The Yield of Sedimentary Aquifers of the Coastal Plain Southeast River Basins

By JOSEPH T. CALLAHAN

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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THE YIELD OF SEDIMENTARY AQUIFERS OF THE COASTAL PLAIN, SOUTHEAST RIVER BASINS

By JOSEPH T. CALLAHAN

ABSTRACT

The estimated safe yield of the sedimentary aquifers of the Coastal Plain of the Southeast River Basins is about 24 billion gallons per day. The volume of fresh water in storage, if one assumes an average thickness of 1,500 feet of sedimentary rocks and an average porosity of 30 percent, is about 21 billion acre-feet. The ratio of ground water in storage to safe yield is about 1 acre-foot to 1 gallon per day.

The aquifer systems of the study area, from lowermost to uppermost, include: the sand aquifers of Cretaceous age; the limestone and sand aquifers of early Tertiary age; the principal artesian aquifer of Eocene, Oligocene, and Miocene age; the sand and gravel aquifers of Miocene and post-Miocene age of the southwestern area; and the sand aquifers of Miocene and Pliocene to Recent age of the Atlantic coast.

The safe yield of the aquifer systems was estimated from known geologic and hydrologic data and by making broad assumptions regarding the extent, thickness, and permeability of the aquifers and the continuity of physical conditions that control the occurrence and movement of ground water.

More water recharges the aquifers during the nongrowing, or recharge season (November through March), than during the growing season. Most of the ground water that is recharged to these aquifers is discharged to streams in the recharge area; the amount is as much as 40 inches per year per square mile in a few places but is commonly 10 inches per year. The remainder of the recharge moves downdip. Ground water that moves downdip below the confining beds toward discharge areas on the sea floor probably averages about 1 inch per year per square mile in the recharge areas, except perhaps that from the Miocene to Recent sand aquifers of the Gulf of Mexico and Atlantic coasts. These aquifers occur as a mass of sand that blankets large areas adjacent to and along the shore and from which ground water discharges to streams and the sea, evaporates, and transpires.

Salt-water encroachment is taking or has taken place in the principal artesian aquifers at Savannah, Ga., and in the shallow sand aquifers along the gulf coast.

The full development of the aquifer systems to their safe yields will decrease the flow of major streams, dry up the flow of some minor streams, lessen water losses to evaporation and transpiration, increase recharge, decrease discharge

to the seas, necessitate mining of water at some places and during some seasons, and require the careful management of pumpage in areas adjacent to salt-water bodies to avoid contamination of the aquifers.

The data necessary to provide the knowledge for water management generally are inadequate except for a few small areas.

Artificial recharge of the aquifers by means of recharge wells and spreading areas may increase the safe yield of some of the aquifers and prevent or retard salt-water encroachment. Three major fields in which knowledge is needed are modern topographic mapping, stream-gaging at stations established by geologic control, and detailed studies of ground-water hydrology. Large parts of the study area never have been mapped topographically. In the past, locations of stream-gaging stations were selected by criteria that did not consider geology. Pumping tests and measurements of the capacity of the aquifers to store and transmit ground water have been made at relatively few places and not for all the aquifers.

INTRODUCTION

The Southeast River Basins study area lies within the Blue Ridge, Piedmont, and Coastal Plain provinces. In the approximately 77 percent of the study area that lies within the Coastal Plain province, practically all fresh-water supplies are obtained from aquifers made up of sedimentary rocks. These aquifers contain fresh ground water to known depths as great as 2,800 feet at some places but less than 50 feet at others, especially along the coasts.

The Coastal Plain is divided into several aquifer areas (fig. 1) on the basis determined by the geologic formations making up the aquifers. The aquifer areas have been described in a previous report to the U.S. Study Commission prepared in 1960 by the U.S. Geological Survey entitled "Hydrologic Characteristics of the Southeast River Basins." They include: (1) sand aquifers of Cretaceous age; (2) limestone and sand aquifers of early Tertiary age; (3) the principal artesian (limestone) aquifer of Eocene, Oligocene, and Miocene age; and (4) other aquifers, including the sand-and-gravel aquifer of Miocene and post-Miocene age of the southwestern area and the sand aquifers of Miocene and Pliocene to Recent age of the Atlantic coast.

