John G. Ferris

Relation of Salt-Water Encroachment to the Major Aquifer Zones Savannah Area, Georgia and South Carolina

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1613-D

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

McCollum, Counts—SALT-WATER ENCROACHMENT, SAVANNAH, GA., AREA—Geological Survey Water-Supply Paper 1613-D

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By M. J. McCOLLUM *and* H. B. COUNTS

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RELATION OF SALT-WATER ENCROACHMENT TO THE MAJOR AQUIFER ZONES, SAVANNAH AREA, GEORGIA AND SOUTH CAROLINA

By M. J. McCollum and H. B. Counts

ABSTRACT

The Savannah area, in eastern Georgia and southwestern South Carolina, includes Chatham County, adjacent parts of Bryan, Effingham, and Liberty Counties, Ga., and adjacent parts of Beaufort and Jasper Counties, S.C.

The principal artesian aquifer of the Savannah area and its confining layers are composed of the Lisbon Formation of middle Eocene age, the Ocala Limestone of late Eocene age, and sediments of Oligocene and Miocene ages. The Lisbon Formation consists of granular glauconitic limestone which becomes progressively finer grained toward the northeastern part of the area. The lower part of the Ocala Limestone resembles the granular limestone of the Lisbon Formation and also becomes very fine grained in the northeastern part of the area. The upper part of the Ocala is composed of indurated blue-gray limestone. Overlying the Ocala Limestone unconformably are sediments of Oligocene age which consist of fossiliferous limestone over most of the area. In the extreme eastern and northeastern parts of the area the Oligocene sediments contain fine quartz sand embedded in lime mud. Sediments of Miocene age are divided into two lithologic groups. The upper clayey sand unit consists of two beds separated by a thin layer of sandy dolomitic limestone. The lower unit is a conglomeratic limestone.

In the Savannah area the principal artesian aquifer consists of five major water-yielding zones separated by relatively impermeable zones. Zone 1, the uppermost zone, is at the top of the Ocala Limestone, zone 2 is about 50 feet beneath zone 1, and zone 3 lies at the base of the Ocala Limestone. The other two zones are in the Lisbon Formation, zone 4 at the top of the Lisbon and zone 5 about 70 feet below zone 4. The thickness of the zones varies throughout the area, and the upper zones usually are thicker than the lower zones. More than 70 percent of the water pumped during current-meter tests came from the first two zones. The two lowermost zones yield 10 to 20 percent, while zone 3 yielded less than 8 percent.

The chloride content of the water in each of the water-yielding zones increases eastward and northeastward from the center of pumping at Savannah. The chloride ion concentration increases with increasing depth in those parts of the area.

Heavy pumping from a small area centered at Savannah has created a cone of depression in the piezometric surface of the Savannah area. Water levels at the center of the cone have declined about 160 feet since pumping began in the late

1880's. The cone is broader to the south than to the north because of recharge to the aquifer from the vicinity of Port Royal Sound.

Salt water is present in the upper permeable zones of the aquifer just north of the study area at Parris Island, S.C., and in the lower part of the aquifer north and east of the center of pumping. The salt water in the upper part of the aquifer at Parris Island is believed to be sea water entering the aquifer through leaks in the upper confining layer, but the salty water in the lower part of the aquifer is believed to be unflushed water of an older geologic age. The rate of salt-water movement is slow in the upper permeable zones because of the low hydraulic gradients. It should take more than 400 years for the salt water in the upper water-yielding zones to reach the center of pumping at the present pumping rate of 62 mgd (million gallons per day). The salty water in the lower zones is closer to Savannah where the hydraulic gradient is steeper, and although the permeability of the lower zones is less than the upper zones, salty water would reach Savannah in about 90 years at the present rate of pumping.

Pumping from a relatively small area has caused the formation of a large, deep cone of depression, and thereby has created the problems of salt-water encroachment and aquifer dewatering. Possible solutions to these problems are rearrangement and control of aquifer pumping, conjunctive use of ground and surface water, and use of surface water as the major source of supply.

INTRODUCTION

PURPOSE AND SCOPE

The presence of salt water in the lower part of the artesian aquifer about 12 miles east and northeast of Savannah has been reported by Counts and Donsky (1963). Although they consider the aquifer to consist of about 600 feet of water-yielding sediments, they suggest that the aquifer is made up of a series of permeable zones separated by relatively impermeable zones. Because salt water in the aquifer would move through the permeable zones more rapidly than through the impermeable zones, an investigation was started to define the water-yielding zones within the principal artesian aquifer. This report is based on that investigation. In addition to the delimitation of the permeable and impermeable zones, water-level measurements were recorded of the decline of artesian pressure in the Savannah area, water samples from test wells were analyzed to monitor the encroachment of salt water, and a refinement of the geologic knowledge of the area was made.

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

LOCATION

The Savannah area considered in this report includes Chatham County, adjacent parts of Bryan, Effingham, and Liberty Counties in Georgia, and adjacent parts of Beaufort and Jasper Counties in South Carolina. (See fig. 1.)

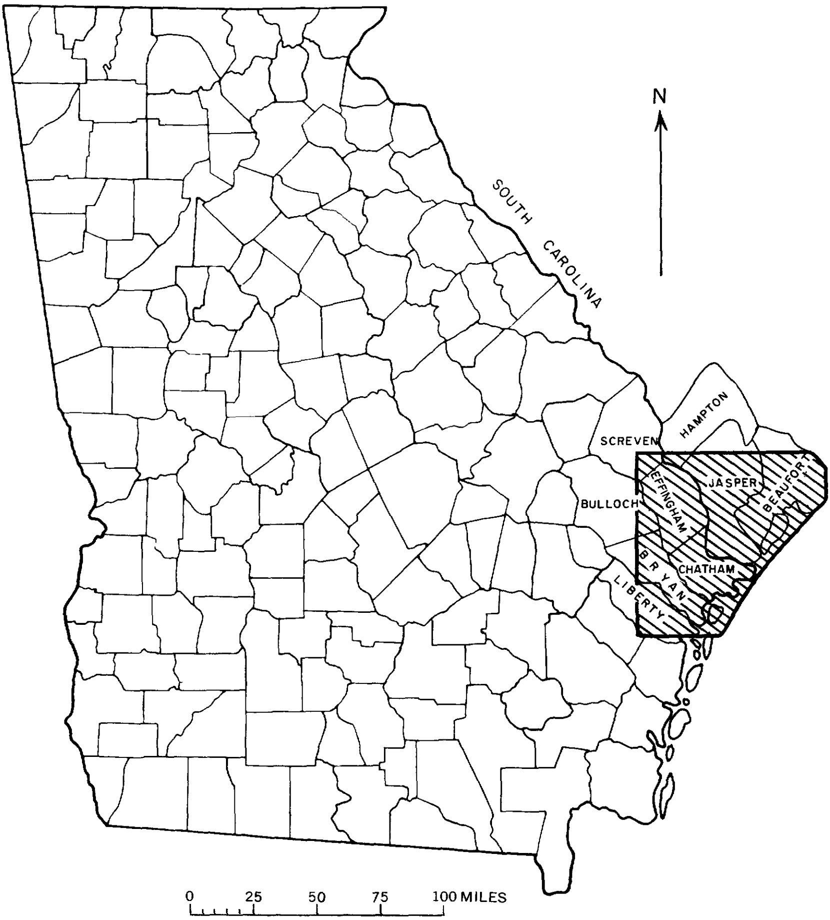

FIGURE 1.—Map of Georgia and part of South Carolina showing Savannah area.

