)
Hermanites? *bassleri* (Ulrich)
Cytheromorpha sp.
Loxoconcha cf. *L. mcbeanensis* Murray
Loxoconcha sp.
Cytherideis sp.

These species are found typically in deposits of middle Eocene age.

A single species, *Cytherura* sp., was obtained from a depth of 78 feet in well AK–03, but its age is not determinable.

Water-Bearing Properties

The clay, claystone, and quartzite in the McBean Formation are not water bearing in the sense that they will not readily yield water to wells. Nevertheless, the beds of sand and limestone in the lower part of the formation in Aiken and Barnwell Counties are fairly permeable and, therefore, yield moderate to sizeable quantities of water to industrial and municipal wells.

The recorded yields of wells tapping the permeable parts of the McBean Formation range from 60 to 660 gpm. The highest yields are recorded for wells 9–TCA and 10–TCA in the western part of the SRP. These wells are reported to yield 650 and 660 gpm, respectively, and have about 50 feet of drawdown. On the other hand, well 14–TCS, a few miles southeast of 9–TCA and 10–TCA, is reported to yield only 173 gpm and has about 50 feet of drawdown. Outside the SRP the highest yields of wells tapping the McBean Formation are recorded for the municipal wells BW-22 and BW-39 at Barnwell, S.C. These wells yield 400 and 350 gpm, respectively, and have about 40 feet of drawdown. The lowest yield, 60 gpm, was recorded for a municipal well at the town of Salley in northeastern Aiken County.

The McBean and Congaree(?) Formations are recharged in the topographically higher regions of the SRP area and discharge into those tributary streams that dissect the overlying confining beds, such as Upper Three Runs, Fourmile Branch, and Steel Creek. Some water is also discharged along the Savannah River, and some migrates down the dip of the beds to discharge by upward vertical leakage. In the vicinity of the F and H areas, water in the aquifer moves from areas of higher head east of the H area to discharge to the northwest, west, and south into Upper Three Runs and Fourmile Branch. In so doing, the water moves 2–4 miles from an altitude of about 260 feet to discharge at an altitude of roughly 130 feet.

Artesian conditions prevail over the greater part of the aquifer's extent, and wells in the southern and southeastern part of the plant site flow quite freely from the calcareous beds of the formation. In the recharge area and in those areas contiguous to the dissecting streams, the water occurs under water-table conditions.

Formational boundaries in both the Tertiary and Cretaceous sections cannot everywhere be defined precisely. Similarly, aquifer boundaries do not everywhere coincide with formational boundaries. In some areas, water in the basal sand of the Barnwell Formation. may be in hydraulic continuity with water in the upper sands of the McBean Formation.

In the F and H areas there is fairly substantial indication that either the marl near the base of the McBean or a greenish-gray clay near the upper part of the Congaree(?) Formation acts as an aquiclude to separate the water in the upper part of the McBean Formation from that in the lower part, or Congaree(?) Formation. The dark-green clay in the Congaree(?) Formation together with stringers of dark-gray clay (similar to that in the underlying Ellenton Formation) probably impede the vertical movement of water between the sandy parts of this unit. The magnitude of the head differential between water in the McBean sand and water in the underlying Congaree(?) sand is indicated by measurements in the area between the F and H areas where the head in the McBean is about 240 feet above mean sea level and that in the Congaree(?) about 179 feet above mean sea level.

Pumping tests were made at three sites within the SRP to determine the hydraulic characterisitics of the McBean and Congaree(?) Formations. The data are summarized in table 5.

A comparison of table 5 with table 3 indicates that the transmissibility of the McBean Formation is generally less than the transmissibility of the Tuscaloosa, although in some areas the permeability of the McBean Formation is greater than that of the Tuscaloosa.

The fairly substantial range in permeability for the McBean Formation within the SRP area may be attributed in part to the predominance of tubular limestone and well-sorted sand in the formation in some localities and to a lesser proportion or predominance of clayey sand in others.

TABLE 5.—*Summary of pumping-test data on the McBean and Congaree Formations*

Pumping well	Observation well	Date of test	SRP process area	Pumping rate (gpm)	Aquifer thickness (feet)	Transmissibility (gpd per ft)	Permeability (gpd per sq ft)	Storage coefficient
10 TCA	9 TCA	4-16-51	Near C	480	60	59,000	980	0.0002
14 TSC	14 TC	4-20-51	CS	175	50	7,200	140	
26 CY	26 CY	10-18-51	Near P	410	105	100,000	950	

BARNWELL FORMATION

GEOLOGIC CHARACTER

The term Barnwell Formation is used in this report to designate the sandy deposits of late Eocene age that unconformably overlie the McBean Formation of middle Eocene age in Aiken and Barnwell Counties. Sloan (1908, p. 454) first applied the name Barnwell to the upper unit of his Buhrstone which characteristically occurs in and adjacent to Barnwell County. Later, Cooke (1936, p. 89) adapted the term from Sloan's description and used it in the sense stated above. According to Cooke (1936, p. 89–90), the Barnwell Formation transgresses northward across the McBean Formation, the Tuscaloosa Formation, and the crystalline rocks of the Piedmont.

The stratigraphic position of the Barnwell makes a late Eocene (Jackson) age classification plausible; however, a lack of definite agreement prevails concerning the origin and dating of this formation. Cooke (1936) mapped all the deposits in the Tertiary overlap in the northern part of Aiken County as the Barnwell Formation. Later, MacNeil (in Cooke and MacNeil, 1952, p. 26) considered as Claiborne (middle Eocene) a large part of the sediments that Cooke (1936) had earlier called Jackson (including the Santee and Barnwell Formations). A small part of Cooke's Barnwell remains as the only outcropping formation of Jackson age. MacNeil (in Cooke and MacNeil, 1952, p. 22) also considered as Claiborne much of the material he had previously mapped as Jackson in east Georgia (MacNeil, 1947).

The Barnwell Formation is exposed in the uplands in most of Aiken and Barnwell Counties, but it has been removed by erosion in the valleys. The formation thickens to the southeast, from 0 in the northern part of Aiken County to approximately 90 feet at the southeast boundary of Barnwell County.

The general appearance and lithology of the Barnwell Formation resembles that of a residuum of sandy limestone strata from which most, if not all, the calcareous material has been removed by solution. The deposits are mainly composed of deep-red fine to coarse clayey sand and compact sandy clay. Other parts of the formation contain beds of mottled-gray or greenish-gray sandy clay and ledges of ferruginous sandstone that range in thickness from 1 inch to 3 feet. The differences in the color of these deposits may be due to differences in the degree of weathering. Nonetheless, the deep-red materials are generally semiconsolidated and are generally exposed in steep-walled cliffs or bluffs such as that shown in figure 18.

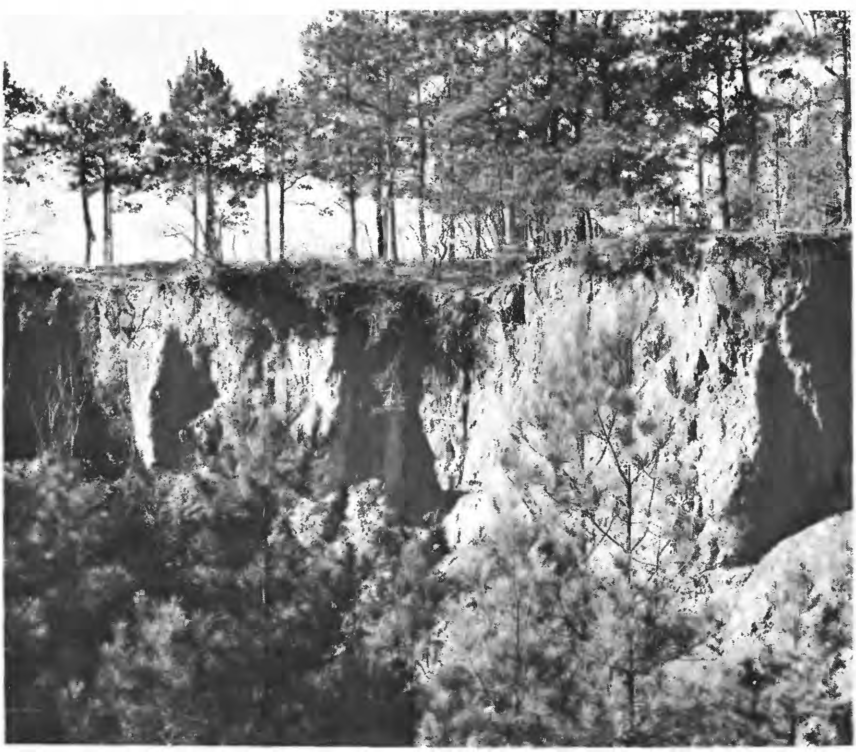


FIGURE 18.—Typical vertical-face weathering of red sandy clay in Barnwell Formation, 5.2 miles southeast of Clearwater.

At Shell Bluff in Burke County, Ga., a shell bed containing the oyster *Ostrea gigantissima* Finch crops out along the west side of the Savannah River at an approximate altitude of 170 feet above mean sea level. This bed reportedly forms the basal part of the formation. At Griffins Landing, 11 air miles downstream, numerous specimens of *O. gigantissima* Finch occur in a bed that crops out at average river level or at an altitude of about 90 feet in an apparent contact with the underlying McBean Formation. The dip of the base of the Barnwell (or the top of the McBean Formation) is thus about 8 feet per mile in a southeast direction. Several of the same species of oyster were recovered from an excavation 2 miles southeast of Ellenton in Barnwell County, but these specimens were probably not in place inasmuch as they occurred at an altitude lower than the top of the McBean Formation. Other specimens were obtained from an exposure that probably represents the base of the Barnwell Formation in the east bank of Lower Three Runs at Usserys Bluff at an altitude of approximately 110 feet above mean sea level.

As indicated above, *Ostrea gigantissima* forms the base of the Barnwell Formation in exposures on the west side of the Savannah River. On the east side of the river and extending across Aiken and Barnwell Counties, this oyster is not ordinarily found at this contact. In its place is commonly found a layer of flat rounded quartz pebbles.

Other than the occurrence of the aforementioned *O. gigantissima* Finch, fossils are rare in the Barnwell Formation. Some cherty layers have yielded fragments of mollusks and bryozoa, and fragments of oyster shells were obtained in the cuttings from several test wells, but the preservation of the oyster shells was inadequate for positive species determination. Some of the macrofauna that have been identified from exposures of the Barnwell Formation in addition to the *O. gigantissima* Finch include *Lepidocyclina ocalana* (found along with bryozoa and other fossils of late Eocene age at Jacksons Landing on the Savannah River), *Turritella* sp., and *Scutella* sp. (found near Lower Three Runs).

Microfossils were obtained from the Barnwell Formation at a depth of 167.5–168.5 feet in test well PG–4 (P area). They were identified by Miss Todd as representative of Jackson age. The specimens included the following species:

Nonion advenum (Cushman)
Elphidium sp.
Valvulineria jacksonensis (Cushman)
Discorbis cocoaenisis (Cushman and Garrett)?
Cibicides lobatulus (Walker and Jacob)

Assignment of a Jackson age to the fossil assemblage was based on the similarity of the species to those in the Twiggs Clay Member of the Barnwell Formation of Jackson age in Georgia. However, it was determined from data in surrounding wells that the interval containing these fossils was several feet below the average altitude of the top of the McBean Formation. These data suggest therefore that either the fauna were not in place or, as believed by the author, that the Twiggs Clay Member as designated in Georgia is equivalent to the Congaree Formation of middle Claiborne age in South Carolina.

Concretionary blocks or boulders of pisolitic clay were observed in the Horse Creek valley, about 2 miles west of Graniteville. Inasmuch as this location is within the outcrop area of the Tuscaloosa Formation, the boulders were probably not in place but had been dislodged from stratigraphically higher Tertiary beds and collected near the base of the valley. This interpretation is based on the fact that beds of pisolitic clay are known to occur generally at the base of deposits of Claiborne age (fig. 16). This occurrence is consistent with available data on the age of bauxitization in the Gulf and Atlantic Coastal Plains, where bauxite is generally considered to have been formed from clay of Cretaceous and early Wilcox ages. Thus, the presence of the transported blocks or boulders of pisolitic clay in strata laid down during the next time of deposition (Claiborne) seems reasonably consistent with the dating of the bauxitization. Additional outcrops of pisolitic clay occur in and around the Bell kaolin pit, 2.3 miles north of New Holland on State Highway 39, Aiken County, and about 4 miles due east of New Holland Crossroads in the Seivern quadrangle. Thus, this part of the Tertiary overlap, previously mapped as Barnwell, is probably Claiborne in age.

Consideration has been given to the possibility that material referred to as the Barnwell Formation was deposited as alluvium in the Savannah River basin during Pliocene to Pleistocene time. Admittedly, some outcrops of the Barnwell Formation exhibit features suggesting alluvial deposition, more particularly in areas within or contiguous to the Savannah River basin (fig. 8). Additional evidence for the alluvial origin hypothesis may be the presence of red compact sandy clay similar to that in the Barnwell Formation along the left banks of other major streams in the State such as those adjacent to the Congaree and Wateree Rivers. But within the red beds along the Wateree River have been found marine macrofauna identified as Eocene in age.

Additional factors unfavorable to an alluvial origin for the Barnwell Formation include (1) its extensive occurrence beyond the probable basinal limits of the Savannah River drainage system and (2) the presence of substantial amounts of limestone in the formation, at least on the Georgia side of the river. Some of these deposits of limestone are sufficiently extensive as to warrant designation as a member, for example, the Sandersville Limestone Member (Cooke, 1943). Moreover, the deposit overlying the oyster bed at Griffins Landing is preponderantly calcareous and could be classified as limestone. Finally, lenses of limestone occur interbedded with the characteristic deep-red clayey sand of the Barnwell in eastern Georgia where the unit has been mapped (MacNeil, 1947) as a continuous formation as far west as the Ocmulgee River in central Georgia. (Here again, exception might be taken to this factor on the basis that there is some indication the limestone previously mapped as the Barnwell Formation in central and eastern Georgia may more accurately represent deposits of Claiborne age; no limestone is recognized in the Barnwell Formation in South Carolina.) However, if the Barnwell Formation, consisting primarily of clastic deposits, is only partly as extensive as mapped in these areas, this distribution seems doubtfully consistent with an alluvial deposition concentrated in the Savannah River basin during Pliocene to Pleistocene time.

These factors indicate that a considerable part of the Barnwell Formation was deposited as an arenaceous limestone in a near-shore or estuarine environment during early to middle Tertiary time. Some evidence of the remnant calcareous nature of the formation is indicated by the comparatively high proportion of calcium carbonate found in ground water circulating through this unit. This constituent is characteristic of natural water circulating through carbonate rocks, but is present in much smaller amounts in water circulating through sand aquifers.

WATER-BEARING PROPERTIES

Even though the Barnwell Formation is composed predominantly of sand, it does not yield water readily to wells, partly because of the small size of the sand particles. It is a well-known hydrologic principle that the smaller or finer the grain size of a granular material, the greater the resistance offered by the material to the flow of water and, under prevailing natural gradients, the smaller the rate of flow of water through the material. Another reason for the low water-yielding capacity of the Barnwell Formation is the presence of admixed amounts of silt- and clay-sized particles which serve to impede the flow of water by occupying and thus reducing the space between individual sand particles.

Nevertheless, in some localities the sand of the Barnwell Formation is sufficiently coarse and free from admixtures of silt and clay as to provide moderate water yields to wells. One example is well BW–10 which is in the town of Willistown about 5 miles northeast of the SRP. This well is 150 feet deep and yields 200 gpm. Elsewhere in the outcrop area of the Barnwell Formation (pl. 1), shallow wells obtain water from the formation for domestic uses and livestock.

HAWTHORN FORMATION

GEOLOGIC CHARACTER

The Hawthorn Formation of Miocene age was named by Dall (1898) from a town in Alachua County, Fla. The name was introduced into South Carolina by Cooke (1936, p. 101) who included within the Hawthorn the stratigraphic units that were previously identified as (1) the Combahee Shale, (2) the Parachucla Marl, (3) the Parachucla Shale, the Marks Head Marl, and part of the Ashley Marl, (4) the Edisto Marl, and (5) the Salkehatchie phase of Sloan (1908).

In most areas where it is recognized, the Hawthorn Formation is separated from the underlying Eocene or Oligocene deposits and from the overlying Pliocene deposits by an erosional unconformity.

The Hawthorn Formation crops out in a very large part of the southeastern Atlantic Coastal Plain and probably represents the most extensive surficial deposit of Tertiary age in this region. The area of outcrop extends northeastward from Alabama and Florida across Georgia into South Carolina. In Aiken County the Hawthorn Formation immediately underlies the land surface in the topographically high areas. Toward the south and east the Hawthorn Formation occurs at progressively lower altitudes and eventually passes beneath a thin mantle of younger deposits that constitute a series of coastal terraces. It thickens from 0 in northwestern Aiken County to approximately 80 feet in the vicinity of the Barnwell-Allendale County line.

The Hawthorn Formation is characteristically composed of fine sandy phosphatic marl or soft limestone and hard brittle shale resembling silicified fuller's earth. In the up-dip area of Aiken and Barnwell Counties, however, it consists mainly of tan, reddish-purple, and gray sandy dense clay that contains coarse gravel and limonitic nodules. Small white flecks of kaolinitic material that are commonly disseminated throughout the formation give it a white mottled appearance (fig. 19). Generally, the color pattern of the deep-red to purple clay resembles that of alligator skin. Coarse angular brown pebbles of ferruginous to phosphatic(?) composition occur commonly as a thin deposit over the outcrop area of the Hawthorn Formation.

The most unusual feature of the Hawthorn Formation is the numerous sediment-filled fissures or clastic dikes crisscrossing the clayey sand. This feature is particularly conspicuous in exposures of the Hawthorn Formation in Barnwell County (fig. 20). The fissures extend to considerable depth, as revealed by excavation, and they are generally filled with a greenish-gray silty to sandy clay. The dike

FIGURE 19.—Crossbedded kaolin-flecked facies of Hawthorn Formation in cut 2.4 miles northwest of Dunbarton.

FIGURE 20.—Clastic dikes in the Hawthorn Formation exposed in a cut 5 miles northwest of Dunbarton.

wall, 0.2–1.0 inch thick, is generally indurated and consists of an iron-oxide-cemented quartz sand. The enclosing sediments consist of tan to red or purple coarse sand and clay. There is also a noticeable degree of orientation or lineation of the dikes. Most of those selected for measurment in Barnwell County showed a strike of either N. 85° E. or N. 5° E. and a dip of 45°–55° in either direction from the line of strike. The consistent alinement of a large percentage of the dikes is their most noticable characteristic and is rather unusual in unconsolidated sediments. Although clastic dikes have been observed elsewhere in the Coastal Plain, they are not so numerous nor so well alined as those in Barnwell County.