Most of these aquifers are actually aquifer systems, as they are not a single water-bearing bed and generally include one or more interconnected or related water-bearing beds. The vertical and lateral extent of the aquifer systems are still incompletely known, but enough data are available to approximate their limits.

This report represents an analysis of data in the files and reports of the Geological Survey in Alabama, Florida, Georgia, and South Carolina. It represents an attempt to evaluate how much ground water is available for development from all the aquifers in the study area. No field studies were made, and no data were collected specifically for this report. Most of the data used were gathered during

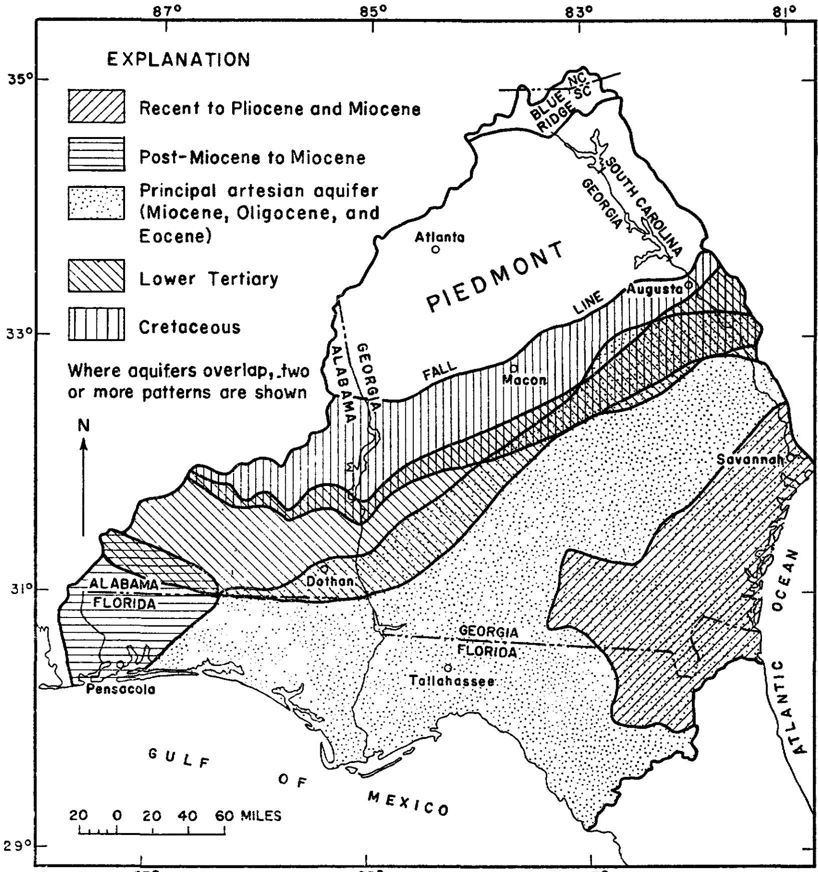

FIGURE 1.—Areal extent and geologic age of aquifers in the Coastal Plain.

the past 20 years. Because the data are from different years, it was not always possible to prepare material such as water-level contour maps to show information for a specific time. An effort, however, was made to combine certain quantitative data in order to bridge gaps in our knowledge of or to make a qualitative picture of hydrologic conditions from which quantitative inferences can be made.

PURPOSE AND SCOPE OF STUDY

This report was prepared on the basis of available data to show approximately how much ground water can be taken on a sustained basis from the aquifer systems of the Coastal Plain. When evaluating water resources it is not possible to divorce the water underground from that on the surface or water in one aquifer from that in another. When the water resources of the study area have been developed to any great extent, withdrawals of water from any source whether stream or aquifer, will have an effect on other sources.

