Salt-Water Encroachment Geology and Ground-Water Resources of Savannah Area Georgia and South Carolina

---

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1611

Prepared in cooperation with the Georgia Department of Mines, Mining and Geology, the city of Savannah, and Chatham County, Georgia

Salt-Water Encroachment Geology and Ground-Water Resources of Savannah Area Georgia and South Carolina

By HARLAN B. COUNTS *and* ELLIS DONSKY

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1611

Prepared in cooperation with the Georgia Department of Mines, Mining and Geology, the city of Savannah, and Chatham County, Georgia

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1963

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

The U.S. Geological Survey Library catalog card for this publication appears after page 100.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C., 20402

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

SALT-WATER ENCROACHMENT, GEOLOGY, AND GROUND-WATER RESOURCES OF SAVANNAH AREA, GEORGIA AND SOUTH CAROLINA

By HARLAN B. COUNTS and ELLIS DONSKY

ABSTRACT

The Savannah area consists of about 2,300 square miles of the Coastal Plain along the coast of eastern Georgia and southeastern South Carolina. Savannah is near the center of the area. Most of the large ground-water developments are in or near Savannah. About 98 percent of the approximately 60 mgd of ground water used is pumped from the principal artesian aquifer, which is composed of about 600 feet of limestone of middle Eocene, Oligocene, and early Miocene ages.

Industrial and other wells of large diameter yield as much as 4,200 gpm from the principal artesian aquifer. Pumping tests and flow-net analyses show that the coefficient of transmissibility averages about 200,000 gpd per ft in the immediate Savannah area. The specific capacity of wells in the principal artesian aquifer generally is about 50 gpm per ft of drawdown. The coefficient of storage of the principal artesian aquifer is about 0.0003 in the Savannah area.

Underlying the Savannah area are a series of unconsolidated and semiconsolidated sediments ranging in age from Late Cretaceous to Recent. The Upper Cretaceous, Paleocene, and lower Eocene sediments supply readily available and usable water in other parts of the Coastal Plain, but although the character and physical properties of these formations are similar in the Savannah area to the same properties in other areas, the hydraulic and structural conditions appear to be different. Deep test wells are needed to evaluate the ground-water potential of these rocks.

The lower part of the sediments of middle Eocene age acts as a confining layer to the vertical movement of water into or out of the principal artesian aquifer. Depending on the location and depth, the principal artesian aquifer consists of from one to five geologic units. The lower boundary of the aquifer is determined by a reduction in permeability and an increase in salt-water content. Although the entire limestone section is considered water bearing, most of the ground water used in the area comes from the upper part of the Ocala limestone of late Eocene age and the limestones of Oligocene age. The greatest volume of water comes from the upper part of the Ocala limestone, but the greatest number of wells are supplied from the rocks of Oligocene age. The Tampa limestone and Hawthorn formation of early Miocene age are generally water bearing; the amount and quality of the water depends on the location. The water from some wells in the Tampa and most of the water from the Hawthorn is high in hydrogen sulfide.

In the northeastern part of the area the principal artesian aquifer is close to the land surface. Here the confining layer is thin and in some of the estauaries it may be completely cut through by the scouring action of the streams during tidal fluctuations. In this part of the area artesian ground

water at one time discharged from the aquifer as submarine springs. Now a reverse effect may be occurring; ocean and river water may be entering the aquifer.

The silts, clays, and very fine sands of the upper Miocene and Pliocene(?) series generally have low permeabilities and form the upper confining layer for the principal artesian aquifer. Although all the sediments overlying the principal artesian aquifer are considered to be part of the confining layer, locally some of the upper units are water bearing.

The uppermost geologic units in the Savannah area are sediments of Pliocene(?) to Recent age and consist of sands, silts, and clays with shell and gravel beds which are a source of water for shallow wells.

The first large ground-water supply from the principal artesian aquifer was developed in 1886 by the city of Savannah. Additional municipal and industrial supplies have been developed since that time. Pumpage progressively increased to a peak of 62 mgd in 1957. Outside of the city and industrial area the 1957 pumpage was about 9 mgd. In 1958 the total pumpage in the Savannah area was about 68 mgd or about 3 mgd less than in 1957. The Industrial and Domestic Water Supply System supplied about 26 mgd of treated surface water to industries in 1958.

Before ground-water supplies were developed in the Savannah area, the artesian head in the principal artesian aquifer generally was above land surface; but with the progressive increase in pumping, the artesian head declined. By 1958 the piezometric surface or artesian head had been lowered more than 145 feet near the center of pumping.

Ground water from the principal artesian aquifer generally has a low mineral content, but in the northeastern part of the Savannah area the lowering of the artesian head has caused highly mineralized water in the lower part of the aquifer to start moving toward Savannah. However, the chemical quality of water pumped from the artesian aquifer has changed little since the first wells were drilled.

Salt water is present in the lower part of the principal artesian aquifer about 15 miles northeast of Savannah and in the materials underlying the aquifer throughout the Savannah area. The salt water appears to be incompletely flushed water of Pleistocene age, and the hydraulic gradient indicates that it is moving laterally toward Savannah at a slow rate. At the present rate of pumping in the city of about 60 mgd, or even at double that rate, many years, perhaps more than a century, probably will elapse before water in the aquifer at Savannah becomes salty.

Most of the ground water pumped in the Savannah area is derived from precipitation on the outcrop of the principal artesian aquifer 60 to 100 miles to the north and northwest. The potential rate of recharge to the aquifer probably exceeds the theoretical maximum quantity that can be transmitted through the aquifer. The rate of recharge, therefore, probably is not a limiting factor determining the quantity of water that can be pumped from the aquifer in the Savannah area.

The pumping has lowered the water level or artesian head in the principal artesian aquifer near the center of pumping so much that very little additional ground water can be safely developed in that part of the area. Additional supplies of ground water can be developed by distributing the pumping over a wider area. Savannah and the surrounding area can support additional water-using industries if new wells are drilled to the northwest, west, and southwest of the city outside the present industrial area.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

Ground water is used in the Savannah area for industrial, public, and domestic purposes. It has been developed chiefly because of its availability everywhere in the area, its uniform temperature and quality, and its relatively low cost.

Over the years water levels have been continually lowered; this has caused concern that the water supply might be depleted seriously by overpumping or improper development, or that the supply might be contaminated by salt water moving into the aquifer where it is exposed on the ocean floor to the east of Savannah.

The value of the ground-water supplies in the Savannah area is difficult to determine accurately because the water is used for many different purposes, but it probably is more than $10 million annually.

Most of the ground water used in the Savannah area is pumped from a limestone aquifer (water-bearing strata) known as the principal artesian aquifer. It is about 600 feet thick and lies from about 100 feet below the surface in the northeastern part to about 350 feet below the surface in the southwestern part of the Savannah area; it includes limestone of Miocene, Oligocene, and Eocene ages. (See pl. 3.) The units of the aquifer are described in the section on geology and water-bearing properties of the rocks.

The possibility of salt-water encroachment due to overdevelopment of ground-water supplies led to the investigation described in this report. The investigation was planned to study the possibility of salt-water contamination of the principal artesian aquifer, and if salt water was present, to determine its vertical and lateral extent, and to trace its movement. Hydrologic data, water samples for chemical analyses, and pumpage data were collected.

To provide a framework for the ground-water investigation, a detailed study was made of the effects of lithologic changes and structure on the occurrence and movement of water in the rocks.

The investigation was made by the U.S. Geological Survey in cooperation with Chatham County, the city of Savannah, and the Georgia Department of Mines, Mining and Geology.

LOCATION OF AREA

The Savannah area as described in this report includes about 2,300 square miles along the Atlantic Coast of eastern Georgia and southeastern South Carolina. The areas of this and other recent reports on ground-water in Georgia are shown in figure 1. The Savannah area includes all of Chatham County and most of Bryan, Effingham, and Liberty Counties in Georgia and parts of Beaufort and Jasper Counties in South Carolina.

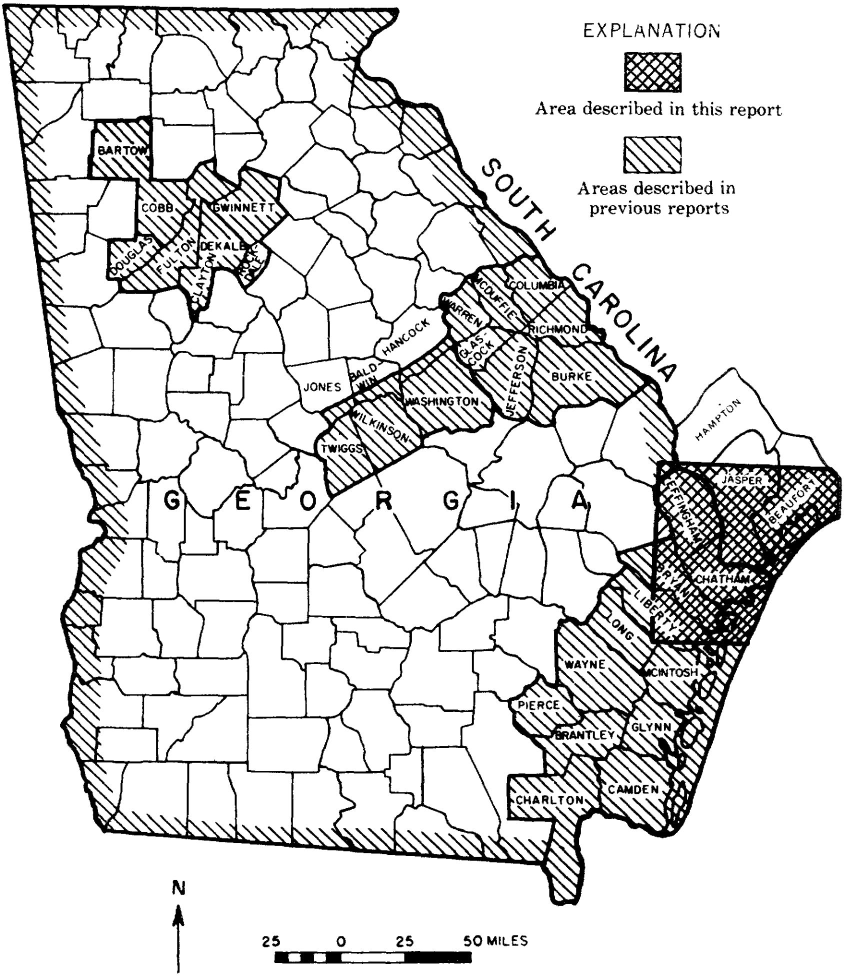

FIGURE 1.—Map of Georgia showing Savannah area in Georgia and South Carolina and areas described in previous reports.

PREVIOUS INVESTIGATIONS

The earlier reports about ground water in the Savannah area were concerned with generalities about the geology of the whole area, detailed descriptions of the geology penetrated by individual wells, or a detailed analysis of the hydrology of the principal artesian aquifer; but none of them were concerned with the interrelationship of the geology, hydrology, and salt water encroachment of the aquifer.

The earliest discussion of ground water in the Savannah area was by McCallie (1898) in his report on the Coastal Plain of Georgia.

A second report by McCallie (1908) described the ground-water conditions in the entire state. Veatch and Stephenson (1911) wrote on the geology of the Georgia Coastal Plain with descriptions of the individual counties. Four years later a more comprehensive report by Stephenson and Veatch (1915) described the occurrence of underground water in the counties of the Coastal Plain of Georgia.

Collins, Lamar, and Lohr (1932) listed information and chemical analyses of the water supply of Savannah, Ga. Lamar (1940b) described the water supply of Savannah and listed analyses of eight city wells. An unpublished report prepared by the East Georgia Planning Council in 1937 listed some records of wells and estimated the amount of artesian water used and wasted in the six coastal counties of Georgia.

A report by Stringfield, Warren, and Cooper (1941) contained some of the early results of an investigation of the ground-water resources of southeastern Georgia.

Until 1955 the Savannah area was included as part of the cooperative investigations of the entire eastern Coastal Plain of Georgia and Florida. Early reports resulting from cooperative studies were Warren's report and supplement (1944a and 1944b), and a report by Cooper and Warren in 1945. Subsequently, a report restricted to the Savannah area was prepared by Warren (1955), and that year Herrick and Wait (1955) prepared a report on test drilling in the Savannah area. Herrick and Wait (1956) described some of the geologic and hydrologic conditions in the Savannah area. Stewart and Counts (1958) described the water-level changes in the coastal counties of Georgia, southeastern South Carolina, and northeastern Florida. Another report by Counts (1958) described the quality of ground water in the Hilton Head Island area.

Stringfield and Cooper (1951) discussed factors affecting the yield of aquifers in the South Atlantic Coastal Plain. Siple (1957b) wrote a memorandum report on the geology and ground-water resources of the nearby Parris Island area, South Carolina.

Four recent reports which discuss regional and state ground-water conditions have been published. In 1953 a brief report related to artesian water in nine southeastern states was published (Stringfield, 1953). Thomson, Herrick, Brown, and others (1956) discussed the occurrence of ground water in the Coastal Plain. Siple (1957a) summarized the ground-water conditions in the Coastal Plain of South Carolina. A short report by Callahan (1958) discussed some basic principles of hydrology and summarized the geology of the major aquifers in Georgia.

Water-level measurements made in observation wells in the Savannah area from 1935 to 1955 have been published in water-supply papers by the U.S. Geological Survey. The water-supply papers listed in the bibliography cover the United States from 1935 to 1939 and the Southeastern States from 1940 to 1955. Subsequent measurements are planned for publication in water-supply papers at later dates.

METHODS OF INVESTIGATION

The investigation began in April 1954 with the drilling of two test wells. Test well CHA–357 was drilled on Cockspur Island, about 18 miles east of Savannah, and test well BFT–101 was drilled on Hilton Head Island, S.C. (See pl. 1.) These test wells were drilled under contract to aid in determining the position of salt water in the coastal parts of the aquifer and to determine the geologic age, character, and thickness of the aquifer and the confining layers above and below it.

In 1956 test well CHA–357 was deepened to determine the thickness and character of the lower confining layers of the principal artesian aquifer. This well was modified by placing well points at different depths and separating them from the rest of the hole with neat-cement plugs. A 1½-inch pipe extends from each isolated well point to the surface. This makes possible the collection of representative water samples from the various depths for chloride analyses. Early in 1957 test well BFT–101 was also modified in the same manner, but was not deepened. In 1958 a third test well, BFT–304, was drilled on the north end of Daufuskie Island, S.C. (pl. 1).

Geologic information was obtained mostly from water-well drill cuttings in the field and from the core library maintained by the Georgia Department of Mines, Mining and Geology in Atlanta, Ga. Valuable suggestions regarding the stratigraphy of the area were made by S. M. Herrick of the U.S. Geological Survey. Additional geologic information was obtained from three holes drilled for mineral investigations and from a few exposures in the western and northwestern part of the area and along the Savannah River. The concentration of well-drilling activity in Chatham County provides closer geologic control in that part of the area.

Hydrologic data included information on water-level fluctuations. Individual water-level measurements of about 65 wells were made monthly, and water levels in 33 wells were measured quarterly. In addition, water-level recorders installed permanently on 15 wells provide a continuous record of water-level fluctuations. Some of the recorders have provided information for nearly 20 years. A few recorders have been in operation less than a year.

Hydrologic information in the form of pumping-test data was used to determine various characteristics of the acquifer.

Chemical analyses of water from many wells in the area provide a record of the chemical constituents in the water. The analyses of water samples from three test wells provide a continually lengthening record of changes in chemical composition which occur at particular depths in the aquifer.

The methods of geologic investigation in the Savannah area are primarily indirect; that is, it is not possible to see the geologic formation and observe or sample it in places. In this area the geologic formations are brought to the surface in the form of cuttings or cores, which have been broken and ground by the drilling bit or recovered in a core barrel. Coring is not commonly practiced in drilling a water well so the majority of well samples are recovered as broken fragments of the rock. Sometimes there is only a muddy suspension as when clay or very fine-grained sediments are disintegrated in drilling fluids; sometimes no samples are recovered.

The samples from each well are preserved, catalogued, examined, described, and a log of the well is made. This log is then studied and compared to logs of other wells. Using these logs as guides, a subsurface section or series of sections of the area can be constructed.

Most of the information regarding the geology of the Savannah area comes from driller's and electrical logs. (See table 2 and fig. 2.) Formations are distinguished by and correlations are made on the basis of composition, fossils, and stratigraphic position. These data are summarized diagrammatically in a fence diagram of the Savannah area. (See pl. 2.) A geologic section based on well data is shown on plate 3.

The descriptions of geologic units in this report are given with the following qualifications:

1. The deeper formations have been tapped less often; therefore, the description from any one well, while considered reliable, may seem to be inconsistent with the description of another well many miles away.
2. The descriptions of well cuttings, whether complete or incomplete, are subjective. One observer may call a sample a calcareous sand, another may call the same sample sandy limestone. Also the determination of grain size usually is done visually, and different observers may describe the same sample somewhat differently.

3. The material as it is recovered from the well is wet and usually soft. However, when the cuttings dry they harden and material that is high in calcium carbonate may be described erroneously as limestone.

ACKNOWLEDGMENTS

The writers are greatly indebted to the representatives of industries and well owners in the area for their cooperation in supplying information on their ground-water developments. Special thanks are due Mr. A. A. Sickel of the Layne-Atlantic Co., and Messrs. Merrel Gray, Andrew E. Cory, H. L. Penton and Son, and T. G. Pinckney for supplying rock samples, well logs, and records of wells.

The U.S. Geological Survey is indebted to Mr. Fred Hack, Vice President of the Hilton Head Co., for the lease of a plot of land upon which to drill test well BFT–101 on Hilton Head Island, S.C., and to Mr. Ralston Lattimore of the National Park Service, U.S. Department of the Interior for permission to drill test well CHA–357 at the Fort Pulaski National Monument, Chatham County, Ga. Thanks are due Dr. M. L. Taylor and Messrs. G. C. Kimble and Maurice Klein of the Union Bag-Camp Paper Corp. for courtesies extended during the investigation. Thanks also are due to the officials of Chatham County, the city of Savannah, and the Savannah Metropolitan Planning Commission for valuable help with the investigation.

WELL-NUMBERING SYSTEM

The well numbers used in this report were assigned to the wells consecutively in each county as the wells were scheduled. An abbreviation for the county in which the well is located precedes the well number distinguishing it from a well with the same number in another county. For example, well CHA–357 is the 357th well scheduled in Chatham County, Ga. The only exception is well PI–2 which is the second test well drilled on Parris Island, Beaufort County, S.C.

GEOGRAPHY

THE ATLANTIC PLAIN

The Savannah area lies within the Sea Island section of the Coastal Plain province, which is a part of the Atlantic Plain (Fenneman, 1938). The Atlantic Plain is subdivided into two parts, the emerged plain or Coastal Plain, and the submerged Continental Shelf. The Atlantic Plain extends from southern Texas eastward to central Georgia and Florida and northward to Cape Cod, Mass.

The Gulf and Atlantic Plains are similar in many respects, but there are also differences, of which the most striking feature is that the Atlantic Plain, excluding the Florida Peninsula, is much narrower than the Gulf Plain. The average width is about 200 miles for both the submerged part and the emerged part. In contrast the Gulf Plain is about 500 miles wide from its inner margin, the Fall Zone, to the outer edge of the Continental Shelf.

The seaward slope of the Coastal Plain is only slightly interrupted by features of the coastal terraces and the present shore. From the Fall Zone near Augusta at an approximate altitude of 450 feet and on a line southeastward through Savannah, the relief is about 450 feet in 125 miles. The gradient of the land surface averages about 3.6 feet per mile, about the same as that of the Continental Shelf. The coastal terraces generally are flatter and their gradients, which are about 1.5 feet per mile, are similar in magnitude to the flattest part of the Continental Shelf.

The Savannah area is drained by two major rivers and many small streams and estuaries. The two major rivers, the Savannah and Ogeechee, generally cross the coastal terraces at right angles and pass through the Savannah area from northwest to southeast and empty into the Atlantic Ocean. (See pl. 1.)

THE CONTINENTAL SHELF

The Continental Shelf is the submerged part of the continent and is the continuation, beneath the sea, of the Atlantic Plain. The inner edge of the Continental Shelf is arbitrarily drawn at the present coastal beaches. The outer edge of the Continental Shelf usually is defined as the 100 fathom line (600 ft below mean sea level). At 600 feet the slope increases markedly, and this increase in slope marks the edge of the continent. A notable exception to this exists in the region extending from Cape Hatteras, N.C., to eastern Florida where the steep slope begins at a depth of about 50 fathoms, or 300 feet. The Continental Shelf varies in width, but near the Savannah area it is about 85 miles wide.

From the coast to the outer edge of the Continental Shelf the overall average gradient is about 3.5 feet per mile. However from the shore to 1 or 2 miles offshore the gradient is greater, about 30 feet per mile. The slope between 10 and 20 fathoms (60 and 120 ft) is about 2 feet per mile, and from 20 to 50 fathoms (120 to 300 ft) gradients average 3.5 feet per mile.

CLIMATE

The climate of the Savannah area is characterized by mild temperatures and abundant rainfall. Winters usually are short and mild, but include occasional cold periods of a few days duration. Summers commonly are long and hot; maximum temperatures range from 95° to 100°F during July and August. According to the U.S. Weather Bureau, the average annual precipitation recorded at Savannah for the period 1874 to 1958 is 45.75 inches, and the average annual temperature for the period 1874 to 1958 is 66.4°F. Rainfall usually is well distributed for agricultural needs, and the largest amounts occur during the spring and summer. The distribution of the average monthly precipitation and temperature at Savannah is given below:

Month	1874–1958	
	Precipitation (inches)	Temperature (°F)
January	2.45	51.6
February	2.82	53.4
March	3.49	58.7
April	2.47	65.7
May	2.91	72.9
June	5.17	79.0
July	7.09	81.2
August	6.25	80.4
September	6.50	76.7
October	2.45	67.0
November	1.51	57.5
December	2.64	51.7

The average frost-free growing season is 273 days; the average date for the last freeze in spring is February 26 and for the first freeze in fall is November 26.

CULTURAL DEVELOPMENT

The population of the area outside of Chatham County has decreased slightly from 1940 to 1950. The 1950 population for the counties covered by this investigation is listed as follows:

County	Total area (sq mi)	Population (rounded)	
		Total (1950)	Average (per sq mi)
Beaufort, S.C	672	27,000	40
Bryan, Ga	439	6,000	14
Chatham, Ga	441	[1] 193,000	400
Effingham, Ga	480	9,000	19
Jasper, S.C	578	11,000	19
Liberty, Ga	510	8,000	17
	3,120	254,000	----------

[1] Estimate of July 1, 1958 by the Georgia Department of Health.

Most of the people are employed by industries in the city of Savannah and Chatham County. There are many farms in the area which grow cotton, corn, tobacco, livestock, and pecans, but nonfarm employees outnumber farm workers by about eight to one.

Many products are manufactured and processed in the Savannah area. The many large industries include the world's largest pulp and paper mill, a sugar refinery, shipbuilding and repair, fertilizer plants, and chemicals. Savannah is a large seaport as well as a large manufacturing centeı. Many of the factories are near the Savannah River where they are served by ocean-going vessels which bring in raw materials and take out manufactured products.

Two military bases, Hunter Air Force Base and Fort Stewart, are in the Savannah area. Parris Island Marine Corps Recruit Depot is located on Parris Island in Beaufort County, S.C.

Savannah is served by five railroads, two major U.S. highways, and three airlines.

GEOLOGY AND WATER-BEARING PROPERTIES OF THE ROCKS

All the sedimentary rocks in the Savannah area are of late Mesozoic and Cenozoic age. Only sand and clay of Pleistocene to Recent age are exposed at the surface, except in the northern part where older rocks crop out along the banks of the Savannah River. Most of the formations were deposited during various transgressions and regressions of ancient seas. Associated with the deposits that were laid down during the marine invasions and retreats are sediments that appear to have been deposited in bays, lagoons and estuaries, or generally in nearshore areas. A lesser amount of the sediment was deposited on river flood plains closely adjacent to the sea.

In the Savannah area the rocks underlying Upper Cretaceous sediments, the lowermost sedimentary rocks, have been called the basement complex. They consist of a wide variety of igneous and metamorphic rocks.

The water-bearing properties of any rock are determined in part by its physical properties such as grain size, texture, porosity, permeability, cementation, compaction, and constituent minerals. The ability of a formation to store and transmit water is determined by its shape, altitude, and position relative to recharge and discharge.

Most of the water used in the Savannah area comes from the principal artesian aquifer, which is composed of limestone and marl of middle Eocene to early Miocene age. The term "marl" in this

690-437—63——2

report will refer to a soft limestone containing varying amounts of clay and other disseminated material such as quartz, mica, and glauconite. Below the aquifer the marl and dense limestone of the Tallahatta formation act as a confining bed. The Lisbon formation of middle Eocene age, which overlies the Tallahatta, is the lowermost unit of the aquifer in the western part of the Savannah area. Toward the east a facies change occurs in the Lisbon causing the permeability to be lowered, and the formation becomes a part of the lower confining bed. In that part of the Savannah area where the Lisbon is a confining bed the overlying Gosport sand is the basal unit of the aquifer. Above the Gosport, the Ocala limestone of late Eocene age and the undifferentiated limestones of Oligocene age are the most productive units of the principal artesian aquifer. The basal portion of the Tampa limestone of early Miocene age is the uppermost unit of the aquifer and overlies the Oligocene beds. The clayey sand and marl of the upper part of the Tampa and the silt and clay of the Hawthorn formation of late Miocene age are the upper confining layers for the principal artesian aquifer in the Savannah area.

The principal artesian aquifer is a source of water for all of the Coastal Plain of Georgia, and it also extends southward into Florida and westward into Alabama.

Locally, shallow sand deposits of Miocene to Recent age above the upper confining layer of the principal artesian aquifer yield water to wells in small amounts. The quantity and quality of the water and the geologic age of the water-bearing formation penetrated depend on the location of the well. Water table conditions probably exist in all shallow deposits.

In the Savannah area there are few surface exposures of water-bearing formations. The presence of springs along the river valleys seems to indicate that the water-bearing formations are close to the surface, particularly in the northwestern part of the area. A generalized description and water-bearing properties of the geologic units underlying the Savannah area is given in table 1.

The location of wells used in the construction of the fence diagram, plate 2, and the geologic section, plate 3, is shown in figure 2. Plate 2 is an interpretive diagram of the subsurface stratigraphy in the Savannah area. This fence diagram is a 30° oblique view of the Savannah area from some point in space over the Atlantic ocean. The top of each well is at its respective land surface elevation and is located in its correct geographical position. Table 2 is a list of wells used in figure 2 and plate 2.

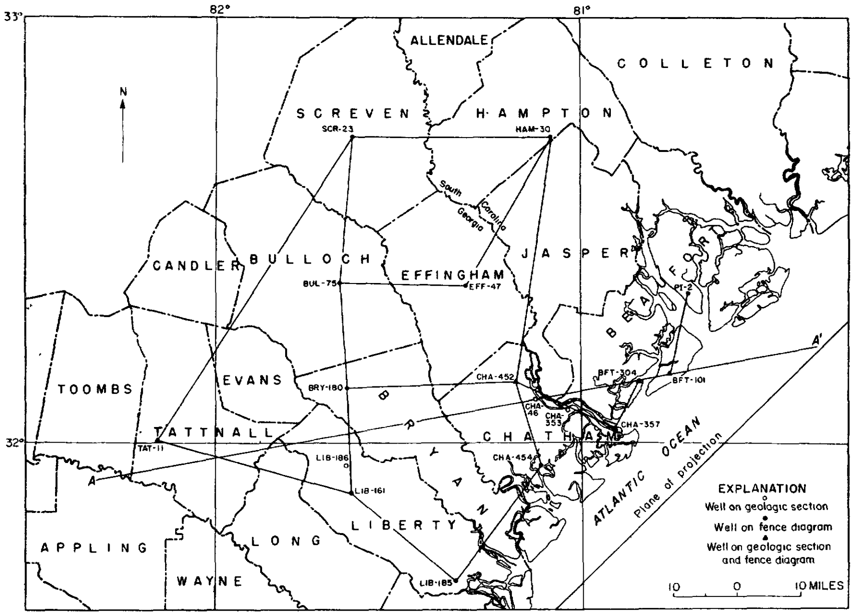

FIGURE 2.—Index map showing location of wells used in fence diagram and section *A-A'*.

CRETACEOUS SYSTEM

UPPER CRETACEOUS SERIES

The oldest sedimentary rocks in the Savannah area were formed during the Late Cretaceous, although other parts of the Coastal Plain Lower Cretaceous rocks have been reported from deep wells. No rocks older than Late Cretaceous age will be discussed in this report.

The Upper Cretaceous deposits in the Savannah area are, in ascending order, the Tuscaloosa, the restricted Eutaw, and the post-Eutaw formations. Applin and Applin (1947) referred the Tuscaloosa formation and the lower part of the Eutaw formation to the Atkinson formation; however, their terminology is not used in this report. The term Tuscaloosa formation for the lowermost Upper Cretaceous rocks has been used and accepted in eastern Georgia and the Savannah area, and the introduction of a new term in this report is not warranted because these deposits were not studied. The term Tuscaloosa formation is retained in this report, and is used in a lithologic sense. It includes the standard Tuscaloosa formation and the lower part of the Eutaw formation.