The origin of the dikes may be attributed to several factors: (1) shrinkage resulting from weathering, (2) seismic activity, and (3) relief of compressional stresses by the upward movement of plastic material. Many similar structural features in consolidated sediments elsewhere are generally explained on the basis of the first hypothesis, and the nonoriented or unalined dikes in this area most probably were formed in this manner. However, this hypothesis does not appear to be a completely satisfactory explanation for the formation of the alined dikes, inasmuch as they are apparently confined to the post-Eocene or at least post-Claiborne sediments. Although the second possibility, seismic activity, is a likely causative force, it also seems probable that the dike itself was formed both by means of infilling, at an equal pace, of overlying material and by the mechanism included in hypothesis 3. So far as is known, there is no material present now in a stratigraphically higher position in the geologic section and similar in composition to the fracture fill that conceivably might have worked down into the fissure as it was being formed. There is, however, greenish-gray clay in the Hawthorn Formation at downdip localities that could have been present in this area in the geologic past and would be a likely source for such filling. There is also similar clay stratigraphically lower in the geologic section—a fact which suggests that possibly some dikes were injected up through the younger Tertiary rocks. Conceivably this injection may have been brought about by the failure of underlying beds to support compressional stresses. Under such conditions the weight of the overlying material would cause a failure in the substructure brought about by groundwater solution of the underlying calcareous beds. When these beds could no longer support the overlying formations, fractures would develop as the superstructure collapsed, and clastic material below would migrate up into the fractures. Some corroborative evidence for such an origin is indicated by the large number of solution inks in the vicinity of the dikes, as for example, in the northeastern quarter of the Ellenton quadrangle. Conversely, dike swarms are indigenous

243-540 O—67——5

to those areas exhibiting other features of solution and collapse.

An interesting speculation concerns the relation, if any, that these fractures may have with the origin of the so-called Carolina bay structure. Such a fracture system might affect or control the orientation of areas of accelerated solution by circulating ground water and thereby produce an incipient sink or bay. Figure 20 shows the characteristic lineation of the dikes. The black and white photograph shows an apparent similarity between the dike fill and the overlying material; however, the two materials are lithologically dissimilar.

The fossil tube, *Halymenites major* Lesquereux[1], occurs quite commonly in the sandy clay of the Hawthorn Formation. The origin of this fossil is uncertain, but it is presently thought to be the borehole of a brackish-water crustacean and indicative of primarily a shallow neritic and littoral environment. The wall is built up of contiguous or separate tubercles. A typical specimen is shown in figure 21. Although the occurrence of *Halymenites* may not be limited to this formation exclusively, it does appear that these borings are more

[1] The generic term *Halymenites* is used here, although relatively similar tubercular structures observed in deposits of Pleistocene to Recent age along the Atlantic seaboard have been identified with the living organism *Callianassa*. The inference has also been drawn, though not proved conclusively, that the fossil structures found in older (Tertiary and Cretaceous) deposits were formed by the burrowing crustacean variously described as *Callianassa* or *Ophiomorpha*.

FIGURE 21.—*Halymenites* in the Hawthorn Formation, 4½ miles northwest of Dunbarton.

prevalent in the Hawthorn than in other formations in the report area. *Halymenites* tubes occur also in some alluvial and colluvial materials that are closely associated with the Hawthorn Formation in the larger stream valleys.

To date no microfauna have been recovered from known exposures or subsurface samples of the Hawthorn Formation. A small assemblage of Foraminifera were recovered from a depth of 14–23 feet (about 270 ft. mean sea level) in test well AK–03, on the southeast bank of Tinker Creek, 2.5 miles upstream from its junction with Upper Three Runs (near Sloan's locality 42, Sloan, 1908). These fauna were identified by S. M. Herrick (written commun. July, 1961) as:

Elphidium poeyanum (d'Orbigny)
Discorbis cf. *D. hemisphaerica* Cushman
Cibicides americanus (Cushman)?
Cibicides lobatulus (Walker and Jacob)
Cibicides cf. *C. concentricus* (Cushman)
Nonion matagordanum Kornfeld
Globigerina sp.

Although the Forominifera were recovered from depths correlative with the Hawthorn Formation, the identity of the assemblage, particularly that of *Cibicides* cf. *C. concentricus*, indicates a closer affinity to deposits of late Miocene age, possibly correlative with the Duplin Marl. The nature and structure of the sediments correlated with the Hawthorn Formation exhibit characteristics indicating considerable caving and slumping within this part of the section, and it seems plausible that these younger fauna slumped in from higher altitudes or else that their recovery from older beds is an accidental consequence of the drilling operation. It is also noted that whereas these are the only representative Duplin fauna recovered in the area, there may have been considerable widespread deposition of sediments here during late Miocene time, most of which have been removed by subsequent erosion or solution. Thin remnants of late Miocene deposits are known to be scattered over the larger part of the Coastal Plain in this State.

The designation of the deposit herein described as the Hawthorn Formation has been subject to as much difference of opinion as that concerning the Barnwell Formation. Doering (1958, 1960) includes all the Hawthorn Formation and part of the Barnwell Formation in his Citronelle Formation of early Pleistocene (preglacial) age.

Here again it must be admitted that such a grouping of all the undifferentiated surficial units of Tertiary age into one formation would appear to simplify the field problem of distinguishing among several outcropping Tertiary deposits (Hawthorn, Barnwell, McBean, and Congaree Formations). Too, some lithologic and structural features discussed above lend additional weight to the classification of the Hawthorn as a soil zone rather than a formational unit.

There are also several factors, however, which do not support this interpretation. As mentioned previously, the age of bauxitization in the southeast has been confined principally to early Claiborne time, and although similar environmental conditions conceivably could have occurred during any subsequent time, no evidence has been found to substantiate a different age for this process in South Carolina. Therefore, the presence of pisolitic clay high in the section (470 ft mean sea level) northeast of Aiken appears inconsistent with the age and environmental conditions proposed in Doering's Citronelle Formation. The presence of middle Claiborne fauna (listed on p. 45), found in place, northeast of Aiken at an altitude of 475 feet above sea level is incompatible with the dating of the Citronelle Formation (Doering, 1960, fig. 7), as is the section southeast of Tinker Creek, where Foraminifera of late Miocene age (listed on p. 61) were found in testhole AK–03 at an altitude of about 270 feet above sea level. In addition the presence and fairly common distribution of *Halymenites major* Lesquereux suggests a brackish-water environment for this deposit.

The significant factor here lies in the fact that whether or not the unit referred to as the Hawthorn Formation is of Miocene age or Pleistocene age, whether it is representative of alluvial, estuarine, or fluvial environments, or whether it represents a peculiar type of soil zone, the unit does constitute a reasonably consistent lithologic entity recognizable over fairly extensive areas, and as such it exhibits distinctive characteristics as a discrete hydrologic unit.

WATER-BEARING PROPERTIES

The fine-grained materials within the Hawthorn Formation, consisting of compact silt and clay, are incapable of yielding water and are therefore considered not suitable for the construction of wells. In fact, so effectively do the silt and clay of the Hawthorn Formation impede the vertical infiltration of water, that bodies of perched ground water are generally present wherever permeable parts of the formation overlie the almost impervious beds of this unit. Such a condition is fairly common in the topographically high places in the southeastern part of the report area.

ALLUVIAL DEPOSITS

Alluvial deposits of late Tertiary age occur irregularly and discontinuously on the interstream divides or plateaus. They are composed of coarse gravel and poorly sorted sand and are tentatively classified in this report as Pliocene in age, owing to their stratigraphic and topographic position above deposits of Eocene and Miocene age. The thickness of these deposits ranges from 5 to 20 feet. Included in this category are the alluvial deposits that occur along the east flank of the Savannah River basin. They probably represent materials reworked from the Tuscaloosa Formation.

Generally, the poorly sorted sand and gravel that constitute the alluvial deposits are considerably above the water table and, consequently, they have little importance as a source of ground water for wells. Nevertheless, these deposits are fairly permeable, and hence are capable of storing and transmitting water. For this reason and because these deposits occur at the land surface, it is presumed that water from precipitation is absorbed by them at land surface and transmitted to underlying permeable formations. This transmitting capability contributes indirectly to the availability of ground water in the area. Moreover, by absorbing a part of the precipitation at the land surface, these deposits actually reduce storm runoff and thereby reduce the threat of floods.

QUATERNARY SYSTEM

MARINE TERRACE DEPOSITS

Cooke (1936, p. 130) recognized seven marine terraces of Pleistocene age on the Atlantic Coastal Plain of South Carolina. He indicated that the four highest terraces are present in the Savannah River valley in the report area. Cooke later (1954, p. 202–204) included a fifth terrace in this sequence. From oldest to youngest, the names and approximate altitudes of the terraces as defined by Cooke are (1) Hazlehurst (formerly called Brandywine in this area), 270 feet; (2) Coharie, 215 feet; (3) Sunderland, 170 feet; (4) Okefenokee, 145 feet; and (5) Wicomico, 100 feet.

Objections have been raised to the designation of the high (and some intermediate) terraces as marine features of Pleistocene age because their present physiographic expression is too nebulous for positive correlation as remnants of (1) former marine plains, (2) marine bars, or (3) wave-cut cliffs, or even as remnants of fluvial plains. Whatever their origin, there is fairly distinct evidence of separate terrace deposits in some areas, as for example in the vicinity of Hamburg, Aiken county, and in parts of the Horse Creek valley.

The terrace deposits, which are considered formations by Cooke and others, are generally not more than a few tens of feet thick, and even though their permeability may be moderately high in places, their importance as water-bearing beds remains unproved. Nonetheless, they probably function hydrologically in much the same manner as that described for the alluvial deposits of Tertiary age—a surficial porous media through which water from precipitation must pass to recharge other water-bearing beds.

ALLUVIUM

Alluvium of Recent age occurs in the tributary and main channels of the Savannah River and in the channels of the South Fork Edisto River. These deposits are generally crossbedded and heterogeneous in composition and range in thickness from about 5 to 30 feet. The poorly sorted sand, clay, and gravel appear to offer poor facilities for ground-water development. However, some of the alluvium in the larger streams, such as that along Horse Creek, may be suitable for development of fair'y large supplies if infiltration of surface water could be induced by vertical wells or horizontal collectors.

WATER-BEARING PROPERTIES OF THE QUATERNARY SEDIMENTS

The reservoirs formed by the water-bearing zones in the Quaternary sediments yield water to many shallow domestic wells southeast of the outcrop area of the Tuscaloosa Formation (pl. 1). Water-table conditions prevail at shallow depths where permeable sediments immediately underlie the land surface and extend to a depth equivalent to or greater than the depth of the water table. Thus, in drilling a well in the outcrop area of the Quaternary sediments, the first water-bearing zone found in the well is likely to contain water under water-table conditions, but the underlying zones in the older formations are likely to contain water under artesian conditions.

MUNICIPAL WATER SUPPLIES

Most of the municipal water supplies in the area utilize ground water as a source. Two cities, Aiken and North Augusta, use surface water. North Augusta is on the Fall Line where the sand aquifers are pinching out and the zone of saturation is too thin to provide the amount of water needed. Aiken, several miles from the Fall Line, is underlain by approximately 500 feet of unconsolidated sand and clay and uses both ground and surface water. Shiloh Springs, in the Tuscaloosa Formation, provides much of the water used.

In Aiken County nearly all the municipal wells are developed in the sand beds of the Tuscaloosa Formation; some exceptions occur in the northeastern part where a few wells are screened in the McBean Formation of Eocene age. In Barnwell County, proportionately more wells utilize the sands of the Barnwell and McBean Formations of Eocene age. Other wells, however, obtain water from the Tuscaloosa and Ellenton Formations of Late Cretaceous age. In Allendale County, the municipal wells are developed in the limestone of Claiborne age and in the underlying sand deposits of Late Cretaceous age.

A description of the municipal water systems and their water utilization is included in the following tabulation:

Municipality	Type	Source	Total capacity (mgd)	Average use (mgd)
Aiken	1 well	Tuscaloosa Formation	0. 45	0. 45
	Spring	Shiloh Springs	1. 6	1. 55
	Surface water	Shaw Creek	[1] 2. 0	
Allendale	3 wells	Eocene limestone Cretaceous sands	1. 4	. 25
Barnwell	8 wells	McBean Formation [2] Tuscaloosa Formation	4. 0	2. 0
Blackville	3 wells		1. 0	. 13
Jackson	2 wells	Tuscaloosa Formation	1. 0	. 04
New Ellenton	do	do	. 84	. 35
North Augusta	Surface water	Springs and Savannah River.	2. 0	. 75
Salley	2 wells	McBean Formation Tuscaloosa Formation	. 3	. 07
Wagener	3 wells	Tuscaloosa Formation	. 8	. 3
Warrenville	5 wells	do	. 12	------
Williston	3 wells	McBean Formation Tuscaloosa Formation	1. 17	. 19
Total			16. 73	5. 65

[1] Auxiliary.
[2] Unrestricted McBean Formation, equivalent to McBean and Congarce(?) Formations.

The quality of water used for municipal supplies is generally satisfactory to good. Some sands in the Ellenton Formation and possibly some of the sands of Eocene age yield water containing relatively high amounts of iron—greater than 1.0 ppm (parts per million). Wells developed in the limestone of Claiborne age generally obtain water that is moderately hard (60–70 ppm) Water from the Tuscaloosa Formation, especially near the outcrop area, is generally acidic and very low in total solids. In addition, in some areas it may contain appreciable amounts of dissolved oxygen and carbon dioxide and thus tends to be corrosive to metal surfaces.

The subject of water quality as it pertains to each separate formation is described in greater detail in pages 81–90.

WATER-LEVEL FLUCTUATIONS

During the investigation, the water level was measured periodically in a series of observation wells within the report area. A total of 93 wells was measured periodically from April 1951 to December 1954. From 1955 through 1960, seven wells were measured periodically or were equipped with automatic recording gages. Of the original 93 observation wells, 24 wells reflected fluctuations in the aquifer of the Tuscaloosa Formation, 2 in the aquifer of the Ellenton Formation, 22 in the aquifer of the McBean Formation, and 45 in the aquifer of the Barnwell and Hawthorn Formations.

Water-level fluctuations due to rainfall are greater in wells tapping water-table aquifers than in those tapping artesian aquifers. Ground-water recharge and ground-water discharge are two of the natural causes of fluctuations in water levels. Variations in recharge in the form of accretion from rainfall, streams, or irrigation cause changes in water levels. When the water table is close enough to the land surface, seasonal and diurnal variations in discharge in the form of evaporation from the ground surface and transpiration through plants and trees likewise cause water levels to fluctuate. The topographic location of a well ending in a water-table aquifer also influences the range of its water-level fluctuations. Water levels generally fluctuate more widely in wells near a topographic divide than in wells near a place of natural discharge, as along a stream.

In the artesian aquifers of this area, variations in rainfall cause conspicuous changes in pressure head more in those wells in or near the recharge area. Variations in pressure head cause the artesian aquifer to contract and expand slightly and thereby change the amount of water stored in the aquifer. The additional load of water in the shallow aquifers and surface streams, added during a period of intensive rainfall, is transmitted to the artesian aquifer, and the resulting contraction raises the water levels of wells in the artesian aquifers (Siple, 1957, p. 295). Changes in atmospheric pressure are recorded in many wells by a rise in water level corresponding to a decline in barometric pressure and by a decline in water level corresponding to a rise in barometric pressure. The ratio of the change in water level to the change in barometric pressure is referred to as the barometric efficiency of the well.

Along coastal areas the water levels in artesian wells fluctuate as a result of the alternate loading and unloading of the aquifer by oceanic tides. In inland areas, earth tides cause slight water-level fluctuations in artesian wells. As with ocean tides the amplitude of earth-tide fluctuations is greatest at new or full moon, when the moon and the sun are in conjunction. Other loading effects such as those caused by passing railroad trains and changes in stage of surface-water bodies overlying an artesian aquifer cause fluctuations in the artesian pressure. Intermittent pumping is one of the most common causes of water-level fluctuations in nearby wells.

The water-level fluctuations indicated in figures 22–31 illustrate the range of water-level fluctuations in wells screened in the Tuscaloosa, Ellenton, McBean, Barnwell, and Hawthorn Formations. The amplitudes of natural fluctuations are greatest in the aquifer comprising parts of both the Barnwell and Hawthorn Formations. Because this aquifer immediately underlies the ground surface over a large part of the project area, it is more susceptible to the wide variations in water level caused by variations in rainfall, evaporation, transpiration, and loss to surface streams.

WATER LEVELS IN THE TUSCALOOSA AND ELLENTON FORMATIONS

Figure 22 shows the hydrographs of wells 21–F and 15–M as constructed from intermittent tape measurements; however, during the period October 1952 to March 1954, water-level measurements were obtained weekly and during this period some of the most significant changes occurred. Both wells are developed in the Tuscaloosa Formation, and the hydrographs are characterized by a period of sharp water-level declines during 1951–53, followed by a period of less extensive declines or even partial recoveries. The recoveries indicated during this period (1954–60) were considerably less than those measured in other observation wells owing to the fact that wells 21–F and 15–M are in areas of heavy pumpage. The total water-level decline in well 15–M approximated 30 feet, the maximum decline recorded for any well obtaining water from Cretaceous formations.

Figure 23 includes the hydrographs of two wells obtaining water from the Tuscaloosa Formation. More than 4,500 feet separates well 4–M from the nearest pumped well. There is no pumped well of

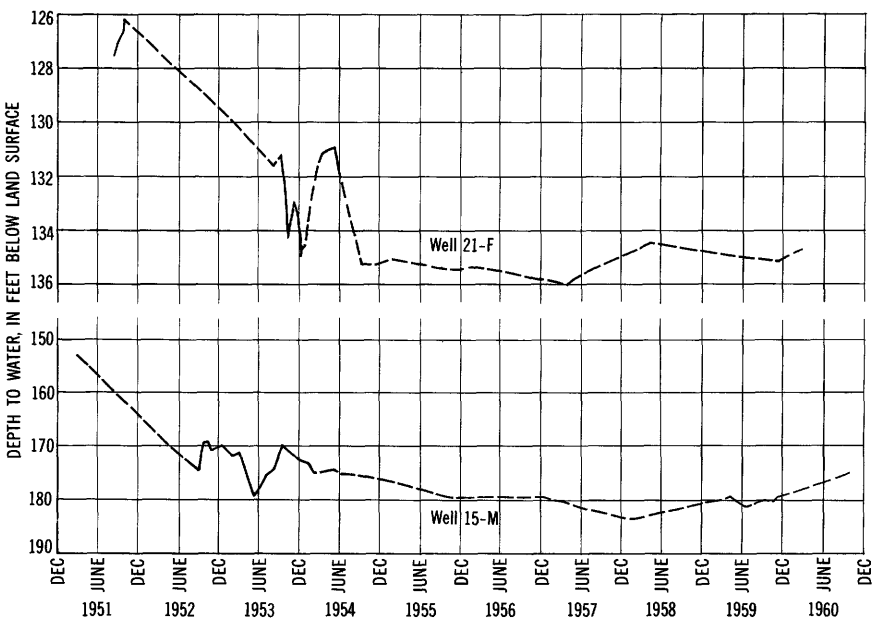


FIGURE 22—Water levels in wells 21–F and 15–M (Tuscaloosa Formation).