PREVIOUS WORK

An investigation of the geology, ground-water resources, and salt-water encroachment in the Savannah area was made by Counts and Donsky. Their report (1963) describes in detail the lithology, distribution, and thickness of the geologic units underlying the Savannah area from the Cretaceous to Recent age. They define the principal artesian aquifer and discuss salt-water intrusion into the aquifer and the quality of water pumped from the aquifer.

Because a detailed list of other previous work is given by Counts and Donsky, such a list is not included in this report.

WELL-NUMBERING SYSTEM

Wells in the study area were numbered consecutively in the order in which they were inventoried in each county. The first three letters of a number designate the county, and the following numerals indicate the serial number of the well in that county. For example, a well numbered CHA 487 would mean that it is the 487th well scheduled in Chatham County. Only those wells used for the collection of data are referred to in this report. (See pl. 1 for well location.)

ACKNOWLEDGMENTS

Many people have been extremely helpful throughout this investigation, and the writers are greatly indebted to them. Especially helpful were Mr. M. M. Gray of the Merrel Gray Drilling Co. and Mr. A. A. Sickel of the Layne-Atlantic Co., who supplied well cuttings and logs and aided the writers in obtaining geologic and hydrologic information. Thanks are also due Mr. Maurice Klein of the Union Bag-Camp Paper Co. Mr. Ralston Lattimore of the National Park Service, U.S. Department of the Interior, Mr. James Brown, Mayor of the city of Savannah Beach, and Mr. Fred Hack and Mr. Olin McIntosh, trustees of the Hilton Head Co., made test-well sites available. The officials of Chatham County and the city of Savannah extended many courtesies during the investigation.

METHODS OF INVESTIGATION

TEST WELLS

During previous investigations, four test wells were drilled to obtain geologic information and to monitor the encroachment of salt water into the principal artesian aquifer. These four wells—CHA 357, BFT 101, BFT 304, and CHA 441—had test points installed near the base of the aquifer, and CHA 357 has two points below the aquifer. (Construction of test points is described in Counts and Donsky, 1963.) Water samples are taken from these wells monthly and are analyzed for chloride content to note any changes.

During the present investigation, three additional test wells were drilled (CHA 484, CHA 487, BFT 315) and a preexisting well (CHA 16) belonging to the city of Savannah was modified for water sampling. In addition to the geologic information obtained from the drilled wells, the position of permeable zones was determined by current-meter traverses run in each well.

In CHA 16 a test point was set just beneath the aquifer. Well CHA 484 was modified by setting a test point near the base of the aquifer, and in wells CHA 487 and BFT 315 two test points each were set near the base of the aquifer. These test points are being sampled to determine the chloride content and to trace any movement of salt water toward Savannah.

CURRENT-METER TESTS

The water-yielding zones in the principal artesian aquifer were determined by the use of a deep-well current meter consisting of a helical vane mounted on pivots in an open-end tube. The current meter is suspended in the well on the end of a single conductor cable, and as water moves up the well bore and passes through the tube it causes the vane to revolve, which causes a magnetic switch to open and close with every revolution. The number of revolutions per minute are counted by means of an electronic counter and stopwatch.

The traverse of the well usually is started in the casing. Two or three readings are taken to obtain a base count of revolutions per minute at the known casing diameter and at the known discharge of the pump. Beneath the casing, readings are usually taken at 5-foot intervals, starting at either the top or the bottom of the well. However, the lower parts of deep wells often do not yield water, and starting readings at the top may save traversing the entire well.

An increase in the number of revolutions per minute when traversing upward in the well indicates an increase in velocity and therefore an increase in the amount of water furnished to the pump. However, a difference in well diameter will change the velocity of the water and the readings may appear erratic. Corrections for irregular diameter are made from a log of the well diameter. The percentage of the total well discharge from any one zone is calculated by using the ratio of the gain in revolutions per minute (corrected to the casing diameter) across the zone tested to the revolutions per minute in the casing.

MECHANICAL LOGS

The availability and use of mechanical logs in the Savannah area has greatly aided the geologic and hydrologic studies. The mechanical logs consist of electrical spontaneous-potential and resistivity logs, logs of gamma radiation, and well-diameter logs. The first two types of logs were run on as many open wells as time would permit. The well-diameter logs were made only in wells in which current-meter tests were made.

Spontaneous-potential and electrical-resistivity logs, commonly called electric logs, were used as an aid in the correlation of stratigraphic units and water-yielding zones. The mechanical logs

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exhibit similar characteristics in the same geologic unit over a large part of the area. For example, they show a change from a hard bed to a soft bed.

Logs of gamma radiation, or gamma-ray logs, were also used to aid in correlation. The limestone and other sediments in the Savannah area contain phosphate and glauconite, both of which emit a relatively high gamma-radiation count. Inasmuch as these beds are fairly persistent, they can be traced from well to well by means of the gamma-ray logs. A sudden change in the gamma-ray count is a good indication of a change in depositional environment. By the use of paleontological evidence of an environmental change, the inflection point on the log can be traced to wells for which only gamma-ray logs are available.

TELEVISION SURVEY

In 1961 a closed-circuit television survey was made in well CHA 452 using equipment owned and operated by Layne-New York City. The camera was suspended in the well by cable and lowered to depths of as much as 1,000 feet. The camera views vertically down the hole. Attached to the camera are three low-voltage 150-watt quartz lamps for illumination. The picture is viewed on a monitor screen set up in the equipment truck at the well site. All the equipment is portable and carried in a panel-type truck; electric power is supplied from a gasoline-engine-driven generator. A short report by Callahan, Wait, and McCollum (1962) describes the use of deep-well television in geologic studies.

Figure 2 illustrates differences in appearance of water-yielding zones and relatively impermeable zones in the limestone of the principal artesian aquifer. These pictures were taken of the TV monitor screen while the camera was traversing well CHA 452.

The use of a television camera in a well makes possible the viewing of the construction of the well and the attitude of the rocks. The observance of rocks in place is advantageous in the study of the permeable zones, because very seldom do core samples or well cuttings of limestone indicate the true permeability of the rock. Limestone, being easily dissolved, owes its permeability largely to solution channels, which are not usually recovered in the small core samples. Therefore, viewing these solution channels through television is an excellent way to determine their exact position in the well. Figure 2 shows pictures of the monitor screen when the television camera was at depths of 377.5 and 451 feet.