TABLE 1.—*Generalized description and water-bearing properties of geologic units in Savannah area*

System	Series	Geologic unit	Thickness (feet)	Lithology	Water-bearing properties
Quaternary and Tertiary.	Recent to Pliocene.	Undifferentiated sediments; include Waccamaw(?) formation of Pliocene age.	0–145	Terrace, flood-plain, alluvial, and beach deposits consisting of silt, sand, and gravel. Blue-gray to brown marl; silty and sandy.	Probably good supplies available from thick sections. Screens and development necessary. Water may be high in iron, sulfate, and nitrate, generally soft. Hydrogen sulfide causes "rotten egg" odor.
		Unconformity			
Tertiary	Miocene	Duplin marl	0–20	Tan to light-brown marl; some shells and clay; not much sand.	Few available data indicate small yields; water reported rather hard.
		Unconformity			
		Hawthorn formation	0–420	Green silt and sand interbedded with clay, marl, and altered limestone.	Probably will yield water for small domestic supplies. Higher yields possible from thick sections with proper development. Water hard and probably high in iron. Important as a confining bed rather than an aquifer.
		Tampa limestone	0–130	Yellowish-green calcareous, argillaceous sand interbedded with dolomitic limestone. Thin conglomeratic unit at the base.	Upper unit of principal artesian aquifer in most places. Yields reported up to 200 gpm. Hydrogen sulfide often detected in water; water moderately hard.
		Unconformity			
	Oligocene	Undifferentiated rocks	0–200?	Loosely consolidated gray to buff limestone. Dense, white sandy and cherty limestone in thin stringers. Thick unit of sand in northwest.	Part of principal artesian aquifer. Yields up to 500 gpm reported. Water is moderately hard.

Tertiary	Eocene	Unconformity				
		Ocala limestone	Upper unit	0-155	Differentiated only in the northeastern part of area. White limestone, fossiliferous, somewhat calcitized, and crystalline.	Major part of principal artesian aquifer. The upper unit of the Ocala and the overlying Oligocene rocks apparently are the most permeable parts of the aquifer. Yields of 500 to 4,200 gpm are possible from wells penetrating the entire principal aquifer. Water is moderately hard, low in iron and chloride. Water from lower part of the aquifer may have relatively high chloride. Temperature ranges from 67° to 76° F, depending on depth.
			Lower unit	0-280	Differentiated only in the northeastern part of area. Buff soft granular limestone. Thin layers and tongues of dense pale-blue calcitized limestone and silty, clayey limestone or marl. Glauconitic in the lower portions. In the southern and western parts of the area the Ocala limestone has not been differentiated into its upper and lower units; the undifferentiated Ocala has a thickness of about 575 ft.	
		Gosport sand		?-400	Cream-colored and white to gray dense sandy fossiliferous limestone and pale-green glauconitic marl.	Yields as much as 650 gpm reported from thick sections of the formation. Water is moderately hard and high in chloride near the coast. Lowest unit of principal artesian aquifer in eastern part of area.
		Lisbon formation		12-405	Mostly soft limestone, white, gray, and buff; but may be massive highly calcitized or glauconitic and dolomitic in some parts of the area. Some silt, clay, and marl in eastern part of area.	Lowest part of principal artesian aquifer in western part of area, part of lower confining bed in eastern part because of change in permeability.

TABLE 1.—*Generalized description and water-bearing properties of geologic units in Savannah area*—Continued

System	Series	Geologic unit	Thickness (feet)	Lithology	Water-bearing properties
Tertiary	Eocene	Tallahatta formation	?–250	Cherty cream-colored glauconitic marl and cream-colored silty, clayey, fossiliferous limestone.	Low yields, highly mineralized water, and depth to the formation minimize usefulness as an aquifer. Important as part of the lower confining layer.
		Unconformity			
		Undifferentiated rocks of Wilcox age.	0–215	Lithology varies; mostly marl and limestone and some sand zones. Dark-brown to cream-colored, silty, carbonaceous, glauconitic, and fossiliferous.	Sand zones may yield water. Few available data on this interval indicate low yields and hard water, high in iron.
		Unconformity			
	Paleocene	Clayton formation	130–385	Sandy limestone and calcareous sand, all argillaceous. Dull-white through gray to dark-brown. Coarsely glauconitic and fossiliferous.	Deeply buried compared to the principal aquifer. Water would be highly mineralized and yields probably low in the Savannah area. Larger yields reported from updip location in South Carolina (215 gpm average).
		Unconformity			
Cretaceous	Upper Cretaceous	Undifferentiated rocks	1970–2125	Marl, becoming silty and sandy, grading down into sand; fine to coarse-grained; micaceous, glauconitic, and fossiliferous. Interbedded with dark-gray fissile carbonaceous, micaceous clay or shale.	Large yields reported in South Carolina (225 gpm average); small yields in southwestern Georgia; not considered to be potential source in Savannah area because of excessive depth and probable poor chemical quality. Water soft and high in bicarbonate, iron, chloride, and fluoride in South Carolina. Temperature reported as high as 103° F at Parris Island, S.C.

TABLE 2.—*Wells used in fence diagram, plate 2, and section A–A′, plate 3*

Well	County, owner, and location	Altitude of surface (in feet)	Depth of well below land surface (feet)
BFT-101	Beaufort County, S.C.—U.S. Geol. Survey (test well 2), 0.5 mile west of old lighthouse on Hilton Head Island.	12	740
BFT-304	Beaufort County, S.C.—U.S. Geological Survey (test well 3), north end of Daufuskie Island.	13	746
BRY-180	Bryan County—city of Pembroke No. 1	94	477
BUL-75	Bulloch County—city of Brooklet No. 1, 0.5 mile west of water tower.	155	515
CHA-46	Chatham County—Union Bag-Camp Corp. No. 5, 2.5 miles west-northwest Savannah City Hall.	14	1,250
CHA-353	Chatham County—American Cyanamid No. 1, 3.5 miles east of Savannah City Hall.	15	650
CHA-357	Chatham County—U.S. Geol. Survey (test well 1), Cockspur Is., 12 miles east-southeast of Savannah City Hall (1 mile west of Fort Pulaski).	8	1,435
CHA-452	Chatham County—Savannah Mineral Development Co., Port Wentworth No. 1.	43	1,088
CHA-454	Chatham County—M. P. Linskey, end of Mendel Ave.	17	350
EFF-47	Effingham County—city of Springfield, west of Ga. Highway No. 21, south of Central of Georgia RR.	47	400
HAM-30	Hampton County, S.C.—Buckfield Plantation No. 1, north of village of Kress.	42	1,387
LIB-161	Liberty County—U.S. Army, Fort Stewart, 1.6 miles northwest of Court House at Hinesville.	85	816
LIB-185	Liberty County—Jelks-Rogers No. 1, lat. 31°41.25′ N., long 81°20.75′ W.	26	4,200(?)
LIB-186	Liberty County—U.S. Army, Fort Stewart, Taylors Creek Road.	*50	468
PI-2	Beaufort County, S.C.—U.S. Marine Corps, Parris Island No. 2, 1.5 miles west of Headquarters Bldg.	18	3,268
SCR-23	Screven County—city of Sylvania No. 3, east side of municipal ball park, 100 yd west of S. & A. RR.	202	490
TAT-11	Tattnall County—Georgia Forestry Commission No. 2, 2 miles west of Reidsville Prison.	*200	678

*Approximate.

UPPER CRETACEOUS FORMATIONS

The Tuscaloosa formation, as used in this report, is not exposed in the Savannah area. It is reported from two wells, LIB–185 and PI–2 (fig. 2). Well LIB–185, the Jelks-Rogers well 1 in Liberty County, Ga., penetrated 635 feet of Tuscaloosa formation at depths of 3,615 to 4,250 feet. Well PI–2 (Parris Island well 2) in Beaufort County, S.C., penetrated 781 feet of Tuscaloosa at depths of 2,669 to 3,450 feet. The beds in both wells consist of thin stringers of varicolored sand, sandy clay and micaceous clay. The Tuscaloosa in well LIB–185 includes 95 feet (3,870 to 3,965 ft) of dark-gray to black, fissile, carbonaceous, micaceous clay or shale which may be the middle marine member of the Atkinson formation of Applin and Applin (1947). This same middle member in well PI–2 consists of 138 feet (3,120 to 3,258 ft) of gray clay, fine-grained sand, and shell fragments (Applin and Applin, 1947).

The restricted Eutaw formation in the Savannah area consists of fine- to medium-grained sand which is indurated, glauconitic, phosphatic, fossiliferous, and is interbedded with thin stringers of gray, micaceous, carbonaceous, and fissile clay. In well LIB–185 the restricted Eutaw is 145 feet thick (3,420–3,615 ft), and in well PI–2 it is 104 feet thick (2,565–2,669 ft).

The post-Eutaw, or uppermost Cretaceous deposits, include marl and sandy marl, which are silty, micaceous, glauconitic and pyritiferous. Some of the lower parts of the deposits contain carbonaceous and fissile clay.

The post-Eutaw deposits probably are equivalent in age to the Austin, Taylor, and Navarro deposits of the Gulf Coastal Plain. In well PI–2 approximately 1,240 feet (1,325–2,565 ft) represents sediments of post-Eutaw age, and in well LIB–185 post-Eutaw is represented by 1,190 feet (2,280–3,470 ft) of sediments.

The regional southeastward dip at the top of the beds of Cretaceous age changes locally to a southward dip according to the available well data. The surface of the Upper Cretaceous probably is an undulating erosional surface. The gradient between well CHA–316 and well LIB–185 is about 21 feet per mile over a distance of 32½ miles, disregarding local relief.

Except in well HAM–30, rocks of the Upper Cretaceous series lie at a depth greater than 1,325 feet, and below the source of large volumes of good quality water in the principal artesian aquifer. Where the principal artesian aquifer is missing in South Carolina the Upper Cretaceous sands may be a source of ground water.

In well HAM–30 in South Carolina the Upper Cretaceous rocks begin at approximately 870 feet. The well originally was drilled to 1,387 feet; however, not much ground water was reported below 950 feet. The well was filled to 650 feet in 1953, and it yielded 780 gpm (gallons per minute) by pumping from Tertiary formations. Drawdown was reported to be approximately 69 feet with the pumping level at 100 feet.

Few data are available about the water-bearing character of the Upper Cretaceous rocks in the Savannah area. Various formations in the Upper Cretaceous series have proved to be satisfactory aquifers in other parts of the Coastal Plain. However, data are insufficient to determine the potentialities of the Upper Cretaceous rocks as aquifers in the Savannah area, and the authors believe that a comprehensive program of test drilling and aquifer studies should precede any plans for large-scale development of the Upper Cretaceous series in the coastal counties of Georgia and South Carolina.

TERTIARY SYSTEM

PALEOCENE SERIES

The Paleocene rocks in the Savannah area include the Midway group, which was once considered to be the oldest division of the Eocene series.

In Alabama, deposits of Midway age include three or more formations of which only the Clayton formation is represented in the Savannah area. The Paleocene series in southeasternmost South Carolina is not named, but S. M. Herrick (written communication, 1956) has applied the name Clayton to subsurface rocks in South Carolina. Cooke and MacNeil (1952, p. 21) previously indicated that what had been mapped as Black Mingo of early Eocene age should, in part, be considered of Paleocene, and probably of Midway, age.

CLAYTON FORMATION

The Clayton formation is the basal formation of Midway age. It crops out in an irregular belt from Quitman County, Ga., northeastward to a point slightly west of the Ocmulgee River in Twiggs County, Ga. The Clayton formation has been traced updip in the subsurface as far east as the Oconee River, Laurens County, Ga. S. M. Herrick (written communication, 1956) believes that with additional data this formation could be extended as far eastward as the Savannah River in southern Screven County, Ga. and Hampton County, S.C.

The Clayton formation lies unconformably on sediments of Late Cretaceous age and is overlain unconformably by overlapping formations of Wilcox and younger ages.

Character, distribution, and thickness.—The Clayton formation apparently underlies all the Savannah area because it is reported in well cuttings from southern and northern extremes of the area. The four well logs in the area showing Clayton deposits suggest two rather distinct lithologic units, which vary from one well to another and change considerably over long distances.

The lower unit is a calcareous sand, generally gray in color but ranging from light gray to dark brown. The unit is glauconitic, especially its lower part, and is generally fossiliferous throughout. This member represents a basal sand formed by a sea transgressing the Coastal Plain during earliest Paleocene time. Common Foraminifera and Ostracoda attest to the marine character of the lower unit. In well LIB–185, 185 feet (2,095–2,280 ft) of this unit is present. Farther north, in well CHA–316, the unit is 80 feet thick (1,150–1,590 ft), but only 50 feet 1,540–1,590 ft) of the unit was sampled. Still farther north, in well HAM–30, the lower unit is only 30 feet (840–870 ft) thick. To the east, in well CHA–357, 21 feet (1,414–1,435 ft) of this unit was penetrated before drilling stopped at 1,435 feet. In this well the lower unit is almost a marl; however, penetration was not deep enough to be certain. One other well, PI–2, reportedly penetrated the entire Paleocene, 260 feet (1,065 to 1,325 ft) thick, but the Clayton was not segregated into the two units in this well.

The upper unit of the Clayton is a sandy limestone. It is dark gray, silty, and clayey and includes stringers of fine- to coarse-grained indurated sand. It is fossiliferous and coarsely glauconitic throughout. The occurrence of *Robulus midwayensis* (Plummer) Cole and Gillespie, a key Foraminifera for the Clayton, indicates that this unit is of marine origin. In wells in Liberty, Chatham, and Hampton Counties the upper unit is from 10 to 200 feet thick.

Water-bearing properties.—In the Savannah area the Clayton lies about 400 to 600 feet below the bottom of the principal artesian aquifer. The Clayton formation is used as an aquifer in the southwestern part of Georgia. In Seminole County the formation attains a thickness of 300 feet or more and yields of 500 to 600 gpm have been obtained (Herrick and Wait, 1956). The water in Seminole County is a hard lime water, although satisfactory for most uses. The Clayton formation in the Savannah area is not regarded as a potential source of useable ground water because the sediments are too fine grained and the water is highly mineralized. Chemical analyses of water from the Clayton at 1,260 feet in well CHA–357 show 21,400 ppm (parts per million) of dissolved solids. (See table 6.)

EOCENE SERIES

ROCKS OF WILCOX AGE

Deposits of Wilcox age have been differentiated into at least three formations in western Georgia, but a similar subdivision in eastern Georgia is not possible at this time. The deposits of Wilcox age in eastern Georgia and in the Savannah area have not been named, but probably are equivalent to the Nanafalia, Tuscahoma, and the Bashi marl member of the Hatchetigbee formation.

Strata of early Eocene age are exposed in a very irregular belt extending from the Chattahoochee Valley, in Clay County, northeastward to Macon County. In the Savannah area deposits of Wilcox age are concealed beneath overlapping sediments of younger Tertiary age (MacNeil, 1944, p. 24 and 1947a, b).

Deposits of Wilcox age lie unconformably on the Clayton formation and in the Savannah area they are overlain by the Tallahatta formation of middle Eocene age. In some wells in the Savannah area deposits of Wilcox age have not been identified, and the Tallahatta lies unconformably on the Clayton formation.

Character, distribution, and thickness.—Deposits of Wilcox age in the Savannah area are composed mostly of marl. Formations of Wilcox age in western Georgia are composed mostly of sand.

In well LIB–185 the Wilcox consists of 55 feet (1,840–1,895 ft) of dark-brown, silty, carbonaceous, fossiliferous, coarsely glauconitic marl. Above the marl is 160 (1,680–1,840 ft) of loosely consolidated, granular, cream-colored limestone, which is argillaceous, phosphatic, and glauconitic. This limestone is similar to the overlying limestone of the Tallahatta formation.

In CHA–357, 102 feet (1,156–1,258 ft) of deposits of Wilcox age consist almost entirely of marl. The marl is cream colored, glauconitic, somewhat granular, and is interbedded with thin tongues of cream-colored, saccharoidal and fossiliferous limestone. The marl is also interbedded with thin stringers of fine- to medium-grained sand.

Formations of Wilcox age may be present in the northern part of the area, as indicated in the log of well HAM–30. In a preliminary study of the cuttings from the well, S. M. Herrick (written communication 1956) has tentatively identified 100 feet (600–700 ft) of sediments to be of Wilcox age.

Water bearing properties.—In southwestern Georgia part of the formations of Wilcox age constitute a major aquifer (Herrick and Wait, 1956, p. 80). Yields of as much as 700 gpm are obtained from sands of the Tuscahoma formation at Albany, in Dougherty County. In the Savannah area, however, the potential water-bearing zones are relatively thin, as in well HAM–30, and the water probably is highly mineralized because in well CHA–357, at depth 1,260 feet, water from the upper portion of the Clayton is highly mineralized. (See table 6.)

ROCKS OF CLAIBORNE AGE

In the Savannah area deposits of Claiborne age are represented by three marine formations: the lower unit is equivalent to the Tallahatta formation, the middle part to the Lisbon (McBean) formation, and the upper part to the Gosport sand. In many instances the group is designated as undifferentiated because of the paucity of diagnostic properties. (See pl. 2.)

TALLAHATTA FORMATION

The Tallahatta formation is the name applied to rocks in the Savannah area, which are equivalent in age to the Tallahatta formation of the eastern Gulf Coast. In the Savannah area the Tallahatta formation unconformably overlies rocks of early Eocene age, and where they are absent, it overlies rocks of Paleocene age. The Tallahatta is in turn overlain by the Lisbon formation of middle Eocene age.

Character, distribution, and thickness.—Although the Tallahatta formation has been noted in only six wells, the distribution of these wells suggests that the Tallahatta underlies most of the Savannah area. The formation consists of limestone and marl. Generally, the lower part of the formation is limestone and top is marl. The limestone is cream colored, granular, and somewhat loosely consolidated; it contains clay, phosphatic minerals, and chert. Coarse glauconite is abundant in the lower part of the limestone section. In the southern part of the area, the Tallahatta is 250 feet thick (1,430–1,680 ft) in well LIB–185 and 200 feet thick (955–1,155 ft) in well CHA–357. Farther north, in well PI–2, only 53 feet (1,017–1,070 ft) of Tallahatta is present and it consists of thin stringers of limestone interbedded with soft, sandy, cream-colored, cherty marl.

Water-bearing properties.—The Tallahatta formation is not a source of water for domestic, municipal, or industrial purposes in the Savannah area because its fine-grained materials yield only small amounts of water and the water is mineralized. The formation is important hydrologically because it forms part of the lower confining layer for the principal artesian aquifer.

LISBON FORMATION

The Lisbon formation occurs only in the subsurface in the Savannah area. In this report it is considered to be equivalent in age to the McBean formation which occurs in updip exposures. It conformably overlies the Tallahatta formation of Claiborne age and is conformably overlain by the Gosport sand of Claiborne age.

Character, distribution, and thickness.—In outcrops the Lisbon (McBean) formation consists of fine- to medium-grained, locally indurated, glauconitic sand interbedded with thin beds of gray, sandy, fossiliferous clay containing hard lime nodules. However, in the subsurface in the Savannah area, the Lisbon formation is mostly a soft, white or gray to cream-colored limestone. Lithologically it is somewhat difficult to differentiate from formations above and below. It is rather massive in some parts of the area, being highly calcitized. In well CHA–452 solid cores of material described as Lisbon are composed mostly of fragments, casts and molds of macrofossils, echinoid and bryozoan remains, and some Foraminifera. The limey pieces are cemented by calcium carbonate. The resulting rock, although generally soft or easily broken, is dense and massive in appearance. In some intervals the occurrence of coarse grains of glauconite slightly changes the color of the rock to pale green. The presence of dolomitic limestone modifies the color to shades of yellow and tan. East of a line between Port Wentworth and Union Bag-Camp Corp. in Savannah the formation contains less limestone and more silt, clay, and marl, and its permeability is lessened.

The Lisbon formation is recorded in all parts of the area from wells penetrating middle Eocene strata.

Water-bearing properties.—In and near the outcrop area the Lisbon yields sufficient water for rural, domestic, and municipal supplies. Downdip, in Screven and Effingham Counties, the Lisbon is reached at greater depths, and its water-bearing characteristics in this area are unknown. Still farther downdip, in western Chatham County, the Lisbon formation in part forms the lowest part of the principal artesian aquifer. In the easternmost part of the area, however, the Lisbon is not considered part of the principal artesian aquifer because of the previously mentioned lithologic changes. Along the coast the Lisbon acts as a barrier to the movement of water and is considered to be part of the lower confining layer.

Base of principal artesian aquifer.—The fence diagram (pl. 2) shows the extent and thickness of the Lisbon formation, and the geologic section *A–A′*, plate 3, illustrates how the bottom of the principal artesian aquifer rises eastward, cutting across time lines because of a facies change in the sediments. In the vicinity of Savannah the upper boundary of the lower confining layer is about the middle of the Lisbon formation at an approximate depth of 850 feet, but along the coast the upper boundary of the lower confining layer and the top of the Lisbon coincide, generally at a depth of about 700 feet.

The bottom of the principal aquifer is in part determined by the chemical content of the water, which increases with depth to the east and northeast. No line or limit can be set as to the depth at which "good" water is available, but an unusably high chloride content will determine the lower limit for developing water. For example, in well BFT–101 on Hilton Head Island, S.C., water with a chloride content of 368 ppm was recovered from a well point isolated at 543 feet. The bottom of the aquifer extends to a depth of approximately 700 feet in this vicinity, but the lower part of the aquifer, below about 500 feet, contains water high in chloride and cannot be regarded as a source of usable water for normal purposes.

GOSPORT SAND

The Gosport sand of middle Eocene age is the uppermost formation of Claiborne age. It is exposed only at a few localities in central Georgia. In the Savannah area, it is entirely in the subsurface. The Lisbon formation of Claiborne age lies conformably beneath the Gosport. In most parts of the Savannah area, the Gosport is conformably overlain by the Ocala limestone of Jackson age; where the Ocala is missing the Gosport is overlain unconformably by rocks of Oligocene age and younger.

Character, distribution, and thickness.—The Gosport sand is predominantly sand only in some updip surface and subsurface locations. In some of the deep wells in the Savannah area, the Gosport sand is composed of cream-colored and white to gray dense sandy fossiliferous limestone and pale-green coarsely glauconitic marl.

The extent and thickness of the Gosport in the Savannah area are shown on plate 2. It is not shown in well LIB–185, although it may be included in the bottom 240 feet of the Ocala limestone of late Eocene age. Approximately 400 feet (80–480 ft), the thickest section of Gosport recorded in the area thus far, was penetrated in well HAM–30.

Water-bearing properties.—In general, the Gosport is water bearing and the quality of water is good for most needs. In the northern and northwestern parts of the area the Gosport sand is as shallow as are the Ocala limestone and the undifferentiated Oligocene series limestone, the upper parts of the principal artesian aquifer, farther south.

ROCKS OF JACKSON AGE

In the Savannah area, and wherever present in the Coastal Plain of Georgia and South Carolina, the Jackson represents strata of late Eocene age. The Jackson formation from east Texas to the Tombigbee River in southwest Alabama is equivalent to the Ocala limestone. Eastward in Alabama and in western Georgia the deposits of Jackson age are represented by the Ocala limestone. Farther east in Georgia and in western South Carolina they are represented by the Barnwell formation in surface exposures; in easternmost Georgia and in South Carolina (Savannah area) they are represented by the Ocala limestone only in the subsurface.

OCALA LIMESTONE

The Ocala limestone is one of a number of water-bearing limestones which collectively constitute the principal artesian aquifer of the Coastal Plain in Georgia and part of South Carolina (Warren, 1944a, p. 17). For this report the Ocala is defined as a limestone of late Eocene age overlying the Gosport sand and undifferentiated Claiborne unit of middle Eocene age and unconformably underlying undifferentiated limestone of Oligocene age or in some places, strata of Miocene age.

A few good exposures of the Ocala limestone occur in the main valleys of the Chattahoochee, Flint, and Ocmulgee Rivers. Where beds equivalent to the Ocala are exposed or lie at shallow depths they are called the Barnwell formation in Georgia and the Barnwell sand in South Carolina (Cooke, 1936 and 1943; LaMoreaux, 1946; LeGrand and Furcron, 1956). The Barnwell beds are exposed over large parts of the Coastal Plain and form the area of recharge for its subsurface equivalent—the Ocala limestone.

Character, distribution, and thickness.—The Ocala limestone is divided into a lower unit and an upper unit in the Savannah area. For this report the division of the Ocala is based mostly on hydrologic properties and electric log correlations; the division is not formally related to that used in other areas. (See MacNeil, 1947b.)

The lower part of the Ocala in the Savannah area is predominantly a buff granular calcitized limestone. It is fossiliferous throughout and contains thin layers or stringers of dense, pale-blue limestone and sandy, silty, argillaceous limestone, or marl. It is glauconitic in the lower part and is somewhat similar to and, except for faunal assemblages, often mistaken for the Gosport sand. The lower unit is more widespread and thicker than the upper unit. Except in the northernmost part of the Savannah area where the entire Ocala limestone is absent, the lower part of the Ocala is 170 to 280 feet thick. The average thickness, based on eight well logs, is about 230 feet. In updip subsurface locations the Ocala is represented only by the lower unit. In the fence diagram, plate 2, the Ocala is not differentiated west of well CHA–452 in Chatham County, but it is thought to consist mostly of the lower unit because it resembles it lithologically. In well HAM–30 the Ocala is not present either because of erosion or lack of deposition. The average thickness of the Ocala (lower unit) in outcrops is much less than subsurface occurrences, but the formation is fairly persistent.

The upper unit is thinner and more limited in areal extent than the lower unit. In 7 wells in the Savannah area the upper unit is 80 to 155 feet thick. The average thickness is about 100 feet.

Because of its stratigraphic position and its proximity to a metropolitan area the upper unit has been penetrated more often than the lower unit and more information is available about its lithology.

The upper unit consists of white to gray limestone; it is somewhat calcitized, crystalline, and abundantly fossiliferous. Certain zones in this part of the formation consist almost entirely of bryozoan remains, echinoid spines, sponge spicules, and foraminifers. In contrast, there are thin (1 or 2 ft) zones of very dense limestone consisting of macroshells and fragments which have been cemented and are apparently somewhat compacted. These dense limestone zones contain numerous solution channels, and although the solid limestone may have a very low permeability, a small solution channel may increase the permeability greatly. (See table 4, well BFT-304, 186–196 ft.) In parts of the area, especially to the south, water-well drillers have reported relatively thick intervals of very hard rock and large cavities. One driller reported that in one well 6 feet of very hard limestone was penetrated, that the drill stem dropped the next 4 feet through a cavity, and that finally another 4 feet of very hard limestone was drilled. Although these conditions are not widespread they do indicate changing geologic conditions which may affect the water supply in the aquifer. In table 3, the two relatively high coefficients of transmissibility (450,000 and 780,000) were obtained as the result of pumping tests in the southern part of the area (Richmond Hill and Fort Stewart). These values were calculated for the entire principal artesian aquifer at those locations. However, it is quite possible that cavernous limestone, with extremely high permeabilities in a small interval, was the cause of the high transmissibilities.

Water-bearing properties.—The Ocala limestone has been known as a source of large supplies of water for many years. The extent of the formation, the amount of yield, and quality of the water are so well known that the Ocala itself has been referred to erroneously as the principal artesian aquifer. In some parts of the Coastal Plain, especially in the southern part of the Savannah and beyond, the Ocala may very well represent the entire principal artesian aquifer. Both the overlying and underlying formations are either altered to a dolomitic limestone or represented by relatively thin water-bearing rocks. The Ocala in Liberty County is thicker than the entire aquifer in some parts of Chatham County.

The quality of water obtained from the Ocala is excellent for most needs. The chemical constituents are within allowable limits although the water is moderately hard (60–120 ppm) and may need some treatment for commercial or industrial purposes. Yields of 2,000 to 3,000 gpm are common from wells utilizing only the Ocala limestone.

OLIGOCENE SERIES

Rocks intermediate in age between the Eocene series below and the Miocene series above have been assigned to the Oligocene series. In the Savannah area the rocks of the Oligocene series are undifferentiated because insufficient evidence exists to attach a formational name to any of the Oligocene deposits.

The undifferentiated Oligocene strata unconformably overlie the Ocala limestone in most of the area. Where successively younger parts of the Ocala are missing, the rocks of Oligocene age have been deposited unconformably on the truncated surfaces of older upper Eocene and middle Eocene rocks. The Oligocene series in turn is unconformably overlain by various facies of rocks equivalent in age to the Tampa limestone, and where the Tampa is overlapped, by sediments of the Hawthorn formation.

The Oligocene rocks are not exposed in the Savannah area, but crop out in the southwest and central parts of Georgia, and near Charleston, S.C.

Character, distribution, and thickness.—Distribution of wells indicates that rocks of Oligocene age underlie the Savannah area except in the northernmost part. No Oligocene was found in well HAM–30, either because of lack of deposition or removal by erosion. Where present, the Oligocene consists of a lower unit of cream-colored, dense, saccharoidal, fossiliferous limestone and an upper unit of loosely consolidated, gray to buff, chalky, nodular limestone. A unit of sand containing lenses and tongues of dense, sandy limestone is present in the northwestern part of the area.

The rocks of the Oligocene series, where present in the Savannah area, average about 25 to 50 feet in thickness. In the northwestern part of the area, however, the Oligocene is from about 100 to more than 200 feet thick. The maximum thickness is not known because the two wells showing the greatest thickness (wells EFF–47, and BUL–75, pl. 2) did not fully penetrate the Oligocene. The northwest thickening probably is the result of less erosion in that direction before the deposition of the Miocene.