The term "safe yield," as defined by Meinzer (1923, p. 55), "is employed to designate the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." For the purposes of this report, the safe yield is defined as the rate at which water can be withdrawn from the aquifers without depleting the supply to such an extent that withdrawal at this rate is no longer feasible and without changing the quality so that the water is no longer usable. This definition does not restrict the use of the water in any way and is not concerned with the economics of drilling, development, pumping, or management costs. Furthermore, the definition does not take into account the esthetic and recreational losses that may occur from changes in the natural regimen of streams, ponds, lakes, and swamps. The factors that will be considered are the relationship of aquifer systems to each other and to the surface-water bodies of the region, the possible effects of ground-water pumpage on the deterioration of fresh-water supplies by salt-water encroachment from the seas and salty ground water in other rocks, and the effect that pumpage from one well field has on adjacent well fields.

It was necessary to extrapolate hydrologic values from one known area to another across large areas where quantitative data are lacking. Because data were very few for permeability, porosity, and transmissibility, and were lacking for the exact vertical and lateral limits of water-bearing zones, many broad assumptions were necessary. However, the magnitude of the quantities of water available for use have been somewhat defined.

On the basis of available data it was impossible to evaluate the amount of water that could be pumped from an aquifer, take all other things into account, and arrive at quantitative solutions that would be absolutely correct. Therefore, the study was approached in the way that was most feasible using existing data, and the following assumptions have been used in this report as guides in the determination of the safe yield of the aquifers:

When computing the amount of water available to any aquifer system, it was assumed (1) that the aquifer is separated from any other system in the study area and that leakage to other aquifer systems is negligible, (2) that the base flow of streams in the recharge area can be captured, (3) that values of permeability and transmissibility are consistent, and (4) that the quantity of water escaping to the ocean may be estimated on the basis of assumed hydraulic gradients and permeabilities. With reference to all the aquifer systems, it was assumed (1) that most fresh water is at depths of 2,000 feet or less but that the average depth is 1,500, and (2) that the average porosity of the 1,500 feet of sediments including aquifers and confining beds is 30 percent.

The Coastal Plain aquifers of the study area contain water that is, for the most part, under artesian pressure. Artesian aquifers function in two ways: (1) they are reservoirs that contain a finite amount of water, and (2) they are conduits through which water moves from one place to another. They transmit water from the recharge areas of the land to the discharge areas beneath the seas. Enroute, some of the discharge is captured by wells, springs, and leakage between aquifer systems.

The volume of water stored in the sedimentary rocks of the Coastal Plain is a function of the porosity of the rocks. Laboratory determinations made from core samples have shown porosity to range from 3 to nearly 60 percent. Ordinarily, an uncompacted clay has a high porosity and a low permeability. However, results obtained from core analyses have not shown this correlation. Some clayey silt had a porosity of 57 percent and a permeability of 0.001 gpd (gallons per day) per sq ft, and a dolomitic limestone had a porosity of 3.5 percent and a permeability of 0.0001 gpd per sq ft. One limestone had a porosity of 19 percent and a permeability of 50 gpd per sq ft, whereas another had a porosity of 50 percent and a permeability of 140 gpd per sq ft. In order to determine the volume of water stored in the rocks, certain broad assumptions were made. If the average porosity of all rocks in the study area is assumed to be 30 percent and fresh water is assumed to be stored to an average depth of 1,500 feet, then 19,000 cubic miles of rocks contain 5,700 cubic miles of fresh water, or about 21 billion acre-feet. This amount would cover the study area to depth of about 500 feet.

The volume of water in storage is important, but the rate at which water moves through the aquifer also is important. Under natural conditions, any aquifer is in dynamic equilibrium with the climate of the region and with the recharge area, discharge area, and the adjacent rocks. When water is withdrawn from an aquifer, the withdrawal must be balanced by an increase in recharge, a decrease in natural discharge, or a dewatering of the aquifer. If recharge cannot be increased or natural discharge decreased, the aquifer, must be dewatered.