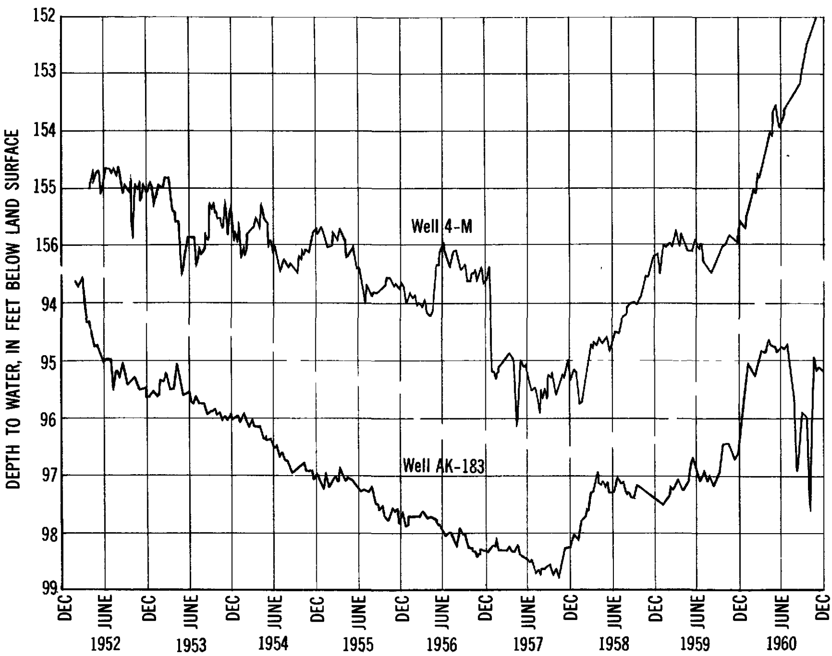


FIGURE 23—Water levels in wells 4–M and AK–183 (aquifer of the Tuscaloosa Formation).

comparable depth within a mile of AK–183. The hydrographs of both wells exhibited a parallelism that is typical of the water-level fluctuations of wells in the Tuscaloosa Formation during the 1952–60 period. The principal characteristic of these hydrographs is the steady decline in water-level during the 1952–57 period. The latter half of this period was coincident with that of deficient rainfall in the general area of Augusta, Ga., and Aiken and Barnwell, S.C. The period from June 1952 to June 1954 included the most intensive constructional activity at the Savannah River Plant, and this activity required an extensive use of ground water.

If the graph showing cumulative rainfall departures (fig. 24) is compared with the hydrograph of well AK–183 (fig. 23), a fairly close correlation is evident between the change in water level and departure curve for rainfall. The barograph of precipitation shown in figure 24 represents the average monthly rainfall as measured and reported by E. I. du Pont de Nemours & Co. at the Savannah River Plant. Similar trends are indicated in the hydrograph for well 4–M, but a noticeable discrepancy is indicated in the correlation, that of the water levels for the period from May 1956 through September 1957. This discrepancy is attributed to mechanical difficulties

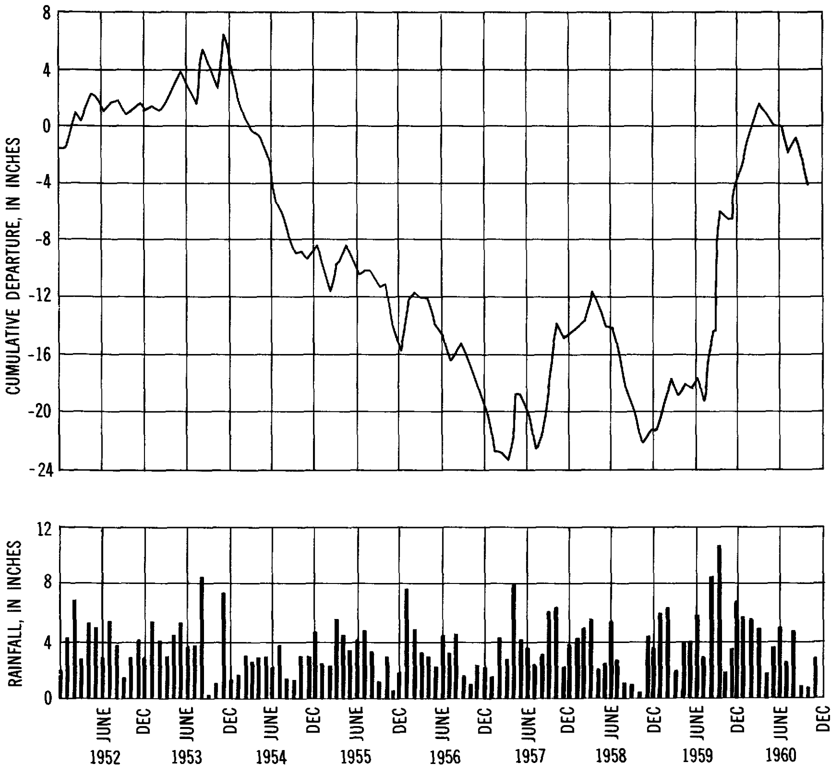


FIGURE 24.—Rainfall and cumulative departure from normal rainfall, Savannah River Plant. (Departure calculated from 83-year record of U.S. Weather Bureau for nearby stations.)

in the recording mechanism or else to lack of good circulation between the well screens and the aquifer. The water level in general reflects the pumpage from the nearby M area, but the correlation is more evident with the combined effect of sustained pumping from all three supply wells in the M area rather than with intermittent pumping from a single well. The prominent saw-tooth fluctuations are produced chiefly by variations in atmospheric pressure and tend to obscure all but the larger effects of pumping.

The hydrographs shown in figure 25, representing water-level fluctuations in wells 27–R, BW–44, and AK–266, also reflect the decline in water stage during the 1952–57 period, followed by a partial recovery from late in 1957 through 1960. These hydrographs reflect the influence of both pumpage and rainfall. The most persistent decline during this period is indicated by the hydrograph for well AK–266, which shows that the water level in October 1958 had dropped about 8 feet from that of 1953. Whereas the hydrographs of

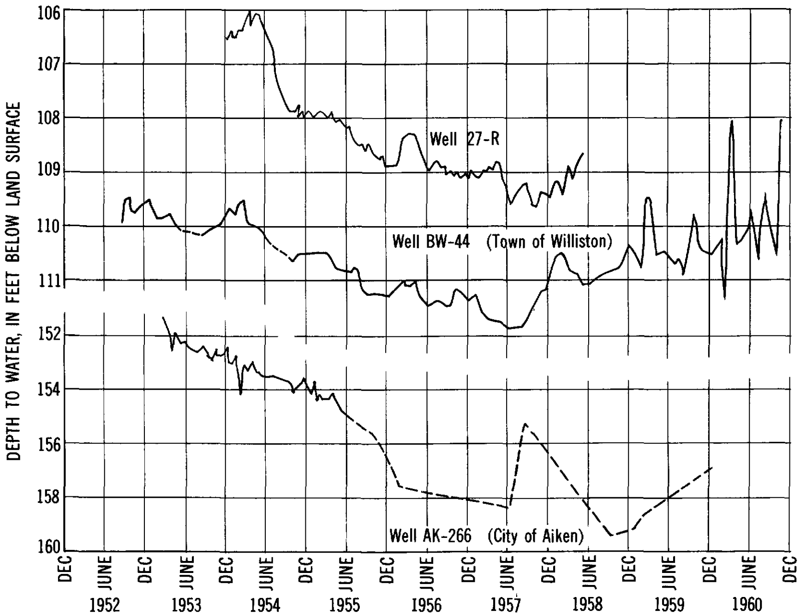


FIGURE 25.—Water levels in wells 27-R, BW-44, and AK-266 (Tuscaloosa Formation).

most other wells in the Tuscaloosa Formation show a recovery in water-level during 1958–60, the trend of water-level decline continued in well AK-266. From the present data, it appears unlikely that pumpage at SRP had any effect on this well. Continuous observations, correlated with pumpage during a more stable rainfall period, will permit more exact determination of this factor. The period of increasing pumpage at SRP does correspond with the period of extensive decline of water level in those wells in the Tuscaloosa Formation situated in peripheral areas surrounding the SRP. If the period of water-level observation had ended with the late 1957 measurements, the decline might have been attributed to the pumpage at SRP (taking into consideration also the contributory factor of substantial rainfall deficiency during this period). The 1957–60 period was characterized by excessive rainfall, whereas the pumpage remained about the same, and the water levels in the observation wells recovered to higher levels. Thus in view of this apparent correlation of water level with rainfall change and the fact that the wells indicated above are near or within the recharge area of the aquifer of the Tuscaloosa Formation, the probabilities are that rainfall, rather than pumpage has had greater effect on the water-level changes in most of the wells.

Figure 26 shows the hydrographs of wells 45–H and 20–M. Well 45–H is approximately 1,900 feet from well 35–H, which was the only well in the H area pumped regularly through April 1954. The low water level in well 45–H in April 1954 was caused by intensive pumping of well 43–H, located approximately 1,200 feet from well 45–H. In the period 1954–60, two additional wells were put into operation in the H area. The present pumping pattern consists normally of pumping either well 44–H or 45–H alternately for a period of about 2 weeks and, during the same period, pumping well 35–H, 43–H, or 48–H. Thus two wells, one from each group, are pumped continuously for a period of about 2 weeks and then alternated with two other wells. The effect of this withdrawal is evidenced on the hydrograph of 45–H which shows that the piezometric decline characteristic of other wells from 1952 to 1957 continued in well 45–H from 1957 through 1959 but at a slower rate. The total pressure drop in December 1959 was approximately 9.0 feet below the original static level.

The hydrograph for well 20–M shows that the largest decline in water level occured in 1952–53, during the constructional phase of the project. Some recovery of water level is indicated in late 1959, probably as a result of the greater than normal rainfall. The total decline in water level as of January 1960 amounted to approximately 11 feet

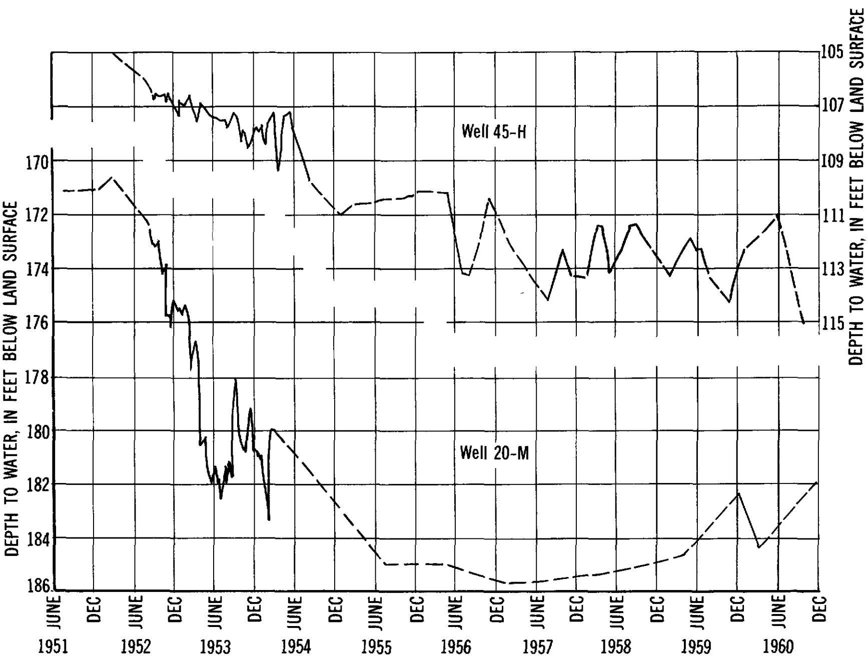


FIGURE 26.—Water levels in wells 45–H and 20–M (Tuscaloosa Formation).

below the original static level of August 1951. This decline was caused by the pumping of well 20-M and, in addition, to that of pumping in the nearby wells.

Figure 27 shows the record of water level in well S–315, near the D area and in well S–411 in the town of Ellenton. Both are flowing wells. Well S–315 flowed continuously until October 21, 1953, at which time a pressure-recording gage was installed on the well, and the shut-in pressure as shown on the hydrograph recovered approximately 4.5 feet. The water level in this well declined progressively until a month before the recording gage was installed. The later records indicate that the head stabilized at approximately 41 feet above land-surface datum. The well is apparently screened in the Ellenton Formation. After prolonged period of flow, the shut-in pressure, as measured with a pressure gage, stabilized only after a considerable lapse of time. In fact, 24 days were required for the pressure to reach stabilization. This time lapse required to establish equilibrium is interpreted to indicate the presence of a considerable amount of intercalated clay lenses within the aquifer.

The casing on well S–411 was extended a sufficient height to permit the installation of a float-type recording gage, and such a gage was used during the periods June 2 to December 8, 1953, and October 10,

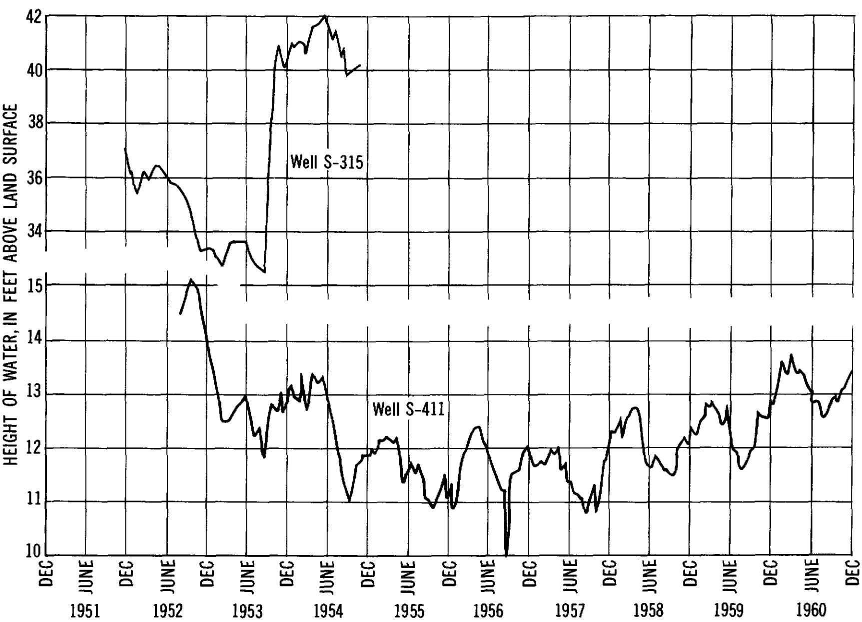


FIGURE 27.—Water levels in wells S–315 and S–411 (aquifer of the Ellenton Formation).

1954, to December 31, 1959. Previously the head in the well was measured with a pressure gage. The well was pumped intermittently for short periods until June 1954. This well is also screened in the Ellenton Formation, and its pressure head reflects a decline similar to that in well S–315 during the period October 1952 to August 1953. The water level in well S–411 is affected by pumping or free flow from the deep wells in the D area. The screened intervals in wells in the D area occur at altitudes ranging from −189 to −353 feet. Well S–411 is screened in the interval −109 to −114 feet. However, the wells in the D area are gravel-packed, and their gravel columns extend higher than the tops of their screens. Consequently, the gravel columns in these wells extend to the same aquifer as that in which well S–411 is screened. Except for the possible extent to which dewatering operations in the area of pumphouse 1 might affect the pressure head in S–411, the decline in head in S–411, due to pumpage in the D area, is a measure of the effect of pumping from the aquifer of the Tuscaloosa Formation on water levels in the Ellenton Formation.

The preceding discussion on water-level fluctuations in wells drilled into the Cretaceous formations is not intended to explain all the detailed fluctuations but rather to identify some of the principal characteristics and trends. The most significant characteristic in the hydrographs of wells ending in the aquifers of the Tuscaloosa and Ellenton Formations is the consistent decline of the piezometric surface from about the middle of 1952 to approximately the same time in 1954. This decline coincides with the period of most intensive construction, when large amounts of water were pumped from the wells. After the summer of 1953, the water levels in some wells recovered to higher levels. The hydrographs also show a continuation of this general trend of declining water levels until the latter part of 1957, and this trend is interpreted to be due for the most part to the subnormal rainfall during this period.

In some of the wells, principally those peripheral to the SRP, a partial recovery of water level began during the latter part of 1957 and continued through 1960. However, in some of the wells more distant from SRP, such as well AK–266, and in some of the wells in or near the more heavily pumped areas, the trend of water-level decline has, for the most part, continued through 1959–1960. The total decline of water levels in the wells in or near the heavily pumped areas ranged from 6 to 30 feet. As of the end of 1959, a general decline of 11 feet (well 20–M) to 26 feet (well 15–M) was noted in the M area, 11 feet (well 2–D) in the D area, 9 feet (well 21–F) in the F area, and 9 feet (well 45–H) in the H area. The water levels of the wells at the end of 1959 are noted here to permit comparison with calculated figures for drawdown given on pages 94–104. The levels for

1960 indicate comparable values with the respective trends of recovery or decline continued during this period. The water levels for other wells in these areas show lesser decline but generally not less than 6 feet. Continued measurement of water levels in these wells in the principal aquifer of Cretaceous age would appear to add significantly to the present knowledge. Such wells as AK–266, AK–183, and BW–44, outside the SRP, together with wells in the heavily pumped areas inside the SRP, and such unpumped wells as 4–M and S–411 are important in this category because of their location and screened intervals and also because of the length of record available. Wells AK–266 and BW–44 are pumped at irregular intervals, but wells 4–M, S–411, and AK–183 are not pumped at any time.

Figure 28 is included to illustrate the comparison between the water levels in wells 27–R and AK–183 and the barometric pressure during the period December 15–28, 1953. Water-level changes correlate closely with barometric fluctuations. The barometric efficiency of these wells is estimated to be approximately 30 percent. The barometric efficiency for well S–411 is about 42 percent and that for well 4–M about 30 percent. However, the barometric efficiency of well 4–M during the hurricane of August 31, 1952, was calculated to be about 40 percent.

WATER LEVELS IN TERTIARY SEDIMENTS

Hydrographs of wells that draw water from the McBean Formation of Claiborne age (middle Eocene) are shown in figures 29 and 30. A recording gage was in operation on well S–138 from April 21, 1954, through December 1960. The daily lowest water levels are shown in figure 29. The water-level trends for 1952 and 1953 correlate closely with one another, but they deviate from the typical cycle of those of other wells throughout the State. This deviation is noted from the fact that the high water level occurs during May, June, and July, whereas in most wells the highest annual water level occurs in the winter or early spring. There is some correlation between high water levels and periods of excessive precipitation, but the correlation is not always consistent with rainfall during other short-term periods. However, a comparison of figure 29 with figure 24 shows a fairly close correlation between long-term water-level trends in well S–138 with the rainfall departure curve for the same period.

The water levels recorded from well BW–14 are influenced by the pumping of two wells about 100 feet away. In November 1953, pumping in the nearby wells was decreased or stopped entirely when two more-distant wells were put into use for the municipal system.

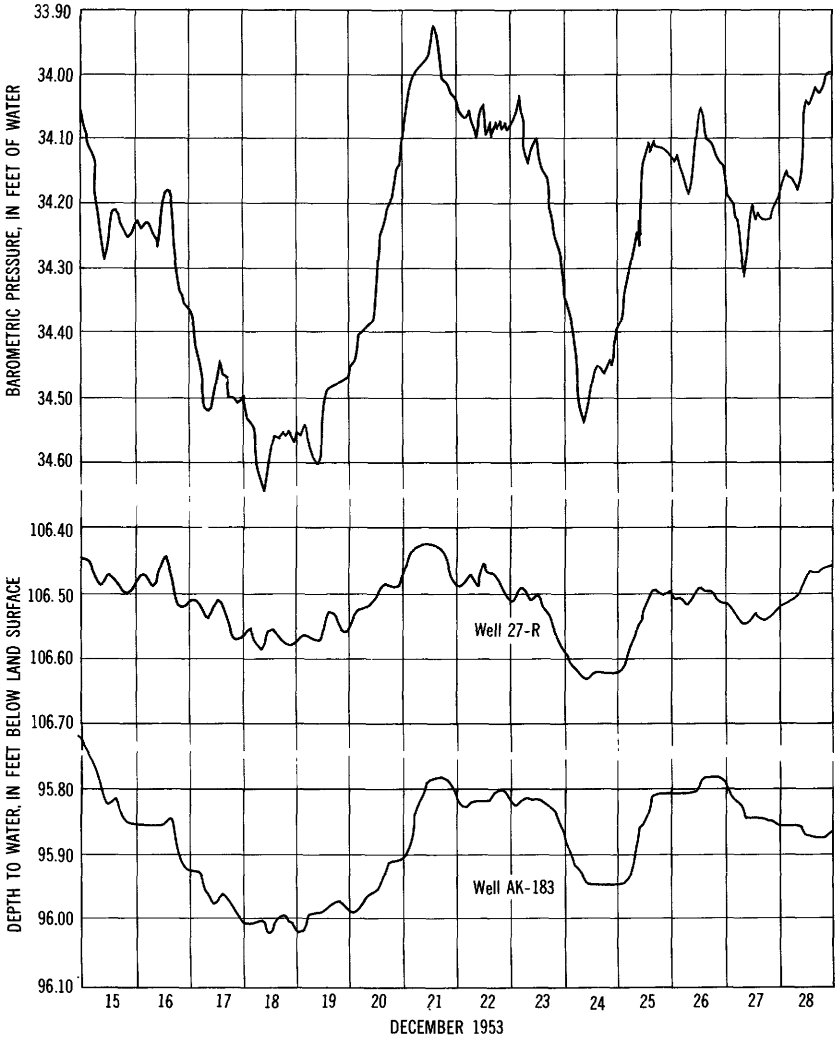


FIGURE 28.—Fluctuations of atmospheric pressure compared with fluctuations of water levels in wells 27-R and AK-183 during the period December 15-28, 1953.