Water-bearing properties.—The Oligocene strata in the Savannah area are water bearing and constitute part of the principal artesian aquifer. Yields of as much as 500 gpm have been reported for wells ending in the Oligocene, and the drawdowns ranged from 1 to 4 feet per 100 gpm.

The quality of the water from Oligocene strata is suitable for most needs. The water is only moderately hard but may require minor softening for large-scale commercial or industrial operations.

MIOCENE SERIES

The Miocene series, as interpreted in this report, includes three formations: the Tampa limestone and the Hawthorn formation of early Miocene age and the Duplin marl of late Miocene age. The Tampa and Hawthorn not only appear to be conformable with one another but seem to merge in parts of the Savannah area. Although lithologically similar, there is no faunal evidence to delineate the

690–437—63——3

boundary between the two formations. Prominent and consistent "kicks" on the electric logs have been selected as indicating a change in depositional environment or perhaps a time break of moderate duration; the zone of these "kicks" has been used to separate the Tampa and Hawthorn. The Duplin marl consists of a few remnants which lie unconformably on the Hawthorn formation in the northwestern part of the area.

TAMPA LIMESTONE

The Tampa limestone unconformably overlies rocks of the Oligocene series in the Savannah area. It is overlain by the Hawthorn formation, which is similar in composition to the upper part of the Tampa in exposures and in the subsurface of the Savannah area. The Tampa is not recognized in South Carolina in surface exposures, but in this report it is recognized in well cuttings from the subsurface.

Character, distribution, and thickness.—The base of the Tampa limestone is the most easily identified zone of the formation. It is a zone of black and gray shell fragments, dark red to brown phosphatic pebbles, frosted quartz pebbles, coarse sand, and pebble-sized fragments of indurated, dark-green to olive argillaceous silt. This unit also contains small fragments of consolidated limestone which appear to have been redeposited. This part of the Tampa grades laterally into sand or clay facies with the shell fragments and phosphatic pebbles persisting. The basal unit is about 5 to 15 feet thick in the Savannah area; the thickness generally is proportional to the overall thickness of the formation. To the northwest the remainder of the Tampa consists of a thick section of yellowish-green arkosic, calcareous, argillaceous sand overlain by a buff sandy weathered dolomitic limestone.

To the south the sand thins out leaving the dolomitic limestone interbeded with tongues and stringers of soft, pale-green to buff marl or silty limestone. This same lithology can be traced eastward. The eastern facies of the dolomitic limestone thins progressively northward and becomes similar to the Hawthorn formation. In well PI–2 from 40 to 90 feet of materials is reported to be Hawthorn, and the Tampa is thought to be nonexistent although cuttings from a well about 5 miles north of well PI–2 are reported as equivalent to basal Miocene.

The Tampa underlies most of the Savannah area and has a maximum thickness of about 130 feet.

Water-bearing properties.—The lower part of the Tampa limestone apparently is connected hydraulically to the other formations which make up the principal artesian aquifer. Because the fragments in the lower part of the Tampa are relatively large as much as 200 gpm may be available to wells from this thin zone.

One drawback to the sole use of the Tampa as an aquifer is the noticeably high content of hydrogen sulfide (H_2S), which imparts the odor of rotten eggs to the water. Numerous wells on Hilton Head Island draw water from the Tampa limestone and the underlying Oligocene strata. In the shallow wells, with only 3 or 4 lengths of casing (63 to 84 ft), there is a noticeable odor of hydrogen sulfide. A few wells with casing set deeper have less hydrogen sulfide. The hydrogen sulfide appears to be confined to the upper part of the Tampa which is a silty limestone or marl and probably has a low permeability. The origin of the hydrogen sulfide in the water is not known, but the low permeability of the rock probably prevented the water with the hydrogen sulfide gas from being completely flushed out of the formation.

Many domestic wells in the Savannah area yield water from the Tampa limestone and the amount of water obtained is sufficient for most needs.

The low permeability of the upper, thicker part of Tampa limestone indicates that it may actually be part of the upper confining layer. This is especially true in locations where the dominant lithology consists of large amounts of silt and clay and is similar to the Hawthorn.

HAWTHORN FORMATION

In Georgia the name Hawthorn formation is applied to a widespread formation of diverse lithology. The formation is exposed in the northwestern Savannah area along the Savannah River in the bluffs on the Georgia side from north of Hudsons Ferry, Screven County to Ebenezer Landing, Effingham County. Cooke (1936, p. 105–114 and 1943, p. 91–95) described many of the more significant exposures along the Savannah River and at other places in South Carolina and Georgia. In other parts of the area it is found in the subsurface.

In the Savannah area the Hawthorn formation lies conformably on the Tampa limestone. In some places it may merge with and be contemporaneous with the Tampa limestone. Elsewhere it overlies the Tampa and lies unconformably on rocks of Oligocene and late Eocene age. The Duplin marl of Miocene age, where present in the Savannah area, unconformably overlies the Hawthorn. Elsewhere the Hawthorn is unconformably overlain by sediments of Pleistocene and Recent age.

Character, distribution, and thickness.—The Hawthorn formation consists of many different lithologies, none of which are characteristic of the formation as a whole. The most obvious lithology in the subsurface in the Savannah area is the thick section of green silt and clay.

The thickest sequence of Hawthorn formation was recorded from the well TAT–11 west of Reidsville, Tattnall County, Ga. In this well 420 feet (35–455 ft) of yellowish-green sandy, silty clay was observed. The clay was interbedded with tongues of gray phosphatic sand, white to pink saccharoidal sand, and white dense sandy limestone.

Near Brooklet in Bulloch County, Ga., the Hawthorn is mostly fine- to coarse-grained sand with green silt and clay. Lenses and tongues of sandy limestone and streaks of dolomitic limestone are also present. The eastern facies of the Hawthorn becomes more silty, retaining the green color with many sequences of blocky sandy clay and tongues of dolomitic limestone. The formation is more calcareous from south to north.

In South Carolina the Hawthorn generally is less than 100 feet thick and in well HAM–30 it is absent. Post-Hawthorn seas, moving inland from the east, eroded the Hawthorn, making it thinner in the eastern part of the Savannah area.

Water-bearing properties.—The water-bearing properties of the Hawthorn formation cannot be summarized simply. The water generally is safe to use and hundreds of wells draw water from this formation, although the yields are small because of low permeabilities and poor recharge. However in certain locations thick sand zones are screened and developed to yield moderately large volumes of water. Elsewhere thick lenses or tongues of limestone yield water to open-casing wells.

The quality of the water varies locally; the most noticeable property of the water from the formation is the odor of hydrogen sulfide gas.

The Hawthorn is important as part of the upper confining layer. Its thickness and low permeability help to prevent the leakage of water from the surface into the principal artesian aquifer. Near the coast, changes in regional dip bring the aquifer close to the surface, and tidal currents have scoured deep holes into the Hawthorn in some of the estuaries. The thickness of the confining layer has been reduced and salt and brackish water probably leak through the Hawthorn into the principal artesian aquifer. Before the piezometric head was lowered to below sea level, artesian ground water probably discharged as submarine springs into the estuaries through the thin spots. Now a reverse effect is occurring—these same openings or thinly covered parts of the formation are points of recharge for salt and brackish water.

DUPLIN MARL

The Duplin marl of late Miocene age lies unconformably on the Hawthorn formation except where the Hawthorn is absent, as in well HAM-30, and the Duplin marl rests unconformably on the Tampa limestone. The Duplin is unconformably overlain by sediments of Pliocene(?) to Recent age.

Character, distribution, and thickness.—The Duplin marl consists of tan to light-brown marl, some shells and clay. Exposures of Duplin marl in bluffs on the Savannah River were described by Veatch and Stephenson (1911, p. 372). It is sandy where exposed and less sandy in the subsurface.

The Duplin marl generally is less than 50 feet thick in surface exposures in South Carolina. It is 5 to 15 feet thick in Georgia where it is exposed, and its thickness is about 20 feet or less in the subsurface of the Savannah area. The Duplin has been identified in well cuttings from a few wells in the vicinity of the Savannah River.

Water-bearing properties.—The Duplin yields small amounts of reportedly hard water. The hardness probably is due to the large amount of finely disseminated calcareous material in the sand. The only municipal well obtaining water from the Duplin marl is in Sumter County, S.C., and reportedly yields 25 gpm. Over most of the area, the Duplin marl probably functions as part of the upper confining layer of the principal artesian aquifer rather than as an aquifer.

PLIOCENE (?) SERIES

The presence of Pliocene deposits in the Savannah area is questionable. Although the striking similarity between the Waccamaw formation in the Carolinas and similar thin discontinuous deposits in the Savannah area suggests a close association between the two, the evidence is far from conclusive and the lack of diagnostic fauna precludes a definite age determination. Deposits of possible Pliocene age have been included with Pleistocene and Recent deposits on the fence diagram (pl. 2).

WACCAMAW (?) FORMATION

In the Savannah area, the Waccamaw(?) formation is identified definitely only in the subsurface. The sharp change in lithology between the green silt, clay, and marl of the Hawthorn and the red and yellow sand of the Waccamaw(?) suggests an unconformity at the base of the Waccamaw(?), although the fossil assemblage is of both late Miocene and Miocene and Pliocene ages. The upper boundary of the Waccamaw cannot be differentiated readily in the subsurface, especially where the Waccamaw(?) sand appears to grade upward into sand of Pliocene age. However, where the Waccamaw(?) is exposed, it appears to be overlain unconformably by a dark-blue-gray silty sand of probable Pleistocene (Pamlico) age.

Character, distribution, and thickness.—In the Savannah area, the Waccamaw(?) formation in the subsurface consists of red and yellow sand. Probable exposures of Waccamaw(?) occur at extreme low tide at the north ends of Hilton Head Island, S.C., and Ossabaw Island, Ga., along the Inter-Coastal Waterway. Here, 1 to 3 feet of indurated red and yellowish-brown argillaceous sand is interbedded with discontinuous thin layers of shells and polished phosphatic pebbles.

The Waccamaw(?) formation is encountered in the subsurface in the Savannah area in a belt 40 to 50 miles wide parallel to the coast. The farthest inland occurrence is in well BUL-75. This shows the landward extent of the Waccamaw(?) sediments, and indicates that the rise of the Pliocene sea probably was not more than 100 feet above present sea level.

In the Savannah area, the Waccamaw(?) formation probably is nowhere more than 15 feet thick, although Cooke (1936, p. 124) and Siple (1959, p. 11) indicated respectively that it was as much as 25 and 35 feet thick in South Carolina.

Water-bearing properties.—The Waccamaw(?) formation, although apparently present over much of the Savannah area, generally is thin and is not a source of water except for small domestic supplies.

Siple (1946, p. 56) reports four municipal wells tapping the Waccamaw formation in South Carolina. The average yield for the four wells was 51 gpm, from a maximum of 132 to a minimum of 20 gpm. The composition of the Waccamaw(?) formation in the Savannah area indicates that it may yield water that is high in iron, sulfate, and nitrate; the water is probably moderately hard where where the formation is marly but generally soft where it is sandy.

QUATERNARY SYSTEM

Ample evidence exists of repeated advances and retreats of glaciers during the Pleistocene epoch. Although the great ice sheets of Quaternary age did not reach Georgia or South Carolina, their influence is seen today in the Coastal Plain as a series of terraces, each at a lower elevation seaward. These were deposited or cut when the sea stood at different levels in response to the effects of climatic changes. The formations cannot be dated accurately because diagnostic faunal evidence is lacking, but in general the available evidence indicates a Pleistocene age for these deposits.

PLEISTOCENE SERIES—LOWER MARINE TERRACES

At least four ancient shorelines exist in the Savannah area. Topographic maps indicate the most apparent shorelines were at 150, 100, 30 and 10 feet, but they were not mapped. These shorelines are correlated with those described by MacNeil (1950, p. 99) as the peaks of marine transgression. The marine terrace deposits represent deposition between two successive stands (shorelines) of the sea. The oldest terrace deposits are the highest; in order of decreasing altitude above sea level and decreasing age, the terrace deposits comprise the Okefenokee, Wicomico, Pamlico, and Silver Bluff(?) (of local usage) formations.

OKEFENOKEE FORMATION

The Okefenokee formation, oldest and highest of the terraces, (MacNeil 1950, p. 101) is confined to the northwestern third of Effingham County and the southeastern part of Bulloch County. The formation consists of as much as 50 feet of fine- to coarse-grained, angular, white to rust-colored arkosic sand interbedded with sandy clay. The clay is mottled red, white, and purple and interbedded with thin stringers of gravel containing pyrite.

The water-bearing properties of the Okefenokee formation are not known, but it yields sufficient water for rural purposes to many shallow dug and drilled wells. The quality of the water is not known, but the color of the formation suggests that the water probably is soft and has a high iron content. Small supplies probably are available wherever this formation underlies the surface.

WICOMICO FORMATION

The Wicomico formation occurs in the Savannah area in patches and narrow ridges between altitudes of 70 and 100 feet bordering the eastern edge of the Okefenokee formation. It is less sharply defined than other terrace deposits, and MacNeil (1950, p. 102) suggests that the sea stood for only a comparatively short time at the level at which this formation was formed. Marine and coastal features such as offshore bars, beach scarps, and sand dunes are fairly well developed along a belt extending from north of Jasper County, S.C., to south of Liberty County, Ga.

The Wicomico formation probably is thin; 30-foot intervals of sand were penetrated in at least three wells, and as much as 13 feet of sand along river banks and flood plains is regarded as Wicomico formation. Elsewhere the Wicomico formation, or remnants of it, occurs as a thin veneer covering the Wicomico terrace.

The formation consists of fine- to medium-grained sand. It is white to gray with streaks of rust-colored, indurated, coarse sand.

Locally, finely disseminated phosphate grains and thin stringers of mottled micaceous clay occur within the Wicomico.

The Wicomico formation is water bearing in places, although little is known about the amount and quality of the water.

PAMLICO FORMATION

The Pamlico formation covers more of the Savannah area than any other formation of Quaternary age. The terrace on which the Pamlico is deposited occupies a belt 20 to 30 miles wide along the coast of Georgia and South Carolina, and the shoreline reached an elevation of approximately 30 feet above mean sea level.

The Pamlico terrace, the Pamlico beach scarp, and the lower part of the Wicomico terrace probably are best seen on the road northeast of Hinesville, Ga.

The formation consists chiefly of sand and clay, and the maximum thickness probably does not exceed 60 feet. The section, as reported by Cooke (1936, p. 150) from 11 wells in Beaufort County, S.C., consists of 10 to 30 feet of dark-gray to blue sandy clay overlain by 20 to 32 feet of yellow, gray, and white fine- to coarse-grained sand. In the rest of the Savannah area the white sand usually interfingers with the dark-gray to blue sandy clay, rather than the two occurring separately as in Beaufort County, S.C. The average thickness of the Pamlico formation is about 15 feet.

In Catham County, Ga., on the sites of Travis Airport and Hunter Air Force Base, remnants of the Pamlico formation include offshore islands or possibly barrier beaches. A large part of the city of Savannah, because of its altitude, also may be situated on a remnant of an island or barrier beach formed during Pamlico time, although good exposures of sand are not available for examination in the city.

The formation is composed of typical beach deposits consisting of very fine- to fine-grained white quartz sand which is well sorted and subrounded. At an approximate altitude of 30 feet above mean sea level the character of the sand changes from very fine to mostly coarse yellow quartz sand. The sand grains range from angular to subrounded and are poorly sorted; the units show some crossbedding.

Most shallow wells probably draw water from the Pamlico formation, in which water is under water-table conditons. Good quality water may be obtained from shallow wells provided necessary measures are taken to avoid contamination. The few analyses of water from the Pamlico formation show it to be soft, and at some places, high in iron content.

SILVER BLUFF (?) FORMATION

The Silver Bluff formation of local usage is represented by sediment deposited on the Silver Bluff terrace. The shoreline of this terrace is represented by a wave-cut bench at about 5 feet above sea level. In southeastern Florida, the Silver Bluff shoreline and terrace can be easily seen. Farther north and in the Savannah area this shoreline is less apparent. The paucity of consolidated rocks along most of the Atlantic Coast prevents the feature of this latest Pleistocene shoreline from being more widely preserved. An indistinct wave-cut bench at about 5 feet above sea level occurs on the seaward side of Ossabaw, Wassaw, Daufuskie, and Hilton Head Islands in Georgia and South Carolina.

In the Savannah area the Silver Bluff(?) formation consists of silty carboneaceous gray to brown sand of the island ridges and sticky gray muck or gumbo of the intercoastal tidal flats and salt marsh savannahs. The Silver Bluff(?) formation, which lies on the Silver Bluff terrace consists of silty carboneacous sand in the Savannah area. The color of the sand varies as does the clay content, grain size, sorting, and roundness.

Local conditions determine the amount and quality of the water available to wells from the Silver Bluff(?) formation. On some of the island ridges, which are as much as 8 to 15 feet above sea level, the cleaner sand deposits may yield small supplies of ground water, the quality of which is unknown. The sticky muck or gumbo is not an aquifer.

RECENT SERIES

The Recent series postdates and is unrelated to the marine terraces or their related formations.

RECENT FORMATIONS

The Recent formations include gravel, sand, silt, mud, and clay deposited on the flood plains of rivers, in sinkholes, lakes, swamps, on beaches, and in the brackish marshland along the coast. Deposition of sediment at the present time varies according to the kind of material available and local topographic features.

Rivers have periodically inundated their valleys, spreading moderately thick deposits of sand and gravel over the flood plains. Streams have been filling their estuaries with sand and mud, converting them into tidal marshes. The drainage in these marshes has been retarded by the accumulation of silt and the growth of plant life.

Windblown and wave-washed sands have been added to the beaches and islands raising the Recent deposits above water level.

The amount and quality of the water available in any Recent deposit is dependent on local conditions. Moderately large supplies of usable water may be available from the thick gravel and sand deposits along river flood plains and from deposits in limestone solution cavities. Near the ocean and along the tidal estuaries fresh water is difficult to find in shallow deposits because of included and infiltrating salt and brackish water.

SURFACE WATER

The Savannah River rises in the Appalachian Mountains and collects water from a number of Piedmont tributaries to become a major river. At the gaging station nearest its mouth, near Clyo, Ga., the Savannah River has a drainage area of 9,850 square miles and had an average flow of 7,220 mgd (million gallons per day) for the years 1930–33 and 1938–58 (U.S. Geological Survey, 1960a). The daily minimum flow during these years was 1,260 mgd in September 1931. The minimum flow required to maintain the new 9-foot navigation channel from Savannah to Augusta, about 125 miles upstream from Savannah, is 5,800 cfs (cubic feet per second) or 3,740 mgd. The flow is now regulated to maintain this necessary minimum by power operations and reservoirs near and above Augusta.

The Ogeechee River, a much smaller river than the Savannah, rises in the Piedmont province. At the gaging station near Eden, Ga., the Ogeechee River has a drainage area of 2,650 sq mi and had an average discharge of 1,357 mgd for the years 1938–58 (U.S. Geological Survey 1960b). The daily minimum flow during these years was 85 mgd in September 1954.

The quality of water from the Savannah and Ogeechee Rivers is similar. The dissolved solids average less than 60 ppm (parts per million), and the hardness averages less than 25 ppm (Thomson and others, 1956).

The Savannah Industrial and Domestic Water Supply System supplies treated river water to parts of Savannah. The surface supply augments the ground water from the principal artesian aquifer and supplies industries with a softer water than is available from the principal artesian aquifer. The system takes surface water from Abercorn Creek about 2½ miles above its junction with the Savannah River. Water from the Savannah River flows in and out of Abercorn Creek with the tidal cycle; thus it is Savannah River water that is obtained most of the time. The intake for the filter plant is about 13 miles north of Savannah City Hall. River water is pumped to the filtration plant located at Cherokee Hill, about 7 miles northwest of the Savannah City Hall, where it is filtered and chlorinated and where lime is added for adjustment of pH before it is pumped into the distribution system. The hardness of the river water averages about 20 ppm and that of the treated water about 34 ppm.

The surface supply system was put in service in May 1948 and treated an average of 11 mgd of river water during the last 7 months of that year. By 1954 peak daily loads were approaching 40 mgd, the original capacity of the plant. The 1954 to 1957 use of treated surface water from this plant averaged about 24 mgd. A 10 mgd addition completed in 1958 makes the total capacity 50 mgd. In 1958 industries used an average of about 25 mgd of treated river water, an amount equal to almost half the ground water used in 1958. Small amounts are used by the city of Savannah when a pump or motor fails or when a well is being repaired. Figure 3 shows the use of treated river water since the plant was put in operation.

The industries and power plants along the Savannah River use more than 200 mgd of untreated river water. This water is withdrawn from the river at plant locations and used largely for cooling of condensers. It is also used for rough washing, flushing of sewers, and emergency fire protection. The quality of the river water, especially its sodium chloride content, varies considerably and is dependent on the discharge of the river, tidal conditions, location of plant, and the depth of the intake pipe. With the deepening and enlargement of the ship channel connecting the port of Savannah with the Atlantic Ocean, waters of high chloride content have advanced farther upstream. In 1959, river water with a chloride content of less than 100 ppm could be obtained at all times south of the costal highway crossing at Port Wentworth.

The total use of treated and untreated surface water in 1958 was more than 225 mgd, which is about 3 times more than the 68 mgd of artesian ground water used in 1958.

GROUND WATER

The principal water-bearing formations in the Savannah area are the limestone sections of the Eocene, Aligocene, and Miocene deposits. These limestone deposits are known collectively as the principal artesian aquifer, and about 98 percent of the ground water used in the area is from this aquifer. The balance of the ground water comes from deposits of Miocene to Recent age. The following sections are concerned mostly with water in the principal artesian aquifer.

Substantial amounts of ground-water may be developed at some place from shallow sand aquifers, which may not yield more than 1 or 2 gpm elsewhere. The sands are variable in thickness, distribution, and grain size. Shallow wells are used for air-conditioner cooling water, but well screens become plugged with limy deposits which must be cleaned by acidizing about once each year. No large well yields have been reported from the upper deposits in the Savannah area, and not enough information is available to predict well yields. However, water supplies from shallow wells for small industries or supplemental supplies for larger users are possible, but must be located by test drilling. Wells in shallow sands are subject to salt-water contamination where located close to estuaries or the ocean.

GENERAL PRINCIPLES OF OCCURRENCE

A detailed treatment of the principles of ground-water hydrology has been given by Meinzer (1923), Tolman (1937), Wenzel (1942), and others. Most of the following discussion is based on the principles given in these reports, as they apply to the Savannah area. Detailed descriptions and analysis of the occurrence of ground water in the Savannah area, given in following sections, make necessary some modification of the following general statements.

The rocks that make up the outer crust of the earth generally have numerous openings, called voids or interstices, which may contain air, natural gas, oil or water. The number, size, shape, and arrangement of these voids vary greatly. The occurrence of water in any region is therefore determined by the geology of the region.

The supplies of ground water in the Savannah area are in the porous rocks, such as the shallow sand and the deeper limestone deposits of the Coastal Plain of Georgia and South Carolina. The ground water contained in these rocks is derived chiefly from precipitation. A part of the precipitation runs off on the land surface and enters streams; a part is evaporated or used by plants; and a part, generally called recharge, passes through voids in the rocks and enters the zone of saturation. The water in this zone is stored only temporarily, because it moves slowly to nearby streams or through ground-water reservoirs and eventually is discharged into streams, the ocean, or directly into the atmosphere.

Ground water occurs under two general conditions: water-table (unconfined) and artesian (confined). Water-table conditions occur where the porous and permeable rocks that make up the ground-water reservoir or aquifer are not overlain by impervious rocks. Most precipitation enters water-table aquifers by downward percolation in the Savannah area. Under artesian conditions water in an aquifer is confined by relatively impervious rock and is under pressure. If the artesian reservoir is penetrated by a well the water rises in the well above the bottom of the upper confining bed. Any well tapping an artesian aquifer is considered an artesian well; there are both flowing and non-flowing artesian wells. As the water in an artesian aquifer is confined by essentially impervious rock there is no "free" water surface or water table; instead, there is an imaginary surface, called the piezometric surface, that coincides with the level to which the confined water rises in wells.

In the Savannah area water-table conditions occur in the shallow sand deposits, and artesian conditions occur in the buried limestone beds that form the principal artesian aquifer and in deeper water-bearing units. At the outcrop area of the principal artesian aquifer, 60 to 100 miles west-northwest of Savannah, water-table conditions occur.

The principal artesian aquifer in the Savannah area and the Coastal Plain of Georgia transmits water from the outcrop area to outlets of natural or artificial discharge. Most natural discharge results from upward seepage through the overlying confining beds over a large area and from leakage in areas that crop out on the Atlantic Ocean floor along the Continental Shelf or Slope east and northeast of the Savannah area. Water is discharged artificially through wells.

In an artesian aquifer water generally is not available from storage by drainage from the saturated material, as in water-table conditions. Water is released from storage when the hydrostatic pressure is decreased locally by a means of discharge such as a well. The release of the water is due to the compressibility and elasticity of the aquifer and adjacent confining beds and to the slight expansion of the water itself. The measure of an artesian aquifer's ability to release water from storage is called the coefficient of storage, and for artesian aquifers this coefficient generally is in the magnitude of less than a thousandth of aquifer volume. Nevertheless, if the reduction in hydrostatic pressure is large over a wide area, the quantity of water contributed from artesian storage may be substantial.

Before wells were drilled into the principal artesian aquifer in the Savannah area, the hydraulic system was in balance, and the natural discharge of water was equal to the average rate of recharge on the outcrop area. The hydrostatic pressure was high enough to force fresh water into bodies of salt water at the land surface and into the Atlantic Ocean. Under these conditions, the salt water did not encroach under the land surface.

An increase in discharge caused by pumping wells places a burden on the hydraulic system that has to be balanced by an increase in recharge, a decrease in natural discharge, a reduction in storage in the aquifer, or all three. There must be a corresponding increase in recharge or decrease in natural discharge if the pumping is to continue at the same rate indefinitely. If an adjustment is not possible, the rate of pumping must eventually decrease until it is equal to the quantity of water made available for artificial discharge by the increase in recharge and the decrease in natural discharge. During the adjustment, the water table or piezometric surface is lowered over a large area. If the water table or piezometric surface is lowered below sea level in an area where surface bodies of salt water, or the ocean, are connected hydrologically with the aquifer, salt water moves into the aquifer and the aquifer becomes contaminated with highly mineralized water. One of the chief objectives of this ground-water study is to describe the ground-water developments and to provide an analysis of the effects of these developments on the hydrologic system, which in this area includes fresh and salt water.

PERMEABILITY, TRANSMISSIBILITY, AND STORAGE

The properties of a water-bearing formation or aquifer that determine its capacity to transmit water and to release water from storage are its permeability, transmissibility, and storage. The properties commonly are described by numerical coefficients. Meinzer's coefficient of permeability may be expressed in field terms as the number of gallons of water per day, at 60°F, that is conducted through each mile of the water-bearing bed (measured at right angles to the direction of flow), for each foot of thickness of the bed and for each foot per mile of hydraulic gradient (Stearns, 1928, p. 148). The field coefficient of permeability denotes this rate of flow at the prevailing temperature instead of at 60°F. The coefficient of transmissibility (Theis, 1935, p. 520) is the product of the field coefficient of permeability and the thickness, in feet, of the saturated part of the aquifer. It usually is expressed as the quantity of water, in gallons per day, that flows through a section of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile. The coefficient of storage of an aquifer is defined as the volume of water it releases or takes into storage per unit surface area of the aquifer per unit change in the companent of head normal to that surface.

Many pumping tests have been made in the Savannah area for the determination of the coefficients of transmissibility and storage of the principal artesian aquifer. These are summarized in table 3.

The aquifer coefficients listed in table 3 are based on formulas that assume ideal conditions necessary for mathematical solutions. These assumptions are (a) that the aquifer is infinite in areal extent; (b) that it homogeneous and isotropic—that is, it transmits water equally in all directions; (c) that it is bounded at the top and bottom by impermeable material; (d) that it has a uniform thickness; and (e) that water is released instantaneously from storage with a decline in head. They further assume (f) that the discharging well completely penetrates the aquifer and (g) that the flow of water toward the well is radial or two dimensional. These assumptions are never realized in nature. However, because these assumptions are applied equally to all tests, the results provide useful indices for comparing aquifer properties. Furthermore, tests in many areas have shown that the results of these tests, if used judiciously and with consideration for the geologic framework of the individual areas, provide coefficients in the general magnitude of the actual field conditions.

TABLE 3.—*Summary of transmissibility and storage coefficients for the principal artesian aquifer in Savannah area*

[Data from this investigation unless otherwise referenced]

Location of test	Date	Type of test	Coefficients (rounded)		Remarks
			Transmissibility (*T*) (gpd per ft)	Storage (*S*) (cu ft per ft)	
Union Bag-Camp Paper Corp., Savannah.	1939 and 1956.	Pumping	250,000	0.0003	Average of 6 values 1939 value from Warren (1944a).
Town of Port Wentworth	1943	do	250,000		
Savannah Electric and Power Co., Port Wentworth Plant.	1957	do	200,000	.0002	Average of 7 values.
Savannah Electric and Power Co., Savannah, Riverside Plant.	1957	do	250,000		
U.S. Post Office, Savannah	1958	do	150,000	.0003	
American Cyanamid Co, Savannah	1954	do	200,000		Average of 2 values.
Naval Air Station, Burton, S.C.	1944	do	45,000 to 90,000.		From Siple (1957b).
Fort Pulaski, Cockspur Island, Ga.	1956	do	600,000	.005	Average of 2 values.
Daufuskie Island	1958	do	400,000	.0003	
Richmond Hill, Bryan County, Ga.	1955	do	450,000	.0002	
Fort Stewart, Liberty County, Ga.	1940	do	780,000		From Warren (1944a).
Hazen and Sawyer test wells, 1.4 miles north of junction of S.C. 170 and S.C. 462, Jasper County, S.C.	1957	do	350,000	.0005	Average of 3 values.
Analysis of cone of depression inside the 0 contour on piezometric maps. Covers the general Savannah area.	1939 to 1957.	Equilibrium.	250,000		Average of upgradient and downgradient for 8 maps.
Do	1939 to 1957.	Flow-net	250,000		Average for 8 maps.