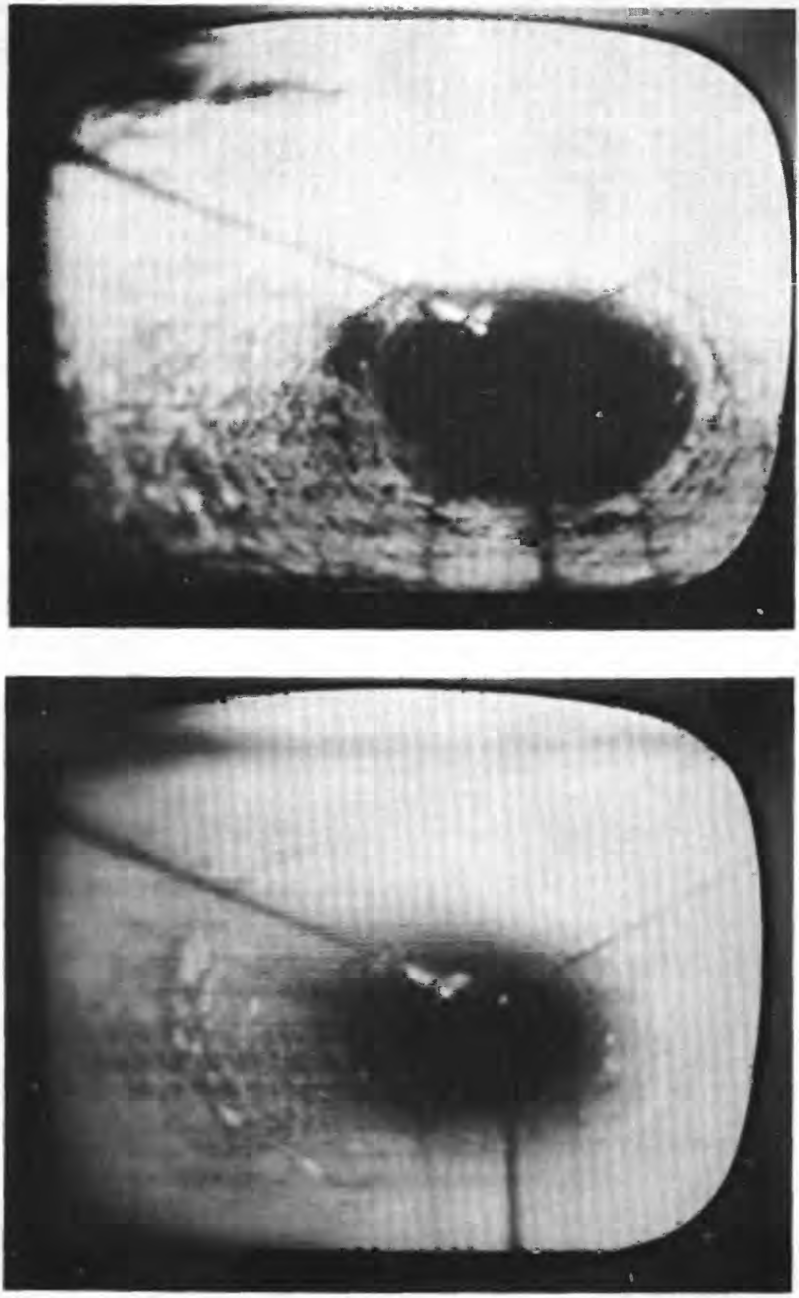

FIGURE 2.—Well-bore television pictures made in well CHA–452.

GEOLOGY

In the Savannah area the principal artesian aquifer and its confining layers consist of rocks of middle Eocene to early Miocene age. Counts and Donsky (1963) listed the formations of the aquifer and its confining layers as follows: the Lisbon [1] and Gosport Formations of middle Eocene age, the Ocala Limestone of late Eocene age, undifferentiated formations of Oligocene age, and the lower part of the Tampa Limestone of early Miocene age. This report, however, will follow Herrick (1961) who differs from Counts and Donsky in the following ways: (1) the Gosport Sand of middle Eocene age is not recognized and these sediments are included in sediments of middle Eocene age except in well CHA 452 where new paleontologic evidence indicates they are of late Eocene age, and (2) the Tampa Limestone is not recognized, being grouped together with other sediments of Miocene age and called Miocene undifferentiated. Figure 3 shows the differences in the nomenclature used by Counts and Donsky (1963) and that used by Herrick (1961) and in this report.

The Lisbon Formation of middle Eocene age conformably overlies the Tallahatta Formation of middle Eocene age. It consists of granular glauconitic limestone composed mostly of fossil fragments, chiefly Bryoza, in the central and southern parts of the area. Toward the northern and eastern parts of the area the sediments of the Lisbon Formation become progressively less consolidated and exhibit interbedding of fine-grained sediments of an "ooze" nature. The permeable zones are usually cemented and have large pores formed by the dissolution of the fossil shell material. A hard tan limestone about 10 feet thick, which gives a high "kick" to the electrical resistivity log, is characteristic of the top of the Lisbon in some parts of the area.

The Lisbon Formation in the Savannah area appears to average about 300 feet thick. Very few wells penetrate its full thickness because it is not water yielding in the lower part.

Above the Lisbon Formation and conformable with it is the Ocala Limestone of late Eocene age. The top part of the Ocala Limestone is composed of fossiliferous indurated limestone, which is blue-gray in most of the area. On the resistivity log it has a typically high "kick," but on the gamma-radiation log the "kick" is typically very low. (See fig. 3.) The variation in thickness of the upper part of the Ocala in the Savannah area from about 200 feet in the southern

[1] Counts and Donsky (1963) used the name Lisbon in the subsurface and stated that the formation was considered to be equivalent in age to the McBean Formation in the outcrop area. The usage of Lisbon in their report included the rocks in the subsurface between the Tallahatta Formation and the Ocala Limestone.

part to about 60 feet in the northeastern part indicates an unconformity between the Ocala Limestone and sediments of Oligocene age.

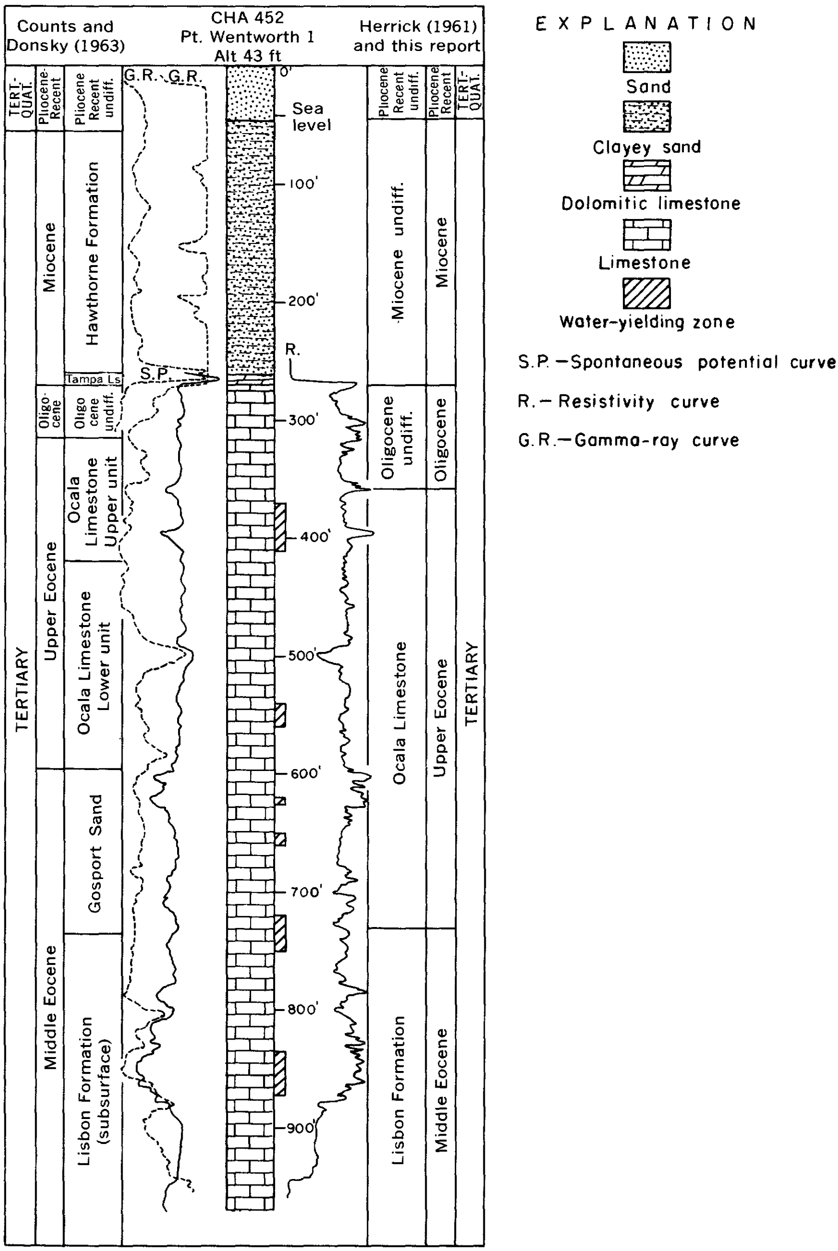

FIGURE 3.—Stratigraphic section of the principal artesian aquifer and its confining beds in Savannah area.