This reduced pumping in the nearby wells is readily apparent in its effect on the water levels in well BW-14.

Water-level fluctuations caused by the loading effect of passing railroad trains were observed in well S-419 in the D area. This well is drilled into the McBean Formation at a depth of 151 feet. Automatic recording-gage records indicate that fast-moving trains have no obvious effect on the water level, but slow-moving trains

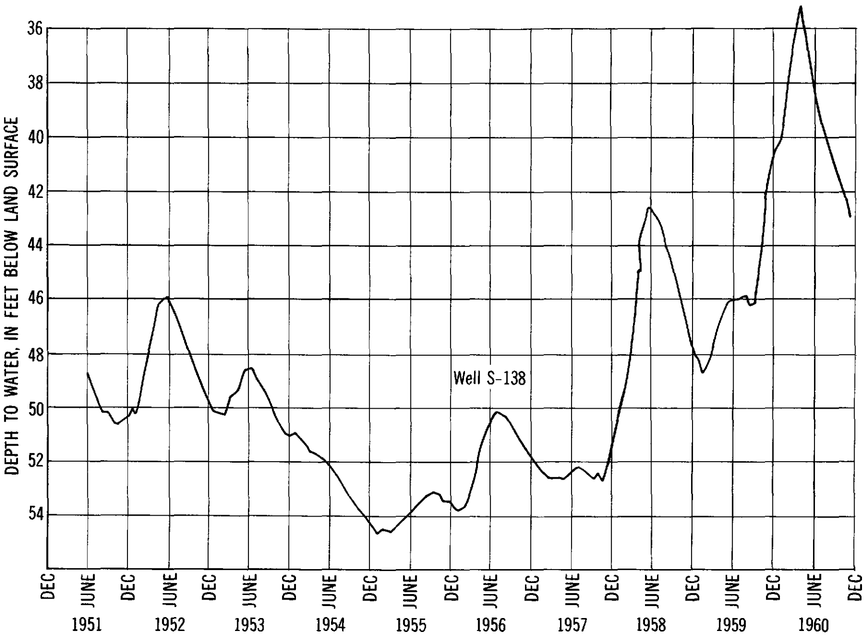


FIGURE 29.—Water level in well S–138 (McBean Formation).

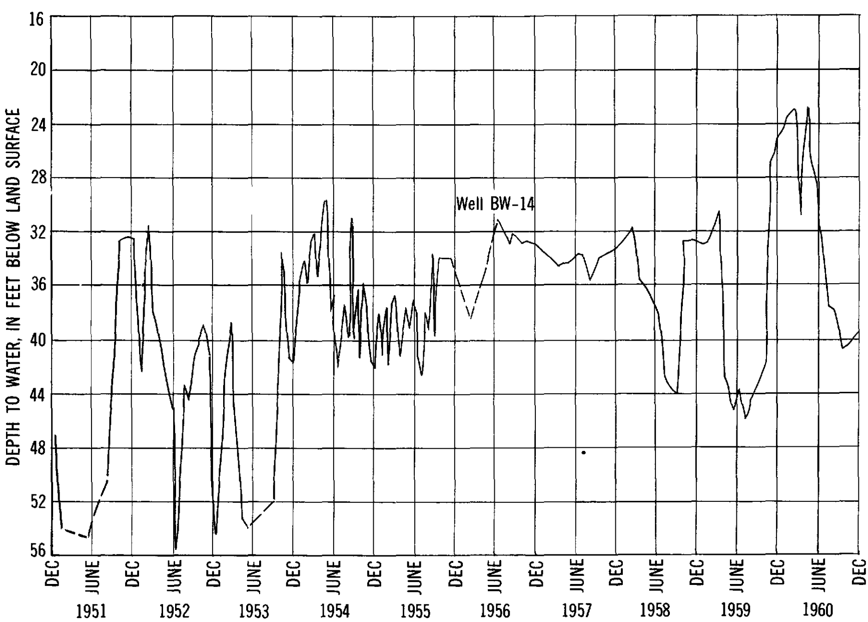


FIGURE 30.—Water level in well BW–14 (McBean Formation).

and especially switching operations on the siding cause fluctuations of as much as 0.07 foot.

Figure 31 shows the hydrographs of two dug wells that draw water from the aquifer of the Barnwell and Hawthorn Formations. This aquifer underlies the ground surface in the upland plateau areas in the eastern part of the project area. The wells used in the illustration reflect water-table conditions almost exclusively.

The hydrographs are plotted from weekly and monthly tape measurements and hence do not reflect short-term fluctuations.

The hydrographs of wells S–53 and S–39 show a recovery from low water levels in the late fall of the year to maximum highs in the spring; a decline in water levels began in late spring and reached maximum lows in early fall. This decline is typical of the usual cycle of water-level change as recorded from other water-table wells throughout the State. Probably the water-level changes in wells S–39 and S–53, and in other wells in the Barnwell and Hawthorn Formations, would correlate closely with the amount of rainfall falling in the immediate area. Normally, rainfall for the area is greatest during the months of

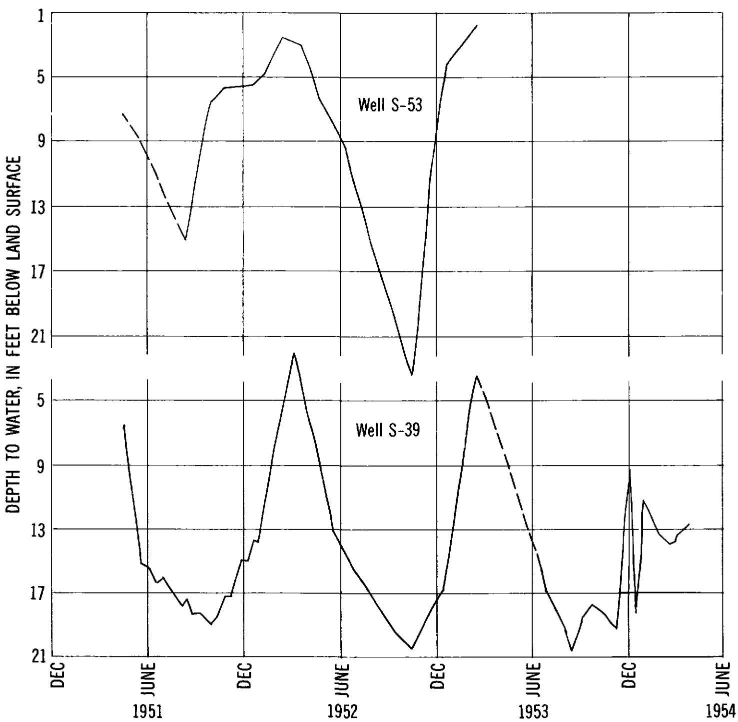


FIGURE 31.—Water levels in wells S–53 and S–39 (Barnwell and Hawthorn Formations).

March, July, and December and is lowest during May and November. The average monthly rainfall is highest during the month of July, but its distribution is also more erratic at this time and a large proportion is lost to surface runoff. The degree of correlation between water-level fluctuations and rainfall depends largely upon the proportionate amount of rainfall that reaches the water table. This amount is affected by the intensity of rainfall and runoff, the infiltration capacity of the soil, and the steepness of the topographic slope in the vicinity the well.

The most definitive feature of the hydrographs of wells ending in the aquifer of the Barnwell and Hawthorn Formations is the large amplitude of water-level fluctuations. Other factors being equal, fluctuations are greatest in wells ending in the Barnwell and Hawthorn Formations and are progressively smaller in wells screened in the older and, deeper formations. This attribute applies specifically to the fluctuations that are not caused by pumping and to many fluctuations that are affected by pumping.

It was indicated earlier that one of the objectives of the present study was to determine the extent to which water levels in wells developed in the Tertiary formations fluctuate in response to pumping from wells in the Tuscaloosa Formation. Some indication of this fluctuation is illustrated in figure 32, which compares the water levels measured in wells ZW–7 and ZW–15 (developed in Tertiary formations) with the pumpage recorded for well 35–H (developed in the Tuscaloosa Formation) during the period November 12, 1952, through January 19, 1953.

The water-level fluctuation in well ZW–7 appears to result partly from changes in recharge but mostly from changes in the rate of pumping from well 35–H. This factor is quite noticeable in the decline from December 10 to December 17, and corresponds to an increase in pumpage of well 35–H and a water-level decline in well 45–H during the same period. (Water-levels in well 45–H do not correspond exactly with pumpage rates on the illustration because exact times of each can not feasily be identified and because of the loading effect which rainfall has on water levels in the Tuscaloosa Formation.)

The water level in well Z–15 declined during the weeks ending November 19 and January 12 in contrast to an increase in rainfall during these periods, but during the same periods there was an increase in pumping from well 35–H. Thus pumpage from well 35–H appears to have a recognizable effect on the change of water levels in the Tertiary aquifers.

Evaporation and transpiration losses were at a minimum during the period of measurement, owing to the abundant precipitation

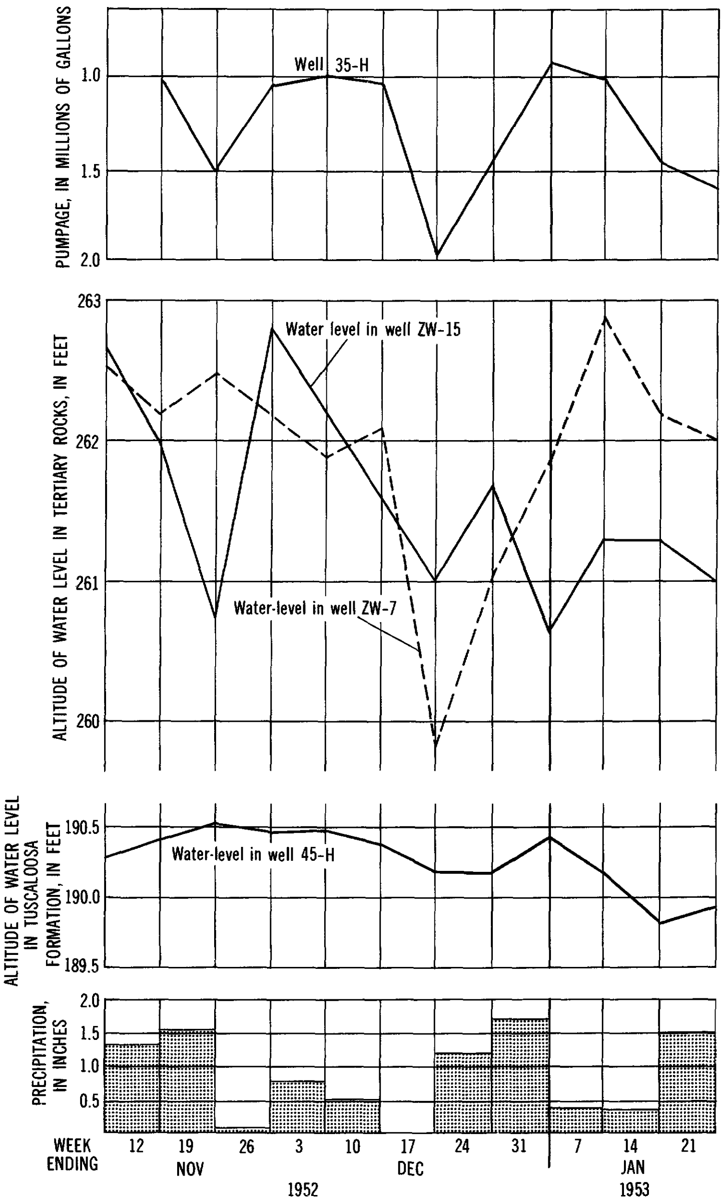


FIGURE 32.—Relation of water-level fluctuations in Tertiary rocks to pumping from Tuscaloosa Formation and precipitation.

during this season of the year. Moreover, the rate of such losses, except for small diurnal differences, should have been fairly constant during the period.

Therefore, there is a fair amount of evidence indicating that substantial pumping from the aquifer(s) in the Tuscaloosa Formation results in a decline of water level in the overlying aquifers of Tertiary age (in the vicinity of the pumped well). Some measure of this decline is indicated roughly in the preceding discussion but additional tests would be required to confirm and define it more precisely.

SUBSIDENCE

Wherever water is drawn from an artesian aquifer and a lowering of the piezometric surface results, there is a compression of the aquifer and a consequent subsidence of the land surface. The compression results from the fact that the load of material overlying the aquifer is borne partly by the solid "skeleton" of the aquifer and partly by the hydrostatic pressure of the water. A reduction in the hydrostatic pressure, as would be caused by pumping, shifts a larger part of the load onto the solid skeleton and thereby causes the aquifer to compress.

The compression consists of two components: (1) A compression resulting from elastic deformation of the individual particles composing the aquifer and (2) a compression resulting from a rolling and sliding adjustment of the individual grains into a more compact arrangement. The first is an elastic deformation and the second a plastic one.

The magnitude of the subsidence cannot be predicted reliably without extensive studies and tests of the material of which the aquifer is composed. Theoretically it could be estimated from the storage coefficient. As pointed out by Jacob (1946), the water released from storage in an artesian aquifer is derived partly from an expansion of the confined water and partly from a contraction of the aquifer. The water derived from contraction of the aquifer is understood to include also water derived from compaction of included and contiguous clay beds. Ordinarily, the storage derived from expansion of the confined water is very small as compared with that from compaction of the aquifer and may be neglected for the purpose at hand. Thus, it can be assumed that all the storage is derived from compaction of the aquifer and will result in a corresponding subsidence of the land surface. Under this assumption the subsidence at a given place may be shown to be equal to the storage coefficient multiplied by the drawdown at that place caused by pumping. That is, if the storage coefficient is 0.001 and the drawdown at the place in question is 50 feet, the subsidence would amount to 0.05 feet. As an example, the maximum depression of the piezometric surface in the M area was recorded at 30 feet. The pumping tests indicated above show a storage coefficient of 0.0003. Therefore the subsidence due to pumping could be roughly estimated to be a maximum of 0.009 foot in the area. The objection to using this method, however, is that the storage coefficient obtained as a result of a short-term pumping test may represent only a very small fraction of the total storage that would be derived from the aquifer after prolonged pumping. Upon a reduction in the hydrostatic pressure, clay and silt will, after a long time, compress much more than beds of quartz sand. Because clay and silt have very low permeabilities, however, they release water very slowly, and the effects of their compaction will not be registered during short-term pumping tests, such as those from which the storage coefficient has been obtained.

In March 1961, several first-order vertical-control profiles were made across selected process areas within the SRP by the U.S. Coast and Geodetic Survey. The areas selected for measurement represented those subject to the heaviest ground-water withdrawal from the principal sand aquifer in the Tuscaloosa Formation. The purpose of the leveling was twofold: (1) to determine if the ground water withdrawn by pumpage was of sufficient quantity to cause a ground-surface subsidence of measurable amount, and (2) to establish first-order bench marks in these areas as a basis for future measurement of subsidence.

A comparison of the altitudes determined in 1961 with those obtained previously by second- and third-order leveling does not afford an accurate determination of the extent, if any, of land subsidence. The altitudes established during the 1961 survey included nine stations on which previous altitudes were available. Of these, the new altitude was 0.065–0.141 foot lower on seven stations, 0.030 foot higher on one station, and no change on one station. The maximum apparent decrease in altitude of 0.141 foot was determined for a station in the H area of the SRP. One bench mark in the M area reflected a −0.064 foot difference from previous leveling. Although this measurement is one order of magnitude greater than the sample calculation given above for the H area, the calculated figure is affected by the probable error in storage coefficient and the observed figure by those errors inherent in a comparison of first- and third-order leveling. Thus, whereas there is a definite possibility that the predominantly lower altitudes obtained in 1961 indicate some amount of subsidence, the evidence is insufficient to establish this amount conclusively on the basis of the present data.

QUALITY OF WATER

Samples of water were collected from 75 wells in Aiken, Barnwell, and Allendale Counties and analyzed by the U.S. Geological Survey. The results are summarized in table 6. As indicated by the data, the ground water in the area is potable and has a chemical composition suitable for a wide range of industrial purposes. Moreover, the concentrations of all chemical constituents except those of iron and nitrate are well within the maximum limits that have been established by the U.S. Public Health Service (1961) for water to be used on interstate carriers or in public water-supply systems in general. The chemical character of the water from four principal aquifers and two streams in the area is illustrated in figure 33. The chemical quality of the four major ground-water sources is discussed briefly below.

THE TUSCALOOSA FORMATION

Water from wells in the Tuscaloosa Formation is generally soft, acidic, and low in dissolved solids (table 6). Characteristically, the concentration of alkaline ions (sodium and potassium) is about equal

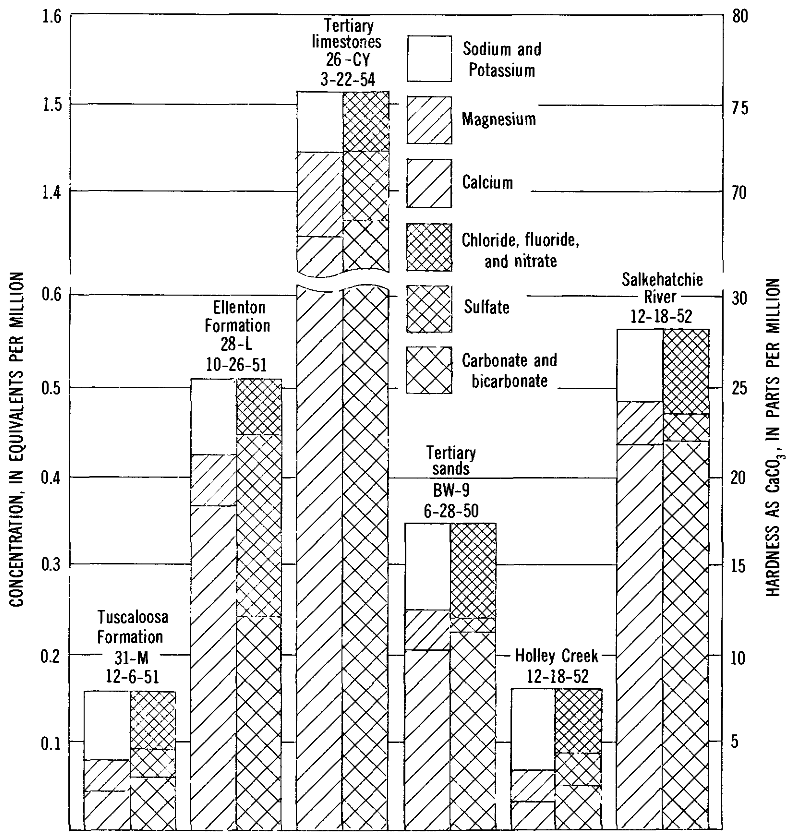


FIGURE 33.—Chemical composition of characteristic ground and surface waters in and near the Savannah River Plant.