The average for the first 6 values for the coefficient of transmissibility in table 3 is about 200,000 to 250,000 gpd per ft and the average for the first 3 values for the coefficient of storage is about 0.0003. Although these values for the coefficient of transmissibility appear to be reasonable for the vicinity of Savannah they probably are too low for the report area, as other values in table 3 indicate. Warren (1944a, p. 117) concluded that the coefficient of transmissibility for the general Savannah area must be higher than that which he had calculated for the immediate Savannah area. Warren had concluded that the coefficient of transmissibility in the immediate Savannah area was about 250,000 gpd per ft, which checks closely with 3 of the first 6 values and the flow net analysis of 8 piezometric maps listed in table 3. The coefficient of transmissibility is much larger north, east, south, and southwest of Savannah than at Savannah. At Fort Stewart, 35 miles southwest of Savannah, a pumping test indicates the coefficient of transmissibility to be about 780,000 gpd per foot or about 3 times as high as in the immediate Savannah area. At Cockspur Island, about 15 miles east of Savannah, a pumping test indicates the coefficient of transmissibility to be about 600,000 gpd per ft or more than twice as high as at Savannah. At a test site in Jasper County, S.C., about 23 miles northeast of Savannah (the 12th test in table 3), the coefficient of transmissibility is about 350,000 gpd per ft or about 1.5 times as high as in the immediate Savannah area.

In general, the coefficient of transmissibility in the Savannah area probably ranges from less than 200,000 to as much as 1,000,000 gpd per ft. At the Naval Air Station and the Burton well field near Burton in Beaufort County, S.C., M. J. Mundorff in 1944 calculated the coefficient of transmissibility to be about 45,000 and 90,000 gpd per ft respectively after testing two wells (Siple, 1957b, p. 17).

The average coefficient of permeability for the immediate Savannah area is about 400 gpd per sq ft (the average transmissibility divided by the average thickness of the aquifer, or about 600 ft) and about 970 gpd per sq ft at Cockspur Island.

Samples of materials from the aquifer and the confining layers were tested at the U.S. Geological Survey's hydrologic laboratory in Denver, Colo., for determination of porosity and the coefficients of permeability. The results are listed in table 4.

YIELD OF WELLS

The yields of wells penetrating the principal artesian aquifer provide a general index of the permeability of the aquifer, although the yields also depend on the thickness of the aquifer penetrated, the efficiency of the well, and the drawdown. In the Savannah area

TABLE 4.—*Summary of laboratory analyses of material samples, Savannah area*

[Analyses by U.S. Geol. Survey]

Description	Depth of sample (ft)	Percent porosity	Coefficient of permeability (gpd per sq ft at 60° F)
Chunk sample of clayey silt from the Hawthorn formation at an outcrop along the Savannah River in Effingham County about 30 miles northwest of Savannah. Material is the main upper confining layer for the principal artesian aquifer.	Near surface		0.001
Limestone from well CHA-471 at U.S. Post Office, Savannah (5-in. core samples).	372-393.5	43.7	[1] 480
			[2] 1,260
	393.5-413.5	33.1	[2] 360
	413.5-434	52.9	[1] 58
			[2] 53
Limestone from well BFT-304 (test well 3) on north end of Daufuskie Island, S.C. (two ⅜-inch core samples).	146-166	13.0	[2] 0.01
	186-196	30.4	[2] 15
	186-196	25.7	[2] 12
	186-196	19.4	[2] 0.04
	386-406	46.9	[2] 3
	726-746	41.4	[1] 0.02
			[2] 0.5
Limestone from test well drilled near Port Wentworth for mineral exploration, CHA-452 (5-in. core samples).	801.5-802.5	32.3	.04
Clayey silt from well CHA-452 that is part of the lower confining layer for the principal artesian aquifer (5-inch core samples).	1,025	42.5	.005

[1] Vertical.
[2] Horizontal.

most of the wells do not penetrate the full thickness of the aquifer. Therefore, many of them yield much less than the maximum that could be developed, although there is some question as to how much yield is gained by drilling through the last 200 feet or so of the aquifer.

Large-diameter wells penetrating the full thickness of the aquifer yield up to 4,200 gpm and could yield much more with larger pumps.

The specific capacity of a well is the yield per unit of drawdown and generally is expressed in gallons per minute per foot of drawdown. Specific capacity is a more accurate measure of an aquifer's capacity to yield water than is the actual yield of a well because it relates yield to drawdown in the well, an important variable in considering yield. However, the specific-capacity measurements of aquifer yield vary for each aquifer because individual measurements are affected by the efficiency of the well, the thickness of aquifer penetrated, and by the duration of pumping during which the specific-capacity test is made.

The specific capacity of wells in the Savannah area ranges from about 20 gpm per ft of drawdown for small-diameter wells in Bryan

690-437—63——4

County to as much as 197 gpm per ft of drawdown for a 10-inch well at Savannah Beach in Chatham County. Generally the specific capacity of large-diameter wells ranges from about 45 to 65 gpm per ft of drawdown in most of the Savannah area.

GROUND-WATER DISCHARGE

Ground water is discharged both naturally and artificially from the principal artesian aquifer. Water is discharged naturally over a large area, whereas the artificial discharge, the withdrawal of water through wells, is confined largely to areas such as Savannah, Brunswick, St. Marys, and other cities.

NATURAL DISCHARGE

Some of the natural recharge in the outcrop area of the principal artesian aquifer is discharged naturally through springs, seepage into streams, and by evaporation and transpiration. Seepage into streams and flow from springs form the base flow of streams and maintain streamflow during periods of little or no rainfall. The approximate rate of discharge to streams may be determined directly by streamflow measurements across the outcrop of the aquifer during prolonged dry periods. The rate of discharge by evapotranspiration is much more difficult to determine directly because it varies with locality and in time. The rate of natural discharge to streams and the quantity of water discharged by evapotranspiration vary in accordance with the amount and intensity of precipitation, season of the year, and type and density of plants. The natural discharge to streams is greatest in the spring when the rainfall is high and before plant growth is fully developed. The discharge by evaporation and transpiration by plants is highest in summer and early fall when temperatures are highest and the plants are in full growth.

Some ground water is discharged naturally from the principal artesian aquifer in the Savannah area by seepage through the confining beds into the shallow Quaternary sands or into the Atlantic Ocean. This occurs where the hydrostatic head in the principal artesian aquifer exceeds that in the overlying formations or is above ocean level. The rate of seepage through the confining beds depends on (a) the difference in altitude between the hydrostatic head of the principal artesian aquifer and the water table in the shallow sediments and (b) on the permeability and thickness of the material through which the water passes. In those parts of the Savannah area where pumping has lowered the hydrostatic head in the principal artesian aquifer below the altitude of the water table there can be no natural discharge upward, but instead, water in the shallow deposits may move downward. Ground water was also discharged through submarine outcrops of the aquifer off the Atlantic Coast east and northeast of Savannah. (See section on "Piezometric Surface.")

DISCHARGE FROM WELLS

The first artesian well in the Savannah area was drilled in Savannah near Laurel Grove Cemetery in 1885 by Capt. D. G. Purse (McCallie, 1898, p. 64). This well had a depth of 500 feet and, because the elevation of the land surface at the well site was relatively high, the water rose only 18 inches above the land surface. In 1886 the city of Savannah began its first well field, on the south bank of the Savannah River about 2 miles upstream from the present City Hall, and by 1888 the entire municipal supply of about 5.8 mgd was obtained from artesian wells. A second well field, consisting of 12 wells, was constructed in 1892 and 1893 along Stiles Avenue north of Gwinnett Street. This well field furnished nearly all the municipal supply from 1893 to about 1920. Since the installation of electrically driven deep-well turbine pumps in the 1920's, municipal pumpage has been distributed throughout the city. In 1959 the municipal water supply was obtained from 13 active wells equipped with electrically driven deep-well turbine pumps, 6 of which are equipped with auxiliary gasoline-engine drives.

Figure 3 shows the approximate quantities of artesian ground water and treated river water used in the Savannah area during the period 1887 to 1958. The Savannah area, for the purpose of compiling pumpage figures, includes the area within the corporate city limits of Savannah, Thunderbolt, Garden City, and Port Wentworth, plus Hutchinson Island and the industrial areas near the cities (pl. 1). It also includes Hunter Air Force Base and an area 2 miles wide and 2 miles long south of the Savannah city limits.

The lower curve in figure 3 shows how the quantity of water pumped by the Savannah Municipal Water Department has changed since 1886. From 1887 through 1949 artesian wells provided almost all the water for the municipal system. The records of annual municipal use from 1886 to 1918 and in 1923 and 1935 were obtained from the Mayor's Annual Reports, and records for the period 1937 to 1958 were obtained from the Savannah Municipal Water Department. From 1889 through 1901 the consumption from flowing artesian wells averaged a nearly constant 6.3 mgd, although it declined slightly during the latter part of this period, owing to a decrease in artesian pressure. In 1902 the 12 wells along Stiles Avenue were pumped with compressed air, and their yields are reported to have nearly doubled. The more abundant supply of water

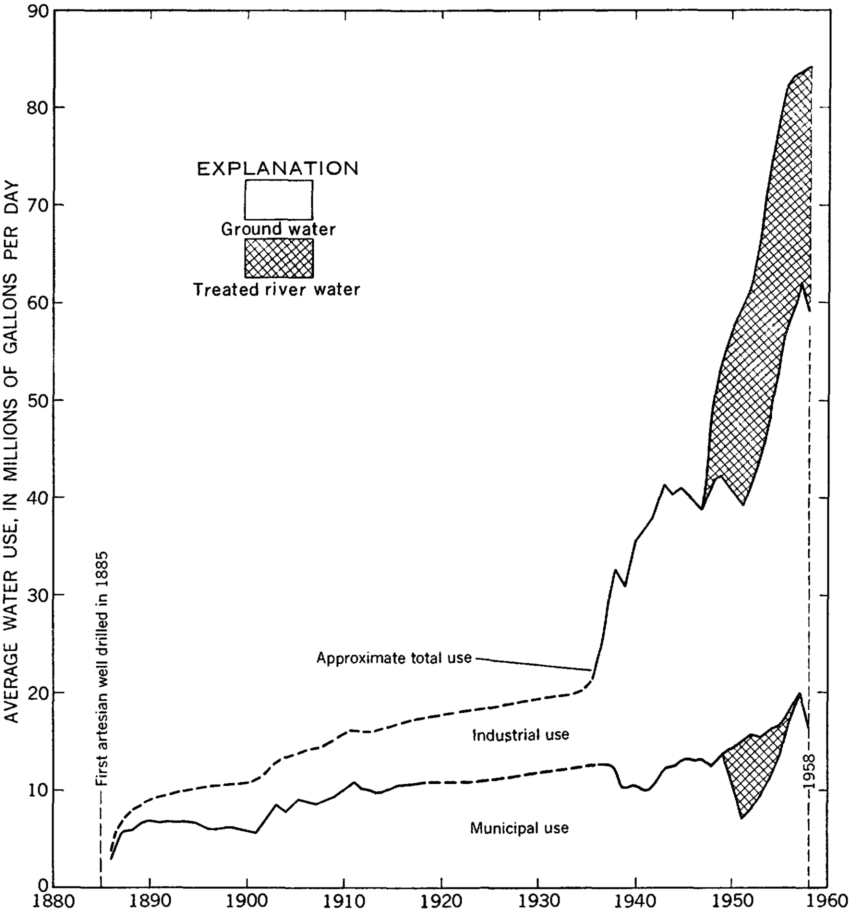

FIGURE 3.—Water use in Savannah area.

is reflected in the increased use of water in 1902 and the following years. From 1902 to 1937 the average annual use of water paralleling the growth of the city, increased from about 7.5 to 12.5 mgd. In 1939 the use of water declined by about 2 mgd owing to the installation of meters on domestic outlets and the advent of a water charge based on use instead of a fixed monthly rate. Since 1943 water consumption has increased in proportion to the growth of the city.

During the years 1950 and 1955 the city of Savannah purchased treated river water from the Savannah Industrial and Domestic Water Supply System and pumped it into the municipal distribution system. As a result of this use of treated river water, municipal pumpage of ground water in 1951 declined to about 7 mgd, the lowest that it had been at any time since 1902. During 1954 the average municipal pumpage of ground water was 11.5 mgd and by 1956 it had increased to 18.1 mgd. In 1957 the average pumpage rose to 20.2 mgd, and in 1958 it declined to 16.9 mgd. This sharp increase in pumpage during 1956 and 1957 was due to a decrease in use of treated river water by the city. By 1956 only 34.5 million gallons (0.095 mgd) of river water was used, and in 1957 the use of river water dropped to 5.5 million gallons (0.015 mgd). However, in 1958 the city of Savannah used 135.5 million gallons (0.37 mgd) of treated river water.

The upper curve in figure 3 shows approximately the total water use in the Savannah area. Since 1935 the total consumption has increased four times. In 1957 and 1958 the pumpage of artesian ground water was three times that in 1935. From 1936 to 1943 the pumpage of ground water rose from about 20 mgd to about 42 mgd. From 1943 to 1947 the pumpage declined slightly, but in 1948 and 1949 it was about as high as or slightly higher than in 1943. From 1949 to 1951 it declined slightly, owing to the use of treated river water by the city of Savannah. The total pumpage rose from 40 mgd in 1951 to about 62 mgd in 1957. The industrial pumpage may be determined by subtracting from the total pumpage the pumpage of the city of Savannah in figure 3.

Outside the Savannah area, the pumpage of ground water in Chatham County is estimated to be about 3 mgd. Bryan and Effingham Counties, Ga., and Beaufort and Jasper Counties, S.C., use about 6 mgd. The total water use in 1958 for the report area was about 68 mgd from artesian wells and about 26 mgd of treated river water.

The use of artesian ground water may more than double in the next 20 years. At the present time only a few hundred acres of agricultural land receive supplemental irrigation. The drought of 1954 and the dry spring of 1955 accented the advantages of supplemental irrigation as insurance against crop failure. The Savannah Metropolitan Planning Commission estimates that from 1957 to 1980 the population of Chatham County will increase by about 65 percent and that the land acreage occupied by industries will increase by about 110 percent over the same period (M. H. Smith, Jr., oral communication, 1958). Thus, it appears that with continued growth of the city and industries in the Savannah area, the average annual pumpage of ground water within the next 20 years may be as much as 170 mgd. If necessary, much of the increase can be supplied by expanding the surface-water supply system.

WATER-LEVEL FLUCTUATIONS

Water levels fluctuate constantly in response to many natural and artificial forces that vary in direction, time, and magnitude. The fluctuations often form an irregular and complicated pattern. An accurate record and a detailed analysis of the fluctuations are an essential part of a quantitative study of ground water resources.

Water levels are measured by automatic water-level recorder, steel tape, pressure gage, and electrical tape. Observation wells cannot always be established at all desired locations because their location is determined to some extent by the availability of abandoned or infrequently pumped wells.

CAUSES OF FLUCTUATIONS

The water table in the outcrop area of water-bearing formations, where not affected by pumping, fluctuates in accordance with the rates of (a) recharge from precipitation, (b) discharge by seepage into streams, (c) movement of water down the dip, (d) evaporation, and (e) transpiration by vegetation. Farther downdip, in the artesian parts of the aquifers the fluctuations caused by recharge and natural discharge in the outcrops are progressively less pronounced. In the principal artesian aquifer in the Savannah area variations in precipitation probably would cause no appreciable fluctuations in the artesian pressure unless there was a long series of wet or dry years. Nevertheless, water levels fluctuate in many artesian wells even though they are not affected by pumping. For example, artesian wells act as barometers—that is, the water level in them fluctuates with the barometric pressure. When the barometric pressure increases, the additional weight of the air column on the water depresses the water level in the well; when the pressure decreases and the air column is lighter, the water level rises. No special study was made of the barometric fluctuation in the Savannah area. However, well JAS–46 shows a barometric fluctuation of about 0.35 ft. with a change in barometric pressure of 0.56 inches of mercury or 0.63 feet of water (fig. 4). Other wells were checked, but fluctuation due to other causes was such that the fluctuations due to barometric pressure change could not be determined with certainty. Probably no well in the Savannah area fluctuates more than 1 foot because of barometric pressure changes, and the normal fluctuation is probably less than 0.5 ft.

Applications of heavy loads on the land surface above the principal artesian aquifer may compress the aquifer causing the water level in wells to rise. When the load is removed the water levels fall. Such water-level fluctuations in the Savannah area are caused by tides and by trains that pass close to wells. Figure 4 shows parts

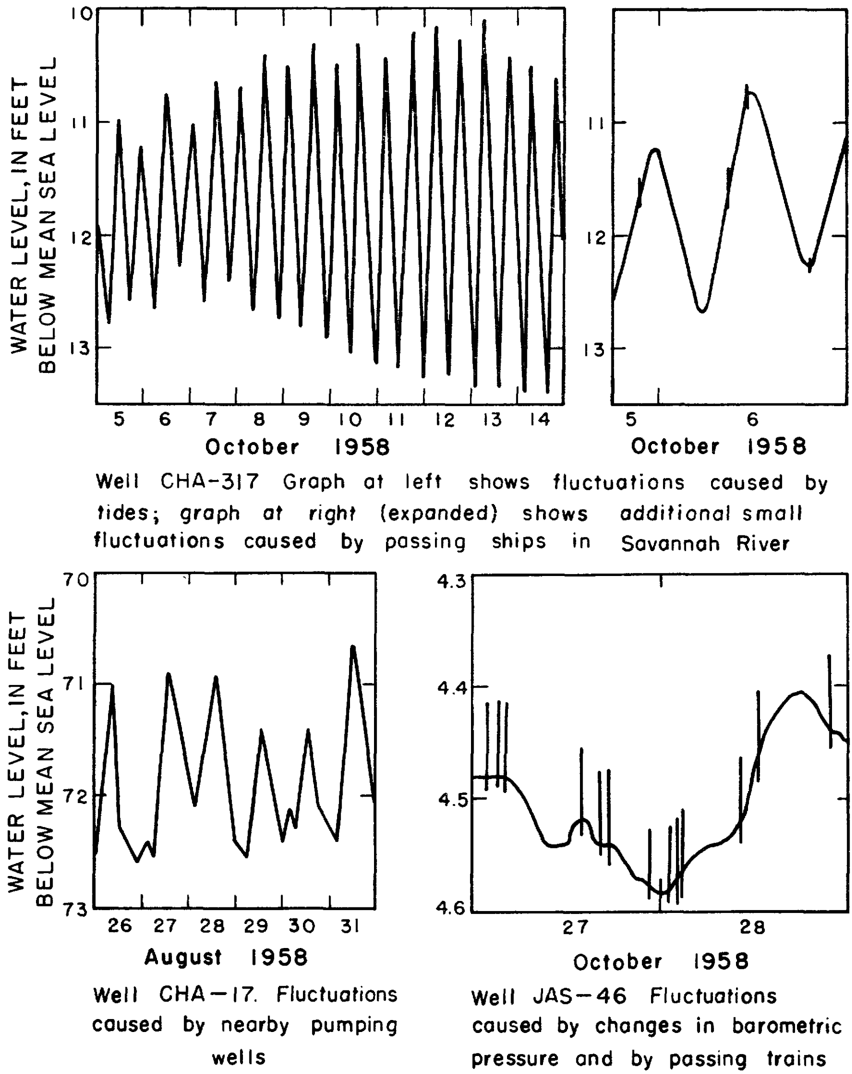

FIGURE 4.—Parts of well hydrographs showing effects of surface loads and nearby pumping on the water level in the principal artesian aquifer.

of water-level records obtained by use of automatic water-level recorders. Well JAS-46 shows fluctuations produced by passing trains and changes in barometric pressure, and well CHA-317 shows the effect of tidal loading. The small ticks shown on the expanded part of the hydrograph for well CHA-317 for October 5 and 6 are caused by ships passing through the ship channel of the Savannah River. This fluctuation is similar to that caused by trains and indicated by ticks in the hydrograph for well JAS-46.

The fluctuation of water level in response to loading at the surface shows that the principal artesian aquifer is slightly elastic and capable of being compressed without appreciable permanent deformation when loads similar to those described above act upon it.

The largest fluctuations of the water levels in wells in the principal artesian aquifer are caused by changes in the rates of pumping, particularly where the observation well is close to a well that is pumped intermittently. Figure 4 shows a portion of a hydrograph for well CHA–17. The changes in water levels are due to intermittent pumping from nearby wells.

GENERAL HISTORY OF WATER-LEVEL FLUCTUATIONS

Prior to the development of ground water in the Savannah area all the aquifers were in a state of approximate dynamic equilibrium in which the natural discharge equaled the average recharge from precipitation. During periods in which there was little or no precipitation, the water that was discharged was derived chiefly from water stored in the aquifer, and the water level declined, showing that the hydraulic system was temporarily unbalanced. However, this unbalance was corrected by a gradual reduction in the natural discharge and a recurrence of recharge from precipitation. Thus, the water table in the shallow sands and in the outcrop areas of the principal artesian aquifer fluctuated in accordance with the rates of recharge and natural discharge.

The natural pattern of water-table fluctuations in shallow sand aquifers in the Savannah area is characterized by a high water table in early spring when the rate of recharge is high and evaporation and transpiration low, and a low water table in late summer or fall when the rate of recharge is low and the rate of evaporation and transpiration is high. Figure 5 shows a hydrograph of water-level fluctions in well CHA–343, Chatham County, and the daily rainfall for the weather station at the well for 1957. The well and weather station are located about 12 miles southwest of Savannah on the U.S. Dept. of Agriculture Plant Introduction Station, better known as the Bamboo Farm. Well CHA–343 is about 15 feet deep and is representative of wells in water-table aquifers in the Savannah area. The fall and winter of 1956–1957 were dry. The rainfall for 1956 was 11.92 inches below normal, and rainfall during the first 2 months of 1957 was about 3.21 inches below normal. This accounts for the low water level in well CHA–343 during the first part of 1957. Rainfall was excessive for the rest of 1957. The total rainfall for 1957 was 65.09 inches, 13.81 inches above normal. The water level began to rise in March and by July 28, after the heavy rainfall of July 27, was only 0.2 feet below the land surface. The water level during

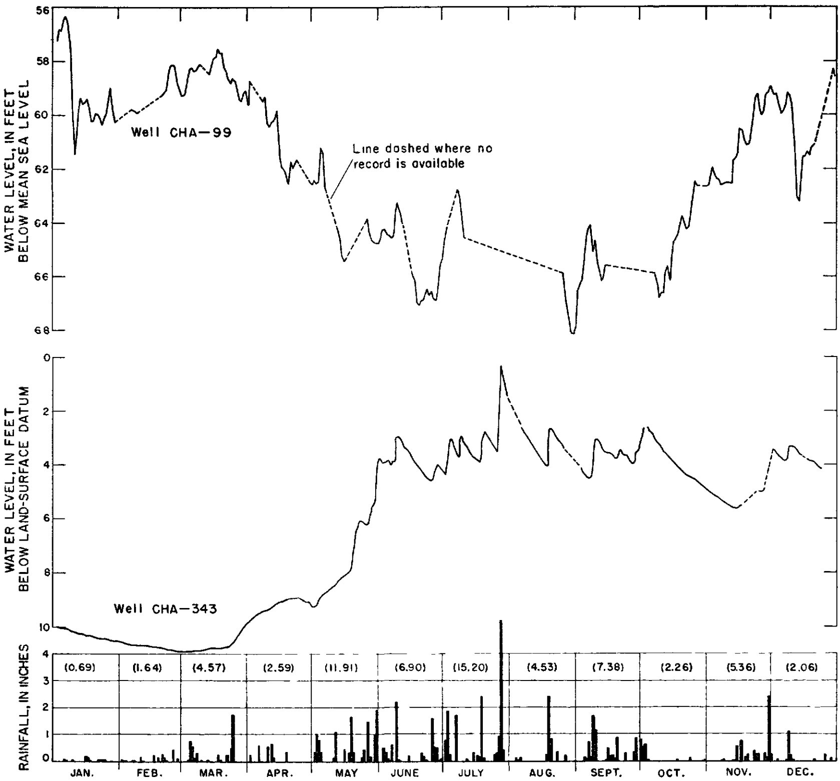

FIGURE 5.—Hydrograph of water-level fluctuations in wells CHA-99 and CHA-343, and daily rainfall at well CHA-343, 1957.

late summer and fall was higher than normal for that time of year owing to the excessive rainfall. (See fig. 5.)

Rainfall does not affect water levels in the principal artesian aquifer in the Savannah area as described above. The thick clayey silt layer above the aquifer prevents the direct penetration of rainfall. The water levels fluctuate with the seasons of the year similar to the shallow aquifers, but the fluctuations are due almost entirely to seasonal changes in the rate of pumping.

Figure 5 also shows a hydrograph for well CHA-99 for the year 1957. This well is 500 feet deep and represents the water level in the principal artesian aquifer. Well CHA-99 is 1.5 miles southeast of the center of pumping. The water level trend is downward from January to October when pumping increases. The trend is upward from October to December when pumping decreases. (See pl. 4.) This is opposite to the water-level trend for well CHA-343 because there is no pumpage from the shallow sand aquifer near this well, and there is practically no recharge to the principal artesian aquifer at well CHA-99.

The fluctuations of artesian pressure in the Savannah area, before the development of ground-water supplies, probably were relatively small and mostly tidal. When the first well was drilled in Savannah in 1885 the artesian pressure was about 37 feet above sea level. In the latter part of 1887 the city of Savannah had 14 flowing wells in operation, and by 1890 when there were 23 wells in operation it was noted that the supply had been decreasing, and it was necessary to supplement the supply with river water. Thus, it appears that the artesian head began to decline immediately upon development of the ground-water supply for Savannah. Figure 6 shows a hydrograph of fluctuations in the artesian head for well CHA–28 and well EFF–7 from before 1890 to 1958. The record for well EFF–7 is missing from 1945 to 1951, and the dashed line in this interval indicates the same change in water level as occurred in a nearby well. The record for well CHA–28 is missing for 1944 to 1952 and the dashed line in this interval represents water-level measurements in a nearby well. When the curve is compared with figure 3 it can be clearly seen that the decline of artesian head is due almost entirely to pumpage from the principal artesian aquifer. The trend of the artesian head has been downward for the entire period of record, and the rate of decline has varied with the rate of pumping in the Savannah area.

WATER-LEVEL FLUCTUATIONS IN OBSERVATION WELLS

Water levels in observation wells in the Savannah area were measured at frequent intervals or continuously by means of automatic water-level recorders. Graphs of representative water-level fluctuations in eight wells are shown on plate 4. Also shown on plate 4 is the estimated monthly pumpage for the Savannah area. The eight hydrographs show water levels in wells 0.4 mile to 25 miles from the center of pumping. The dashed lines in the hydrographs represent measurements made semi-annually. The solid lines represent measurements made monthly and daily.

The water level in well CHA–76, which is 0.4 mile east of the center of pumping, has declined about 70 feet since 1939. The original water level was about 38 feet above sea level. The total water-level decline has been about 148 feet since about 1895. The present water level is about 110 feet below sea level.

The present water level in well CHA–330, which is 8 miles southwest of the center of pumping, is about 8 feet below sea level. The water level in 1941 was about 10 feet above sea level, and the original piezometric surface appears to have been about 44 feet above sea level. Thus, there has been a total decline of about 54 feet since 1885.

The water level in well BRY-146, which is 25 miles west of the center of pumping, has declined about 12 feet since 1941 and about 25 feet from the level of about 1895.