Beneath the hard limestone at the top of the Ocala are softer calcareous sediments also composed mostly of fossil fragments. These beds differ from the upper part by their lack of consolidation. The fossil fragments are compacted and the rock becomes more glauconitic with increasing depth. Soft fine-grained "oozes" are difficult to detect in drill cuttings and were not reported in the older drilled wells. Recovered core samples of the "oozes" in well CHA 484 gave a basis for identification of these fine-grained sediments in drill cuttings, and they have been recognized in wells drilled since the drilling of CHA 484. However, because no wells have been drilled in the southern part of the area since CHA 484 was drilled, the "oozes," if present, have not been reported in that part of the area. The "oozes" move up in the section from the center of the area to the northern part of the area. In the extreme northern part they appear to compose most of the lower part of the Ocala. Occasional hard zones are present in the lower part of the Ocala near the center of the area and southward. These zones are cemented with calcium carbonate; the shell material of the fossils has been dissolved and removed and only casts and molds of the fossils remain.

The lower part of the Ocala is about 250 feet thick over most of the area, but appears to be somewhat thicker in the southern part.

The sediments of Oligocene age unconformably overlie the Ocala Limestone; they are composed of limestone and soft sandy calcareous rocks. The fossiliferous limestone is found in the central and southern parts of the area and the sandy calcareous rocks are found in the eastern and northeastern parts of the area. On Tybee Island and Hilton Head Island, the Oligocene sediments consist of about 50 percent fine quartz sand embedded in soft calcium carbonate. Counts and Donsky (1963) also reported a wedge of sand in Oligocene rocks in the northwestern part of the Savannah area.

The Oligocene is fairly uniform in thickness (80–100 ft) over most of the Savannah area except the northeastern part, where it has been partially eroded before deposition of the overlying Miocene sediments and is 40 to 60 feet thick.

Lithologically, Miocene sediments are divided into two units. The lower unit is a conglomeratic limestone and the upper unit is a clayey sand. The upper sand unit can be subdivided into two sand beds separated by a sandy dolomitic limestone 1 to 2 feet thick. Despite its thinness, this limestone layer is persistent throughout the Savannah area. Both sand beds are typically green to olive and contain phosphate in the form of black to brown shiny sand-size pellets, which may be locally concentrated. The two sand beds differ, in that the lower is mottled with a fuller's earth-type clay and is more calcareous. The conglomeratic limestone unit is composed of limestone cobbles in a matrix of tan fine-grained limestone. The unit is highly phosphatic, and the phosphate occurs in voids and fractures and as embedded shiny brown to black pellets.

The sand beds range in thickness from 40 feet in the northeastern part of the area to as much as 250 feet in the southern part. The lower of the two sand beds thins toward the northeast and is not present in the extreme northeastern part of the area. The upper sand bed seems to be present everywhere in the Savannah area. However, Siple (1957) reported that Miocene sediments are not present just north of the study area. The conglomeratic limestone is present throughout the Savannah area except in the northeastern part, where it probably was not deposited; its thickness ranges from zero to 30 feet.

A contour map showing the top of the limestone in the Savannah area is included as a guide to show the length of casing needed in well construction (pl. 1). To seal out contamination from surface water, especially in the coastal area, and to avoid caving of the material above the limestone, well casings should extend into the limestone. Over most of the area the top of the limestone is composed of the conglomeratic limestone of Miocene age, which affords a good foundation for well casings. In the eastern and northeastern parts of the area (vicinity of Tybee and Hilton Head Islands), the hard limestone may be missing or may be underlain by sandy limestone of Oligocene age. In this area the casing should extend below the sandy material to prevent sand from entering the wells.

WATER-YIELDING ZONES IN THE AQUIFER

Current-meter tests have indicated five major water-yielding zones in the principal artesian aquifer near the center of the Savannah area, but in the extreme northeastern part of the area (north end Hilton Head Island) there are only two major water-yielding zones indicated. Of the limestone formations of four different ages formerly considered to be part of the principal artesian aquifer, only two contain major water-yielding zones—the Ocala Limestone and the Lisbon Formation. Geologic sections *A–A′* and *B–B′* (pl. 2), north-south and east-west, respectively, show the principal water-yielding zones in relation to their stratigraphic position in the Savannah area. All the current-meter tests were made in the central, eastern, and northeastern parts of the area. Possibly rocks of Oligocene age and Miocene age are water yielding in the southern and western parts of the area. For the purpose of this report, only five major zones east and northeast of the center of pumping are considered.

Zone 1 occurs at the top of the Ocala Limestone. In some wells the current-meter tests indicate that the zone may include a few feet of the overlying Oligocene sediments. This zone is about 50 feet thick in well CHA 452, but thins in an easterly and northeasterly direction to only 15 to 20 feet. Plate 2 indicates the depths from sea level to this zone.

Zone 2 occurs about 50 feet below zone 1 except in the northeastern part of the area, where the distance between the first and second zones becomes progressively less. In the extreme northeastern part of the area it is only 10 to 15 feet below zone 1, and the two zones eventually merge. The top part of the Ocala has been eroded in a northeasterly direction, and the upper water-yielding zone is lower in the formation and therefore closer vertically to the second water-yielding zone. Zone 2 is thickest (50–70 ft) in the eastern part of the area in the vicinity of wells CHA 484 and CHA 487. In the northeastern part it is about 25 feet thick. Near the center of pumping, in well CHA 452, it appears to be absent, but a water-yielding zone about 50 feet lower in depth, which does not correlate stratigraphically with other zones, may be equivalent to zone 2 of the eastern and northeastern parts of the area.

Zone 3 occurs near the base of the Ocala Limestone. It is 10 to 30 feet thick near the center of the area and eastward. This zone was not found in well BFT 315 on the north end of Hilton Head Island. Well CHA 452 near the center of the area has two small water-yielding zones separated by about 15 feet of non-water-yielding material at the stratigraphic position of the third zone. These two zones have been included in the third zone.

Zone 4 occurs at the top of the Lisbon Formation. It is not present in the extreme northeastern part of the area and follows the same trend as zone 3. Its thickness ranges from 10 to 30 feet in the three wells from which current-meter test data are available.

Zone 5 occurs in the upper part of the Lisbon Formation about 70 feet beneath zone 4. Current-meter test data are available for four wells which penetrated this zone. However, one well (CHA 484) had filled in above zone 5 before the test could be run, and data from another well (BFT 315) indicated that no water was being furnished to the pump from zone 5. Current-meter test data from well CHA 452 indicated the zone was about 40 feet thick. In well CHA 487 only the upper 10 feet of zone 5 was penetrated during drilling. A current-meter test in well CHA 46 was made by the Union Bag-Camp Paper Co. The test indicated that the fifth zone was present in that well and that there was flow between zone 5 and zone 1 under static conditions. The direction of the flow, which was not determined, is probably upward.

The relative yield of the five zones varies from well to well, but generally more than 70 percent of the water pumped during the current-meter tests came from the upper two zones. The third zone yielded the least amount of water (2–8 percent) while the lower zones each yielded about 3–20 percent in different wells.

There does not seem to be interconnection between the water-yielding zones because the material between them is relatively impermeable, and because analyses of water from test points set in the permeable zones indicate differences in the chemical quality of water from the several zones.