TABLE 6.—*Range and median of observed values for common constituents and properties of water from four major ground-water sources in and near the Savannah River Plant, Aiken and Barnwell Counties, S.C.*

[Parts per million]

Number of analyses		Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue on evaporation at 180°C)	Hardness as $CaCO_3$	pH
	Tuscaloosa Formation												
13	Maximum	0.77	1.4	0.9	6.7	17	4.8	4.0	0.1	8.8	28	7	6.9
	Median	.16	.9	.5	2.1	3	1.4	2.2	.0	.6	19	5	5.4
	Minimum	.00	.3	.0	.9	0	.5	.8	.00	.0	14	2	4.4
	Ellenton Formation												
16	Maximum	4.1	8.7	1.3	4.2	23	27	6.0	0.2	0.9	54	30	6.8
	Median	1.1	6.4	1.0	2.7	12	11	2.1	.1	.0	41	19	5.9
	Minimum	.10	3.9	.4	1.5	4	7.4	1.5	.0	.0	36	10	4.4
	Eocene limestone												
15	Maximum	1.0	47	9.4	19	171	14	4.5	0.5	6.2	192	132	7.6
	Median	.25	27	2.0	1.7	94	4.3	2.8	.1	.2	95	72	7.1
	Minimum	.00	17	.3	.4	55	.8	.4	.0	.0	75	50	6.8
	Eocene sand												
9	Maximum	1.84	8.7	4.2	2.4	17	9.3	4.0	0.3	2.3	29	15	6.1
	Median	.16	1.5	.7	2.1	5.5	1.9	2.7	.1	1.3	21	8	5.5
	Minimum	.04	.5	.3	.4	1	.8	1.5	.00	0	20	4	4.2

to that of the alkaline earths (calcium and magnesium), and the number of sulfate, chloride, and nitrate ions exceed the number of bicarbonate ions. Although most of the samples analyzed generally contained no flouride, some of the samples contained as much as 0.1 ppm flouride. The ratio of calcium+magnesium ions to the total cation concentration (expressed in equivalents per million) averages 0.56. The lowest such ratio, 0.204, was determined for water from well AK–202 which is at a kaolin mine. Comparable ratios of calcium+magnesium ions to the total cation concentration are 0.75 for water from the Ellenton Formation and 0.95 for water from the Tertiary limestone.

Owing to the very low concentration of dissolved solids in the water and the low pH values, water from the Tuscaloosa Formation has a tendency to be corrosive to most metal surfaces. This is especially true where the water contains appreciable amounts of dissolved oxygen and carbon dioxide. Such water causes iron pipe to deteriorate rapidly, and discolors the water circulating through it.

THE ELLENTON FORMATION

Water from the Ellenton Formation is characterized by a low content of dissolved solids (average of 16 observed values is 41 ppm), a low hardness (10–30 ppm, slightly greater than that of water from the Tuscaloosa), a high content of iron (average of 16 observed values is 1.1 ppm), and a comparatively high proportion of sulfate among the anions. Moreover, the concentration of alkaline earth metals is greater than that of the alkali metals.

The most distinguishing characteristic of water from the Ellenton Formation is the comparatively high proportion of sulfate in the anion concentration. As shown by figure 33, the concentration of sulfate in water from well 28–L is higher than that in any of the other analyses shown in the figure. The percentage of the sulfate to the total anion concentration (expressed in equivalents per million), ranges from 35 to 65 percent in the 16 samples of water obtained from this formation (table 6). A consistent ratio is also indicated for the silica-dissolved solids concentration, ranging from 22 to 28 percent.

Figure 33 shows that water from the Ellenton Formation has a concentration of calcium ions in excess of the concentration of bicarbonate ions. This suggests the presence of "noncarbonate" or "permanent" hardness in the water which might be caused by the presence of scattered crystals of gypsum (calcium sulfate) in the Ellenton Formation.

Water from the Ellenton Formation has some similarities in chemical composition with that from the Black Creek Formation of Late Cretaceous age, found elsewhere in the state. Nonetheless, if the Ellenton Formation is accurately correlative with the Black Creek Formation, there is an exchange of sodium for calcium and a decrease in sulfate content as the water moves downdip toward the coast. The exchange of sodium for calcium commonly occurs as water moves downdip in coastal aquifers. A reduction in sulfate content, on the other hand, has been attributed to the reaction of sulfate with carbonaceous materials, anion exchange, or the presence of anaerobic bacteria.

THE TERTIARY (EOCENE) LIMESTONE

Water circulating through beds of limestone in the Eocene sediments contains more dissolved solids and has a higher hardness than water from any other sedimentary formation in the area studied. (See table 6.) Characteristically, the alkaline earth metals are in excess of the alkali metals, and the bicarbonate ion is similarly in excess of the total concentration of the other anionic constituents (fig. 33). This composition is commonly found in waters circulating through deposits made up predominately of calcium carbonate.

Ground water derived from the Eocene limestone contains higher concentrations of silica than does the water from any other formation in the area of study. In several areas (Montmorenci, Upper Three Runs, and parts of Lexington County) where the limestone bed is exposed at the surface, the calcium carbonate is largely replaced by silica.

THE TERTIARY (EOCENE) SANDS

Water from the sandy aquifers of Tertiary age is similar in chemical composition to that from the Tuscaloosa Formation except that some constituents occur in dissimilar proportions. In general, the water from these deposits is acidic and low in dissolved-solids content. Some analyses of water from Tertiary sands, however, reflect the presence of residual amounts of calcareous material in the formation by higher proportionate concentrations of calcium and bicarbonate ions. Other water samples collected from wells in the Tertiary sands have unusually high proportions of sulfate, chloride, or nitrate ions and little, if any, bicarbonate. An adequate explanation for this disproportionate composition is not presently known, but there is a possibility that these samples have been contaminated, possibly from a surface source.

THE CRYSTALLINE ROCK

Only five wells in the crystalline rock were sampled and chemically analyzed. The results indicate the wells are probably obtaining water from different rock units ranging from a granite to a hornblende gneiss. The water is generally higher in dissolved solids than in the unconsolidated sediments, has a pH between 7.0 and 8.0, and has a comparatively high concentration of calcium, sodium, bicarbonate, and chloride. The dissolved silica ranges from 30 to 39 ppm.

SURFACE WATER

Chemical analyses were made on six samples of surface water from the area, and they show that this water is very low in dissolved solids, iron, and total hardness. The pH of all samples except that from the Salkehatchie River near Barnwell ranged from 6 to 7 and were thus slightly acidic. The sample obtained near Barnwell had a pH of 7.3 and was also the hardest of the surface-water samples. Figure 33 shows that the chemical composition of the Salkehatchie River near Barnwell is closely analogous to that of the ground water derived from Tertiary limestone. The area around Barnwell is underlain by calcareous deposits or a residuum therefrom, and hence the surface stream, fed by effluent seepage from the formation, reflects the similar chemical composition.

Similarly, the composition of the water from Holley Creek is comparable to that of well 31–M, as shown in figure 33. Holley Creek is an effluent stream fed by water from the Tuscaloosa Formation, which crops out along most reaches of this stream. Well 31–M is likewise developed in the sands of the Tuscaloosa Formation.

TEMPERATURE

The temperature of the shallow ground water approximates that of the mean annual air temperature in the surrounding area, although it may vary several degrees in the aquifers that are within approximately 30 feet of the ground surface. Water in the deeper aquifers is more consistently affected at any particular place by the earth's thermal gradient, a factor which causes an increase of about 1°F for each 60–100 feet of depth. The ground-water temperatures observed in the area of Aiken, Barnwell, and Allendale Counties range from 65.5° to 71°F, the deepest artesian aquifers having the warmest water.

RADIOACTIVITY OF GROUND WATER

The radium content and beta-gamma activity for seven samples of water from as many wells in and near the SRP were measured in order to determine the background characteristics of the radioactivity of ground water in the vicinity of the SRP. The results are summarized in table 7.

Sample AEC–SRP–2 has the highest radium content of the samples analyzed. This water was obtained chiefly from the Peedee and Black Creek Formations which are presumed to be correlative with the Ellenton Formation. Inasmuch as these formations are composed of considerable amounts of gray to black clay, they probably have larger amounts of radium per unit of rock mass than does the sandstone, limestone, or light-gray shale.

Sample AEC–SRP–1 from well BW–2 contained the smallest amount of radium. This water was obtained from the Tertiary limestone which overlies the Tuscaloosa Formation. The low radium content is consistent with results reported elsewhere for samples from limestone that has been found to contain lesser amounts of radium per unit mass than does light- or dark-colored shale. However, the analysis of sample AEC–SRP–7 indicates an anomalous condition because the radium content of 49 picocuries is the second highest determination of all the samples analyzed even though the sample was obtained from a well that taps a bed of limestone and hence should yield water of relatively low radium content.

CLAY MINERALS AND ION-EXCHANGE CAPACITIES OF THE UPPER CRETACEOUS AND TERTIARY SEDIMENTS

The ion-exchange capacities of subsurface formations is a critical factor in determining the rate of dispersion of radionuclides in the geo-

TABLE 7.—*Radiochemical analyses of ground-water samples from Aiken, Barnwell, and Allendale Counties, S.C.*

[Determinations made by the U.S. Geol. Survey unless otherwise indicated]

Sample	Well	Location	Beta-gamma activity of dry residue, in picocuries per liter	Radium, in picocuries per liter
AEC-SRP-1	AL-9	Allendale County Hospital	<50	0.20
2	AL-8	Sycamore, S.C	<50	72
3	S-377	Ellenton, S.C	<50	26
4	BW-2	Barnwell, S.C	<50	1
5	S-348A	3 miles northwest from Ellenton, S.C.	<50	30
6	BW-22	Barnwell, S.C	<50	13
7	AL-16	About 1 mile north from Martin, S.C.	<100	[1] 49
T	AK-146	About 1 mile west from Town Creek along State Highway 145.	<12	.4
	AK-337	14 miles northeast of Aiken, S.C.	<13	2.0

[1] Radium determination made by the National Bureau of Standards.

logic environment. For this reason, knowledge of ion-exchange capacities is a prerequisite to an evaluation of the suitability of particular sites for the disposal of radioactive wastes.

Because of the necessity of disposing of radioactive wastes in the SRP area, the ion-exchange capacities and compositions of 18 samples of sand and clay from the upper Cretaceous and Tertiary formations in the report area were determined by the Geological Survey. The material was collected from both the surface and the subsurface parts of the formations, when both were available. The subsurface samples were obtained with a rotary drill, but an effort was made, insofar as feasible, to obtain a representative formational fraction. Some contamination by the drilling fluid was probably inevitable, but an attempt was made to keep this to a minimum in the sample preparation. Table 8 lists the source of each sample, the proportions of clay minerals present, and the ion-exchange capacities of the total sample, expressed in milliequivalents per 100 grams.

The results indicate that a large percentage of the material of the Tuscaloosa Formation is kaolinitic, whereas the McBean Formation contains almost all of the montmorillonite found in the entire suite. The clay of the Barnwell and Hawthorn Formations also contains a high percentage of kaolin in the clay fraction and a comparatively high amount of quartz in the silt fraction. Zeolite was found in sand of the Tuscaloosa Formation collected at the Anchor Corp. mine near Aiken and also in the sample of clay of Claiborne age from upper Three Runs. As expected, those samples containing the highest percentages of montmorillonite exhibited the highest ion-exchange capacities. One exception was sample 18, which had a fairly high ion-exchange capacity but reportedly contained no montmorillonite.

Figure 34 is a histogram of comparative ion-exchange capacities as determined on the above samples. The figure indicates that the

TABLE 8.—*Clay-mineral composition and ion-exchange capacities of surface and subsurface samples of Upper Cretaceous and Tertiary formations from Aiken and Barnwell Counties, S.C.*

[Each sample composed of clay and silt. "Minerals present" columns: upper figures, clay fraction; lower, silt]

Sample	Unit represented and origin of sample	Ion-exchange capacity of total sample (meg per 100g)	Minerals present (parts in ten)				
			Mont-moril-lonite	Kao-lin	Mica	Quartz	Other
1........	Hawthorn Formation. Surface clay from Alligator clays on old Augusta-Charleston road.	3.2	Tr. --------	9 3	------ 2	-------- 4	
2........	Hawthorn Formation. Surface clay (kaolin-flecked) near Dunbarton.	3.3	-------- --------	9 5	------ 1	-------- 3	
3........	Barnwell Formation. Surface, clay and sand, 0.4 mile east of Upper Three Runs on Mossy School road.	1.7	-------- --------	8 2	------ 1	-------- 5	Chlorite?, (tr.).
4........	Barnwell Formation. Subsurface clay sand from 3TCS, depth 67–74 ft.	1.5	-------- --------	9 4	------ 1	Tr. 4	
5........	McBean Formation. Subsurface sand from 43-H, depth 245–255 ft.	2.4	5 --------	3 2	1 1	-------- 6	
6........	McBean Formation. Subsurface clay from 21-F, depth 175–185 ft.	15.2	4 3	4 1	1 1	-------- 3	Calcite, (tr.).
7........	McBean Formation. Surface sand, east side of SC–19, 0.1 mile north of Tims Branch.	3.0	-------- --------	6 4	------ 1	Tr. 1	
8........	McBean Formation. Surface clay, south of Mossy School road near Upper Three Runs.	14.2	9 1	------ ------	1 1	-------- 1	Feldspar Zeolite [1].
9........	Ellenton Formation. Subsurface clay from 21-F, depth 295–305 ft.	5.4	1 --------	7 2	1 1	-------- 5	Calcite, (tr.).
10........	Ellenton Formation. Subsurface sand from 21-F, depth 305–315 ft.	.9	1 --------	7 4	1 2	Tr. 3	
11........	Tuscaloosa Formation. Subsurface sand from 35-H, depth 815–825 ft.	.2	1 Tr.	7 3	Tr. 1	1 4	Calcite, (tr.).
12........	Tuscaloosa Formation. Subsurface clay from 43-H, depth 650–660 ft.	.4	Tr. --------	9 4	------ 2	-------- 3	
13........	Tuscaloosa Formation. Subsurface clay from 8-TCA, depth 285–295 ft.	7.0	-------- --------	9 6	------ 2	-------- 1	
14........	Tuscaloosa Formation. Surface sand from Anchor Corp. mine near Aiken.	.3	-------- --------	8 2	Tr. 2	Tr. 5	Zeolite?, (tr.).
15........	Tuscaloosa Formation. Surface sand, south side of SC–26, 0.3 mile west of Shaw Creek.	.4	-------- --------	9 5	------ 1	Tr. 3	
16........	Tuscaloosa Formation. Surface clay, kaolin pit, north side of SC–26, 0.9 mile east of Shaw Creek.	4.6	-------- --------	9 9	------ ------	-------- --------	
17........	Tuscaloosa Formation. Surface clay, 1 mile northwest of Caper Chapel.	2.7	-------- --------	9 9	------ Tr.	-------- Tr.	
18........	Tuscaloosa Formation. Surface clay, US–1, 2.2 miles east of Clearwater-Belvedere road.	11.0	-------- --------	9 8	------ 1	-------- Tr.	

[1] Zeolite is probably heulandite or phillipsite.

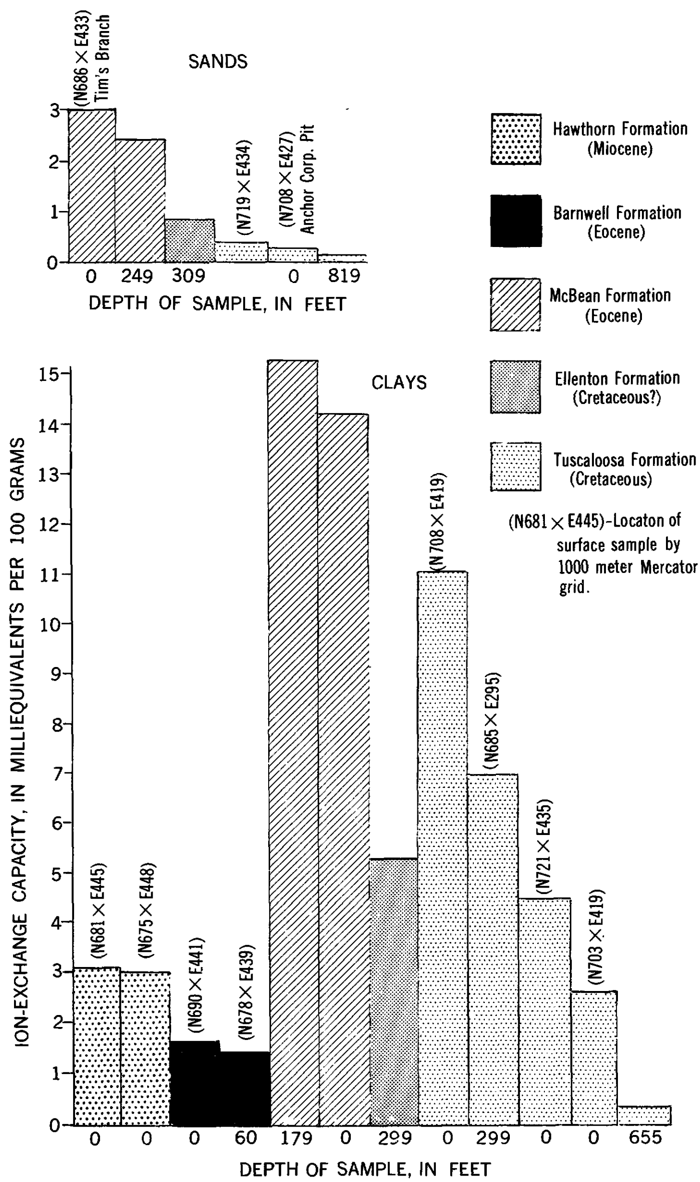


FIGURE 34.—Ion-exchange capacities of surface and subsurface samples of sands and clays.

ion-exchange capacities of the sand can be more readily correlated by geologic formation than those of the clay, which exhibits less uniform values. As expected, however, the clay exhibits greater exchange capacities than the sand. Analyses of samples from the Tuscaloosa

Formation reflect the greatest range in ion-exchange capacities. Although this greater range may be attributed in part to the fact that more samples were taken from the Tuscaloosa than from other formations, additional factors appear to have some bearing on the result. One or more samples selected as representative of the Tuscaloosa Formation may be from younger formations. The formational designation of samples 13 and 18 in table 8 may be questionable in this respect, as might be surmised from the results of the analyses. Sample 13 was obtained from well cuttings from the uppermost part of the Tuscaloosa Formation and may have been mixed with cuttings from the overlying Ellenton Formation or McBean Formation. Sample 18 was taken from an outcrop in the Horse Creek valley where considerable slumping of the McBeam Formation has occurred, and thus the sample was subject to possible contamination by these rocks. The smallest ion-exchange capacity of the clay in the Tuscaloosa was reported from a subsurface sample of clay, significantly from the lower part of the formation and in no proximity to the younger rocks of Cretaceous and Claiborne ages. The highest ion-exchange capacities, in both the sand and the clay, were found in the samples of the McBean Formation. Furthermore, the ion-exchange capacities of samples from this formation were more uniform in value than those from other formations.