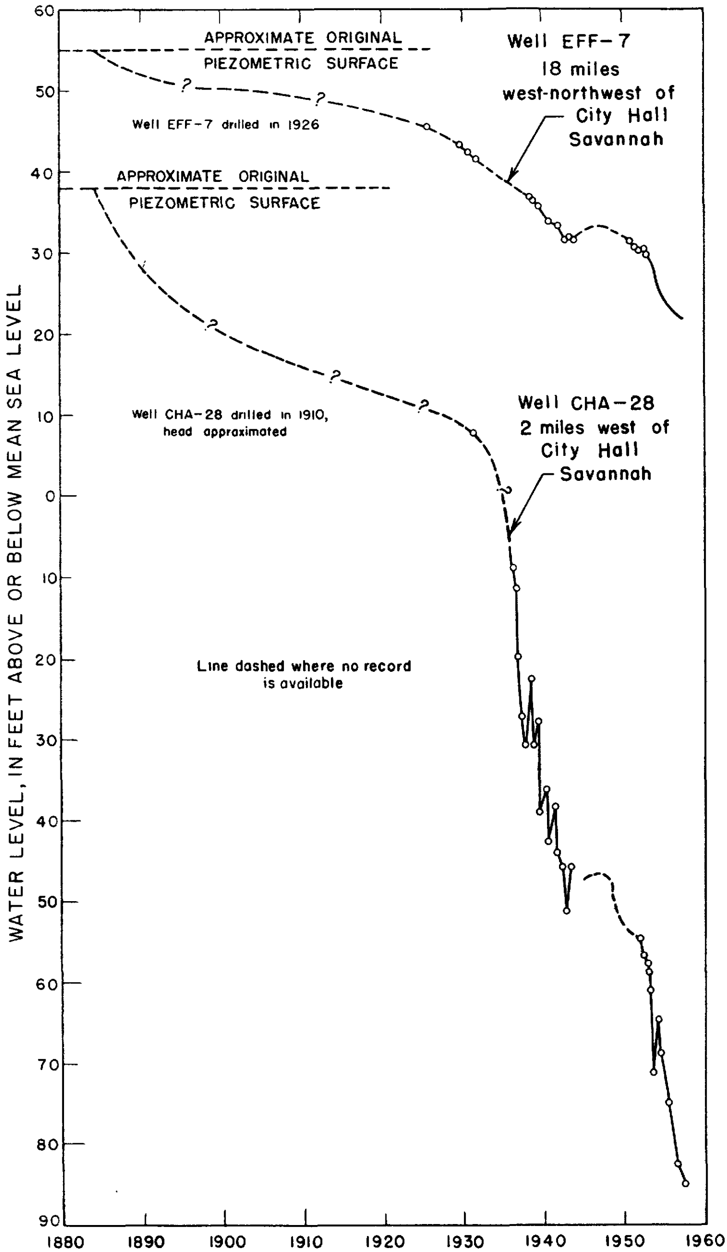

FIGURE 6.—Hydrograph showing approximate total decline in artesian head at two well sites, Savannah area.

The data in figure 5 indicate a close relationship between pumpage and decline in water levels. In 1939, when the pumping rate was 31 mgd, about one-half the 1957 rate, the water levels in most wells had declined about one-half of the total decline up to the present time (1959). Also, during the period 1943–1952, when the yearly pumpage was nearly constant, the water levels in the observation wells showed little overall decline, indicating that the water levels had nearly stabilized at an average pumping rate of 41 mgd. By 1954 the rate of pumping had increased to about 51 mgd, and the water levels began the sharp decline that has continued to 1958. The rate of pumping increased to 62 mgd in 1957, but declined to 59 mgd in 1958. Should the rate of pumping not increase for the next 1 to 2 years the water levels would approximately stabilize slightly below their present levels. As long as the rate of pumping increases the water levels in wells will continue to decline. For each million gallons per day increase in the pumping rate, the water levels will decline the approximate amounts shown in figure 7 after 1 year pumping at the increased rate.

Plate 5*A* shows the approximate total decline of the artesian water levels in the Savannah area to 1958. The greatest decline, more than 120 feet, has occurred at and near the center of pumping at Savannah. Throughout most of Chatham County the decline has been more than 40 feet. In Bryan and Liberty Counties it has been more than 30 feet, and in Effingham County the decline has been from 10 feet in the northern part to 40 feet in the southeasternmost part. In Jasper County, S.C., the decline has been from 10 feet in the northern part to more than 100 feet in the southern part near Savannah. In Beaufort County, S.C., the decline has been from less than 10 feet near the Broad River to more than 30 feet on the south end of Daufuskie Island.

The 30 to 40 foot decline in water level in the large area of Bryan and Liberty Counties is due to pumping southwest of Savannah at Fort Stewart, Jesup, and Brunswick. The combined pumping at these places was more than 100 mgd in 1956.

PIEZOMETRIC SURFACE

Prior to development of ground water in the Savannah area the configuration of the piezometric surface was controlled chiefly by the hydrologic characteristics of the aquifer and intervening confining beds and the topography and altitude of the outcrop areas. The original piezometric surface, as shown on plate 5*B*, was reconstructed by Warren (1944a, p. 26) using the elevation of the static water levels of the first wells drilled into the principal artesian

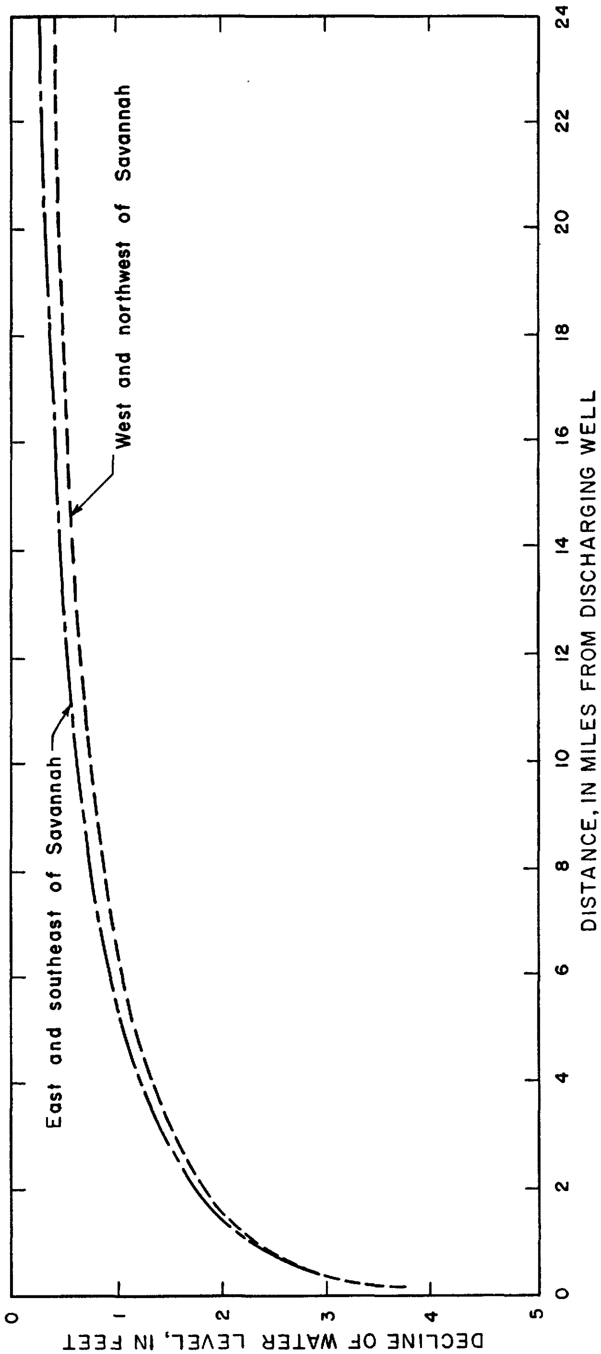

FIGURE 7.—Approximate decline of artesian water levels caused by each 1 mgd increase in pumpage after 1-year period. From Warren (1944a; 1955), revised in 1957 by Counts.

aquifer in each locality. The map indicates that originally the hydraulic gradient in the Savannah area sloped eastward at the rate of about 1 foot to the mile. The arrows on the map indicate the general direction of ground-water movement. Estimates based on the slope of the hydraulic gradient and the convergence of the flow lines suggest that the natural discharge area was about 30 to 35 miles northeast of Savannah, near St. Helena Island, S.C. This means that ground-water discharged through the limestone into the Atlantic Ocean as submarine springs or into streams in the area through thin places in the top confining layer. (See pl. 3.) Old-time residents report that during the years past submarine springs had been noted in the Beaufort River near Port Royal. Assuming that ground water discharged in this area until recent years, then salt water can and will move into the principal artesian aquifer when the artesian head in this area declines to or below sea level.

Plate *5C* shows the piezometric surface for December 1957 and represents the height in feet to which water would rise with reference to sea level in tightly cased wells penetrating the principal artesian aquifer. This map shows a deep cone of depression centered at the northwestern edge of Savannah, into which ground water is moving from all directions. The contours are based on measured depths to water level in wells, adjusted to sea-level datum.

Figure 8 shows the profiles of the original water level and of the cones of depression for June 1939, August 1943, December 1957 (pl. *5C*), and for the predicted piezometric surface for a pumpage of 125 mgd for the Savannah area.

The piezometric surface shown on plate *5C* is similar to that given by Warren (1944a, p. 115) for 1943 except that the cone of depression is deeper and has broadened as a result of increased pumpage. The slope or gradient of the piezometric surface toward Savannah has steepened, which means that the velocity of movement toward the center of the cone of depression has increased. This also means that the velocity of any salt water moving toward Savannah also has increased. (See section on Movement of Ground Water.)

The distance from the deepest part of the cone of depression to the zero contour is greater to the east than it is to the west. The distance is about 8 to 10 miles on the west side of Savannah, about 18 miles on the south side, and about 25 miles on the northeast side, where the cone reaches its maximum extent in the vicinity of Hilton Head, S.C. The cone slopes more steeply on the west side than on the east side. If the pumping were increased to about twice the 1957 rate of 62 mgd, or to 125 mgd, the zero contour might be as far as 30 miles northeast of Savannah and 15 miles west of Savannah, but if ocean water moves into the aquifer in the Port Royal

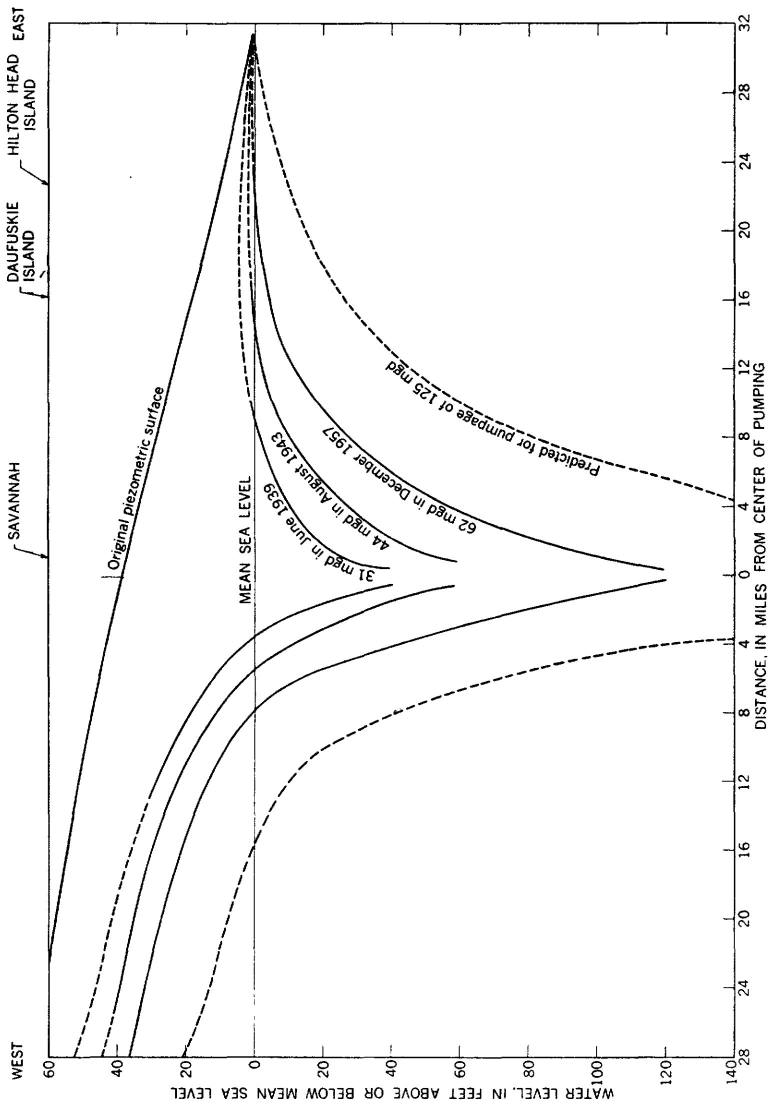

FIGURE 8.—Recorded and predicted water-level profiles in Savannah area.

Sound area, the zero contour will not move much further northeastward than its present position. Plate 5*D* shows the predicted piezometric surface for a pumpage of 125 mgd in the Savannah area.

MOVEMENT OF GROUND WATER

Ground water moves from points at which the artesian head or water table is high to points at which it is low; it moves in the direction of the steepest hydraulic gradient. In general, the pattern of movement of water in the principal artesian aquifer in the Savannah area is simple. The water moves from the outcrop areas, where the water table is at a relatively high altitude, downdip toward the southeast with progressive lowering of hydrostatic head due to frictional loss. In detail, however, the movement of water is complex owing to the nonhomogeneity of the rocks, the differences in transmissibility and porosity, the leakage through confining beds, and because the movement is three dimensional.

In the outcrop areas of the water-bearing formations the general pattern of movement is controlled largely by the configuration of the land surface. The rocks are incised by numerous streams, and the direction of movement of ground water has little uniformity. Most of the water moves slowly from the interstream areas to the streams where it is discharged, but some water moves downdip into the artesian parts of the aquifers. The direction of ground-water movement in the confined parts of the aquifer is more uniform.

The general pattern of ground-water flow before pumping began was greatly different from the present pattern. The arrows on plate 5*B* show the general pattern of movement in the principal artesian aquifer before pumping began. Water moved down the hydraulic gradient toward the east and discharged into the estuaries and Atlantic Ocean in the vicinity of Parris and St. Helena Islands, S.C. Water also moved slowly upward through the confining layers and discharged into salt-water estuaries, fresh-water streams, or into the upper shallow sands and was evaporated, transpired by plants, or moved laterally to surface streams. This upward movement of water from the aquifer into salt-water estuaries was a factor that prevented salt water from moving downward and contaminating the aquifer.

The pumping of large quantities of ground water in the Savannah area has changed considerably the direction and rate of ground-water movement. The lowering of artesian head that has accompanied the withdrawal of ground water has established a hydraulic gradient from all directions to the center of pumping at the northwest edge of the city of Savannah. Consequently, at the present time the pattern of flow in the principal artesian aquifer represents a slow movement of ground water from all directions into the Savannah area. The piezometric map for December 1957 (pl. 5*C*) shows the large cone of depression in the Savannah area. The general direction of movement is indicated by the arrows on the map. Wherever the piezometric surface is below the water level in the shallow sands or below sea level in areas covered by ocean water, water is now seeping downward through the confining layer into the principal artesian aquifer. However, the quantity of water per unit area moving laterally into the Savannah area greatly exceeds the quantity moving downward through the confining beds.

As the steepest hydraulic gradient would be approximately perpendicular to the contours of equal artesian head shown on the maps, the piezometric map shows the approximate direction of the movement of ground water in the principal artesian aquifer. The actual movement may differ from that inferred from the piezometric contours because the motion of ground water is three-dimensional whereas the map shows only two dimensions. Moreover, the direction of movement is influenced by differences in transmissibility. For example, if the transmissibility of the aquifer is higher in a certain direction, as it appears to be, more water would move in that direction than would be indicated by the piezometric contours. If the effect of these limitations is taken into account, the piezometric maps serve well to indicate the general direction of groundwater movement.

Water moves very slowly in the principal artesian aquifer. This can be shown by computing the approximate rate of movement in the northeastern part of the Savannah area, where the transmissibility of the principal artesian aquifer is higher than in the immediate vicinity of Savannah, although not as high as near Hinesville in Liberty County. The northeastern part of the Savannah area is considered here because this is the direction from which salt water is most likely to move. The approximate velocity of ground water moving through rocks may be computed by the following equation:

$$v=\frac{0.925\,PI}{p}$$

where v=velocity, in feet per year

P=permeability, in gallons per day per square foot

I=hydraulic gradient, in feet per mile

p=porosity, expressed as percent.

According to analyses of pumping tests, the coefficient of transmissibility is about 400,000 gpd per ft. Well logs show the average

690-437—63——5

thickness of the principal artesian aquifer to be about 600 feet. The average coefficient of permeability is, therefore, about 670 gpd per sq ft. The porosity of the limestone is about 35 percent as indicated by average of 9 well samples (table 4). The piezometric map for December 1957 (pl. 5*C*) indicates that the hydraulic gradient 16 miles northeast of Savannah, near well BFT-304, was about 1 foot per mile for a pumping rate of 62 mgd in Savannah; therefore, the velocity is about 18 feet per year. The rate of movement is directly proportional to the hydraulic gradient; therefore, the velocity for a gradient of 10 feet per mile would be 10 times 18 or 180 feet per year.

Further movement of ground-water and the possible movement of salt water into the Savannah area are discussed under following sections of the report.

CHEMICAL CHARACTER OF THE GROUND WATER

All the mineral components in rocks are soluble in water to some extent, and ground water becomes mineralized in passing through the rocks. The character and the degree of mineralization depend on many complex factors but in general are controlled by the type of minerals in the rocks and by the solvent power of the water. Solvent power generally varies with the amount of dissolved carbon dioxide and oganic acids in the water.

In the Savannah area, the principal artesian aquifer is made up of limestone beds ranging in age from middle Eocene to early Miocene. The principal minerals found in limestone are the carbonates of calcium and magnesium.

In general, the principal artesian aquifer in the Savannah area yields water in which calcium and magnesium (cations) and bicarbonate (anion) predominate. Exceptions are samples collected from the lower part of the aquifer at Hilton Head (well BFT-101) and Daufuskie Island (well BFT-304) in which sodium (cation) and chloride (anion) predominate.

The general chemical composition of the ground water in the Savannah area is indicated by 111 analyses of water from 64 wells listed in tables 5 and 6. Table 5 gives 96 analyses of water from 55 wells in the principal artesian aquifer (limestone), and table 6 gives 8 analyses of water from 2 wells in deposits of Claiborne age and 7 analyses of water from 7 shallow wells in deposits of Quaternary age. The chemical analyses show the suitability of water for industrial use, boiler supply, and laundries. However, they give no indication of the bacteriological quality of the water. The water from the principal artesian aquifer is of suitable chemical quality for most uses.

TABLE 5.—*Quality of water from the principal artesian aquifer (limestone) in Savannah area*

[Results in parts per million except as indicated. Analyses by the U.S. Geol. Survey]

Well (pl. 1)	Owner	Depth of well (feet)	Date of collection	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$: Calcium, Magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)	pH
Bryan County, Ga.																					
119	M. LaVain	----	Nov. 15, 1957	----	35	0.15	21	13	18	4.0	146	0	26	4.0	1.1	0.1	194	106	0	286	7.6
131	City of Pembroke	429	Mar. 6, 1941	----	50	.02	32	5.1	8.1	1.6	133	0	6.9	3.8	.2	.0	171	101	0	----	----
133	J. T. Stubbs	443	Oct. 25, 1940	75	39	----	28	21	----	----	39	0	92	4.0	----	----	187	156	124	----	8.1
147	----	440	June 4, 1941	73	44	.01	22	9.3	14	2.4	138	0	5.7	4.1	.4	.0	164	93	0	----	----
Chatham County, Ga.																					
15	City of Savannah	500	Feb. 9, 1938	73	53	0.01	26	9.7	9.5	1.4	131	3	6.9	5.0	0.0	0.0	173	105	0	----	----
17	do	505	do	73	53	.00	27	10	11	1.4	137	4	6.3	5.2	.0	.1	181	108	0	----	----
18	do	540	do	71	52	.01	27	9.1	10	1.1	129	4	7.1	5.5	.0	.0	174	105	0	----	----
18	do	700	May 25, 1955	75	45	.00	23	10	9.1	1.4	133	0	6.8	5.8	.4	.0	168	98	0	233	7.9
19	do	603	Feb. 9, 1938	73	53	.01	26	10	10	1.4	134	2	6.8	5.8	.0	.0	176	106	0	----	----
19	do	603	May 25, 1955	----	47	.03	25	8.7	9.5	1.9	130	0	6.5	6.0	.4	.0	172	98	0	226	7.6
20	do	525	Feb. 9, 1938	67	54	.01	27	11	10	1.2	135	5	6.4	6.0	.0	.0	182	113	0	----	----
21	do	550	do	72	56	.04	30	11	4.3	2	139	----	7.2	6.0	.0	.0	180	120	6	----	----
22	do	595	do	72	55	.01	27	11	9.4	1.4	134	6	6.7	5.5	.0	.0	183	113	0	----	----
22	do	595	May 25, 1955	----	47	.10	26	8.1	11	2.0	134	0	5.8	7.0	.4	.1	170	98	0	243	7.6
85	do	696	Jan. 29, 1941	73	50	.01	25	9.2	13	2.0	135	0	10	8.5	.4	.0	179	100	0	----	----
117	City of Savannah Beach	602	Feb. 1, 1941	72	40	.02	28	20	56	4.2	145	0	85	52	.6	.2	347	152	33	----	----
117	do	602	Apr. 12, 1955	----	36	.03	24	14	30	2.7	143	0	34	21	.6	.1	231	117	0	370	7.9

TABLE 5.—*Quality of water from the principal artesian aquifer (limestone) in Savannah area*—Continued

Well (pl. 1)	Owner	Depth of well (feet)	Date of collection	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$: Calcium, Magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)	pH
Chatham County, Ga.—Continued																					
117	do	602	July 25, 1958	----	38	.00	29	22	60	4.2	146	0	100	58	.8	.0	384	163	43	601	7.7
118	do	402	Apr. 12, 1955	----	33	.19	32	23	50	3.7	145	0	109	38	.6	.2	359	174	55	570	7.9
118	do	402	Nov. 20, 1957	----	37	.1	43	33	78	6.0	144	0	200	68	1.2	.3	538	243	125	814	7.5
118	do	402	July 28, 1958	----	35	.08	45	25	64	5.3	146	0	165	53	.8	.4	466	216	96	721	7.9
121	Estate of Robert Schneider.	174	May 25, 1941	70	45	.04	22	11	15	2.6	128	5	7.8	6.6	.5	.1	170	100	0	--------	----
121	do	174	Mar. 29, 1955	----	40	.07	21	11	19	2.4	139	0	6.5	12	.5	.1	182	98	0	274	7.9
121	do	174	Nov. 20, 1957	----	43	.12	28	14	62	5.2	136	0	4.0	104	.6	.1	329	127	16	560	7.7
122	State Highway Department.	245	Oct. 10, 1957	----	47	.04	24	8.8	11	2.5	131	0	6.0	5.5	.6	.0	170	96	0	241	7.6
128a	U.S. Public Health Service.	592	Oct. 7, 1957	----	53	.10	27	8.4	10	1.7	137	0	5.8	6.0	.5	.0	180	102	0	237	7.7
270	City of Savannah Beach.	402	Nov. 20, 1957	----	37	.06	31	23	52	4.6	146	0	109	44	.8	.2	374	172	52	570	7.6
270	do	402	July 28, 1958	----	38	.00	31	22	47	3.9	148	0	100	40	.7	.2	356	168	46	550	7.7
279	General Oglethorpe Hotel.	480	Oct. 7, 1957	----	43	.06	22	8.3	13	2.1	129	0	5.5	4.8	.6	.4	164	89	0	221	7.6
288	Henry and Joseph Parson.	----------	Oct. 9, 1957	----	36	.24	21	13	29	3.6	136	0	20	28	.8	.1	219	106	0	339	7.8
293	Wm. Ford Torrey	500±	Aug. 26, 1957	----	35	.53	24	13	15	2.9	132	0	32	5.0	.5	.1	193	114	6	284	7.7

Ca Mg

296	do	367	June 9, 1941	74	35	.04	21	12	17	3.4	141	0	17	4.0	.7	.0	169	102	0		
296	do	367	Aug. 26, 1957		32	.12	20	11	18	3.4	145	0	14	4.0	.7	.3	174	95	0	266	7.6
310	O. E. Bright	300	Nov. 14, 1957		43	.02	23	8.9	14	2.4	140	0	5.0	5.0	.5	.1	171	94	0	236	7.6
324	Hunter Air Force Base	550	Apr. 27, 1951	67	46	1.0	25	8.6	12		131	0	6.4	5.6	.3	.1	170	98	0	235	7.5
324	do	550	Jan. 7, 1952	67	52	.16	28	9.3	7.3		130	0	6.3	6.9	.4	.1	172	108	0	241	7.6
324	do	550	Dec. 10, 1952	67	50	.06	27	8.4	11		134	0	6.3	6.0	.5	.1	175	102	0	240	6.7
337	Travis Air Field	652	Dec. 7, 1942	68	56	.03	29	8.6	8.6		132	0	9.1	5.6	.3	.0	179	108	0		7.9
337	do	652	Mar. 22, 1950	70	57	.25	28	8.0	10		130	0	7.1	6.8	.3	.1	180	103	0	237	7.7
338	do	681	Feb. 2, 1943	68	56	.03	33	9.0	3.3		142	0	7.6	1.0	.3	.0	192	119	0		
338	do	681	Mar. 22, 1950	70	56	.07	29	8.3	8.4		132	0	7.3	5.9	.3	.0	181	106	0		7.7
344	Hunter Air Force Base	555	Apr. 27, 1951	68	51	.64	27	8.8	9.5		134	0	6.3	5.2	.2	.0	175	104	0	241	7.6
344	do	555	Jan. 7, 1952	68	51	.15	27	9.2	9.0		131	0	6.2	6.8	.5	.1	173	105	0	241	7.3
344	do	555	Dec. 10, 1952	70	49	.05	27	8.6	11		135	0	7.1	5.8	.5	.1	176	103	0	237	7.4
345	U.S. National Park Service.	535	July 27, 1943		40	.01	18	16		48	149		23	48	.8	.0	260	111	0		7.6
345	do	535	July 24, 1955		38	.02	17	16		46	146	0	21	50	.8	.1	264	108	0	420	8.1
346	R. C. Roebling	872	Oct. 11, 1957		44	.01	23	8.1	17	2.5	135	0	7.5	8.2	.6	.3	178	91	0	245	7.9
353	American Cyanamid Co.	650	Oct. 10, 1957	74	46	.97	25	9.8	11	1.8	128	0	16	6.0	.6	.1	179	103	0	242	7.2
354	do	654	Feb. 10, 1954		33	.90	26	10	15		128	0	9.5	16	1.0	.0	183	105	0		8.1
357	U.S. Geol. Survey (test well 1).	[1] 203–215	May 11, 1954		37	.30	8.0	7.8	26	2.9	42	14	9.8	33	.4	.0	162	52	0	236	9.1
357	do	[1] 390–402	May 13, 1954		34	.02	10	6.0	27	2.7	41	13	10	36	.4	.0	169	50	0	243	9.0
357	do	[1] 589–601	May 17, 1954		37	.15	18	9.3	29	2.9	107	0	8.5	41	.4	.2	204	83	0	314	8.3
357	do	[1] 712–745	May 20, 1954		38	.40	20	10	29	2.8	116	0	7.8	40	.4	.1	209	91	0	329	8.0
357	do	745	May 21, 1954		39	.45	22	9.6	27	2.4	122	0	8.2	36	.4	.1	205	94	0	320	8.1
357	do	[2] 695	Mar. 15, 1957		23	.01	30	.0	80	9.0	0	[3] 62	42	89	.6	.0	336	75	0	773	10.9
357	do	[2] 695	Sept. 30, 1957		25	.01	13	1.3	39	8.8	72	5	14	39	.9	.0	181	38	0	300	8.8
357	do	[2] 695	Sept. 4, 1958		12	.16	54	0.4	114	9.6	218	2	13	148	.3	.3	461	136	0	561	8.5
359	City of Savannah	1,000	May 25, 1955	76	44	.00	25	9.4	23	2.9	138	0	12	20	.5	1.0	206	101	0	305	7.9
368	City of Savannah Beach.	645	July 25, 1958		35	.00	34	25	44	4.1	146	0	16	29	.8	.3	360	188	68	570	7.7
387	Travis Field	680	Mar. 22, 1950	70	51	.07	27	7.5	8.6		123	0	6.4	6.2	.3	.0	170	98	3	227	7.7

1.23 29 7.14 24.6 213.9 7.37 5.9 Ca/Mg = 2.08

TABLE 5.—*Quality of water from the principal artesian aquifer (limestone) in Savannah area*—Continued

Well (pl. 1)	Owner	Depth of well (feet)	Date of collection	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$: Calcium, Magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)	pH
Effingham County, S.C.																					
7	Central of Georgia R.R.	431	Mar. 12, 1940	73	56	0.03	29	6.6	11	2.0	120	8	7.0	4.6	0.2	0.1	186	100	0		
16	City of Springfield	400	Jan. 29, 1941	71	39	.04	29	12	11	2.5	158	0	9.0	4.2	.3	.06	173	122	0		
25	City of Guyton	425	do	69	39	.16	24	9.2	15	2.3	146	0	5.2	4.2	.3	.0	163	98	0		
Beaufort County, S.C.																					
10a	J. F. Corburn, Jr.	150	Oct. 8, 1957		41	0.04	21	9.1	14	3.5	135	0	7.2	4.0	0.7	0.0	168	90	0	315	7.7
20a	Harry Hector	110	do		42	.05	24	9.7	21	3.6	124	0	8.2	26	.7	.5	197	100	0	301	7.6
53	Daniel and Jane Seckinger.	133	June 6, 1941	68	52	.03	27	11	11	2.5	148	0	6.1	7.6	.4	.1	183	113	0		
53	do	133	May 23, 1955		50	1.1	37	13	12	2.7	188	0	2.0	14	.4	.2	228	146	0	336	7.6
57	Stiles M. Harper	161	do		46	.47	24	8.3	11	2.0	130	0	7.0	6.8	.4	.1	176	94	0	237	7.8
62	W. W. Graves	100±	Oct. 8, 1957		43	.07	20	10	25	4.4	137	0	18	16	.8	.0	204	91	0	297	7.5
63	Honey Horn Plantation.	172	do		22	.04	58	3.8	20	1.2	208	0	2.8	23	.3	.2	233	160	0	394	7.6
66	Hilton Head Co.	146	Nov. 21, 1957		39	1.8	24	11	49	3.9	152	0	18	53	.8	.2	275	105	0	440	7.4
67	do	130	do		46	2.0	32	8.8	38	1.9	150	0	22	37	.8	.5	261	116	0	394	7.3
101	U.S. Geol. Survey (test well 2).	[2]188–200	June 1, 1954		33	.33	24	12	56	3.2	145	0	30	66	.6	.0	327	109	0	490	8.1

101	do	[2]388–400	June 3, 1954	----	24	.41	26	26	84	8.0	165	0	34	142	.7	.0	468	172	36	789	8.2
101	do	[2]588–600	June 5, 1954	----	29	1.2	26	33	30	18	185	0	128	484	1.2	.5	1,180	200	49	2,080	8.1
101	do	[2]688–740	June 9, 1954	----	26	3.8	38	36	375	18	180	0	207	530	1.2	.0	1,360	243	98	2,340	8.1
101	do	740	do	----	33	.31	25	13	68	3.9	150	0	35	82	.6	.0	353	116	0	578	8.1
101	do	[3]543	Jan. 17, 1958	----	32	.03	28	27	206	14	168	0	110	295	1.2	.0	796	181	44	1,370	7.9
101	do	[3]543	Sept. 5, 1958	----	30	.34	29	33	240	16	170	0	98	340	1.2	6.3	1,040	208	68	1,580	8.1
101	do	[3]609	June 4, 1957	----	25	.08	21	13	228	12	32	30	129	290	1.0	.4	765	106	80	1,330	9.6
101	do	[3]609	Oct. 2, 1957	----	30	.17	34	27	269	15	161	0	120	385	1.3	.0	960	196	64	1,700	8.2
101	do	[3]609	Jan. 17, 1958	----	35	.05	28	33	331	19	180	0	138	490	1.7	5.3	1,170	206	58	2,030	7.9
101	do	[3]609	Sept. 5, 1958	----	32	.16	31	26	360	20	180	0	139	518	1.6	.8	1,220	184	37	2,250	8.1
101	do	[3]693	June 4, 1957	----	39	.13	82	124	1,350	36	256	0	750	1,950	2.4	.6	4,460	714	504	7,190	8.1
101	do	[3]693	Oct. 2, 1957	----	41	.21	84	128	1,360	54	256	0	750	2,000	2.5	.5	4,550	736	526	7,390	7.7
101	do	[3]693	Jan. 17, 1958	----	46	.19	96	122	1,320	55	260	0	775	2,020	2.6	5.5	4,570	741	528	7,310	7.9
101	do	[3]693	Sept. 5, 1958	----	43	.05	90	122	1,420	54	260	0	760	1,950	2.5	1.0	4,620	726	513	7,490	8.1
206	Seaboard Air Line RR.	281	Nov. 22, 1957	----	42	.07	20	8.8	13	2.7	128	0	6.0	4.0	.7	.0	160	86	0	224	7.6
222	W. L. Mingledorff, Sr.	485	July 21, 1955	----	43	.00	18	8.8	19	2.6	135	0	10	4.5	.6	.3	174	81	0	243	7.6
275	Union Bag-Camp	300	Mar. 24, 1954	----	38	.31	20	9.0	22	2.6	120	0	11	22	.5	.1	189	87	0	282	8.0
287	Hilton Head Co.	195	do	----	44	.17	66	7.6	24	2.0	232	0	1.5	34	.2	.8	306	196	6	467	7.7
304	U.S. Geol. Survey (test well 3).	746	Nov. 20, 1958	----	46	.04	22	10	14	2.3	128	0	13	8.0	.1	.1	178	96	0	242	7.9
304	do	[3]692	Dec. 5, 1958	----	32	.06	41	23	355	20	157	7	184	480	1.3	.1	1,220	197	57	2,150	8.4
Jasper County, S.C.																					
1	U.S. Fish and Wildlife Service.	503	Aug. 13, 1957	----	50	0.09	22	8.5	9.0	2.0	120	0	6.5	6.0	0.5	0.1	164	90	0	216	7.7
5	J. H. Denham, Delta Plantation.	300	Nov. 13, 1957	----	53	.10	26	6.3	22	5.8	156	0	3.5	8.0	.5	1.0	203	91	0	267	7.5
52	E. C. Gale, Red-Bluff Plantation.	400±	do	----	55	.09	26	6.3	11	2.7	130	0	6.0	5.5	.5	.6	178	91	0	222	7.6

[1] Collected as well was drilled by means of packers.