QUALITY OF THE WATER

A variation in chemical quality of the ground water occurs in each of the five major water-yielding zones of the principal artesian aquifer in the Savannah area. Major differences are in chloride ion concentration and total hardness. Generally, both increase with depth, especially in the eastern and northeastern parts of the area. The chloride ion concentration in the water in each water-yielding zone increases from the center of pumping toward the east and northeast. Chemical analyses of water from each zone in different parts of the area are not available, but composite chemical analyses are listed in table 1 along with chemical analyses of treated and untreated surface water from the Savannah Industrial and Domestic Water Supply system. Counts and Donsky (1963) give a more complete list of chemical constituents of water from the principal artesian aquifer of the Savannah area.

The increase in chloride ion concentration eastward and northeastward from the center of pumping is more pronounced in the lower permeable zones. A composite sample from CHA 14, near the center of pumping, contains only 6 ppm (parts per million) chloride. At Tybee Island, in the eastern part of the area, a composite sample from zones 1 and 2 contained water with a chloride content of 40 to 50 ppm, and at the north end of Hilton Head Island a composite sample from the same zones contained 89 ppm chloride. Only one sample is available from zone 3; that sample, from CHA 345 on Cockspur Island, contained 56 ppm chloride. The progressive increase in chloride content eastward is illustrated in analyses of zone 4 samples from CHA 484, CHA 441, and CHA 487, 8.5, 14, and 16.5 miles east of the center of pumping, respectively. A sample from CHA 484 had 38 ppm chloride, CHA 441 had 168 ppm, and CHA 487 had 423 ppm. Water in the same zone in BFT 101, 22 miles northeast of the center of pumping, had a chloride content of 420 ppm. The only available samples from zone 5 came from CHA 487 and BFT 101 and contained 711 and 553 ppm chloride.

TABLE 1.—*Chemical analyses of water from principal*

[Analyses by U.S.

Well	Owner	Location	Depth of well (feet)	Date of collection	Parts per million					
					Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
BFT-304	U.S. Geological Survey.	North end Daufuskie Island, S.C.	649	1-28-60	48	0.08	23	11	11	2.3
BRY-131	City of Pembroke.	Pembroke, Ga.	429	12-14-59	51	.06	30	5.6	8.4	1.8
CHA-14	City of Savannah.	Stiles Ave. and Gwinett St., Savannah, Ga.	540	8-30-61	53	.02	28	8.3	9.0	1.7
EFF-16	City of Springfield.	Springfield, Ga.	400	12-14-59	39	.14	32	9.7	9.8	2.6
LIB-161	U.S. Army	Ft. Stewart, Hinesville, Ga.	816	12- 8-59	35	.04	20	8.5	16	2.8
Surface-water supply	City of Savannah (Savannah Industrial and Domestic Water Supply).	Port Wentworth, Ga.	-------	8-30-61	10	.27	4	.9	3.5	1.0
				8-30-61	9.4	.00	18	1.1	4.2	1.0

WATER-LEVEL DECLINES

Water levels began declining in the principal artesian aquifer of the Savannah area in the 1880's after Savannah began using water from the aquifer. Industrial development in and around Savannah resulted in greater ground-water use which further lowered the artesian pressure. A cone of depression, centered at Savannah, formed in the piezometric surface and altered the original flow of water in the aquifer. As pumping increased, the cone of depression spread laterally until it now covers hundreds of square miles.

Water enters the middle Tertiary limestones comprising the aquifer at their outcrop area 60–100 miles northwest of Savannah. In the outcrop area the water is under water-table conditions but, as the rocks dip toward the coast, relatively impermeable sediments overlie the aquifer and confine the water. Because the water at the outcrop area is at a higher elevation than the confined water, the confined water is under pressure and rises above the top of the aquifer in wells penetrating it. When this occurs, the aquifer is *artesian aquifer of Savannah area and from surface supply*

Geol. Survey]

Parts per million—Continued										Specific conductance (micromhos at 25°C)	pH	Remarks
Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Dissolved solids (residue at 180°C)	Hardness as ($CaCO_3$) Calcium, magnesium	Hardness as ($CaCO_3$) Noncarbonate			
134	0	5.8	6.0	0.5	0.0	174	156	102	0	239	7.9	
133	0	5.6	4.0	.4	.1	173	166	98	0	225	8.0	
133	0	7.2	6.0	.5	.0	180	184	104	0	236	8.0	
160	0	7.6	4.0	.5	.1	184	181	120	0	269	7.7	
136	0	7.4	3.5	.6	.2	161	166	85	0	233	7.8	
18	0	5.2	4.5	.2	.7	39	53	14	0	45	6.6	Untreated surface water from Industrial and Domestic Water Supply.
35	0	16	9.5	.2	.3	77	91	50	21	129	7.3	Treated surface water from Industrial and Domestic Water Supply.

considered to be artesian and the level to which water will rise in wells is called the "piezometric surface."

Before pumping began at Savannah, water moved from the outcrop area to a discharge point in the vicinity of Port Royal Sound. The map of the original piezometric surface (pl. 3*A*) indicates that water was discharged in this area. Pumping at Savannah produced a cone of depression and reversed the ground-water gradient in the eastern part of the area. Water began to move toward Savannah from all directions. Salty water entered the aquifer where fresh water formerly was discharged.

The cone of depression in the piezometric surface of the Savannah area, December 1961, is depicted on plate 3*B*. This figure shows the height, in reference to mean sea level, to which water will rise in a well tapping the principal artesian aquifer. Water levels range from about 50 feet above sea level in northern Effingham County to more than 120 feet below sea level at Savannah. The cone of depression at Savannah is influenced by pumping at Brunswick in Glynn County and at Jesup in Wayne County, by the recharge area about 90 miles northwest of Savannah, and by recharge in the vicinity of Port Royal Sound. Pumping at Savannah also influences the cones of depression at Brunswick and Jesup.

The original piezometric map shows that water levels at the city of Savannah were 30 to 40 feet above sea level. By 1939 the water level had declined until it was 30 to 40 feet below sea level. The piezometric map of December 1961 shown on plate 3*B* indicates that water levels are more than 120 feet below sea level. This depth represents a decline of about 160 feet since pumping began. The decline of artesian water levels in the Savannah area during the period 1880–1961 is shown on plate 4. Water levels have declined more than 50 feet as far from the center of pumping as the Chatham-Bryan County and Chatham-Effingham County lines. When the piezometric map (pl. 3*B*) is compared with the same map in Counts and Donsky (1963) for 1958, it is noted that the 10- and 20-foot contours are approximately in the same position in the Hilton Head Island area—an indication that ocean water is recharged into the aquifer. Further water-level declines have occurred in the remainder of the area.

Pumpage from the aquifer is directly related to the decline of artesian pressure. Figure 4 shows estimated monthly pumpage from the principal artesian aquifer and hydrographs of eight wells in the Savannah area. The steady increase in pumpage from 1939 to 1942 resulted in a steady decline in water levels. During the period 1943 to 1947, pumpage remained nearly constant at about 40 mgd (million gallons per day) and the water levels also remained fairly steady. A slight increase in pumpage in 1948 to 43 mgd lowered water levels accordingly. From 1953 to 1960, a steady increase in pumpage and a steady decrease in artesian pressure occurred. However, during the last year of record (1961) pumpage decreased but water levels continued to decline. Either the water levels have not had sufficient time to stabilize or, because recharge to the aquifer is not sufficient to replenish the supply of water withdrawn, water must be used from storage. Water levels will probably stabilize if the quantity of water pumped from the aquifer is not increased for several years.