The data do not verify a definite relationship of ion-exchange capacity with depth, although the analyses of the sand as shown on plate 5 indicate a close approximation of this relationship in that the capacities decrease from a high in deposits of middle Tertiary age to a low in those of Late Cretaceous age. A tentative conclusion, which appears reasonable on the basis of these data, is that for disposal purposes the greatest amount of ion-exchange activity might be expected in those areas where the effluent is discharged or brought into contact with the clayey parts of the McBean Formation.

EXPECTED DRAWDOWNS FROM GROUND-WATER WITHDRAWAL

The rate at which water can be withdrawn from a given well or group of wells is limited by the extent to which water levels may be lowered or drawn down by pumping without causing the cost of lifting water to the surface to become uneconomic. The allowable drawdown may also be limited by the depth to and the thickness of the aquifer. Thus, in a thick aquifer a relatively large drawdown may be created without unwatering the lower part of the aquifer in which a well is screened, but in a thin aquifer a drawdown of equal magnitude may cause unwatering and well failure. Some drawdown around a pumped well is necessary, however, to cause movement of ground water toward a well. In general, the free water surface is drawn down in the shape of an inverted cone with the apex of the depression at the well site. The theoretical drawdowns of water levels in and around a well or well field for different rates of pumping and for different lengths of time may be computed mathematically by the Theis (1935) nonequilibrium formula. This formula assumes, among other things, that the aquifer being pumped has an infinite areal extent and that the water being discharged from the well is derived entirely from storage within the aquifer. Thus, the drawdown computed from the Theis formula will not approach a limit but will continue to increase indefinitely with time, at a constantly decreasing rate.

The principal aquifer in and near the SRP area, however, does not have an infinite areal extent but is bounded by its outcrop and by areas of recharge or discharge. As water levels are lowered by pumping, the natural hydraulic gradient toward the areas of discharge (as for instance along the Savannah River) may locally be reversed, and some of the discharge will be diverted toward pumping wells. For example, pumping at the Savannah River Plant from the principal artesian aquifer will first divert water which otherwise would discharge into the Savannah River or Holley Creek, and eventually, if the head is lowered enough, the pumping will reverse the movement of water and cause the Savannah River and perhaps Holley Creek to become sources of recharge to the aquifer of the Tuscaloosa Formation. The induction of recharge from these sources would tend to limit the amount of drawdown, and thus the sources of recharge would approximate a mathematical line source—a straight line along which the head or water level in an aquifer will remain virtually constant.

An analogous condition exists when the cone of depression approaches an area where a lowering of head in the aquifer causes a decrease in proportion to the head loss in the amount of ground water discharged into surface streams or lost by evaporation and transpiration. Mathematically, these areas also constitute a line source.

If pumping is continued long enough, the diversion of water from areas of natural recharge and discharge will ultimately tend to balance withdrawals from wells after which steady-state conditions will be established and water levels will become virtually stable.

DRAWDOWNS WHEN WITHDRAWAL IS BALANCED WHOLLY BY CAPTURE FROM A LINE SOURCE

A convenient method for calculating the steady state or ultimate drawdown to be expected in an area in the vicinity of a line source of infinite length is described by Muskat (1937). This method utilizes the expedient analogy between the effect produced by an "image" recharging well, whose rate of recharge is equal to the pumping rate of

243-540 O—67——7

the discharge well and whose location would be the reflected image of the pumped well if the line source were considered to be a mirror. As computed by the method of images, the net drawdown that would occur at any given point is the algebraic sum of the drawdown that would be produced at that point by the discharge well and the "negative" drawdowns (rise in the water level) that would be produced by the recharging image well. The alegebraic sum, constituting the net drawdown, may be computed from the Thiem formula (1906) as follows:

$$s_n = s_r + s_i = \frac{527.7Q}{T} \log \left(\frac{r_i}{r_r}\right) \qquad (2)$$

where

s_n=net drawdown in feet;
s_r=drawdown in feet produced by pumping real well;
s_i=negative drawdown in feet produced by recharging image well;
Q=rate of discharge in gallons per minute;
r_r=distance in feet from point at which drawdown is to be determined to real well;
r_i=distance in feet from point at which drawdown is to be determined to image well;
T=coefficient of transmissibility in gallons per day per foot.

Where more than one pumped well is involved, each pumping well has an image, and the net drawdown is the algebraic sum of the drawdowns and negative drawdowns produced respectively by all the pumped wells and their images.

The effects of two possible boundaries may be examined in consideration of ultimate (or steady-state) drawdowns in selected parts of the SRP area as a result of pumping from the principal aquifer in the F, H, M, and D areas. One boundary is that reach of the Savannah River along which discharge from the artesian system occurs. The boundary could be ideally represented as a line source occupying the general position shown by line *R–S* in figure 35. The other possible boundary is at Holley Creek, into which water is also being discharged from the artesian system. This boundary also can be ideally represented as a line source occupying the general position shown by line *A–B* in figure 35. In the computations that follow it will be convenient to examine first the separate effects of each of these two boundaries, attention being given first to the boundary designated by line *R–S*. Subsequently, the combined effects of the two boundary systems will be analyzed.

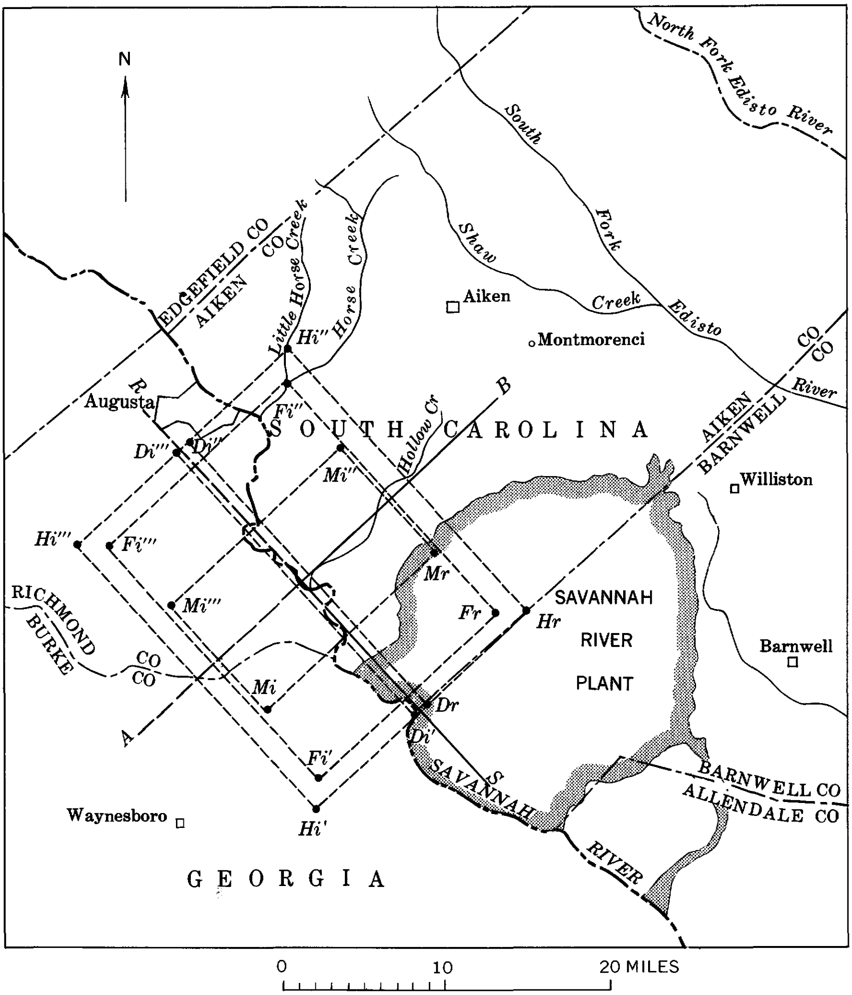


FIGURE 35.—Location of real and image well fields used in computing drawdowns.

EFFECTS OF SAVANNAH RIVER AS A LINE SOURCE OF RECHARGE

According to administrative sources at the SRP, the total use of ground water from the artesian system in the SRP area was expected to approximate the following quantities: 3,000 gpm from the well field in area H, 3,500 gpm from the well field in area F, 2,000 gpm from the well field in area D, and 1,500 gpm from the well field in area M. The locations of these well fields and their respective images are shown in figure 35.

If it is assumed (1) that the total pumpage of 3,000 gpm in the H area well field is distributed equally among the five wells (35–H, 43–H, 44–H, 45–H, and 48–H), (2) that the total discharge from the F, D, and M areas is as indicated above, (3) that the transmissibility of the principal aquifer tapped by the wells is 200,000 gpd, (4) that the line source of captured discharge is of infinite length, oriented along *R–S*, and (5) that the pumpage is derived wholly from capture along this line, then by applying Thiem's formula to the method of images the ultimate total drawdown to be expected at any point in the aquifer system can be computed. In the present example a point 1 foot from well 48–H has been selected for determining the ultimate drawdown because the distribution of wells in the H area well field indicates that maximum drawdown in that area would occur at a point near well 48–H. Table 9 illustrates the component parts of the drawdown and shows that the ultimate drawdown to be expected at a point 1 foot from well 48–H is 31.5 feet.

TABLE 9.—*Calculation of ultimate drawdown at a point 1 foot from well 48–H (H area), based on the presence of an infinite line source oriented along line R–S as shown in figure 35.*

[Wells 35–H, 43–H, 44–H, 45–H, and 48–H are being pumped at a constant rate of 600 gpm and pumping is steady in the F, D, and M areas as indicated]

Well or area	r_r	r_i	$\log \frac{r_i}{r_r}$	Q	s_n
48–H	1	9.5×10^4	4.978	600	7.9
35–H	1,300	9.5×10^4	1.864	600	3.0
43–H	800	9.5×10^4	2.074	600	3.3
44–H	600	9.5×10^4	2.199	600	3.5
45–H	900	9.5×10^4	2.023	600	3.2
F area	1.0×10^4	8.8×10^4	.944	3,500	8.7
D area	4.4×10^4	5.1×10^4	.064	2,000	.3
M area	3.6×10^4	9.3×10^4	.412	1,500	1.6
Total					31.5

$$s_n=\frac{527.7Q}{T}\log\frac{r_i}{r_r} \tag{2}$$

where

s_n=net drawdown in feet;
Q=discharge in gallons per minute;
T=200,000 gpd per ft=coefficient of transmissibility;
r_i=distance in feet from point at which drawdown is to be determined to image well;
r_r=distance in feet from point at which drawdown is to be determined to real well.

Ultimate drawdown at other points in the aquifer system may be computed using the same procedure as before and the same line source (line *R–S*). Table 10 gives the calculation of the total drawdown in the vicinity of well 15–M in the M area well field when well 31–M, at a distance of 700 feet, is pumping 800 gpm; well 20–M, at a distance of 700 feet, is pumping 1,500 gpm; and wells in the F, D, and H areas are pumping 3,500, 2,000, and 3,000 gpm, respectively. The total drawdown is calculated to be 26.9 feet.

TABLE 10.—*Calculation of ultimate drawdown at a point 1 foot from well 15–M, based on the presence of an infinite line source oriented along line* R–S *in figure 35*

[Terms as defined in table 9]

Well or area	r_r (feet)	r_i (feet)	$\log \frac{r_i}{r_r}$	Q (gpm)	s_n (feet)
15–M	1	7.8×10^4	4.892	500	6.5
31–M	700	7.8×10^4	2.045	800	4.3
20–M	700	7.8×10^4	2.045	1,500	8.1
F area	2.8×10^4	8.4×10^4	.447	3,500	4.4
D area	4.9×10^4	5.5×10^4	.05	2,000	.3
H area	3.6×10^4	9.4×10^4	.417	3,000	3.3
Total drawdown in feet					26.9

$$s_n=\frac{527.7Q}{T}\log\frac{r_i}{r_r} \qquad (2)$$

EFFECTS OF HOLLEY CREEK AS A LINE SOURCE OF RECHARGE

The effects of Holley Creek as a line source of recharge can be calculated in exactly the same way as that used to calculate the effects of the Savannah River as a line source of recharge. The conditions are the same except that the line source of captured discharge is oriented along line *A–B* in figure 35 instead of along *R–S*. Hence, by applying as before the Thiem (1906) formula (equation 2) to the method of images, the ultimate drawdown can be calculated for any point in the aquifer system.

The ultimate drawdown to be expected at a point 1 foot from well LA–48, using the line *A–B* (fig. 35) as a line source, is 35.0 feet as shown in table 11.

TABLE 11.—*Calculation of ultimate drawdown at a point 1 foot from well 48–H (H area), based on the presence of an infinite line source oriented along line* A–B *as shown in figure 35*

[Wells 35–H, 43–H, 44–H, 45–H, and 48–H are being pumped at a constant rate of 600 gpm and pumping is steady in the F, D, and M areas as indicated. Terms as defined in table 9]

Well or area	r_r (feet)	r_i (feet)	$\log \frac{r_i}{r_r}$	Q (gpm)	s_n (feet)
48–H	1	1.2×10^5	5.079	600	8.0
35–H	1,300	1.2×10^5	1.964	600	3.1
43–H	800	1.2×10^5	2.176	600	3.4
44–H	600	1.2×10^5	2.301	600	3.6
45–H	900	1.2×10^5	2.087	600	3.3
F area	1.0×10^4	1.1×10^5	1.041	3,500	9.6
D area	4.4×10^4	1.3×10^5	.470	2,000	2.5
M area	3.6×10^4	8.4×10^4	.368	1,500	1.5
Total					35.0

$$s_n=\frac{527.7Q}{T}\log\frac{r_i}{r_r} \qquad (2)$$

COMBINED EFFECTS OF SAVANNAH RIVER AND HOLLEY CREEK AS SOURCES OF RECHARGE

If the Savannah River and Holley Creek function simultaneously as infinite straight-line sources of recharge, the principal artesian aquifer beneath the SRP is limited by two converging boundaries of like character and is therefore wedge-shaped. The number, position, and character of image wells that are required to balance withdrawals from a wedge-shaped aquifer is dependent upon the character of the boundaries and size of the angle θ, included between them. From the solution of the wedge problem by Carslaw and Jaeger (1947, p. 234), the exact number of image wells, N, is

$$N=\frac{360°}{\theta}-1 \qquad (3)$$

Inasmuch as the angle between the lines *R–S* and *A–B* (fig. 35), approximates 90°, the number of images required to balance each discharging well in the intervening wedge-shaped aquifer is three (equation 3).

The position of each image well is determined by the circumference of a circle whose center coincides with the intersection of the boundaries and whose radius is equal to the distance from the apex of the aquifer wedge to the real well. Moreover, the image wells are the same distance from the reflecting boundaries as the real well.

The character of each image well in the wedge system of boundaries is dependent upon the character of the intersecting boundaries. According to the image-well theory, positive or recharging boundaries reflect images of opposite character and negative or discharging boundaries reflect images of like character. Therefore, each pumping well field at the SRP is reflected in both positive boundaries (lines *R–S* and *A–B* in fig. 35) as negative or recharging images. The negative images are, in turn, reflected in the boundary projections as a single positive or discharging image. The number, location, and character of the image well fields associated with the 90° wedge-shaped aquifer of the Tuscaloosa Formation underlying the SRP area are shown in figure 35.

An exact solution to the problem of calculating the ultimate drawdown in the 90° wedge-shaped aquifer system is possible by applying the Thiem formula (equation 2) to the method of images. According to Jacob (1950, p. 355), if the intersecting boundaries are of like character, the ultimate drawdown at any point in the system caused by a discharging well is

$$s_n=\frac{527.7Q}{T}\log\left[\frac{r_i'\cdot r_i''}{r_r\cdot r_i'''}\right] \qquad (4)$$

where

Q=rate of discharge of well in gallons per minute;
T=transmissibility in gallons per day per foot;
r_r=distance, in feet, from point at which drawdown is to be determined to real well;
r_i'=distance, in feet, from point at which drawdown is to be determined to recharging image of real well opposite nearest boundary;
r_i''=distance, in feet, from point at which drawdown is to be determined to recharging image of real well opposite most distant boundary;
r_i'''=distance, in feet, from point at which drawdown is to be determined to discharging image of recharging image wells.

Using equation 4, it is possible to calculate the effects of the simultaneous functioning of the two possible line sources of recharge, the Savannah River and Holley Creek. According to table 12 the total drawdown at a point 1 foot from well 48–H is 28.9 feet. This amount is 2.6 feet less than the calculation of drawdown based on the presence of a single line source of recharge corresponding to the Savannah River (line *R–S*, fig. 35). Hence, it can be concluded that the difference in drawdowns shown in tables 9 and 12 is attributable to the presence of a line source of recharge corresponding to Holley Creek. Similarly, the difference of 6.1 feet between the total drawdown as computed in tables 11 and 12 reflects the relative importance of the Savannah River as a source of recharge.

TABLE 12.—*Calculation of ultimate drawdown at a point 1 foot from well 48–H (H area), based on the presence of two infinite line sources of recharge oriented along lines R–S and A–B as shown in figure 35*

Well or area	r_r (feet)	r_i' (feet)	r_i'' (feet)	r_i''' (feet)	$\log \frac{r_i' r_i''}{r_r r_i'''}$	Q gpm	s_n (feet)
48–H	1	9.5×10^4	1.2×10^5	1.5×10^5	4.881	600	7.7
35–H	1300	9.5×10^4	1.2×10^5	1.5×10^5	1.767	600	2.8
43–H	800	9.5×10^4	1.2×10^5	1.5×10^5	1.978	600	3.1
44–H	600	9.5×10^4	1.2×10^5	1.5×10^5	2.102	600	3.3
45–H	900	9.5×10^4	1.2×10^5	1.5×10^5	1.927	600	3.0
F area	1.0×10^4	8.8×10^4	1.1×10^5	1.4×10^5	.839	3,500	7.7
D area	4.4×10^4	5.1×10^4	1.3×10^5	1.3×10^5	.064	2,000	.3
M area	3.6×10^4	9.3×10^4	8.4×10^4	1.2×10^5	.257	1,500	1.0
Total							28.9

$$s_n=\frac{527.7Q}{T}\log\frac{(r_i' r_i'')}{(r_r r_i''')}$$

where

s_n=ultimate drawdown, in feet;
Q=rate of discharge of real well, in gallons per minute;
T=coefficient of transmissibility=200,000 gpd per ft;
r_r=distance, in feet, from point at which drawdown is to be determined to real well;
r_i'=distance, in feet, from point at which drawdown is to be determined to recharging image well opposite line *R–S*.
r_i''=distance, in feet, from point at which drawdown is to be determined to recharging image well opposite line *A–B*;
r_i'''=distance, in feet, from point at which drawdown is to be determined to discharging image well.

DRAWDOWN WHEN WITHDRAWAL IS BALANCED WHOLLY BY LEAKAGE THROUGH CONFINING BEDS

The preceding computations of drawdown were based on the assumption that all the withdrawal from wells is balanced by diversion from a line source. A different and perhaps more realistic analysis can be made by considering another factor which affects the drawdowns—leakage through confining beds. The concept of an artesian system predicates the existence of a comparatively impermeable confining bed or aquiclude. Actually, artesian conditions require only that the confining bed be relatively less permeable than the aquifer. In nature, no stratum is entirely impermeable because even fine-grained clay has finite permeabilities and hence will transmit finite quantities of water wherever head differentials exist. Thus, all confining beds in artesian systems are "leaky" to a greater or lesser extent, depending on the character and thickness of the rock materials comprising the confining bed. Jacob (1946) has described these conditions and has published equations for computing drawdowns in an artesian aquifer with a leaky confining bed.