[2] Collected through sampling pipe at depth indicated.

[3] Total alkalinity (as $CaCO_3$)=62 ppm. This figure indicates the $CaCO_3$ equivalent of 24 ppm hydroxide (OH).

TABLE 6.—*Quality of water from deposits of Claiborne age and shallow wells in deposits of Pleistocene age, Chatham County*

[Results in parts per million except as indicated. Analyses by the U.S. Geol. Survey]

Well (pl. 1)	Owner	Depth of well (feet)	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)	pH
Deposits of Claiborne age and older																				
316	Cherokee Hill Oil Test	[1]1,630–2,160	May 20, 1939		8.0							532	2,600							7.5
357	U.S. Geol. Survey (test well 1)	[2]900	Mar. 15, 1957	31	.16	116	94	1,520	48	140	14	635	2,290	1.3	3.2	4,820	676	538	7,850	8.7
357	do	[2]900	Sept. 30, 1957	41	.13	155	178	2,410	74	195	0	1,080	3,690	2.0	5.0	7,730	1,120	958	12,000	8.0
357	do	[2]900	Sept. 4, 1958	43	.09	205	243	3,290	83	211	0	1,360	4,730	2.6	1.1	10,100	1,500	1,330	15,300	7.8
357	do	[1]1,232–1,435	Nov. 29, 1956	14	2.9	192	80	1,880	35	110	0	525	3,100	1.2	.8	5,880	808	718	9,890	7.4
357	do	[1]1,260	Mar. 15, 1957	44	.72	317	290	4,590	91	142	0	1,390	7,540	1.0	2.2	14,300	1,980	1,870	20,800	7.1
357	do	[1]1,260	Sept. 30, 1957	38	.62	431	354	5,740	134	144	0	1,900	9,500	1.7	2.4	18,200	2,530	2,410	26,600	7.4
357	do	[1]1,260	Sept. 4, 1958	39	.06	545	376	6,920	98	148	0	2,110	11,200	2.0	1.2	21,400	2,910	2,780	30,600	7.8
Deposits of Pleistocene age																				
603	Rockingham Plantation.	85	Aug. 1955		0.00							7.5	18				34		124	
605	Warren Candler Hospital.	54	Sept. 1955		1.0							45	26				75		233	
610	Rainbow Court	68	do		.03							12	21				24		127	
611	W. A. Bland	65	Sept. 30, 1955		.30							29	20				42		165	
616	C. Vic Reynolds	59	Apr. 8, 1958	42	.34	48	3.9	16	1.2	169	0	.0	26	0.4	0.4	221	136	0	312	7.1
617	B. C. Hinely		Mar. 20, 1945	4	.40	11	7.0					3.0	5.0			211	26			7.1
618	T. W. Williams	25	Mar. 19, 1941		28					0		130	352		.0		300			3.5

[1] Depth of sample or interval.

CONSTITUENTS AND PROPERTIES OF THE GROUND WATER

SILICA

Silica is dissolved from almost all rocks and rock materials. Its state in natural waters is not definitely known, although most silica is believed to be present in a nonionized form. In the Savannah area, the concentration of silica in waters from the principal artesian aquifer ranged from 12 to 57 ppm with an average of 38 ppm. The silica in water may be precipitated with other scale-forming materials in steam boilers. This may be a serious matter in the operation of high pressure boilers. Otherwise, silica is of comparatively little importance in the determination of water use.

IRON

Iron is dissolved from many rocks and soils and frequently from pipes. The quantity of iron in ground water is not as uniform over large areas as the quantity of calcium and other constituents. Wells close together have been found to differ considerably in the quantity of iron in their waters, and frequently the iron content of water samples taken at different times from the same well will vary. Because iron is readily precipitated as the hydroxide, it rarely is a major constituent of natural water.

Large amounts of iron may interfere with efficient operation of zeolite-type water softeners. Iron in water may cause reddish-brown stains on white porcelain or enamelware, fixtures, and fabrics. Many industrial plants, including those manufacturing and preparing foods, carbonated beverages, beer, textiles, dyed fabrics, high-grade paper, and rice must have water practically free of iron. The U.S. Public Health Service (1946) suggests a maximum concentration of 0.3 ppm of iron and manganese together in drinking and culinary water on carriers subject to Federal quarantine regulations. Excessive iron may be removed from most water by simple aeration and by filtration.

The iron content of water samples from the principal artesian aquifer in the Savannah area ranged from 0 to 3.8 ppm. Most samples contained less than 0.1 ppm.

A sample from shallow well CHA–618 had 28 ppm iron, but this relatively high iron content probably resulted from reaction between the acidic water (pH 3.5) and the steel casing.

CALCIUM AND MAGNESIUM

Calcium and magnesium cations are two of the most prevalent constituents of natural water. The principal sources of calcium are limestone, dolomite, and gypsum, whereas for magnesium they are the ferro-magnesian minerals and magnesium carbonate. All these minerals are readily soluble in water containing carbon dioxide.

Calcium and magnesium combine with silica and other constituents of water to form objectionable scale deposits in boilers and in other heat exchange equipment.

Magnesium is one of the abundant constituents of sea water. Therefore, more magnesium is found in ground water contaminated with sea water or salts from marine deposits than is usually found in natural water.

The analyses for the principal artesian aquifer show a range in calcium content from 8 to 96 ppm, with most samples having less than 30 ppm of calcium, and a range in magnesium content from 0 to 128 ppm, with most samples having less than 15 ppm of magnesium.

SODIUM AND POTASSIUM

All natural water contains compounds of sodium and potassium. The fitness of water for most industrial or domestic uses is not affected by moderate amounts of these two elements, though quantities larger than about 50 ppm may cause foaming in boiler water. For high-pressure boiler feed water, a limiting concentration of 2 or 3 ppm has been recommended.

Sodium and potassium make up only a small part of the dissolved mineral matter in most of the ground water in the Savannah area. As sodium ion is one of the principal constituents of sea water, considerable quantities of this ion are found in waters contaminated with sea water or in waters from older marine deposits that have embedded salts or contain connate water. The analyses show a range in sodium content from 4.3 to 1,420 ppm and in potassium content from 1.2 to 55 ppm. In some analyses the sodium and potassium combined were reported as sodium.

BICARBONATE AND CARBONATE

Bicarbonate and carbonate are common to natural water because of the abundance of carbonate minerals in nature and because carbon dioxide, which helps dissolve them and other minerals, is readily available.

Bicarbonate is the chief anion in all but the most highly mineralized water in the Savannah area. The range in bicarbonate content is from 0 to 260 ppm, with most samples containing less than 150 ppm bicarbonate, and only 14 of 109 samples containing any carbonate.

SULFATE

Sulfate is dissolved from most sedimentary rocks. Large quantities may be derived from beds of gypsum, deposits of sodium sulfate and anhydrite, and from some types of shale. The U.S. Public Health Service (1946) recommends that the maximum sulfate content shall not exceed 250 ppm in drinking water and in culinary water on carriers subject to Federal quarantine regulations. Most of the samples in the Savannah area had a sulfate content of less than 10 ppm.

CHLORIDE

Because the chlorides of calcium, magnesium, and sodium are readily soluble, chloride is normally present in natural water. The chloride content of natural water ranges from less than 1 ppm in dilute water to several thousand ppm in some brines. Water high in chloride may corrode plumbing and steam boilers and harm irrigated crops.

The chloride content of water samples from the principal artesian aquifer ranged from 1 to 1,950 ppm. One-half of the samples had less than 10 ppm. The samples with chlorides of more than about 15 ppm appear to be contaminated with salt water. Although water having 1,000 ppm chloride may be physiologically safe, the U.S. Public Health Service (1946) recommends that the maximum chloride content not exceed 250 ppm in drinking water on carriers subject to Federal quarantine regulations.

FLUORIDE

Fluoride has been reported to be as prevalent as chloride in rocks (Shepherd, 1940, p. 117). However, the quantity in natural waters is very much less than that of chloride. Fluoride content of most samples was less than 1 ppm but was as high as 2.6 ppm from water in the bottom part of the principal aquifer at well BFT–101. The U.S. Public Health Service (1946) has set a mandatory limit of 1.5 ppm fluoride in drinking water on carriers subject to federal quarantine regulations.

NITRATE

Nitrate present as NO_3 in amounts greater than about 44 ppm may cause methemoglobinemia, or cyanosis, in infants whose feeding formulas are mixed with the water (Maxcy, 1950). Nitrate may indicate previous contamination by sewage, fertilizer, or other organic matter.

Nitrate is a relatively unimportant constituent of the analyses given in this report. Most samples contained less than 0.5 ppm and 36 samples contained no nitrate. Only 17 samples had more than 0.5 ppm nitrate, the highest concentration being 6.3 ppm. These small quantities have little effect on the value of water for ordinary uses.

DISSOLVED SOLIDS

Results reported as dissolved solids represent an approximation of the total quantity of dissolved mineral matter in a water sample.

The U.S. Public Health Service (1946) recommends that the maximum dissolved-solids content not exceed 500 ppm in drinking and culinary water on carriers subject to Federal quarantine regulations but permits 1,000 ppm if no better water is available.

The dissolved-solids content of ground waters of the Savannah area ranged from 160 to 4,710 ppm. Most samples contained less than 200 ppm; only 16 samples contained more than 400 ppm, and these were from the bottom part of the aquifer along the coast at wells CHA–118 and CHA–357, and BFT–101 and BFT–304.

HARDNESS

Hardness is the property of water attributable to the presence of alkaline earth elements. Calcium and magnesium are the principal alkaline earth elements in natural waters, although strontium and barium may be present in small quantities. Hardness is usually expressed in terms of an equivalent amount of calcium carbonate.

The acceptable hardness of water depends upon the intended use of the water. Hardness of water used for ordinary domestic purposes is not particularly objectionable unless it is greater than 100 ppm (Hem, 1959, p. 147). Hardness tolerances of water for industrial uses vary from one industry to another. A range of hardness from less than 10 to several hundred ppm for process waters has been reported by the California State Water Pollution Control Board (1952, p. 267).

Samples from the principal aquifer had a range of hardness from 38 to 741 ppm, with most samples having a hardness of less than 120 ppm. Thus the hardness of most samples would not be objectionable for ordinary domestic use.

SPECIFIC CONDUCTANCE

The specific conductance of water is a measure of its ability to conduct an electric current and is dependent on the concentration and degree of ionization of the different minerals present. Specific conductance, within limits, is an indication of the dissolved-solids content of water. In the Savannah area, specific conductance of water samples from the principal aquifer ranged from 216 to 7,490 micromhos (at 25°C). The conductance of most samples was less than 400 micromhos. The highest values were in the bottom part of the principal artesian aquifer at wells CHA–357 and BFT–101 and BFT–304.

HYDROGEN-ION CONCENTRATION (pH)

By definition hydrogen-ion concentration, or pH, (generally) is the logarithm (to the base 10) of the reciprocal of the hydrogen-ion concentration in moles per liter. The pH scale ranges between 0 and 14 and denotes various degrees of acidity or alkalinity of a solution. A pH of 7 is considered to denote the neutral point. Values below 7 and approaching 0 denotes increasing acidity, whereas values from 7 to 14 denote increasing alkalinity. Water having a low pH is likely to be corrosive to metal. The pH of the samples ranged from 3.5 to 10.9, but for most samples it was between 7.5 and 8.0, which is typical of natural water.

The low pH (3.5) for well CHA–618 probably is due to salt-water contamination from Bull River. The high pH values (9.6 and 10.9) for wells CHA–357 and BFT–101 probably are due to cement contamination after installation of sampling pipes.

EXPRESSION OF WATER-ANALYSIS DATA

Chemical constituents of water are commonly expressed as weight-per-weight units, which generally may be parts per hundred, parts per thousand, parts per million, or parts per billion. For many years the U.S. Geological Survey and many business organizations in the United States have reported water analyses in parts per million (ppm), where 1 part per million represents 1 unit weight of constituent per million unit weights of water. This has been suitable for all but some minor constituents where parts per billion are more practical.

The relationship among ions in solution frequently is expressed also in terms of chemical equivalence. This is accomplished by dividing the concentration value of a given constituent in parts per million, or other units, by the combining weight (atomic or molecular weight of ion per ionic charge) of that constituent. The resulting unit is called equivalents per million (epm), if concentration values are in parts per million. More precisely, equivalents per million represents milligram equivalents per kilogram if derived from data expressed in parts per million. Parts per million also can be converted to equivalents per million by multiplying by the reciprocal of combining weights of the appropriate ions.

SALT-WATER CONTAMINATION IN THE PRINCIPAL ARTESIAN AQUIFER

The Savannah area uses ground water from one of the most highly productive aquifers in the United States. The problem of most concern is the possible encroachment of salt water into the principal artesian aquifer from the Atlantic Ocean or tidal estuaries. Heavy pumping in the Savannah area has lowered the piezometric surface below sea level as far as 25 miles east of Savannah. (See pl. 5*C*.) Sea water ordinarily contains between 19,000 and 20,000 ppm of chloride. Water containing 500 ppm tastes salty to most persons; water having a chloride content of more than 1,500 ppm is intolerable for human consumption.

Ground water with a chloride content of 2,000 ppm is present in the lower part of the principal artesian aquifer at well BFT–101 on Hilton Head Island, S.C., and the hydraulic gradient indicates that it is moving toward Savannah.

GHYBEN-HERZBERG PRINCIPLE AND ITS APPLICATION TO THE CONTAMINATION OF GROUND WATER BY SALT WATER

The basic principles governing the relation between fresh and salt water were established through the work of Ghyben (1889) and Herzberg (1901) and many others. Ghyben and Herzberg found that in wells drilled near the seashore fresh water occurred below sea level to a depth equal to about 40 times the height of the fresh water above sea level. As the average specific gravity of sea water is about 1.025 and fresh water about 1.0, it was concluded that the fresh water and salt water were in a state of equilibrium when a vertical column of salt water 40 feet high balanced a proportionately longer vertical column of the less dense fresh water 41 feet high. This relationship, which generally is applied to salt water having the density of sea water, has led to a general rule of a 40 to 1 ratio; that is, the depth in feet below sea level to the contact between fresh and salt water theoretically will be 40 times the number of feet the static level of the fresh water is above sea level. This relation, of course, will differ with any change in the specific gravity of the salt water; that is, the higher the specific gravity of salt water, the shallower the fresh water-salt water contact, and the lower the specific gravity of the salt water, the deeper the fresh water-salt water contact.

The principle was first discovered for water-table conditions, but it has been applied to artesian conditions where the aquifers are connected hydraulically to the sea and fresh and salt water are in dynamic equilibrium. If the aquifer crops out on the sea floor and is confined by layers of impermeable materials, the only source of salt water will be at the submarine outcrop of the aquifer. Such a condition has been suggested for the Atlantic City, N.J., area (Barksdale and others, 1936). The head of the fresh water will be determined by the altitude of the aquifer intake area less friction loss due to movement of the water through the aquifer. The head of the salt water will be determined by sea level. If the fresh-water head in the aquifer is sufficient at the submarine outcrop to overcome the weight of the salt water, a submarine spring will result. Such springs have been reported off the coast of Southern California (Poland and others, 1956), Florida (Ferguson and others, 1947, p. 9–10), and in the Savannah area. (See p. 56.)

The conditions in the principal artesian aquifer in the Savannah area are similar to that described above. The aquifer generally slopes east-southeast in the Savannah area and is overlain and underlain by relatively impermeable material. The pattern of fresh-water circulation is shown in figure 9.

The confining beds that overlie the principal artesian aquifer are not completely impermeable, and water can move downdip through the aquifer and then upward to surface streams, the atmosphere, or the ocean. This movement of water cannot occur without a hydraulic gradient; therefore, under natural conditions the piezometric surface would slope east-southeastward toward the Atlantic Ocean. If the transmissibility of the aquifer were uniform the piezometric surface would slope at a decreasing rate toward the east-southeast because the quantity of water flowing through the aquifer would decrease in that direction as the water leaked upward through the confining beds. The natural hydraulic gradient in the Savannah area, before pumping, was the altitude of the water table in the outcrop area of the aquifer minus head losses due to friction and to leakage through the confining beds.

The altitude of the original piezometric surface at well BFT–101 on Hilton Head Island was about 10 feet above sea level, at well BFT–304 on the north end of Daufuskie Island about 18 feet above sea level, and at well CHA–357 on Cockspur Island about 25 feet above sea level. If we apply the Ghyben-Herzberg principle (ratio 40 to 1) at these wells the fresh water-salt water contact should be about 400 feet below sea level at well BFT–101, about 720 feet below sea level at well BFT–304, and about 1,000 feet below sea level at well CHA–357. Although the lower part of the aquifer contains high chloride water, the chloride content of water samples from the bottom of the principal artesian aquifer at these test wells is much less than that of sea water. (See pl. 3 and tables 5–8.) These samples were taken about 60 years after pumping started in the Savannah area and about 17 years after the piezometric surface was lowered to sea level or below at well CHA–357, 15 years after it was lowered at well BFT–304, and about 3 years after it was lowered at well BFT–101. The influence of pumping at Savannah probably reached all of the test well sites early in the 20th century, and from that time to the present (1959) the salt water has tended to move higher up in the formations and horizontally toward Savannah as the piezometric surface declined. The short record of chloride analysis from wells CHA–357 and BFT–101 shows this generally to be true in the lower part of the aquifer as well as in the deposits of Claiborne age that underlie the aquifer on Cockspur Island. (See table 8.)

From the preceding discussion it appears that the Ghyben-Herzberg principle is not valid for the Savannah area. During the

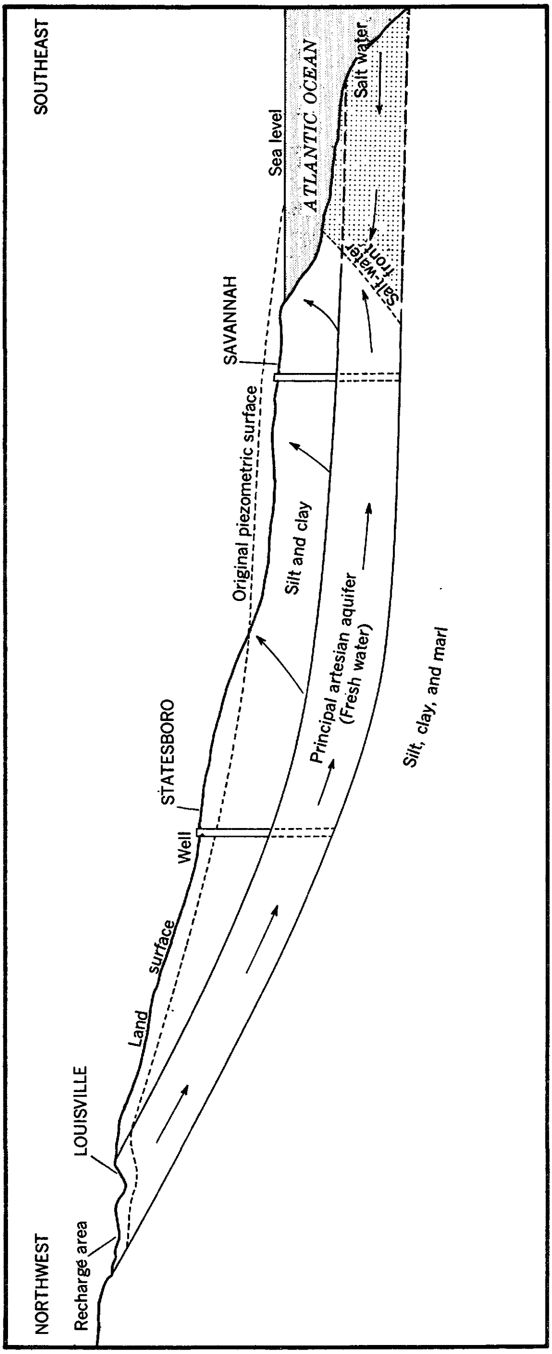

FIGURE 9.—Diagrammatic section of principal artesian aquifer, showing theoretical fresh water-salt water interface.

climax of the last (Wisconsin) glacial stage, about 10,000 years ago, the sea level was possibly as much as 300 feet lower that at present, and the Georgia shoreline was many miles farther east than it is today. If this were true then the salt water that was left in the principal artesian aquifer after the last advance of the sea prior to the Wisconsin stage probably was flushed out by fresh water to a greater distance seaward than is indicated now to be the theoretical location of the fresh water-salt water contact. As sea level rose there probably was a lag in the landward movement of the salt water as it tended to come into balance with the fresh water. This may account for the fresh water-salt water contact being farther seaward than the Ghyben-Herzberg principle would indicate.

SOURCES OF SALT-WATER CONTAMINATION

In the Savannah area the heavily pumped principal artesian aquifer contains salty water (about 500 ppm chloride) to within about 15 miles of the area of large withdrawals. Salty water (about 4,000 ppm chloride) is present also in the materials underlying the aquifer throughout the immediate Savannah area. In the lower reaches of the Savannah River and estuaries, the aquifer is overlain by salty surface water. Consequently, there are three directions from which salt water could invade the aquifer: laterally from the east-northeast, from below, and from above.

LATERAL MIGRATION THROUGH THE AQUIFER

Lateral migration through the aquifer is the most likely source of contamination and should receive first consideration. This type of contamination has been observed in many areas of the United States and in other countries.

Before any ground water was withdrawn in the Savannah area, the piezometric surface sloped gently toward the Atlantic Ocean; that is, the hydraulic gradient was toward the coast and the water was moving through the aquifer in that direction and was being discharged from the upper part of the aquifer into the estuaries and Atlantic Ocean. As pumping began, a cone of depression was formed and water began to move from all directions toward the center of pumping located at Savannah. As the piezometric surface in the aquifer dropped below sea level in the vicinity of fresh-water discharge into the ocean, ocean water moved into the aquifer to contaminate it. (See pl. 3.) As pumping continues the hydraulic gradient will continue to increase, and the salt water will move at an increasing velocity toward Savannah.

Current-meter tests in pumping wells indicate that most of the water flowing into the wells comes from the upper part of the aquifer. This indicates that the upper part of the aquifer probably

690-437—63——6

is much more permeable than the lower part. This is supported by the coefficients of permeability listed in table 4 for well CHA-471 at the U.S. Post Office at Savannah and the fact that cores from the most permeable parts of the aquifer could not be recovered while coring well BFT-304 on Daufuskie Island. Thus, water probably moves much more freely through the upper part of the aquifer than through the lower part, and Pleistocene or older sea water may have been almost completely flushed in the upper part, whereas the lower part of the aquifer may not have been as completely flushed and may contain water with a higher chloride content than water in the upper part. This is suggested by the results of analyses of water samples collected with a point sampler from well CHA-425 at Savannah Electric and Power Company. (See table 7.) Water samples from well CHA-425 had a chloride content of 37 ppm at 650 feet, 140 ppm at 850 feet, and 188 ppm at 990 feet. The samples were taken soon after the well had been test pumped, and it is believed that they are representative of the water in the lower part of the aquifer. At least they are an indication of high-chloride water in the lower part of the aquifer as far east as the city of Savannah.

Regardless of whether the salt water in the principal artesian aquifer in the northeastern part of the Savannah area is a mixture of sea water and aquifer water or is incompletely flushed connate or Pleistocene water, it is surely moving toward Savannah and will eventually contaminate the aquifer to the center of the cone of depression.

At the present rate of pumping, about 60 mgd, it appears that less than one-third of the total water pumped in the Savannah area is being replaced by the encroachment of salty water toward the center of the cone of depression; two-thirds or more of the water is moving in from areas where the formation contains fresh water. (See pl. 5*C*.) Owing to the less permeable zones in the limestone, the encroaching salt water does not drive all the fresh water ahead of it, but bypasses and mixes with some of it. The salt water moves faster through the upper part of the aquifer; then because of its greater density, it sinks to the lower part and mingles with fresh water. The chloride content of the mixture is appreciably less than that of the source water, but the mixture encroaches at a faster rate than it would if the aquifer were uniformly permeable.

VERTICAL UPWARD MOVEMENT THROUGH UNDERLYING MATERIALS

The possibility of serious salt-water contamination by upward movement through the materials underlying the principal artesian aquifer appears to be unlikely in the Savannah area. Logs of test holes and wells show about 100 feet of clay, silt, and marl between the bottom of the aquifer and the first salt-water sand. The underlying material is not impermeable, but water will move through it only slowly. The coefficient of permeability for a sample of the lower confining layer is 0.005 (table 4), which is low compared to the permeability of the principal aquifer. The ground water is moving laterally through the aquifer at relatively high velocities and will dilute the comparatively small amount of water discharged into the limestone from the material below, even though the vertical hydraulic gradient may be large.

One observation well is available (well CHA–357 on Cockspur Island) for water-level measurements in the materials underlying the principal aquifer. For the period of record, 1958–59, water levels in this well have declined at about the same rate as the water levels in the principal artesian aquifer at the same location. This means that the artesian pressure is being relieved by leakage into the principal artesian aquifer above and (or) by expansion of the underlying materials as the artesian head is lowered in the aquifer. Because no other observation wells penetrate the underlying deposits of Claiborne age, the available information is insufficient to determine the artesian head that might be causing water to move upward into the principal artesian aquifer. At test well CHA–357, the water levels in the underlying Claiborne deposits, adjusted on basis of density, are at about the same elevation as the water level in the principal artesian aquifer. Under this condition there is little, if any, upward leakage at this location at the present time (1959). Without more information it is impossible to make a reliable estimate of the amount of upward leakage into the principal artesian aquifer. However, the information available indicated that the deposits underlying the principal aquifer probably are not an important source of contamination in the Savannah area.