SALT-WATER ENCROACHMENT

Salty water is present in the lower permeable zones of the principal artesian aquifer in the Savannah area and in the upper permeable zones just north of the Savannah area at Parris Island. The salty water in the lower permeable zones is thought to be unflushed water of an older age while the salty water at Parris Island is thought to be sea water entering the aquifer through leaks in the upper confining

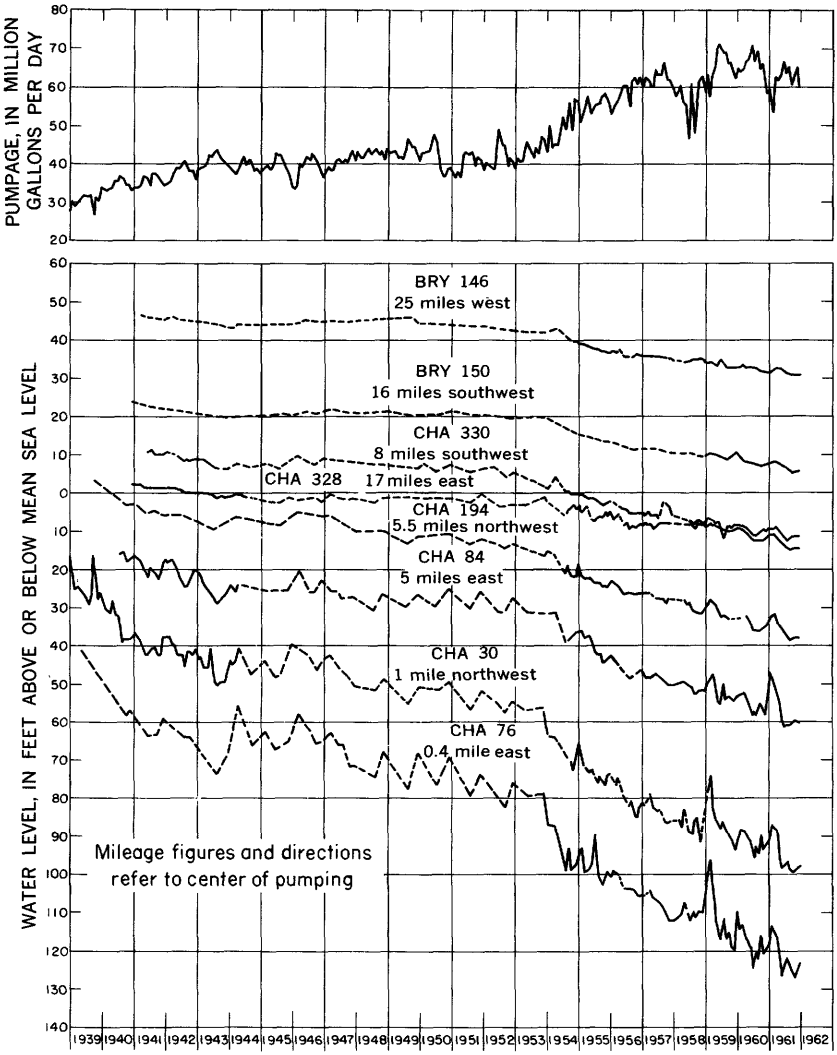

FIGURE 4.—Hydrographs of eight observation wells and estimated monthly pumpage from the principal artesian aquifer in Savannah area.

layer. Because the piezometric surface in the areas where salt water is present in the aquifer slopes toward the center of the cone of depression at Savannah, salt-water movement is in that direction. The rate of movement depends on the hydraulic gradient and on the permeability of the aquifer material.

The possibility of salt-water encroachment into the principal artesian aquifer of the Savannah area was reported by Stringfield, Warren, and Cooper (1941). Warren (1944) reported that the aquifer on Parris Island, just north of the study area, was contaminated by salt water and that deeper wells on Tybee and Hilton Head Islands yielded water with a chloride content several times greater than deep wells at Savannah. He thought the presence of water with high chloride content in the lower part of the aquifer was due to the differences in permeability between the lower and upper parts of the aquifer, and that these differences caused the more permeable upper part to be flushed of salty water to a greater degree than the less permeable lower part. Chloride analyses of water samples indicate an increase in chloride to the east and northeast of Savannah. The increase in chloride concentration is much greater in the lower permeable zones than in the upper permeable zones. As determined by current-meter tests, the relative permeability of the upper water-yielding zones compared with the lower water-yielding zones is much greater. Flushing, therefore, would have been more complete in the upper zones, and thus Warren's theory is affirmed.

The map of the original piezometric surface (Warren, 1944) shown on plate 3*A* indicates that before pumping began at Savannah water flowed across the Savannah area and discharged in the vicinity of Port Royal Sound. When the hydraulic gradient was reversed, after formation of the cone of depression at Savannah, the flow of water was reversed and as the water level declined to near sea level the discharge area became a recharge area. In the vicinity of Port Royal Sound, the limestone of the aquifer is less than 100 feet below sea level and the uppermost water-yielding zone lies very near the top of the limestone. Many of the tidal estuaries near Port Royal Sound are deep enough to channel the top of the limestone, and Siple (1957) reports the absence of the Hawthorn Formation or upper confining layer in parts of that area. Limestone, resembling the limestone at the top of the aquifer, has been dredged from the Beaufort River adjacent to Parris Island. This evidence of the lack of an upper confining layer in the vicinity of Port Royal Sound and the presence of salty water in the upper permeable zones on Parris Island appears to be adequate proof that this area, once a discharge area, is now an area for recharge of salty water to the principal artesian aquifer.

Chloride analyses of water from isolated points in the aquifer and beneath the aquifer indicate a very gradual increase in chloride content since the beginning of record. The chloride content from zone 4 in well CHA 441, about 14 miles from the center of pumping, increased approximately 8 ppm (160–168 ppm) from October 1959 to December 1961. Twenty-two miles from the center of pumping at BFT 101 the increase in chloride in zone 4 has been about 20 ppm (400–420 ppm) in the same length of time. Zone 5 in the same well, however, has shown only a 10 ppm (540–550 ppm) increase during the same period. Beneath the aquifer in well CHA 357, 14 miles east of the center of pumping, the chloride in the water has increased about 200 ppm (5,000–5,200 ppm) at the 900-foot depth. There has been no noticeable increase in chloride content in samples from BFT 101 at a depth of 693 feet. The small increase in chloride content from the various zones in the aquifer illustrates the slowness of the movement of salty water toward Savannah.

The rate of water movement in the aquifer depends on the hydraulic gradient or slope of the piezometric surface, the permeability, and the porosity of the water-bearing material. Counts and Donsky (1963) computed the velocity of water movement using the formula:

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

where

v=velocity in feet per year,

P=permeability gpd (gallons per day) per sq ft,

I=hydraulic gradient in feet per mile,

p=porosity, expressed as percent.

They assumed the aquifer to be of uniform permeability in its entire thickness of 600 feet, to have a transmissibility of 400,000 gpd per ft (permeability is transmissibility divided by the aquifer thickness or 670 gpd per sq ft), and a porosity of 35 percent. For a gradient of 1 foot per mile the velocity of water movement would be 18 feet per year. More recent evidence, however, has shown that the aquifer is not of uniform permeability but contains zones of high permeability separated by zones of relatively low permeability. The salt water will move the most rapidly through the zones of high permeability. If the average thickness of the two upper pérmeable zones is 50 feet and the permeability of these zones as determined from a pumping test on Daufuskie Island is 8,000 gpd per sq ft, computation by the formula above shows that it would take more than 400 years for salt water to reach the center of the cone of depression at Savannah from the vicinity of Port Royal Sound at the present rate of pumping (62 mgd). Figure 5 shows the predicted rate of salt-water movement in the upper permeable zones from the vicinity of Port Royal Sound to the center of pumping at Savannah at a pumping rate of 62 mgd.