In an artesian aquifer the cone of depression created by a pumping well expands rapidly and within a relatively short time will encompass a large area. As a result, the aggregate contribution by vertical seepage through confining beds may be very large notwithstanding the comparatively low permeability of these beds. It is pertinent, therefore, to consider the effect of vertical leakage in lessening the amount of drawdown.

Jacob's equation (1946) for the drawdown in an artesian aquifer of infinite area, under steady-state conditions and with a leaky confining bed is

$$s=\frac{QK_o}{2\pi T}(x) \tag{5}$$

where

$$x=r\sqrt{\frac{P'}{Tm'}}. \tag{6}$$

In the system of units used in this report, equation 5 reduces to

$$s=\frac{229Q}{T}K_o(x) \tag{7}$$

where

T=coefficient of transmissibility, in gallons per day per foot, of the artesian aquifer;

P'=coefficient of permeability (in the vertical direction) of the confining bed, in gallons per day per square foot;

Q=rate of withdrawal by pumped well, in gallons per minute;

m'=thickness of confining bed, in feet;
r=distance from pumped well to point at which drawdown is to be determined, in feet;
s=drawdown in feet;
$K_o(x)$=modified Bessel function of the second kind of zero order (Gray and others, 1931, p. 313–315).

The extent to which leakage will limit the drawdown caused by pumping from an artesian aquifer is shown in figure 36, which is a semilogarithmic plot of the ultimate drawdowns that would be developed by pumping a well when the water being pumped is obtained wholly from vertical leakage through the confining bed. The drawdowns were computed from Jacob's formula (equation 7). The curves represent the cone of depression that would ultimately be produced by pumping 1,000 gpm from an artesian aquifer having a transmissibility of 200,000 gpd per sq ft, overlain by a confining bed having a thickness of 100 feet and permeability of 1.0, 0.1, 0.01, and 0.001, respectively. A significant fact pointed up by the curves is that large differences in the vertical permeabilities result in relatively slight differences in drawdown. It may be observed that at any given distance from the pumping well the difference in draw-

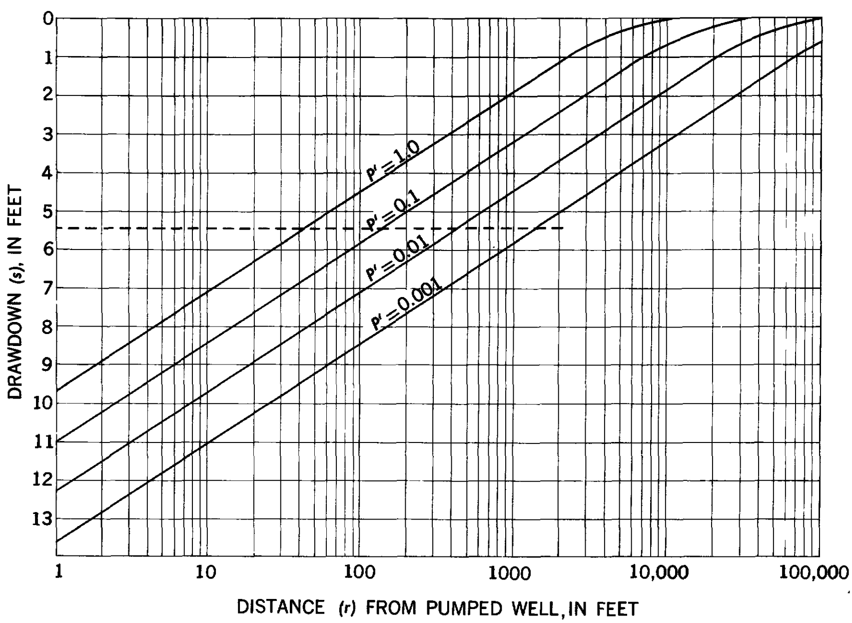


FIGURE 36.—Ultimate drawdown in a leaky artesian aquifer of infinite areal extent. Drawdowns greater than 5.4 feet are extrapolated.

down corresponding to a tenfold difference in the permeability is no more than 1.3 feet.

It is possible to calculate the drawdown at a point 1 foot from well 48–H on the assumption that all water withdrawn is balanced by vertical leakage by use of the curves in figure 36. Assuming the same conditions of pumping and transmissibility as before, drawdowns can be computed by reading directly from the appropriate curve in figure 36 the amount of drawdown at 1,000 gpm and multiplying that amount by the factor $Q/1{,}000$. The computations of ultimate drawdown at a point 1 foot from well 48–H for two values of P', 0.01 gpd per sq ft and 0.001 gpd per sq ft, are given in table 13. The results show that under the assumed conditions, 27.6 feet of drawdown can be expected at a point 1 foot from well 48–H if the confining bed has a permeability (P') of 0.01 gpd per sq ft, and 40.3 feet of drawdown can be expected if the permeability of the confining bed is 0.001 gpd per sq ft, a difference of 12.7 feet.

TABLE 13.—*Calculation of ultimate drawdown at a point 1 foot from well 48–H (H area) based on capture derived entirely from leakage through confining beds that have a vertical thickness (m') of 100 feet and a permeability (P') equal to 0.01 gpd per sq ft and 0.001 gpd per sq ft.*

Well or area	r (feet)	Q (gpm)	P'=0.01		P'=0.001	
			s(1,000) (feet)	s_Q (feet)	s(1,000) (feet)	s_Q (feet)
48–H	1	600	12.3	7.4	13.7	8.2
35–H	1,300	600	4.3	2.6	5.6	3.4
43–H	800	600	4.8	2.9	6.1	3.7
44–H	600	600	5.1	3.1	6.4	3.8
45–H	600	600	5.1	3.1	6.4	3.8
F area	10,500	3,500	1.9	6.6	3.2	11.2
D area	40,000	2,000	.5	1.0	1.7	3.4
M area	35,000	1,500	.6	.9	1.9	2.8
Ultimate drawdown at a point 1 foot from well 48–H	--------	--------	--------	27.6	--------	40.3

$$s_Q = s(1{,}000)\left[\frac{Q}{1{,}000}\right]$$

s_Q=drawdown, in feet, at a distance r from a well pumping at a discharge rate Q;

$s(1{,}000)$=drawdown, in feet, at a distance r from a well discharging at 1,000 gpm (values are obtained by reading directly from the appropriate curve as shown in fig. 36);

Q=rate of discharge, in gallons per minute.

The approximate vertical permeability can be calculated by considering the low-water discharge of the streams in the area of outcrop of the Tuscaloosa Formation. Table 4 shows the recorded discharge

of streams crossing the Tuscaloosa Formation in the outcrop area. These discharges were obtained from miscellaneous discharge measurements or were calculated from the rating curve for a regular gaging station. The average minimum daily discharge for the streams approximates 0.58 cfs per sq mi. This rate of flow indicates that the ground-water discharge from the Tuscaloosa Formation approximates 375,000 gpd per sq mi or 0.013 gpd per sq ft. If it is assumed that the loss of water from the principal artesian aquifer is recharged wholly by leakage through the overlying Tertiary sediments as is indicated by the piezometric map (pl. 6), then the quantity 0.013 gpd per sq ft represents the amount of vertical leakage per unit area through the overlying Tertiary sediments.
Thus

$$0.013 \text{ gpd per sq ft} = Q'/A = \frac{P'h'}{m'} \qquad (8)$$

where

Q'/A = amount of vertical leakage per unit area through confining bed, in gallons per day per square foot;
P' = vertical permeability of confining bed in gallons per day per square foot;
h' = difference in head, in feet, between the top and bottom of the confining bed;
m' = thickness, in feet, of confining bed;

hence

$$P' = \frac{0.013m'}{h'}. \qquad (9)$$

East and southeast of Aiken in the Shaw Creek valley, h' has an approximate value of 80 feet and m' about 60 feet. Therefore, from equation 9,

$$P' = \frac{0.013 \times 60}{80}$$

$$P' = 0.01 \text{ (approximately).}$$

EFFECTS OF CYCLIC PUMPING

In the preceding calculations it was assumed that each of the five wells in the H area well field would be pumped at a rate of 600 gpm, 24 hours a day. If, instead, each of the wells were to be pumped at a rate of 1,200 gpm for a period of 12 hours each day, the total volume of water pumped each day would remain exactly the same, but a cyclic pattern of fluctuation would be superimposed upon the long-term water-level trend. The effects of the cyclic pumping would be to increase the drawdown during 12 hours each day and decrease the drawdown during the remaining 12 hours. Hence, the amount of increase in drawdown would be directly proportional to the increase in the rate of pumpage or approximately equal to the drawdown that would be developed by pumping the wells at 600 gpm for 12 hours. To calculate the short-term effects of discharging wells it is necessary to use the Theis nonequilibrium formula which is given in figure 9. Table 14 shows the computation of the additional drawdown to be expected at a point 1 foot from well 48–H as a result of cyclic pumping in the H area well field. As itemized in table 14, the additional drawdown amounts to 12.5 feet.

TABLE 14.—*Calculation of additional drawdown at a point 1 foot from well 48–H due to cyclic pumping of wells in the H area well field at 1,200 gpm for 12 hours each day instead of continuous pumping of the same wells at 600 gpm*

[Other terms as defined in fig. 9]

Well	r (feet)	$\frac{r^2}{t}$ (sq ft per day)	u	$W(u)$	s (feet)
48–H	1	2.0×10^{0}	7.5×10^{-9}	18.1	6.2
35–H	1,300	3.38×10^{6}	1.26×10^{-2}	3.8	1.3
43–H	800	12.8×10^{5}	4.8×10^{-3}	4.8	1.7
44–H	600	7.2×10^{5}	2.7×10^{-3}	5.3	1.8
45–H	900	16.2×10^{5}	6.0×10^{-3}	4.5	1.5
Total					12.5

$$s=\frac{114.6QW(u)}{T}$$

where

$u=\frac{1.87S}{T}\frac{r^2}{t}$;
$Q=600$ gpm;
$T=200{,}000$ gpd per ft;
$S=4.0\times10^{-4}$;
$t=\frac{1}{2}$ day.

WELL-ENTRANCE LOSSES

Calculation of the ultimate or steady-state drawdown at any point within a given aquifer system by means of the Thiem formula (equation 2) does not take into account the losses in head that occur at the interface between a pumping well and the aquifer yielding water to the well, nor does it take into account the additional drawdown that occurs as a result of the fact that the pumped well was not screened throughout the thickness of the aquifer. These losses are collectively referred to as well-entrance losses because they are determined mostly by the construction of the well rather than by the characteristics of the aquifer. In general, well-entrance losses are caused by (1) turbulence in the region of the well face, (2) frictional resistance to the flow of water through the well bore to the pump intake, and (3) partial penetration or incomplete screening of the aquifer that supplies water to the well.

Well-entrance losses are known to vary directly with the rate of discharge. Doubtless, the well-entrance losses associated with turbulence or with friction in the pumping well are proportional to some power of the discharge rate greater than 1. On the other hand, the losses due to partial penetration or incomplete screening of the aquifer are likely to be proportional to the first power of the discharge. Therefore, as the rate of discharge increases, the head losses caused by turbulence and friction increase more rapidly than the losses caused by partial penetration or incomplete screening. It follows that as the discharge of a well increases, the well-entrance losses due to turbulence and friction constitute an ever-increasing percentage of the total well-entrance losses. For this reason, well-entrance losses are generally considered to be more nearly proportional to the second power of the discharge rate rather than to the first power. Hence, by dividing the total well-entrance loss observed in a given well at a given rate of discharge by the square of the given rate of discharge, a specific well-entrance loss is obtained that enables the calculation of the head loss (in feet) caused by the well at any specified rate of discharge.

The amount of drawdown inside a pumping well that can be ascribed to well losses is obtained by subtracting the theoretical drawdown at the well face from the observed drawdown inside the pumping well. Under steady-state conditions the theoretical drawdown at the face of a pumped well can be computed by means of a modification of the Thiem formula if the transmissibility of the aquifer is known and if observations are made of the drawdown in a nearby observation well.

Thus

$$s_w = s_o + \frac{527.7Q}{T} \log r_o/r_w \qquad (10)$$

where

s_w=drawdown at a distance from the axis of the pumping well, in feet, equal to the radius of the pumping well;

s_o=drawdown in observation well, in feet;

Q=rate of discharge, in gallons per minute;

T=coefficient of transmissibility in gallons per day per foot;

r_o=distance from pumping well to observation well, in feet;

r_w=radius of pumping well.

For a given well and given rate of discharge, the total well-entrance loss is equal to the difference between the theoretical drawdown obtained using equation 10 and the observed drawdown inside the pumped well. Table 15 shows the computation of well losses in five selected wells in the SRP area. In addition, the specific well-entrance loss is given for each well to permit the computation of the total well-entrance loss at any specified rate of discharge.

TABLE 15.—*Computation of well losses in five selected wells within the Savannah River plant area*

Well	Q (gpm)	Drawdown in pumped well		Well loss (feet)	Specific well loss (ft per gpm²)
		Theoretical (feet)	Observed (feet)		
21-F	1,870	16.9	44.0	27.1	7.7×10^{-6}
24-F	600	5.4	17.1	11.7	3.2×10^{-5}
27-R	440	10.7	15.2	4.5	2.4×10^{-5}
31-M	1,500	25.7	52.0	26.3	1.2×10^{-5}
35-H	1,530	12.3	41.5	29.2	1.2×10^{-5}

It should be noted that well-entrance losses are losses in head in addition to those caused by the resistance of the aquifer to the movement of ground water. For example, if it is desired to know the drawdown inside well 48-H instead of 1 foot from well 48-H, each of the previous tables of calculation (tables 9, 11-13) would need to be adjusted for the amount of well-entrance losses in well 48-H. Assuming, for purposes of compution, that the specific well-entrance loss for well 48-H is the same as that calculated for well 35-H (table 15), then the total well-entrance loss in well 48-H discharging at 600 gpm would be 1.2×10^{-5} ft per gpm$^2\times600$ gpm^2 or 4.3 feet. Hence, the total drawdown to be expected inside well 48-H when it is discharging at the rate of 600 gpm is approximately 4.3 feet more than the total drawdown computed for a point 1 foot from well 48-H. Although the specific well loss in well 48-H might not be the same as that determined for well 35-H, it is almost certain to be in the same order of magnitude because of the similarities in the details of well construction. For this reason it seems appropriate to add 4 or 5 feet to the drawdowns computed in tables 9, 11-13 to obtain a realistic value for the drawdown inside well 48-H.

EVALUATION OF DRAWDOWN COMPUTATIONS

The computations made under the assumption of two line sources of recharge are summarized in table 12. This analysis is based on infinite-line sources, whereas the outcrop of the Tuscaloosa in the

Savannah River, which represents one of the sources, extends only to the midpoint of the Savannah River Plant reservation, and so it is actually a finite source. If this source had been considered to be of the appropriate finite length (Muskat, 1937), the drawdowns computed would have been some 10–15 percent greater than those given in table 12. On the other hand, this analysis neglects the effect of recharge through the confining bed, which factor would tend to make the actual drawdown less than the computed value.

The computations summarized in table 13 ignore the termination of the aquifer against the crystalline rocks at the Fall Line, which is about 20 miles northwest of the H area, and the gradual thickening of the confining bed overlying the aquifer of the Tuscaloosa Formation with the consequent probable decrease in the value of $\frac{P'}{m'}$ in the southeastern direction. These factors tend to make the computed value of the drawdown less than the actual drawdown. The computations in table 13 also ignore the effect of the breaching of the Tuscaloosa in Horse Creek and in the upper Savannah River valley, factors which would make the computed value for drawdown greater than the actual drawdown.

Probably not all the factors involved can be explicitly considered in computations of the expected drawdown in the Tuscaloosa Formation. Because of the uncertainty as to the exact value to be ascribed to the transmissibility of the aquifer throughout the area that will be affected by the pumping, it is doubtful if refinement in the computations, if they could be made, would be justified.

The computation of drawdown in tables 12 and 13 are based on an estimate made in 1955 of the rate of pumpage from wells in the four principal process areas within the SRP. However, the actual rate and distribution of pumpage in the SRP during the 5-year period beginning in 1955 differed substantially from the 1955 estimates. For this reason it will be necessary to adjust the computed drawdowns given in tables 12 and 13 for the difference between the estimated and actual rates and distribution of pumpage before the accuracy of the results and, hence, the assumptions can be ascertained.

The actual rates of pumpage from wells in the four principal process areas of the SRP are shown graphically in figure 37. By averaging the daily rate shown for each area for each year of the 5-year period beginning in 1955, the following rates are obtained:

Area	*Gallons per minute*
H	1,200
F	1,200
D	500
M	1.200

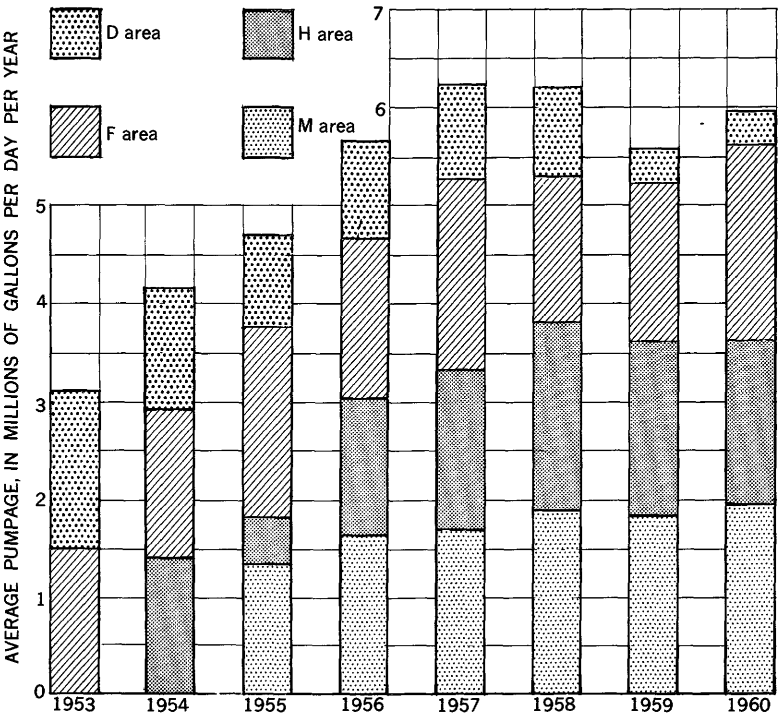


FIGURE 37.—Average pumpage from wells in the four principal process areas.

By substituting the above pumpage rates for those shown in the columns headed Q in tables 12 and 13, the ultimate drawdowns in the H area can be recomputed as follows:

In table—	*Feet*
12	11. 5
13	10. 9, if P (permeability) = 0. 01 gpd per sq ft
13	16. 2, if P = 0. 001 gpd per sq ft

The actual effects of pumpage from wells within the SRP on water levels in the principal artesian aquifer are indicated in figures 22, 23, 25, and 26. The hydrographs for wells BW–44, AK–183, and AK–266 are included to show the magnitude and trend of water-level fluctuations in the principal artesian aquifer in areas removed from heavy pumping. The remaining wells reflect the type of fluctuations in three of the four major process areas. A feature common to all of the hydrographs is a persistent decline of the piezometric surface from early 1952 to late 1957. Although this decline coincides with a period of deficient rainfall it also coincides with the period of plant construction when large amounts of water were pumped from the wells (fig. 37). In those wells peripheral to the SRP, such as BW-14, a recovery of water level began during the latter part of 1957 coincident with greater than normal rainfall and continued through 1960. In the wells in or near the more heavily pumped areas within the SRP, however, the downward trend in water levels has either been maintained during the subsequent period of greater than normal rainfall or the water-level recovery has been of a lesser degree than those characteristic of wells outside the SRP and unaffected by pumping. As shown in figures 22 and 26, by the end of 1959 or early 1960 a general decline of 11 feet (well 20-M) to 26 feet (well 15-M) was noted in the M area, 9 feet (well 21-F) in the F area, and 9 feet (well 45-H) in the H area. The last figure compares with the calculated drawdown of 11.5 feet for the H area. Other wells in these areas show lesser amounts of water-level decline but generally not less than 6 feet.