DOWNWARD SEEPAGE FROM SURFACE SOURCES

Salt-water contamination from surface sources has been observed in many areas of the United States. There are many tidal salt-water streams in the Savannah area, and downward seepage of salt water from the surface should be considered as a possible source of contamination. Tidal water may be disregarded as a serious source, however, because of the thick, predominantly clayey silt section (Hawthorn formation) overlying the aquifer over most of the entire area. This section becomes thin only in the northeast part of the Savannah area about 20 to 30 miles from Savannah.

A sample of the clayey silt that overlies the principal artesian aquifer had a coefficient of permeability of 0.001. (See table 4.) The clayey-silt section averages about 150 feet in thickness in the immediate Savannah area. The water level in the aquifer ranges from about 200 feet below sea level at the center of pumping to about 50 feet below sea level 8 to 10 miles from the center of pumping. The downward leakage at the center of pumping would be about 37,000 gpd per sq mi, and 8 to 10 miles from the center of pumping it would be about 9,300 gpd per sq mi.

Although surface salt water probably is seeping downward where the piezometric surface is below sea level, the rate of movement through the upper confining layer is small in comparison to lateral movement through the aquifer, and the comparatively small amount of salt water discharged into the aquifer will have little or no noticeable effect on the quality of the water.

Some shallow wells in the upper sand aquifers near open bodies of salt water have been reported to yield water high in chloride content. (See well CHA-618, table 6.)

CONTAMINATION THROUGH LEAKING WELLS

Fresh-water aquifers may be contaminated through defective wells and several such instances are known. Improperly cased or corroded wells drilled near salt-water marshes, tidal streams, or the ocean may permit salt water to leak into the fresh-water aquifer. Such wells should be carefully plugged by cementing from the bottom up before being abandoned. However, leakage through defective wells should not develop into a serious problem unless these wells become numerous.

GEOCHEMICAL TESTS FOR SALT-WATER ENCROACHMENT

In the Savannah area the chloride content of uncontaminated ground water from the principal artesian aquifer ranges from less than 4 to about 15 ppm. Consequently, where the original content is low and contamination is so slight that the resulting content is less than about 15 ppm, it may not be possible to determine from a single chloride analysis whether the ground water is contaminated. Geochemical studies, however, reveal salt-water contamination when the chloride content has been increased by only a few parts per million. Table 7 and 8 are a complete record of chloride determination for all wells that have been sampled in the Savannah area.

TABLE 7.—*Chloride content, in parts per million, of water from principal artesian aquifer*

Well	Depth of well (feet)	Date of collection	Chloride (Cl)
Bryan County, Ga.			
119	----------	Nov. 15, 1957	4.0
131	429	Mar. 6, 1941	3.8
133	443	Oct. 25, 1940	4.0
147	440	June 4, 1941	4.1
Chatham County, Ga.			
13	1,500	Dec. 15, 1904	12
15	[1]500	Feb. 9, 1938	5.0
16	[1]100	Jan. 30, 1956	54
16	[1]200	do	52
16	[1]300	do	52
16	[1]400	do	51
16	[1]500	do	51
16	[1]600	do	51
16	[1]700	do	47
16	[1]800	do	55
16	[1]900	do	63
16	[1]1,000	do	66
16	[1]1,100	do	1,100
16	[1]1,200	do	1,180
17	505	Feb. 9, 1938	5.2
18	540	do	5.5
18	700	May 25, 1955	5.8
19	603	Feb. 9, 1938	5.8
19	603	May 25, 1955	6.0
20	525	Feb. 9, 1938	6.0
21	550	do	6.0
22	595	do	5.5
22	595	May 25, 1955	7.0
36	575	Feb. 26, 1954	[2]10
36	575	Mar. 5, 1954	[2]9.0
36	575	Mar. 10, 1954	[2]6.0
36	575	Mar. 20, 1954	[2]7.0
36	575	July 15, 1954	[2]8.0
36	575	July 20, 1954	[2]10
36	575	Aug. 13, 1954	[2]4.5
36	575	June, 1955	[2]4.5
36	575	Sept. 29, 1955	[2]6.5
36	575	Jan. 27, 1956	[2]6.2
38	1,027	Feb. 26, 1954	11
38	1,027	Mar. 5, 1954	11
38	1,027	Mar. 10, 1954	9.0
38	1,027	May 28, 1954	6.0
38	1,027	July 15, 1954	10
38	1,027	July 20, 1954	9.0
38	1,027	May 19, 1955	[2]5.5
38	1,027	Oct. 25, 1955	[2]9.0
38	1,027	Jan. 27, 1956	[2]13
39	1,043	Feb. 26, 1954	[2]10
39	1,043	Mar. 5, 1954	[2]11
39	1,043	Mar. 10, 1954	[2]13
39	1,043	June 17, 1954	[2]8.0
39	1,043	July 15, 1954	[2]10
39	1,043	July 20, 1954	[2]11
39	1,043	Feb. 16, 1954	[2]8.0
39	1,043	Dec. 19, 1955	[2]9.0
39	1,043	Jan. 27, 1956	[2]7.8
43	1,000	do	9.8
46	872	Nov. 28, 1939	10
46	872	Aug. 18, 1942	7.1
46	872	Aug. 5, 1943	7.4
46	872	Feb. 15, 1945	7.5
46	872	Mar. 7, 1946	12
46	872	Oct. 15, 1947	5.2
Chatham County, Ga.—Continued			
46	872	Nov. 3, 1947	6.0
46	872	June 14, 1948	6.8
46	872	Nov. 30, 1951	8.0
46	872	Oct. 1, 1952	14
46	872	Feb. 26, 1954	[2]11
46	872	Mar. 5, 1954	[2]11
46	872	Mar. 10, 1954	[2]12
46	872	July 15, 1954	[2]10
46	872	July 20, 1954	[2]9.0
46	872	do	[2]6.0
46	872	Jan. 18, 1955	[2]4.5
46	872	Apr. 14, 1955	[2]7.5
46	872	Jan. 29, 1955	[2]6.0
46	872	Nov. 22, 1955	[2]6.0
46	872	Jan. 27, 1956	[2]9.0
84	652	Jan. 20, 1955	6.0
85	696	Jan. 29, 1941	8.5
117	602	Aug. 3, 1939	46
117	602	Sept. 3, 1939	57
117	602	Oct. 5, 1939	55
117	602	May 31, 1940	47
117	602	Feb. 1, 1941	52
117	602	Aug. 22, 1942	58
117	602	July 10, 1943	49
117	602	Feb. 18, 1945	46
117	602	Mar. 8, 1946	47
117	602	June 16, 1948	52
117	602	Nov. 27, 1951	49
117	602	Apr. 12, 1955	21
117	602	July 25, 1958	58
118	402	Aug. 20, 1939	50
118	402	Apr. 12, 1955	38
118	402	Nov. 20, 1957	68
118	402	July 28, 1958	53
121	174	Oct. 5, 1939	7.0
121	174	May 25, 1941	6.6
121	174	Aug. 22, 1942	11
121	174	July 27, 1943	10
121	174	Feb. 13, 1945	7.0
121	174	Mar. 8, 1946	11
121	174	June 16, 1948	10
121	174	Nov. 27, 1951	10
121	174	Sept. 29, 1952	7.0
121	174	Jan. 21, 1955	43
121	174	Mar. 29, 1955	12
121	174	Nov. 20, 1957	104
122	245	Aug. 15, 1942	4.9
122	245	July 27, 1943	5.5
122	245	Feb. 13, 1945	4.5
122	245	Mar. 18, 1946	4.9
122	245	June 16, 1948	5.0
122	245	Nov. 27, 1951	7.0
122	245	Sept. 29, 1952	5.0
122	245	Jan. 21, 1955	5.0
122	245	Oct. 10, 1957	5.5
123	235	July 25, 1942	11
123	235	Mar. 18, 1946	15
123	235	Sept. 29, 1952	8.0
128	627	Aug. 1, 1939	5.6
128	627	Aug. 15, 1942	5.5
128	627	July 27, 1943	5.2
128	627	Mar. 8, 1946	5.6
128a	592	June 16, 1948	6.0
128a	592	Nov. 28, 1951	7.0
128a	592	Sept. 30, 1952	7.0
128a	592	Jan. 20, 1955	5.0

See footnotes at end of table.

TABLE 7.—*Chloride content, in parts per million, of water from principal artesian aquifer*—Continued

Well	Depth of well (feet)	Date of collection	Chloride (Cl)
Chatham County, Ga.—Continued			
128a	592	Oct. 7, 1957	6.0
138a	606	Jan. 24, 1955	5.0
270	402	July 30, 1939	44
270	402	Aug. 3, 1939	36
270	402	Aug. 20, 1939	37
270	402	Sept. 4, 1939	37
270	402	Sept. 23, 1939	36
270	402	Oct. 5, 1939	38
270	402	Aug. 22, 1942	40
270	402	July 10, 1943	39
270	402	Feb. 13, 1945	39
270	402	Mar. 8, 1946	42
270	402	June 16, 1948	41
270	402	Nov. 27, 1951	67
270	402	Sept. 29, 1952	48
270	402	Dec. 23, 1954	54
270	402	Jan. 21, 1955	42
270	402	July 6, 1955	48
270	402	Nov. 20, 1957	44
270	402	July 28, 1958	40
279	480	Aug. 1, 1939	5.1
279	480	Aug. 15, 1942	4.4
279	480	July 27, 1943	4.8
279	480	Feb. 13, 1945	4.2
279	480	Mar. 8, 1946	4.5
279	480	Oct. 29, 1947	3.5
279	480	June 16, 1948	4.0
279	480	Nov. 27, 1951	6.0
279	480	Sept. 30, 1952	4.0
279	480	Oct. 7, 1957	4.8
285	340	Mar. 28, 1957	21
288	------	Oct. 9, 1957	28
293	500±	June 16, 1948	5.0
293	500±	Nov. 27, 1951	5.5
293	500±	Sept. 30, 1952	8.0
293	500±	Aug. 26, 1957	5.0
296	367	June 9, 1941	4.0
296	367	Sept. 18, 1942	7.0
296	367	June 16, 1948	4.0
296	367	Nov. 27, 1951	7.0
296	367	Sept. 30, 1952	5.0
296	367	Aug. 26, 1957	4.0
310	300±	Sept. 18, 1942	4.2
310	300±	July 7, 1943	4.4
310	300±	Feb. 15, 1945	4.4
310	300±	Mar. 8, 1946	4.4
310	300±	June 17, 1948	4.0
310	300±	Nov. 28, 1951	5.6
310	300±	Oct. 2, 1952	6.0
310	300±	Jan. 24, 1955	5.0
310	300±	Nov. 14, 1957	5.0
324	550	Apr. 27, 1951	5.6
324	550	Jan. 7, 1952	6.9
324	550	Dec. 10, 1952	6.0
336	610	July 10, 1943	34
336	[1] 290	July 24, 1955	34
336	[1] 570	Feb. 24, 1955	47
337	652	Dec. 7, 1942	5.6
337	652	Mar. 22, 1950	6.8
338	681	Feb. 2, 1943	1.0
338	681	Mar. 22, 1950	5.9
344	555	Apr. 27, 1951	5.2
344	555	Jan. 7, 1952	6.8

Well	Depth of well (feet)	Date of collection	Chloride (Cl)
Chatham County, Ga.—Continued			
344	555	Dec. 10, 1952	5.8
345	535	July 27, 1943	48
345	535	Jan. 21, 1955	50
345	535	Feb. 24, 1955	50
346	872	Oct. 11, 1957	8.2
349	335	Jan. 21, 1955	7.0
352	438	do	4.0
353	650	Oct. 10, 1957	6.0
354	654	Feb. 18, 1954	16
357	[3] 203–215	May 11, 1954	33
357	[3] 390–402	May 13, 1954	36
357	[3] 589–601	May 15, 1954	41
357	[3] 712–745	May 20, 1954	40
357	745	June 21, 1954	36
357	745	Feb. 28, 1956	26
357	745	Mar. 6, 1956	16
357	[4] 695	Mar. 15, 1957	89
357	[4] 695	Sept. 30, 1957	39
357	[4] 695	Jan. 20, 1958	41
357	[4] 695	Mar. 12, 1958	42
357	[4] 695	May 1, 1958	44
357	[4] 695	July 2, 1958	27
357	[4] 695	Aug. 5, 1958	52
357	[4] 695	Sept. 4, 1958	148
357	[4] 695	Nov. 6, 1958	295
357	[4] 695	Dec. 4, 1958	599
357	[4] 695	Jan. 6, 1959	673
359	1,000	May 25, 1955	20
367	300	Jan. 20, 1955	9.0
368	645	Jan. 21, 1955	42
368	645	Feb. 24, 1955	43
368	645	July 25, 1958	29
381	611	Feb. 2, 1956	12
387	680	Mar. 22, 1950	6.2
425	[1] 350	Aug. 28, 1955	36
425	[1] 450	do	33
425	[1] 650	do	37
425	[1] 850	do	140
425	[1] 990	do	188
425	1,000	do	30
428	1,010	Feb. 26, 1954	[2] 11
428	1,010	Mar. 5, 1954	[2] 11
428	1,010	Mar. 10, 1954	[2] 10
428	1,010	Apr. 12, 1954	[2] 9.0
428	1,010	July 15, 1954	[2] 11
428	1,010	Mar. 20, 1954	[2] 12
428	1,010	Sept., 1954	[2] 7.0
428	1,010	Jan. 27, 1955	[2] 10
428	1,010	Mar. 21, 1955	[2] 8.0
428	1,010	Aug. 30, 1955	[2] 10
441	160	Feb. 22, 1956	8.0
Effingham County, Ga.			
7	431	Mar. 12, 1940	4.6
16	400	Jan. 29, 1941	4.2
25	425	do	4.2
Beaufort County, S.C.			
10	130	Aug. 19, 1942	4.2
10	130	July 9, 1943	3.9
10	130	Feb. 14, 1945	4.1

See footnotes at end of table.

TABLE 7.—*Chloride content, in parts per million, of water from principal artesian aquifer*—Continued

Well	Depth of well (feet)	Date of collection	Chloride (Cl)
Beaufort County, S.C.—Continued			
10	130	Mar. 7, 1946	4.2
10	130	June 14, 1948	4.0
10	130	Jan. 26, 1955	4.0
10a	150	Nov. 28, 1951	5.5
10a	150	Oct. 1, 1952	6.0
10a	150	Oct. 8, 1957	4.0
18	232	Aug. 19, 1942	3.9
18	232	July 9, 1943	3.8
18	232	Feb. 14, 1945	4.0
18	232	Mar. 7, 1946	4.0
18	232	June 14, 1948	4.0
18	232	Nov. 28, 1951	5.5
20	76	Aug. 19, 1942	18
20	76	July 9, 1943	76
20	76	Mar. 7, 1946	38
20a	110	June 14, 1948	14
20a	110	Oct. 1, 1952	13
20a	110	Oct. 8, 1957	26
53	133	Sept. 17, 1940	12
53	133	June 6, 1941	7.6
53	133	Sept. 15, 1942	8.9
53	133	June 15, 1948	14
53	133	Sept. 29, 1952	6.0
53	133	May 23, 1955	14
53	133	Apr. 3, 1957	15
54	168	June 15, 1948	11
54	168	Nov. 26, 1951	8.0
54	168	Sept. 29, 1952	8.0
54	168	Apr. 3, 1957	11
57	161	May 23, 1955	6.8
57	161	Apr. 3, 1957	8.0
62	100±	Aug. 21, 1941	24
62	100±	Aug. 20, 1942	17
62	100±	June 15, 1948	17
62	100±	Nov. 26, 1951	16
62	100±	Jan. 26, 1955	16
62	100±	Oct. 8, 1957	16
62a	100	Nov. 26, 1951	11
62a	100	Sept. 29, 1952	14
62a	100	Jan. 26, 1955	35
63	172	Aug. 21, 1941	28
63	172	Aug. 20, 1942	28
63	172	June 15, 1948	27
63	172	Nov. 26, 1951	35
63	172	Sept. 29, 1952	20
63	172	Oct. 8, 1957	23
66	146	Aug. 21, 1941	54
66	146	Aug. 20, 1942	54
66	146	Nov. 21, 1957	53
67	130	Nov. 21, 1957	37
101	[3] 188–200	June 1, 1954	66
101	[3] 388–400	June 3, 1954	142
101	[3] 588–600	June 5, 1954	484
101	[3] 668–740	June 9, 1954	530
101	740	do	82
101	[4] 543	Jan. 17, 1958	295
101	[4] 543	Mar. 11, 1958	300
101	[4] 543	Apr. 30, 1958	303
101	[4] 543	July 3, 1958	317
101	[4] 543	Aug. 6, 1958	332
101	[4] 543	Sept. 5, 1958	340
101	[4] 543	Oct. 10, 1958	342
101	[4] 543	Nov. 7, 1958	360
101	[4] 543	Dec. 5, 1958	368
101	[4] 543	Jan. 6, 1959	368
101	[4] 609	June 4, 1957	290
101	[4] 609	Oct. 2, 1957	385
101	[4] 609	Jan. 17, 1958	490
101	[4] 609	Mar. 11, 1958	500
101	[4] 609	Apr. 30, 1958	504
101	[4] 609	July 3, 1958	512
101	[4] 609	Aug. 6, 1958	521
101	[4] 609	Sept. 5, 1958	518
101	[4] 609	Oct. 10, 1958	512
101	[4] 609	Nov. 7, 1958	526
101	[4] 609	Dec. 5, 1958	545
101	[4] 609	Jan. 6, 1959	535
101	[4] 693	June 4, 1957	1,950
101	[4] 693	Oct. 2, 1957	2,000
101	[4] 693	Jan. 17, 1958	2,020
101	[4] 693	Mar. 11, 1958	2,010
101	[4] 693	Apr. 30, 1958	2,010
101	[4] 693	July 3, 1958	2,010
101	[4] 693	Aug. 6, 1958	2,000
101	[4] 693	Sept. 5, 1958	1,950
101	[4] 693	Oct. 10, 1958	1,970
101	[4] 693	Nov. 7, 1958	2,030
101	[4] 693	Dec. 5, 1958	2,020
101	[4] 693	Jan. 6, 1959	2,020
201	165	Jan. 18, 1955	60
201	165	Dec. 20, 1955	70
202		do	70
204		Jan. 26, 1955	47
206	281	do	22
206	281	Nov. 22, 1957	4.0
207	100	Jan. 26, 1955	9.0
222	485	Jan. 21, 1955	4.5
225	80	July 6, 1955	59
233	90	May 19, 1955	6.5
234		do	10
235	171	June 15, 1948	5.8
235	171	Nov. 26, 1951	7.0
235	171	Sept. 29, 1952	6.0
235	171	Apr. 3, 1957	6.0
236	200	June 27, 1955	30
273	226	Nov. 16, 1955	22
275	300	Mar. 24, 1954	22
287	195	do	34
288	190	Feb. 9, 1956	9.0
289	80	do	10
293	268	do	8.2
293	120	do	8.2
294	80	do	12
295	180	do	12
297	125	do	30
300	148	Apr. 3, 1957	10
301	148	do	7.0
303	98	Nov. 26, 1951	28
303	98	Sept. 29, 1952	27
304	746	Nov. 20, 1958	8.0
304	[4] 692	Dec. 5, 1958	480
304	[4] 692	Jan. 6, 1959	502
Jasper County, S.C.			
1	503	Jan. 18, 1955	5.0
1	503	Aug. 13, 1957	6.0
5	300	Jan. 18, 1955	6 0
5	300	Nov. 13, 1957	8.0
36	420±	Jan. 18, 1955	5.0
52	400±	do	5.0
52	400±	Nov. 13, 1957	5.5

[1] Collected with point sampler at depth indicated.
[2] Analysis by Union Bag-Camp Paper Corp.
[3] Collected as well was drilled by means of packers.
[4] Collected through sampling pipe at depth indicated.

TABLE 8.—*Chloride content, in parts per million, of water from wells in deposits of Claiborne age and shallow wells in deposits of Pleistocene age, Chatham County*

Well	Depth of sample or interval (feet)	Date of collection	Chloride (Cl)
Deposits of Claiborne age			
316	1,630–2,120	May 20, 1939	2,600
357	900	Mar. 15, 1957	2,290
357	900	Sept. 30, 1957	3,690
357	900	Jan. 20, 1958	3,920
357	900	Mar. 12, 1958	4,130
357	900	May 1, 1958	4,240
357	900	July 2, 1958	4,430
357	900	Aug. 5, 1958	4,620
357	900	Sept. 4, 1958	4,730
357	900	Oct. 9, 1958	4,760
357	900	Nov. 6, 1958	4,890
357	900	Dec. 4, 1958	4,960
357	900	Jan. 6, 1959	5,010
357	1,232–1,435	Nov. 29, 1956	3,100
357	1,260	Mar. 15, 1957	7,540
357	1,260	Sept. 30, 1957	9,500
357	1,260	Jan. 20, 1958	10,400
357	1,260	Mar. 12, 1958	10,300
Deposits of Claiborne age—Continued			
357	1,260	May 1, 1958	9,140
357	1,260	July 2, 1958	11,100
357	1,260	Aug. 5, 1958	11,000
357	1,260	Sept. 4, 1958	11,200
357	1,260	Oct. 9, 1958	10,900
357	1,260	Nov. 6, 1958	10,600
357	1,260	Dec. 4, 1958	11,500
357	1,260	Jan. 6, 1959	11,600
Shallow wells in deposits of Pleistocene age			
603	[1] 85	Aug., 1955	18
605	[1] 54	Sept., 1955	26
610	[1] 68	do	21
611	[1] 65	Sept. 30, 1955	20
616	[1] 59	Apr. 8, 1958	26
617		Mar. 20, 1945	5.0
618	[1] 25	Mar. 19, 1941	352

[1] Depth of well.

A bar diagram of the percentage of equivalents per million (pl. 6), calculated from parts per million data in tables 5 and 6, is a useful illustration of the salt-water contamination and of the changes in chemical character of the ground water in the Savannah area. For example, on plate 6, the distribution of the percentage equivalents per million of analyses 1 to 7, 9 to 10, 14, 17, and 19 to 24 indicates no salt-water contamination. Water containing minerals introduced by salt-water contamination shows a different pattern than the aforementioned analyses. A relative increase is shown in the percentage of the equivalents per million of sodium and chloride (to which, for convenience in plotting, the equivalents per million of potassium and nitrate, respectively, have been added). For example, the diagrams for analyses 15 and 16 show a progressive increase in the percentage of equivalents per million of sodium and chloride over analysis 14, indicating that the chemical character of the water has been changed by salt-water contamination. Although the chloride contents given for analysis 14 and 15 do not indicate salt-water contamination, the 104 ppm of chloride given for analysis 16 exceeds the amount of chloride usually found in uncontaminated ground water.

This method of presentation permits an early detection of salt-water contamination. It also is a means of comparing analyses of water from different aquifers, analyses of water from zones within the same aquifer, progressive changes in chemical quality of water as it moves downdip toward discharge areas within the same zones of an aquifer, and changes in chemical quality of the water with depth in an aquifer. A change in chemical quality with depth within the principal artesian aquifer is shown on plate 6 by diagrams 29 to 33, for well BFT-101.

Many of the equivalents-per-million data were plotted on the trilinear diagram (Piper, 1945) to determine if the contaminated water was a mixture of ocean water and native ground water. None of the contaminated water from the lower part of the aquifer appears to be a direct mixture of ocean water and native ground water. Also, a direct mixture of bottom-aquifer water and upper-aquifer water is not indicated for middle-aquifer water. Bottom-aquifer water does not appear to be a direct mixture of water from the deposits of Claiborne age and upper-aquifer water. Neither does bottom-aquifer water appear to be a direct mixture of ocean water and water from the deposits of Claiborne age. Unless there has been alteration of the chemical quality of these waters by ion exchange (Foster, 1942), there appears to be no encroachment of ocean water into the Savannah area at the present time, but there probably has been and will be a change in chemical character as encroaching ocean water moves toward the center of pumping. It will require considerably more study to determine the source of the salt water in the lower part of the principal artesian aquifer in the northeastern part of the Savannah area. If the salt water now present is incompletely flushed Pleistocene or older sea water, it is either moving ahead of or being replaced by ocean water moving toward Savannah.

THEORETICAL AND ACTUAL EFFECTS OF PUMPING ON ARTESIAN HEAD AND SALT-WATER MOVEMENT

Before the development of large ground-water supplies in the Savannah area, the natural recharge equaled the natural discharge. The water that entered the aquifer, chiefly in the outcrop area, moved eastward into the Savannah area and was discharged naturally by movement through the confining beds and through outcrop areas in estuaries and on the ocean floor. Under natural conditions the quantity of water that flowed through a unit cross-sectional area of the aquifer was relatively small, and therefore, the natural discharge per unit area was correspondingly small; but the amount of natural discharge over an extensive area, such as along the coast from Beaufort, S.C. to Liberty County, Ga., would be large. The withdrawal of water through wells is an additional discharge from the previously balanced hydraulic system.

When a well in the principal artesian aquifer is pumped, the artesian head around the well declines to form a cone of depression with the apex or deepest part of the cone at the pumped well. Before the cone of depression can become stable it must deepen and expand until it causes a reduction in the natural discharge or increase in the recharge equal to the quantity of water being pumped from the well. In the Savannah area additional water probably is gained both by increased recharge and decreased natural discharge.

The water pumped from the principal artesian aquifer during the period in which the cone of depression is expanding and deepening is derived from storage within the aquifer, although the sediments are not drained of water as they are when the water table declines in an unconfined aquifer. The artesian aquifer, its confining layers, and the water it contains are slightly elastic, and when the head is lowered a little water is squeezed out of storage by compaction of the formations, and the water itself expands slightly. The coefficients of storage and of transmissibility and the rate of pumping are the controlling factors that determine the rate of growth of the cone of depression, and accordingly the amount and rate of decline in artesian head.

The theoretical decline in hydrostatic head at any distance and within any length of time after pumping is started can be computed by the Theis nonequilibrium formula (Theis, 1935). Although aquifers do not conform completely to the assumptions on which the formula is based it has been demonstrated that in aquifers that are reasonably uniform the formula may be used to determine fairly accurately the changes in hydrostatic head accompanying changes in rates of pumping (Guyton, 1942).

By using the coefficients of storage and transmissibility within the range determined by the most reliable pumping tests, application of the Theis nonequilibrium formula indicates that there has been ample time for the major cone of depression to reach the recharge and natural discharge areas of the principal artesian aquifer. The discharged areas probably are now recharge areas for salt water. At least this is true where the confining layer is thin or has been cut into by estuaries inside the zero contour on the piezometric map (pl. 5*C*). Because the present rate of discharge probably is less than the rate of recharge, the hydraulic system is approximately in equilibrium. If the pumping from the aquifer is continued at the same rate and at the same localities, the water levels in wells ending in the principal artesian aquifer will not decline appreciably in the future. This conclusion is supported somewhat by records of water-level fluctuations in observation wells from 1943 to 1947 (pl. 4) when the average withdrawal was about

40 mgd. Although the average rate of pumping in 1957 was about 62 mgd, the decline in the piezometric surface has been just enough to increase the hydraulic gradient sufficiently to cause movement of the additional amount of water into the well fields.

The mathematical theory of ground-water hydraulics and the observed water-level fluctuations show clearly that pumping from the principal artesian aquifer has a widespread effect on the hydrostatic head; consequently pumping from one well eventually will affect most or all of the other wells ending in the aquifer in the Savannah area. Thus, if an additional quantity of water is pumped from an existing or newly developed well field, some decline in head or reduction in yields will take place at all or nearly all other wells ending in the aquifer. If the distance from the new center of pumping to the affected wells is great, the amount of decrease in head or yield may be inappreciable, but in the immediate Savannah area most of the well fields are sufficiently close to each other that appreciable interference will result from new withdrawals.

The Theis formula generally is useful in evaluating the magnitude of this interference; however, the hydrologic characteristics of the principal artesian aquifer in the Savannah area are irregular, and the formula can be used only over relatively small areas to predict approximate decreases in head due to pumping. A better prediction for the Savannah area can be made by using the curves shown in figure 7. The curves show the actual observed water-level decline that has occurred for each one million gallons per day of pumpage. These curves were originally made by Warren in 1944 and were checked in 1955 and 1957. The water level declines shown by figure 7 are slightly less than the theoretical declines calculated by the Theis formula (Warren 1944a, p. 118).