Velocity of water movement in the lower permeable zones will be less than in the upper permeable zones because the lower zones are less permeable. However, inasmuch as salty water in the lower zones is less than half the distance away from the center of pumping than is the salty water in the upper zones, the overall encroachment time may be less. It is difficult to compute the rate of movement because

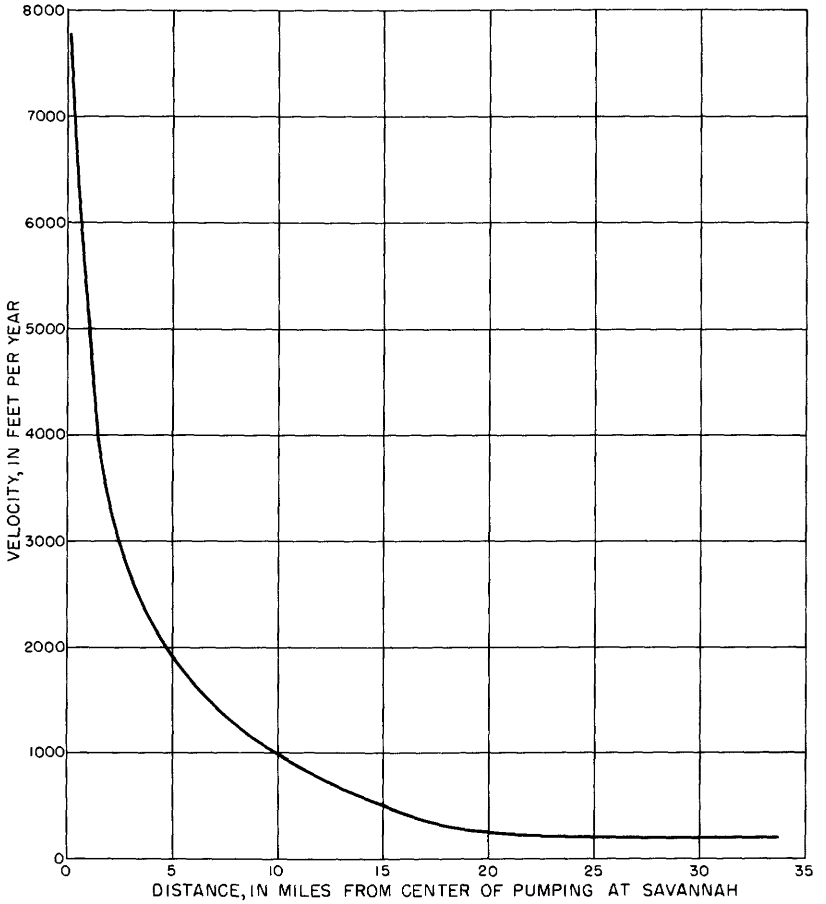

FIGURE 5.—Graph showing predicted rate of salt-water movement from vicinity of Port Royal Sound to center of pumping at Savannah at pumping rate of 62 mgd.

the transmissibility of the lower zones is not known. If the transmissibility of the lower zones is approximately one-fourth that of the upper zones or 100,000 gpd per sq ft and each has an average thickness of about 20 feet, it will take at least 90 years for the salty water to reach the center of pumping from Cockspur Island.

RECHARGE OF COOLING WATER THROUGH A CLOSED SYSTEM

Water that is used for cooling purposes can be recharged to the aquifer through a closed system to alleviate waste. In areas where the slope of the piezometric surface is relatively steep, the water should be recharged to the aquifer downgradient from the supply well with reference to the slope of the piezometric surface before operation of the recharge system. Recharge in this manner will prevent rapid movement of the heated water to the supply well.

Two systems of recharge to a confined aquifer through a closed system are illustrated on figure 6. Diagram *A* of figure 6 shows the supply well to be downgradient from the recharge well. The natural flow of water is from the recharge well to the supply well. When the system is placed in operation, the natural gradient is increased by the cone of depression around the supply well and the cone of impression around the recharge well. The velocity of the water is greatly increased by the head differences between the recharge well and the supply well. Even when the system is not in operation, heated water put into the aquifer through the recharge well will flow toward the supply well under the natural ground-water gradient.

Diagram *B* of figure 6 shows the proper placement of wells in this type of a recharge system—where the supply well is upgradient from the recharge well. The natural flow of water when the system is not in operation tends to carry the heated water away from both the

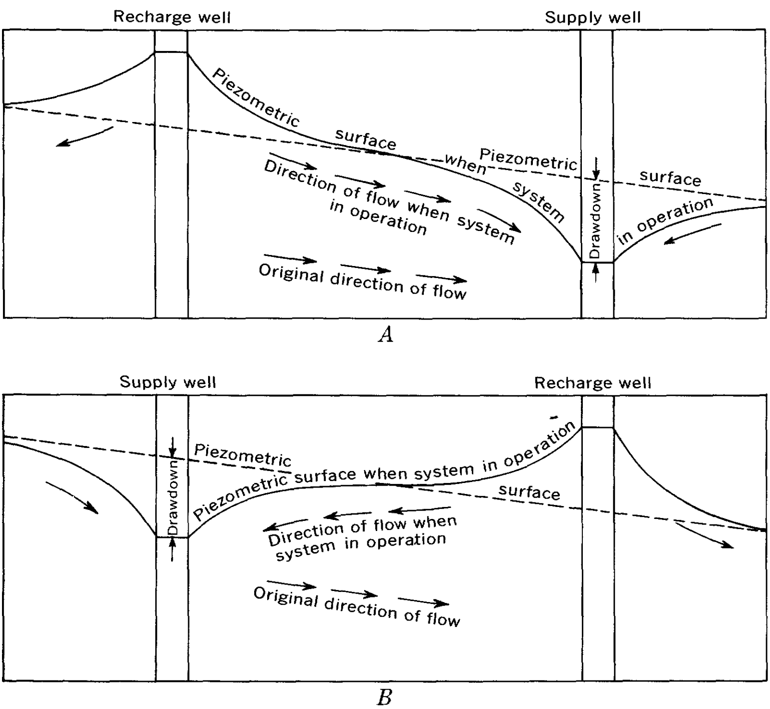

FIGURE 6.—Diagram showing recharge to a confined aquifer of water used for cooling through a closed system. *A*, Upgradient recharge well; movement of heated water to supply well increased. *B*, Downgradient recharge well; movement of heated water to supply well retarded.

recharge well and the supply well. When the system is placed in operation, the cones of depression and impression tend to reverse the natural gradient, but the resulting gradient is not nearly as steep as illustrated in diagram *A* of figure 6. Therefore, when a recharge system to return heated water to the aquifer is installed, the system should be so constructed that the supply well is upgradient from the recharge well in order to reduce to a minimum the movement of heated water from the recharge well to the supply well. If the supply well is of sufficient distance upgradient from the recharge well, there will be no circulation of water between wells.

In the Savannah area the principal artesian aquifer is composed of five water-yielding zones separated by relatively impermeable zones. A system of recharge of water used for cooling purposes could be installed in which water pumped from one zone would be returned to another zone; the problem of heat contamination to the supply well would thus be eliminated.

Because of the insulation of hundreds of feet of sediments overlying the aquifer, little heat is lost from the hot water recharged to the aquifer. Therefore, a system combining both heating and cooling could be easily installed. Heated water injected into the aquifer during the summer months could be pumped out of the aquifer, used for heating, and then returned to the aquifer during the winter months. The cooled water could then be pumped in the summer again for cooling purposes. This type of system would probably prevent movement of heated water from the recharge well to the supply well which might occur if the system were used only for cooling.