Inasmuch as the total drop in water level in the H area that can be attributed to pumpage in the SRP is about 9 feet (fig. 22), the most nearly correct computation of drawdown is the value obtained in table 13 when P, the vertical permeability of the upper confining beds, is assumed to be equal to 0.01 gpd per sq ft. Thus, it appears that the most nearly correct set of assumptions for evaluating the effects of withdrawals from the Tuscaloosa Formation are those on which table 13 is based, namely (1) that most of the recharge to the principal artesian aquifer in the SRP is obtained by leakage through the upper confining beds and (2) the upper confining beds have a vertical permeability of at least 0.01 gpd per sq ft.

EFFECT OF WASTE DISPOSAL ON THE QUALITY OF GROUND WATER

The operation of the SRP results in the accumulation of a variety of radioactive wastes with a wide range of volume and activity. The management of these wastes is given careful attention. The policy with regard to the disposal of radioactive wastes has been and continues to be primarily one of total containment.

The liquid wastes that have a high level of radioactivity are all stored in underground carbon steel tanks contained in concrete vaults. To date (1960) this method of containment has proved successful in protecting the natural environment from release of the toxic material. However, the tanks have a limited life and in a matter of decades may require replacement. Thus, alternate methods that might provide a more permanent means of storage are being studied. One such alternative being studied would involve the storage of these high-level wastes in caverns excavated in the basement rock at depths of approximately 1,500 feet below the land surface.

Exceptions to the policy of total containment are made in the disposal of solid wastes and low-level liquid wastes. Solid wastes are disposed of by burial in the area between the F and H process areas at a ground surface altitude of 260–280 feet above mean sea level. The contaminated material is buried in trenches which are about 20 feet deep. The topmost 3 feet of the trenches are backfilled with soil. The burial ground is surrounded by monitoring wells which are checked continuously for evidence of contamination.

The disposal of low-level liquid wastes is made directly into the geological environment by means of open seepage basins that are constructed in a series of three consisting generally of one large basin (350 ft by 750 ft approximately) and two smaller basins. Although a series of disposal basins has been constructed at most of the process areas within the SRP, only those basins in the F and H process areas are in fairly constant use. The effluent pumped into the basins in those areas ranges in pH from 2.0 to 10.0. It consists mostly of nitrate solutions that have been discharged from overhead evaporators.

The rate of seepage from the basins appears to be related in part to the pH value of the effluent. In general an increase in the pH value tends to coagulate the effluent and retard the seepage rate. On the other hand, a low pH value of 3.0 or less favors a rapid movement of strontium, one of the more hazardous radionuclides, through the soil column. The optimum pH is thought to range from 6 and 10.

Although the maximum allowable beta activity in the F and H area basins is 8 curies, of which 0.1 curie may be strontium 90, none of the radioactive isotopes except plutonium are completely absorbed by the soil (Brown and others, 1958, p. 100). Radioactive iodine was detected in some of the monitering wells as were some of the nonvolatile beta emitters including ruthenium, zirconium-niobium, strontium-yttrium, and rare-earth isotopes. Uranium of natural origin, was the only alpha emitter detected in the ground water. Since 1958, tritium has been found to move through the disposal system in the H area and has been detected in the discharge area along Four Mile Creek. Tritium in this sense is regarded as a precurser of other radioactive wastes and thus provides a good indication of the paths that will subsequently be followed by these wastes.

The volume of effluent discharged into the basins is said to average about 100,000 gpd per system. Brown, Parker, and Smith (1958, p. 95) report that the cumlative (4-year) ground disposal at the SRP was 5.0×10^8 liters (132 million gal).

The effect of geologic control is exemplified in the H area basins where the presence of cracks and fissures in the Hawthorn Formation has caused a high concentration of beta emitters to collect in the monitoring wells that intersect these fissures.

Detailed descriptions of the research and methods involved in the disposal of low-level liquid radioactive wastes may be found in several published reports including, in addition to those previously cited, reports by Brown, Parker, and Smith (1956), Clark and Pohl (1956), Reichert (1958), Theis (1956), and Horton and Patterson (1959).

CONCLUSIONS

The SRP area is underlain by a sequence of unconsolidated Upper Cretaceous, Tertiary, and Quaternary sediments that were deposited on an eroded basement of Precambrian(?) and Paleozoic igneous and metamorphic rocks. The basement rocks consist of granite, gneiss, schist, and slate into which has been downfaulted a Triassic basin of indefinite extent containing arkosic sandstone and siltstone. The surface of the basement rocks strikes approximately N. 66° E., and dips to the southeast at an average rate of 36 feet per mile.

The Cretaceous and younger sediments form a wedge ranging in thickness from a few feet on the northwest side of the area to more than 1,200 feet on the southeast side. They strike in an average direction of N. 60° E. and dip to the southeast 6–20 feet per mile.

The principal aquifer beneath the Savannah River Plant consists of the coarse sand and gravel of the Tuscaloosa and Ellenton Formations. Although the permeable zones in the two formations appear to be separated locally by interbeds of nonwater-bearing silt and clay, the permeable zones are hydraulically connected owing to the discontinuity of the silt and clay beds. Consequently, the permeable zones in the two formations are considered to be a single ground-water reservoir.

The principal aquifer is recharged by leakage through the Tertiary sediments, and discharge occurs in the outcrop area of the Tuscaloosa Formation. Doubtless, water is also discharged from the principal aquifer by moving downdip toward the coast and thence leaking upward through the upper confining beds.

The principal aquifer can supply 10,000 gpm for the operation of the SRP without exceeding the allowable drawdown in existing (1960) production wells. Potentially, the aquifer can produce more than the required amount, if additional wells are drilled and spaced so as to minimize interference between wells. For any given distribution of pumpage, however, the amount of drawdown will be directly proportional to the amount of water pumped.

The results of pumping tests on wells screened in the Tuscaloosa Formation indicate values for the coefficient of transmissibility ranging from 34,000 to 400,000 gpd per ft, for the coefficient of storage ranging from 0.0002 to 0.0008, and for the coefficient of permeability ranging from 360 to 1,500 gpd per sq ft. Although many wells obtain water from the Ellenton Formation, the uppermost part of the principal aquifer, most such wells are also screened in the middle or lowermost part opposite the Tuscaloosa Formation. The results of pumping tests on such wells are therefore not applicable exclusively to either of these formations. However, the difference between the capacities of these doubly screened wells and the capacities of wells screened only in the Tuscaloosa Formation indicates that the permeability of the Ellenton Formation is generally less than that of the Tuscaloosa.

Of secondary importance as aquifers are the permeable parts of zones within the sequence of sediments of Tertiary age. These aquifers overlie the Tuscaloosa in the southeastern half of the area. They have the same general strike as the Tuscaloosa but dip more gently to the southeast. The coefficient of transmissibility of the McBean Formation was calculated to range from 7,000 to 100,000 gpd per ft, and on the basis of one pumping test the coefficient of storage was calculated as 0.0002.

Because the principal aquifer obtains recharge through leakage from overlying sediments of Tertiary age, there is a hydrologic connection between the principal aquifer and the overlying sediments. Hence, pumping from the principal aquifer may eventually lower the water table. This lowering will cause reduced hydaulic gradients to the streams and the resultant decrease in stream discharge will balance in whole or in part the pumpage from the Tuscaloosa.

Water from the Tuscaloosa Formation has a low amount of mineralization and is quite soft. It is also slightly acidic, as indicated by pH values; this acidity, coupled with the low mineralization, makes the water somewhat corrosive to metallic surfaces.

The disposal of radioactive wastes has not seriously affected the quality of the ground water in the report area, but other methods of disposal are being studied and evaluated in order to enhance the protection of water supplies in the area.

REFERENCES

Berry, E. W., 1914, The Upper Cretaceous and Eocene floras of South Carolina and Georgia: U.S. Geol. Survey Prof. Paper 84, 200 p.

Bonini, W. E., and Woollard, G. P., 1960, Subsurface geology of N.C.–S.C. Coastal Plain from seismic data: Am. Assoc. Petroleum Geologists Bull., v. 44, no. 3, pt. 1, p. 298–315.

Brown, R. E., Parker, H. M., and Smith, J. M., 1956, Disposal of liquid wastes to the ground: United Nations, United Nations Internat. Conf. on the Peaceful Uses of Atomic Energy Proc., Geneva, 1955, v. 9, p. 565.

Brown, R. E., Pearce, D. W., Horton, J. H., Jr., and Patterson, C. M., 1958, Experience in the disposal of radioactive wastes to the ground at two production sites, *in* United Nations, Waste treatment and enviromental aspects of atomic energy: Second United Nations Internat. Conf. on the Peaceful Uses of Atomic Energy Proc., New York, v. 18, p. 95–100.

Brown, R. H., 1953, Selected procedures for analyzing aquifer-test data: Am. Water Works Assoc. Jour., v. 45, no. 8, p. 844–866.

Carslaw, H. S., and Jaeger, J. C., 1947, Conduction of heat in solids: Oxford Univ. Press, p. 234.

Clark, J. R., and Pohl, H. A., 1956, Earth disposal of radioactive wastes at SRP: U.S. Atomic Energy Comm. TID–7517 (pt. 1a), p. 162–169.

Cooke, C. W., 1925, Physical geography of Georgia, the Coastal Plain: Georgia Geol. Survey Bull. 42, p. 19–56.

——— 1933, Origin of the so-called meteorite scars of South Carolina: Jour. Geology, v. 42, no. 1, p. 88–96.

——— 1936, Geology of the Coastal Plain of South Carolina: U.S. Geol. Survey Bull. 867, 196 p.

——— 1940, Elliptical bays in South Carolina and the shape of eddies: Jour. Geology, v. 48, no. 2, p. 205–211.

——— 1943, Geology of the Coastal Plain of Georgia: U.S. Geol. Survey Bull. 941, 121 p.

——— 1954, Carolina bays and the shapes of eddies: U.S. Geol. Survey Prof. Paper 254–I, p. 195–206.

Cooke, C. W., and MacNeil, F. S., 1952, Tertiary stratigraphy of South Carolina: U.S. Geol. Survey Prof. Paper 243–B, p. 19–29.

Cooke, C. W., and Shearer, H. K., 1918, Deposits of Claiborne and Jackson age in Georgia: U.S. Geol. Survey Prof. Paper 120–C, p. 41–81.

Cooper, H. H., Jr., and Jacob, C. E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: Am. Geophys. Union Trans., v. 27, no. 4, p. 526–534.

Dall, W. H., 1898, A table of North American Tertiary horizons, correlated with one another and with those of western Europe, with annotations: U.S. Geol. Survey 18th Ann. Rept., pt. 2–C, p. 323–348.

Darton, N. H., 1896, Notes on relations of lower members of the Coastal Plain series in South Carolina: Geol. Soc. America Bull., v. 7, p. 516.

Doering, J. A., 1958, Citronelle age problem: Am. Assoc. Petroleum Geologists, v. 42, no. 4, p. 764–786.

——— 1960, Quaternary surface formations of southern part of Atlantic Coastal Plain: Jour. Geology, v. 68, no. 2, p. 182–202.

Dorf, Erling, 1952, Critical analysis of Cretaceous stratigraphy and paleobotany of Atlantic Coastal Plain: Am. Assoc. Petroleum Geologists Bull., v. 36, no. 11 p. 2161–2184.

Eargle, D. H., 1955, Stratigraphy of the outcropping Cretaceous rocks of Georgia: U.S. Geol. Survey Bull. 1014, 101 p.

Eckelmann, W. R., and Kulp, J. L., 1957, Uranium-lead method of age determination, pt. 2, North American localities: Geol. Soc. America Bull., v. 68, no. 9, p. 1117–1140.

Ferrel, W., 1859, Mathematical Monthly, p. 300.

Flint, R. F., 1940, Pleistocene features of the Atlantic Coastal Plain: Am. Jour. Sci. v. 238, no. 11, p. 757–787.

Glenn, L. C., 1895, Some notes on Darlington "bays": Science, new ser., v. 2, p. 472–475.

Glenn, L. C., 1905, South Carolina, *in* Underground waters of eastern United States: U.S. Geol. Survey Water-Supply Paper 114, p. 140–152.

Gray, Andrew, and Mathews, G. B., 1931, Treatise on Bessel functions and their application to physics: 2d ed. prepared by A. Gray and T. M. MacRobert, London, Macmillan Co., Ltd., 327 p.

Horton, J. H., Jr., and Patterson, C. M., 1959, Experience in the disposal of radioactive wastes to the ground—Savannah River Plant experience, *in* Radioactive waste disposal: Washington, D.C., U.S. 86th Cong., 1st sess., Hearing on Industrial Radioactive Waste Disposal, v. 2, p. 1213–1217.

Jacob, C. E., 1946, Radial flow in a leaky artesian aquifer: Am. Geophys. Union Trans., v. 27, no. 2, p. 198–208.

——— 1950, Flow of ground water: Engineering Hydraulics, p. 321–386, New York, John Wiley & Sons, Inc.

Johnson, Douglas, 1942, The origin of the Carolina bays: New York, Columbia Univ. Press, 341 p.

King, P. B., 1955, Appalachian field trip, *in* Guides to Southeastern Geology Guidebook for the 1955 Ann. Mt. Geol. Soc. America and Assoc. Soc.: p. 332–373.

Lang, W. B., and others, 1940, Clay investigations in the Southern States, 1934–35: U.S. Geol. Survey Bull. 901, p. 23–81.

LeGrand, H. E., 1953, Streamlining of the Carolina Bays: Jour. Geology, v. 61, no. 3, p. 263–274.

LeGrand, H. E., and Furcron, A. S., 1956, Geology and ground-water resources of central-east Georgia: Georgia Dept. Mines, Mining, and Geology Bull. 64, 174 p.

MacNeil, F. S., 1947, Geologic map of the Tertiary and Quaternary formations of Georgia: U.S. Geol. Survey Oil and Gas Inv. Prelim. Map 72.

Melton, F. A., and Schriever, William, 1933, The Carolina "Bays"—are they meteorite scars?: Jour. Geology, v. 41, p. 52–66.

Muskat, Morris, 1937, The flow of homogeneous fluids through porous media: New York, McGraw-Hill Book Co.

Petty, A. J., Petrafeso, F. A., and Moore, F. C., Jr., 1965, Aeromagnetic map of the Savannah River Plant area South Carolina and Georgia: U.S. Geol. Survey Geophys. Inv. Map GP–489.

Peyton, A. L., and Cofer, H. E., Jr., 1950, Magruder and Chambers copper deposits, Lincoln and Wilkes Counties, Georgia: U.S. Bur. Mines Rept. Inv. 4667.

Reichert, S. O., 1958, Geology and hydrology for disposal of radioactive wastes to ground at the Savannah River Plant: U.S. Dept. Commerce, Tech. Services Office, Atomic Energy Comm. Research and Development Rept. DP–341.

Salisbury, R. D., 1898, The physical geography of New Jersey, with an appendix by Cornelius Clarkson Vermeule, *in* New Jersey Geological Survey Final Report of State Geologist: J. L. Murphy, Trenton, N. J., 1880, v. 4, 170 p.

Schriever, William, 1951, On the origin of the Carolina bays: Am. Geophys. Union Trans., v. 32, no. 1, p. 87–95.

——— 1955, Were the Carolina bays oriented by gyroscopic action?: Am. Geophys. Union Trans., v. 36, no. 3, p. 465–469.

Shockley, N. G., Kolb, C. R., and Steinriede, W. B., 1956, Discussion of "Were the Carolina bays oriented by gyroscopic action?" by William Schriever: Am. Geophys. Union Trans., v. 37, no. 1, p. 112–115.

Siple, G. E., 1946, Progress report on ground-water investigations in South Carolina: South Carolina Research, Plan. and Devel. Board, Bull. 15, 116 p.

Siple, G. E., 1957, Ground water in the South Carolina Coastal Plain: Am. Water Works Assn. Jour., v. 49, no. 3, p. 283–300.

——— 1960a, Piezometric levels in the Cretaceous sand aquifer of the Savannah River Basin: Georgia Mineral News Letter, v. 13, no. 4.

——— 1960b, Some geologic and hydrologic factors affecting limestone terranes of Tertiary age in South Carolina: Southeastern Geology, v. 2, no. 1, August.

Siple, G. E., Brown, P. M., and LeGrand, H. E., 1956, Stratigraphic significance of Foraminifera from an outcrop of the Tuscaloosa Formation at Cheraw, S.C. [abs.]: Geol. Soc. America Bull., v. 67, no. 12, pt. 2, p. 1757.

Sloan, Earle, 1908, Catalogue of the mineral localities of South Carolina: South Carolina Geol. Survey Bull. 2, ser. 4, 505 p.

Smith, E. A., and Johnson, L. C., 1887, Tertiary and Cretaceous strata of the Tuscaloosa, Tombigbee, and Alabama Rivers: U.S. Geol. Survey Bull. 43, 189 p.

Smith, L. L., 1931, Solution depressions in sandy sediments of the Coastal Plain in South Carolina: Jour. Geology, v. 39, p. 641–652.

Spencer, J. W. W., 1890, "Southern Drift" and its agricultural relation: Agr. Expt. Sta. Bull. 6, p. 90–94.

Stose, G. W., and Stose, A. J., 1949, Ocoee series of the southern Appalachians: Geol. Soc. America Bull., v. 60, p. 267–320.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., v. 16, pt. 2, p. 519–524, 889–902.

——— 1956, Ground disposal of nuclear wastes, *in* Reactor technology and chemical processing: United Nations Internat. Conf. Peaceful Uses Atomic Energy Proc., Geneva, 1955, v. 9, p. 679–683.

Thiem, Gunther, 1906, Hydrologische methoden (Hydrologic methods): Leipzig, J. M. Gebhardt, 56 p.

Tuomey, Michael, 1848, Report on the geology of South Carolina: Columbia, S.C., v. i, 293 p.

U.S. Army, Corps of Engineers, 1952, Geologic-engineering investigation, Savannah River Plant, by Charleston District, published by Waterways Experiment Station, Vicksburg, Miss. (v. 1, 2).

U.S. Geological Survey, 1953, Surface water supply of the United States, pt. 2A, South Atlantic Slope Basin, James River to Savannah River: U.S. Geol. Survey Water-Supply Paper 1203 (published annually).

U.S. Public Health Service, 1961, Report of the advisory committee on revision of USPHS 1946 drinking water standards: Am. Water Works Assoc. Jour., v. 53, no. 8, p. 935–945.

Veatch, Otto, and Stephenson, L. W., 1911, Geology of the Coastal Plain of Georgia: Georgia Geol. Survey Bull. 26, 463 p.

Watson, T. L., and Powell S. L., 1911, Fossil evidence of the age of the Virginia Piedmont slates: Am. Jour. Sci., 4th ser., v. 31, p. 33–44.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods: U.S. Geol. Survey Water-Supply Paper 887, 192 p.

Woollard, G. P., Bonini, W. E., and Meyer, R. P., 1957, A seismic refraction study of the subsurface geology of the Atlantic Coastal Plain and Continental Shelf between Virginia and Florida: Wisconsin Univ. Dept. Geology Tech. Rept., Contract N7ONR–28512.

U.S. GOVERNMENT PRINTING OFFICE : 1967—O-243-540