Permeabilities of the upper part of the principal artesian aquifer, which is more permeable than the lower part, can be used as a basis for estimating the rate of salt-water encroachment. Aquifer samples from a well at the U.S. Post Office in Savannah had a coefficient of permeability of 1,260 gpd per sq ft at a depth of 372 to 394 feet, 360 gpd per sq ft at 394 to 413 feet, and 53 gpd per sq ft at 413 to 434 feet. The coefficient of permeability for samples of the aquifer from well BFT–304 on Daufuskie Island ranged from 0.01 to 15 gpd per sq ft from 146 to 746 feet. (See table 4.) The highly permeable parts of the aquifer were not recovered and represent the interval from 196 to 386 feet. The coefficient of transmissibility derived from a pumping test on this well was 380,000 gpd per ft. Calculations indicate an average coefficient of permeability of 2,000 gpd per sq ft for the permeable 190-foot interval. The coefficient of permeability of the most productive parts of the aquifer probably is more than 2,500—perhaps as much as 5,000. Using a value of 5,000 gpd per sq ft for the coefficient of permeability, 35 percent for porosity, and a hydraulic gradient of 1 foot per mile, the velocity of ground water moving toward Savannah in the vicinity of Daufuskie Island would be about 130 feet per year for a rate of pumping of 62 mgd at Savannah. This is more than seven times the velocity calculated using the average coefficient of permeability for the total thickness of the aquifer. (See section, "Movement of Ground Water.") If the pumpage in Savannah were increased to about 125 mgd the hydraulic gradient would be about 3 feet per mile and the velocity of water moving toward Savannah would be about 400 feet per year. It would take approximately 13 years for salt water to move 1 mile at Daufuskie Island with a pumping rate of 125 mgd in Savannah.

As the salt-water front moves closer to Savannah it will increase in velocity directly with the hydraulic gradient. Eight miles east of Savannah the hydraulic gradient for a pumpage of 62 mgd is about 6 feet per mile, which under conditions assumed above would cause ground water to move at a velocity of about 800 feet per year. For a pumpage of 125 mgd the hydraulic gradient would be about 14 feet per mile and would cause water to move at a velocity of 1,800 feet per year. At this rate it would take about 3 years for water to travel 1 mile.

Although the permeability decreases toward Savannah, the porosity also may decrease, and the effects of the two decreases would tend to offset each other.

Thus, salt water apparently will not reach Savannah for many years, perhaps as long as a century, even if the pumpage increases to 125 mgd.

The coefficient of permeability of the principal artesian aquifer in the vertical direction generally is much lower than in the horizontal direction. (See table 4.) This means that water can move more freely horizontally through the aquifer than either upward or downward. In the Hilton Head Island area high-chloride water is in the aquifer at a depth of 543 feet. (See well BFT–101, table 7.) Wells that obtain water from the top of the aquifer will be the last to yield salty water. With the slow upward ground-water movement, it will be many years before water in the upper part of the aquifer will begin to have a noticeably salty taste. As long as no large water supplies are developed in the Hilton Head Island area, there should be an ample supply of fresh ground water for domestic use from the upper part of the aquifer for many years, perhaps for a century.

Lowering the water level in an artesian aquifer below the bottom of the upper confining layer may reduce well yields by reducing the thickness of aquifer contributing to the wells. The pumping level in the center of the cone of depression at Savannah is nearing the top of the principal artesian aquifer as a result of the concentration of pumping. If the pumping rate were increased to 125 mgd with the same distribution of pumping, the top of the aquifer would soon be dewatered over a few square miles in the center of the cone of depression. Future increases in pumping should be more widely distributed if this situation is to be avoided.

SUMMARY AND CONCLUSIONS

Most of the large ground-water developments in the Savannah area are concentrated in Savannah and in the industrial areas near the city. About 98 percent of the approximately 60 mgd of water used is pumped from limestone strata of Eocene, Oligocene, and Miocene ages, which collectively form the principal artesian aquifer.

Before ground-water supplies were developed in the Savannah area, the artesian head in the principal artesian aquifer generally was above the land surface, but with progressive increase in pumping the artesian head has declined. The total lowering of the piezometric surface, or artesian head, from the first year of pumping until 1958 has been more than 145 feet near the center of pumping. Eight miles southwest of the center of pumping the decline has been about 54 feet, 23 miles west it has been about 25 feet, and about 20 miles east the decline has been about 20 feet.

Salt water is in the lower part of the principal artesian aquifer about 15 miles northeast of Savannah and in the rocks underlying the aquifer throughout the Savannah area. The salt water appears to be incompletely flushed Pleistocene sea water, and the hydraulic gradient indicates that it is moving laterally toward Savannah from the northeast at a slow rate. If the present rate of pumping is continued, or even if it is doubled, it probably will be many years, perhaps more than a century, before the salt water in the aquifer will reach the immediate vicinity of Savannah.

Underlying the Savannah area are a series of unconsolidated and semiconsolidated sedimentary rocks ranging in age from Late Cretaceous to Recent. In other parts of the Coastal Plain the Upper Cretaceous, Paleocene, and lower Eocene sediments supply a readily available and usable supply of water. The character and physical properties of these formations in the Savannah area are similar to those in other areas, but the hydraulic and structural conditions and the quality of the water apparently are different. Deep test wells would be needed to evaluate the ground-water potential of the rocks in the lower part of the geologic column.

The principal artesian aquifer is considered to be a single hydraulic unit; it consists mostly of marine limestone and includes some sandy limestone and marl. According to location and depth, the principal artesian aquifer consists of 1 to 5 geologic units. The lower confining layer for the principal artesian aquifer consists of the lower part of the middle Eocene sediments. The upper confining layer is the Hawthorn formation of Miocene age.

In the western and southern parts of the Savannah area the lowest unit of the principal artesian aquifer is the Lisbon formation of middle Eocene age. To the east and northeast, however, this formation is known to contain highly mineralized water and forms a part of the lower confining layer. The Gosport sand overlies the Lisbon formation. In the Savannah area, the Gosport, a soft sandy limestone or marl, locally is as much as 400 feet thick.

The Ocala limestone of late Eocene age conformably overlies the Gosport and has been subdivided into lower and upper units. The lower unit is somewhat similar to the Gosport; it is sandy and commonly contains marl and clay stringers. The upper unit is predominantly a calcitized, crystalline, abundantly fossiliferous limestone that contains practically no clay, sand, or marl. This part of the Ocala contains many voids and apparently it is the most permeable part of the principal artesian aquifer.

Undifferentiated sediments of the Oligocene series, also a part of the principal artesian aquifer, overlie the Ocala except in the northern and northwestern parts of the area, where Oligocene rocks overlie rocks of middle Eocene age. The Oligocene sequence is similar in part to the highly porous sections of the Ocala, but more commonly it is a loosely consolidated limestone. To the northwest the Oligocene contains a thick unit of sand which disappears southward. The entire Oligocene series thins toward the southwest.

Overlying the undifferentiated rocks of the Oligocene series is the Tampa limestone of early Miocene age. The formation grades from broken shelly, sandy limestone to hard dolomitic limestone and sandy, silty limestone. Although the Tampa is considered the upper part of the principal artesian aquifer, it only yields small quantities of water, and locally the water contains hydrogen sulfide. Commonly the Tampa is cased out in wells, and more desirable water is obtained from older units of the principal artesian aquifer below the Tampa.

Overlying the Tampa limestone and the principal artesian aquifer are the Hawthorn formation of early and middle Miocene age and the Duplin marl of late Miocene age. The Hawthorn formation is the upper confining layer for the principal aquifer and, except in one well in Hampton County, S.C., occurs everywhere in the Savannah area.

The Hawthorn formation is commonly a clayey silt. Its permeability is low and it is sufficiently thick to act as a barrier to water leakage from above and below. However, some leakage may occur near the coast, where the formation is close to the surface. In the same part of the area some of the stream channels have cut down through or nearly through the Hawthorn, and it no longer acts as a barrier to contamination by salt or brackish water from above. This is especially true about 16 to 20 miles northeast of Savannah, where the fresh-water head has declined to sea level or below. Where the confining bed is thin or absent, artesian ground water at one time discharged from the aquifer as submarine springs. Now a reverse effect may be occurring; ocean and river water may be entering the aquifer. Locally the Hawthorn yields small amounts of water to wells.

The Duplin marl is recognized only in the Savannah River valley. Although locally it may be a source of small supplies of nonartesian ground water, it is considered to be a part of the upper confining layer.

The uppermost geologic units in the Savannah area are the Pliocene to Recent marine and river-terrace deposits, flood-plain deposits, and beach and lagoonal deposits. The surface deposits are mostly sand and are variable in thickness, distribution, and grain size. These units are a source of water for shallow wells throughout the Savannah area.

The water pumped from the principal artesian aquifer in the Savannah area enters the aquifer in the recharge (outcrop) area 60 to 100 miles west-northwest of Savannah and moves downdip through the permeable part of the limestone to areas of natural or artificial discharge. The quantity of water that can be pumped from the principal artesian aquifer is probably limited, not by the potential recharge, but by the transmissibility of the aquifer between Savannah and the recharge area. Heavy pumping over a period of many years at Savannah has caused a lowering of the artesian head to below sea level over a large area and in the northeastern part of the Savannah area has caused salt water in the aquifer to move toward the center of the cone of depression in the city. However, the movement is slow at present.

The yields of large-diameter wells penetrating the principal artesian aquifer in Savannah and in the industrial area near the city generally range from 1,000 to 4,200 gpm. The specific capacity of wells in most of the Savannah area ranges from 45 to 65 gpm per foot of drawdown. Pumping tests and flow-net analyses show that the coefficient of transmissibility of the principal artesian aquifer has a wide range, averaging about 250,000 gpd per foot in the vicinity of Savannah. It is as high as 780,000 at Fort Stewart in Liberty County and as low as 160,000 in Savannah. It is also higher in the northeastern and eastern parts of the Savannah area than in the city.

The coefficient of storage of the principal artesian aquifer, according to the most reliable pumping tests, averages 0.0003 in Savannah and its immediate vicinity.

Ground-water supplies may be developed from shallow sand aquifers at some places. Shallow wells furnish cooling water for air conditioning, but the well screens become plugged with what appears to be a deposit of calcium carbonate and must be cleaned by acidizing about once each year. Some of the shallow ground water has a high iron content. Test drilling is necessary to determine if wells can be developed from shallow sources at any given place. It may be possible to develop water supplies from shallow wells for small industries or supplemental supplies for larger users, but not enough information is available for the prediction of well yields.

The water in the principal artesian aquifer is of suitable chemical quality for most uses. The temperature is nearly constant in any one well but ranges from about 68° to 74°F from well to well. Hardness as calcium carbonate generally is less than 120 ppm, and dissolved-solids content generally is less than 200 ppm. The pH usually is in the range from 7.5 to 8.0. The chloride content normally is less than about 15 ppm. The chloride content of water from five Savannah city wells, all less than 700 feet deep, is less than 8.5 ppm. Water from a 1,000-foot city well has a chloride content of 20 ppm.

Tests were made to determine if salt water is present in the principal artesian aquifer northeast of Savannah near the Atlantic Coast. The chloride content of the water samples was found to increase with depth and has increased with time. The lower part of the aquifer contains salty water (2,000 ppm chloride) along the Atlantic Coast east-northeast of Savannah, and water of relatively high chloride content (about 100 to 150 ppm) in the lower part of the aquifer may extend westward to Savannah or beyond.

The chemical quality of the water pumped from the artesian aquifer in the Savannah area has changed very little since the first wells were drilled late in the 19th century, and it is not likely to change appreciably in many years—perhaps not for a century.

The salty water in the lower part of the principal artesian aquifer in the northeastern part of the Savannah area appears not to be a direct mixture of sea water and uncontaminated ground water. However, the chemical character of such a mixture could have been effected by ion exchange. It also appears not to be a direct mixture of fresh water and salt water from deposits of Claiborne age which underlie the principal artesian aquifer.

Whatever its source, the salty water is moving toward Savannah, and if pumping continues at or above the present rate, salt water eventually will contaminate the aquifer to the center of the cone of depression. There is some indication that the lower part of the principal artesian aquifer may not be as completely flushed as the upper part; therefore, there may be water of relatively high chloride content in the lower part of the aquifer as far west as the city of Savannah.

Salt water could invade the aquifer from three directions—laterally from the east and vertically from below and from above. The thick clayey-silt confining layers above and below the aquifer will limit the rate of upward or downward leakage of salt water to relatively small amounts. Thus lateral migration through the aquifer is the most likely source of contamination. The areas of natural discharge now have become areas of recharge by salty water from the Atlantic Ocean and estuaries in the Hilton Head Island area of South Carolina.

The Ghyben-Herzberg principle is not exactly applicable to the Savannah area. Salt water is not present as far west or with as high a concentration of chloride as that principle would indicate. Also the salt water—fresh water interface probably has not reached equilibrium in the thousands of years since the last substantial changes in sea level in late-glacial or postglacial time.

Additional large supplies of ground water can be developed in the Savannah area if the pumping is distributed more widely. New wells of large yield could be drilled 15 to 20 miles to the northwest, west, and southwest without excessive water-level declines, and water could be supplied to users from pipelines. The surface-water supply also can be used for additional needs.

Ground water that is used for cooling and that is protected from contamination by means of a closed system could be put back into the aquifer through return wells, thereby reducing net pumpage. However, recirculation of cooling water through the aquifer may warm the ground water to the point where it is not usable for cooling. Also a change in chemical quality might result with change in temperature of the cooling water. A study of the resulting temperature rise in relation to head differences between return wells and discharging wells would provide valuable information on the maximum ground-water velocities that might be expected in the Savannah area.

690-437—63——7

The effects of additional development on water levels and on chloride content need careful consideration. The following paragraphs suggest some of the specific measures that would aid in the long-range management of the fresh-water resources in the principal artesian aquifer.

Representative water samples from the bottom part of the aquifer should be analyzed to learn more about the chemical quality of the water. Additional study is needed to determine the sources of the salty water in the lower part of the aquifer in the northeastern part of the Savannah area. The actual velocity of the salt water cannot be determined without a long record of analyses of water samples from the observation wells. These and other wells in the Savannah area should be sampled for as long as necessary to establish a definite trend in the increase of chloride, so that reliable predictions of salt-water movement may be made. It may be desirable to drill additional observation wells to trace the movement of high-chloride water toward Savannah.

Pumping tests should be made on as many wells as possible in order to learn more about the range in transmissibility and storage coefficients of the principal artesian aquifer. Laboratory tests of rock samples from various depths and locations are needed to determine the permeability and porosity of the different zones within the aquifers as a guide to a reliable estimate of the rate of salt-water movement toward Savannah. Satisfactory samples of the aquifer can be obtained only by coring.

Periodic inventories of pumpage and water level measurements in a network of observation wells should be continued indefinitely to determine changes in the water levels due to pumping. A study of the recharge to the principal artesian aquifer and movement of the recharge water into the Savannah area is also needed to aid in the long-range regional development of the aquifer.

A study of shallow aquifers in the area should be made, including a test-drilling and aquifer-testing program, to aid in development of water supplies from the shallow sands. Such development would relieve the draft on the principal artesian aquifer and make available additional supplies of ground water in the Savannah area.

RECORDS OF SELECTED WELLS

The wells listed in the following table are shown on plate 1. The reader is referred to Warren (1944b) for a larger listing of wells in Bryan, Chatham, and Effingham Counties. Records of these and many other wells may be consulted in the office of the Ground Water Branch, U.S. Geological Survey, Savannah, Ga.

Records of selected wells

Well (pl. 1)	Owner	Depth of well below land surface (ft)	Diameter of well (in.)	Use of water	Measuring point			Depth to water below measuring point (ft)	Date of measurement
					Description	Distance above land surface (ft)	Altitude above mean sea level (ft)		
Bryan County, Ga.									
146	Mill Creek School	423	6	School	Top of 6-inch coupling	1.5	68.0	33.62	Feb. 26, 1959
150	Mrs. E. M. Berry	480	4-3	Domestic	Top of 2-inch tee	4.25	16.25	5.8	Mar. 19, 1959
Chatham County, Ga.									
17	City of Savannah	505	16	Observation	Pumphouse floor	0.4	38.2	101.3	Mar. 23, 1959
28	Reliance Fertilizer Co.	480	8	do	Hole in pump base	1.5	17.87	93.93	Feb. 16, 1959
30	Dixie Roofing Mills	608	12	Industrial	do	.2	11.55	85.48	do
76	Pierpont Mfg. Co.	378	3	Observation	Top of 3-inch casing	1.0	13.1	109.15	do
84	Standard Oil Co.	652	10	Industrial	Hole in pump base	.5	6.1	54.34	do
99	Atlantic Coast Line RR	500	6	Observation	Hole in recorder platform	2.1	6.8	58.58	Feb. 24, 1959
118	City of Savannah Beach	402	12	Public supply	Hole in pump base	0	8.0	14.07	Apr. 12, 1955
194	W. W. Keller	350	4	Observation	Top of 4-inch casing	.4	12.75	40.05	Apr. 26, 1959
317	U.S. National Park Service	354	8	do	Floor of recorder shelter	3.26	11.72	22.53	Mar. 2, 1959
328	City of Savannah Beach	136	3	do	Hole in cap on 3-inch casing	0	9.85	17.88	do
330	Georgia Highway Dept	540	3	do	do	2.54	12.56	19.28	Feb. 20, 1959
343	U.S. Dept. of Agriculture	14.8	30	do	Land surface	0	18.7	5.62	Nov. 15, 1957
357	U.S. Geol. Survey (test well 1)	1,260	1½	do	Bottom of opening in 1½-inch tee	1.57	9.27	34.7	Mar. 5, 1959
357	do	900	1½	do	do	.97	8.67	25.79	do
357	do	695	1½	do	do	1.0	8.7	19.89	do
471	U.S. Post Office	695	12	Air conditioning	Top of 12-inch casing	0	41	122.0	Sept. 12, 1958

Records of selected wells—Continued

Well (pl. 1)	Owner	Depth of well below land surface (ft)	Diameter of well (in.)	Use of water	Measuring point			Depth to water below measuring point (ft)	Date of measurement
					Description	Distance above land surface (ft)	Altitude above mean sea level (ft)		
Effingham County, Ga.									
7	Central of Georgia RR	431	8	Observation	Floor of recorder shelter	2.73	34.23	12.87	Feb. 26, 1959
Beaufort County, S.C.									
101	U.S. Geol. Survey (test well 2)	693	1½	Observation	Top of 1½-inch tee	3.2	17.06	19.06	Mar. 6, 1959
101	do	609	1½	do	do	3.12	16.98	17.27	do
101	do	543	1½	do	do	3.53	17.39	17.53	do
304	U.S. Geol. Survey (test well 3)	692	3	do	Top of 3-inch pipe in 8-inch casing	.7	13.45	18.95	Mar. 23, 1959
304	do	649	8	do	Top of 8-inch casing	.2	12.95	18.1	do
Jasper County, S.C.									
46	Seaboard Airline RR	334	8	Observation	Top of 8-inch casing	1.1	18.15	20.70	Mar. 18, 1959

SELECTED REFERENCES

Applin, P. L., and Applin, E. R., 1947, Regional subsurface stratigraphy, structure, and correlations of middle and early Upper Cretaceous rocks in Alabama, Georgia, and North Florida: U.S. Geol. Survey Oil and Gas Inv. Prelim. Chart. 26.

Barksdale, H. C., Sundstrom, R. W., and Brunstein, M. S., 1936, Supplementary report on the ground-water supplies of the Atlantic City region: New Jersey State Water Policy Comm., Spec. Rept. 6.

California State Water Pollution Control Board, 1952, Water quality criteria: Sacramento, Calif., Pub. 3, 512 p.

Callahan, J. T., 1958, Georgia's ground water resources: Georgia Geol. Survey Min. Newsletter, v. 10, no. 3, p. 94–95.

Collins, W. D., Lamar, W. L., and Lohr, E. W., 1932, The industrial utility of public water supplies in the United States: U.S. Geol. Survey Water-Supply Paper 658, 135 p.

Cooke, C. W., 1915, The age of the Ocala limestone: U.S. Geol. Survey Prof. Paper 95, p. 107–117.

——— 1925, Physical geography of Georgia: Georgia Geol. Survey Bull. 42, 184 p.

——— 1930, Correlation of coastal terraces: Jour. Geology, v. 38, p. 577–589.

——— 1936, Geology of the Coastal Plain of South Carolina: U.S. Geol. Survey Bull. 867, 188 p.

——— 1943, Geology of the Coastal Plain of Georgia: U.S. Geol. Survey Bull. 941, 117 p.

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

Cooper, H. H., Jr., and Warren, M. A., 1945, The perennial yield of artesian water in the coastal area of Georgia and northeastern Florida: Econ. Geology, v. 40, no. 4, p. 263–282.

Counts, H. B., 1958, The quality of ground water in the Hilton Head Island area, Beaufort County, South Carolina: Georgia Geol. Survey Min. Newsletter, v. 11, no. 2, p. 50–51.

Fenneman, N. M., 1938, Physiography of eastern United States: New York, McGraw-Hill Book Co., 689 p.

Ferguson, G. E., Lingham, C. W., Love, S. K., and Vernon, R. O., 1947, Springs of Florida: Florida Geol. Survey Bull. 31, 196 p.

Foster, M. D., 1942, Base-exchange and sulfate reduction in salty ground waters along the Atlantic and Gulf Coast: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 5, p. 838–851.

Ghyben, Badon, 1889, Nota in verband met de voorgenomen put boring nabij Amsterdam: Koninski Inst. Ing. Tijdschr., The Hague.

Guyton, W. F., 1942, Results of pumping tests of the Carrizo sand in the Lufkin area, Texas: Am. Geophys. Union Trans., v. 23, p. 40–48.

Hem, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 269 p.

Herrick, S. M., 1946, Ground water for irrigation in Georgia: Agricultural Eng., v. 27, no. 11, p. 521–522.

Herrick, S. M., and Chase, G. H., 1952, Results of chloride determinations of water supplies from observation wells in the Savannah area: U.S. Geol. Survey open-file report.

Herrick, S. M., and LeGrand, H. E., 1947, Interim report on ground water in the Savannah area, Georgia, with special reference to the chloride content of the water: U.S. Geol. Survey open-file report.

Herrick, S. M., and Wait, R. L., 1955, Interim report on results of test drilling in the Savannah area, Georgia and South Carolina: U.S. Geol. Survey open-file report, 48 p.

——— 1956, Ground water in the Coastal Plain of Georgia: Am. Water Works Assn. Jour., Southeastern Section, v. 20, no. 1, p. 73–86.

Herzberg, Baurat, 1901, Die Wasserversorgung einiger Nordseebader: Jour. Gasbeleuchtung und Wasserversorgung, Munich Jahrg., 44.

Jacob, C. E., 1940, The flow of water in an elastic artesian aquifer: Am. Geophys. Union Trans., v. 21, p. 574–586.

Lamar, W. L., 1940a, Salinity of the lower Savannah River in relation to streamflow and tidal action: Am. Geophys. Union Trans., v. 21, p. 464–470.

——— 1940b, Industrial quality of public water supplies in Georgia: U.S. Geol. Survey Water Supply Paper 912.

LaMoreaux, P. E., 1946, Geology and ground-water resources of the Coastal Plain of east-central Georgia: Georgia Geol. Survey Bull. 52, 170 p.

LeGrand, H. E., and Furcron, A. S., 1956, Geology and ground-water resources of central-east Georgia, with a chapter on the surface water resources by R. F. Carter and A. C. Lendo: Georgia Geol. Survey Bull. 64, 170 p.

McCallie, S. W., 1898, A preliminary report on the artesian-well system of Georgia: Georgia Geol. Survey Bull. 7, 209 p.

——— 1908, Underground waters of Georgia: Georgia Geol. Survey Bull. 15, 360 p.

MacNeil, F. S., 1944, The Tertiary formations (of Georgia): Southeastern Geol. Soc. Guidebook 2d Field Trip, p. 21–37.

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

——— 1947b, Correlation chart for the outcropping Tertiary formations of the eastern Gulf region: U.S. Geol. Survey Oil and Gas Inv. Prelim. Chart 29.

——— 1950, Pleistocene shore lines in Florida and Georgia: U.S. Geol. Survey Prof. Paper 221–F, p. 95–106.

Maxcy, K. F., 1950, Report on the relation of nitrate nitrogen concentration in well waters to the occurrence of methemoglobinemia in infants: Natl. Research Council, Bull. Sanitary Eng. and Environment app. D.

Meinzer, O. E., 1923, The occurrence of ground water in the United States: U.S. Geol. Survey Water-Supply Paper 489, 314 p.

Parker, G. G., Ferguson, G. E., Love, S. K., and others, 1955, Water Resources of southeastern Florida: U.S. Geol. Survey Water-Supply Paper 1255, 948 p.

Piper, A. M., 1945, A graphic procedure in the geochemical interpretation of water analyses: Am. Geophys. Union Trans., v. 26, p. 914–923.

Poland, J. F., Piper, A. M., and others, 1956, Ground-water geology of the coastal zone Long Beach-Santa Ana area, California: U.S. Geol. Survey Water-Supply Paper 1109, 159 p.

Shepherd, E. S., 1940, Notes on fluoride content of rocks and ocean-bottom samples: Am. Jour. Sci., v. 238, no. 2, p. 117.

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

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

——— 1957b, Memorandum on the geology and ground water of the Parris Island area, South Carolina: U.S. Geol. Survey open-file report, 27 p.

Siple, G. E., 1959, Guidebook for the South Carolina Coastal Plain field trip of the Carolina Geological Society: South Carolina State Development Board, Div. of Geol., Bull. 24, 27 p.

Sloan, E., 1908, Catalogue of the mineral localities of South Carolina: South Carolina Geol. Survey Bull. 2, 4th ser.

Stearns, N. D., 1928, Laboratory tests on physical properties of water-bearing materials: U.S. Geol. Survey Water-Supply Paper 596–F, p. 121–176.

Stephenson, L. W., 1928, Major marine transgressions and regressions and structural features of the Gulf Coastal Plain: Am. Jour. Sci., 5th ser., v. 16, p. 281–293.

Stephenson, L. W., and Veatch, J. O., 1915, Underground waters of the Coastal Plain of Georgia: U.S. Geol. Survey Water-Supply Paper 341, 532 p.

Stewart, J. W., and Counts, H. B., 1958, Decline of artesian pressure in the Coastal Plain of Georgia, northeastern Florida and southeastern South Carolina: Georgia Geol. Survey Min. Newsletter, v. 11, no. 1, p. 25–31.

Stringfield, V. T., 1953, Artesian water in the southeastern States: Kentucky Geol. Survey Spec. Pub. no. 1, p. 24–38.

Stringfield, V. T., and Cooper, H. H., Jr., 1951, Geologic and hydrologic factors affecting perennial yield of aquifers: Am. Water Works Assoc. Jour., v. 43, no. 10, p. 803–816.

Stringfield, V. T., Warren, M. A., and Cooper, H. H., Jr., 1941, Artesian water in the coastal area of Georgia and northeastern Florida: Econ. Geology, v. 36, no. 7, p. 698–711.

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, p. 519–524.

Thomson, M. T., Herrick, S. M., Brown, Eugene, and others, 1956, The availability and use of water in Georgia: Georgia Geol. Survey Bull. 65, 316 p.

Tolman, C. F., 1937, Ground Water: New York, McGraw-Hill Book Co., 593 p.

U.S. Geological Survey, 1960a, Surface water supply of the United States, 1958, pt. 2A, South Atlantic Slope Basins, James River to Savannah River: U.S. Geol. Survey Water-Supply Paper 1553, 273 p.

——— 1960b, Surface water supply of the United States 1958, pt. 2B, South Atlantic Slope and Eastern Gulf of Mexico Basins, Ogeechee River to Pearl River: U.S. Geol. Survey Water-Supply Paper 1554, 443 p.

U.S. Geological Survey, Water levels and artesian pressures in wells in the United States, published annually: U.S. Geol. Survey Water Supply Papers 777 (1935); 817 (1936); 804 (1937); 845 (1938); 886 (1939); 907 (1940); 937 (1941); 945 (1942); 987 (1943); 1017 (1944); 1024 (1945); 1072 (1946); 1097 (1947); 1127 (1948); 1157 (1949); 1166 (1950); 1192 (1951); 1222 (1952); 1266 (1953); 1322 (1954); 1405 (1955).

U.S. Public Health Service, 1946, Public Health Reports: reprint 2697.

Veatch, J. O. and Stephenson, L. W., 1911, Geology of the Coastal Plain of Georgia: Georgia Geol. Survey Bull. 26, 456 p.

Warren, M. A., 1944a, Artesian water in southeastern Georgia: Georgia Geol. Survey Bull. 49, 140 p., 34 figs.

——— 1944b, Artesian water in southeastern Georgia—well records: Georgia Geol. Survey Bull. 49a, 83 p.

——— 1955, A summary of the artesian water resources in the Savannah area, Georgia: U.S. Geol. Survey open-file report, 21 p.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials: U.S. Geol. Survey Water-Supply Paper 887, 190 p.

INDEX

The U.S. Geological Survey Library has cataloged this publication as follows:

Counts, Harlan B., 1921–

Salt-water encroachment, geology and ground-water resources of Savannah area, Georgia and South Carolina, by Harlan B. Counts and Ellis Donsky. Washington, U.S. Govt. Print. Off., 1963.

v, 100 p. maps, diagrs., tables. 24 cm. (U.S. Geological Survey. Water-supply paper 1611)

Part of illustrative matter folded in pocket.

Prepared in cooperation with the Georgia Department of Mines, Mining and Geology, the city of Savannah, and Chatham County, Georgia.

Bibliography: p. 95–97.

(Continued on next card)

Counts, Harlan B., 1921–

Salt-water encroachment, geology and ground-water resources of Savannah area, Georgia and South Carolina. 1963. (Card 2)

1. Water-supply—Georgia. 2. Water-supply—South Carolina. 3. Water, Underground—Georgia. 4. Water, Underground—South Carolina. 5. Geology—Georgia. 6. Geology—South Carolina. 7. Water—Analysis. I. Donsky, Ellis, 1929–, joint author. II. Title: Salt-water encroachment of Savannah area, Georgia and South Carolina. (Series)