WATER MANAGEMENT

The Savannah area has an ample supply of good quality water available from ground and surface sources for continued use and development. The methods of development and the proper management of the valuable natural resource probably will be dictated by economics and future needs of the area. The following discussion concerns relationships of water supply to development.

The practical maximum amount of surface water available for use from the Savannah River would be well over a billion gallons per day. The minimum flow required to maintain the new 9-foot navigation channel to Augusta is 5,800 cubic feet per second or about 3,750 mgd (Counts and Donsky, 1963).

Warren (1944, p. 126) estimated that no more than about 25 mgd can be pumped from wells as presently distributed in the principal artesian aquifer if a divide in the piezometric surface between Savannah and the natural discharge area near Port Royal Sound is to be maintained. A reexamination of Warren's data after leveling in the measuring points on wells in the Hilton Head and Daufuski Island areas indicates that this maximum might be increased to about 40 mgd. It follows that about 40 mgd is the maximum that can be pumped indefinitely without lateral movement of salt water toward Savannah.

The deep cone of depression at Savannah is caused by pumping from a small area. Further development of ground water will cause a continued lowering of the water levels and will result in more rapid salt-water encroachment and in the mining of water at the center of the cone of depression. If the pumpage was taken from an area twice the size of the present area, it could be doubled without increasing the rate of salt-water movement toward Savannah. Counts and Donsky (1959) suggested that the larger ground-water users in Savannah could be supplied, in part, by pipeline from a well field 15 to 20 miles west of Savannah. Proper construction of a well field to the west and control of ground-water withdrawals over the entire area would cause a broadening of the cone of depression to the west and a rise in water level at the present center of pumpage and eastward. The eastward rise in water level would impede the westward movement of salt water in both the upper and lower permeable zones. Additional ground water could be developed in the vicinity of the Ogeechee River southeast of Savannah; however, at the present rate (62 mgd) and distribution of pumping, the movement of salty water is extremely slow and will present no serious problem for almost a century.

Conjunctive use of ground water and surface water, as in the present system, would permit full development of the available water. The use of surface water as the major source of supply for industrial and domestic consumers could eliminate any future problems of salt-water encroachment and lowering of water levels. The present surface-water treatment plant would have to be expanded to meet the demand. Total water use in the Savannah area averaged about 90.5 mgd in 1961, of which approximately 62 mgd was derived from the principal artesian aquifer and 28.5 mgd from surface water. Use of the treatment plant at full capacity at all times would reduce the per gallon cost of water treatment. The peak demands above plant capacity could be supplied from wells, and the total capacity needed for the surface-water supply would thereby be reduced.

SUMMARY AND CONCLUSIONS

The principal artesian aquifer of the Savannah area, formerly thought to consist of 600 feet of water-yielding sediments, has been found to contain five major permeable zones separated by relatively impermeable zones. These permeable zones occur in sediments of the Ocala Limestone and the Lisbon Formation of late and middle Eocene age, respectively. Confining the water in the permeable zones are sediments of the overlying Oligocene and Miocene formations and the underlying middle and lower Eocene formations. The permeable zones were not defined in the western part of the Savannah area because of lack of information.

The three uppermost permeable zones occur in the Ocala Limestone. The first zone at the top of the Ocala is about 50 feet thick near the center of the area and thins to about 15 feet toward the east and northeast. Zone 2 lies about 50 feet below zone 1 except in the northeast part of the area where the upper part of the Ocala thins, and zone 1 has moved downward in relation to zone 2. The thickest section (50–70 ft) of zone 2 is in the eastern part of the area. It thins to about 25 feet in the northeast. The third major permeable zone is at the base of the Ocala Limestone. This zone ranges from 10 to 30 feet in thickness near the center of the area and eastward but appears to be absent at the north end of Hilton Head Island because of a facies change in the Ocala sediments.

The fourth water-yielding zone occurs at the top of the Lisbon Formation and the fifth zone occurs about 70 feet lower in sediments of Lisbon age. These two zones are missing in the extreme northeast part of the area because of a facies change in the Lisbon sediments. Their thickness varies between 10 and 30 feet in wells from which current-meter data are available.

More than 70 percent of the water pumped during the current-meter tests came from the two uppermost zones. Zone 3 yielded the least amount of water (2–8 percent) and the two lowermost zones yielded about 3–20 percent in different wells.

Heavy pumping from a small area in and around Savannah has resulted in the formation of a deep cone of depression. Water that formerly flowed from the outcrop area of the aquifer formations to a discharge area in the vicinity of Port Royal Sound now flows from all directions toward the center of the cone of depression at Savannah. Before pumping began, the artesian pressure where the cone is now centered was about 40 feet above sea level. In 1962 it was about 120 feet below sea level. Twenty-five miles south of the center of the present cone of depression the decline in water level has been 40 feet, but 25 miles northeast the decline has been only 10 feet. The slow decline of water levels in the northeastern part of the area indicates that water is being recharged to the aquifer in the vicinity of Port Royal Sound where it formerly discharged.

The decline of water levels in the Savannah area is directly related to the amount of water pumped from the aquifer. A steady increase in pumping causes a steady decrease in artesian pressure.

The quality of the water in each of the permeable zones differs. The chloride ion concentration increases eastward and northeastward from the center of pumping at Savannah. The chloride and hardness content increases with increasing depth in the aquifer.

Salty water present in the lower permeable zones is believed to be unflushed water of an older age, and that present in the upper permeable zones just north of the study area is probably a mixture of sea water and ground water. Because the hydraulic gradient slopes toward the center of the cone of depression at Savannah, salty water in both the upper and lower permeable zones is moving toward Savannah. The rate of movement depends on the gradient and transmissibility of the aquifer material. At the present (1962) rate of pumping (62 mgd) it will take more than 400 years for the salty water in the upper permeable zones to reach Savannah from the vicinity of Port Royal Sound. The rate of movement in the lower permeable zones is slower because transmissibility of these zones is less. The salty water in the lower zones, however, is closer to the center of pumping where the gradient is steeper. If their transmissibility is about one-fourth that of the upper zones, it will take more than 90 years for the salty water at Cockspur Island to reach the center of pumping at Savannah.

In areas where the slope of the piezometric surface is steep, water used for cooling purposes through a closed system should be recharged to the aquifer downgradient from the supply well to prevent rapid movement of the heated water to the supply well. In the Savannah area the presence of permeable zones separated by relatively impermeable zones would permit water to be pumped from one zone and recharged to another zone to eliminate movement of heated water directly to the supply well. Water could be cooled in the summer and heated in the winter by returning the heated water from the cooling process into the aquifer during the summer and pumping it back from the aquifer for heat during the winter.

Possible solutions to the problem of salt-water encroachment and the lowering of water levels are: the rearrangement and control of aquifer pumpage, conjunctive use of ground water and surface water, and the use of surface water as the major source of supply. Rearrangement of the pumpage involves the construction of a well field 15–20 miles west of Savannah to supply the large industrial ground-water users. A rise in water levels at the center of the cone of depression and a broadening of the cone of depression to the west would result. The rise in water level would impede the progress of salt water and prevent mining of the water at the center of pumping in the future. Ground water and surface water could be used conjunctively by maintaining the pumping rate at about 40 mgd. Water in excess of this quantity would need to be obtained from the surface-water supply. The use of surface water as the major source of supply would eliminate the problems of salt-water encroachment and of lowering of water levels. Expansion of the present treatment plant would be necessary to furnish the demand from surface water. Peak loads on the system, however, could be met by the use of ground water from existing wells.

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