In extensive parts of most of the recharge areas, ground-water discharge is equal to the base flow of streams. The discharge was computed in terms of drainage areas of minor streams or as the increment of flow added to a major stream crossing an outcrop area

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and was converted to volumes of precipitation ranging from as little as about 1 inch per year per square mile to as much as 40 inches per year per square mile in different aquifers and areas. The aquifers discharge water for two reasons: (1) they have been breached by streams, and the hydraulic gradient between the interstream area and the stream bed is steeper than that between the recharge area and the discharge areas many miles downdip; and (2) the aquifers are full of water from the edge of the confining layer downdip and cannot transmit additional water under existing permeabilities and hydraulic gradients. Futhermore, the increases in the hydraulic gradients that have been caused by pumpage along the coast have been so slight that little additional recharge has taken place. On the other hand, the discharge from some of the aquifers that is being intercepted by wells along the coastal limits of the region has lessened the natural discharge to the ocean floor; at some places the gradients have been reversed from seaward to landward, creating conditions that eventually will lead to salt-water encroachment into the fresh-water aquifers. Futhermore, salt-water encroachment can take place even with a seaward hydraulic gradient. For every foot of head of fresh water above sea level, the fresh water will extend about 40 feet below sea level. If the top of the aquifer is 400 feet below sea level and the head in the aquifer from the cone of depression to the seaward outcrop of the aquifer is at or below an altitude of 10 feet, salt-water will move landward toward the cone.

The safe yield of the Coastal Plain aquifers is dependent on several variables, of which two are most important and limiting—the first is the annual average recharge to the aquifers from precipitation, and the second is the permeability of the rocks.

The one factor that ultimately limits the quantity of ground water that can be developed from any aquifer is the average annual recharge. The quantity of water available for recharge is the part of precipitation that does not become surface runoff or escape by evaporation and transpiration; however, this quantity could be modified by artificial recharge through wells, spreading areas, ponds, and sinkholes.

Recharge is water that percolates downward from the land surface into the aquifer and replenishes the water below the zone of saturation. Not all this water remains in the aquifers; some is discharged within the recharge areas as the base flow of streams, and the recovery of this base flow may be an important aspect of future water development.

The quantity of recharge that will remain in the aquifers and travel through them is limited by the permeability and thickness of the rocks and by the hydraulic gradients. Laboratory and pumping-test data indicate that rocks in the Coastal Plain have coefficients of permeability as low as 0.0004 gpd per sq ft for clay, more than 1,200 gpd per sq ft for some limestones, and as much as 2,600 gpd per sq ft for some sand of the Tuscaloosa Formation.

The permeability of an aquifer system differs from place to place. Relative to the size of the study area, few data about the permeability of the rocks are available. Although the value for permeability of a rock determined in the laboratory is precise for a small sample of a rock, the value for permeability determined from a pumping test is more valid, because it represents an average of a larger segment of the aquifer system.

If the aquifers are rejecting recharge—that is, if they are discharging water in the recharge areas, they are obviously not permeable enough to transmit all the water available to them under existing hydraulic gradients. Gradients are controlled by the altitude of the water table in the recharge area relative to the altitude of discharge points, whether wells, springs, or submarine outcrops on the sea floor. In general, the hydraulic gradients in artesian aquifers in the study area are less than the slope of the rock strata, and—in some places—the gradients are updip or at right angles to the slope.

Additional recharge could be induced in the study area by lowering the water table in the recharge areas. Also, if the gradients could be steepened by increased pumpage downdip, more water would recharge the rocks. This practice should be feasible for future ground-water development from some of the aquifers in areas where salt-water encroachment will not result. The flow will increase in proportion to the steepening of the hydraulic gradient. Available data, however, indicate that for parts of some of the aquifer systems the least permeable parts of the systems are in, or immediately adjacent to, the recharge areas. Therefore, low-permeability areas may have a great effect on the amount of water that can be available many miles downdip.

The centers of greatest ground-water use in the study area are generally along the coasts farthest removed from the recharge areas. Average hydraulic gradients in the aquifers extending from the recharge areas to the coast range generally from 1 to about 5 feet per mile. In the coastal areas the problem of salt-water encroachment must be included as part of the gradient-discharge analysis. For example, at Savannah, Ga., Brunswick, Ga., or Panama City, Fla., water levels are well above the top of the aquifers. Although it would be physically possible to increase pumping substantially and to transmit the additional water under steeper gradients, the lowered water level would upset the density balance, and salt-water contamination would result.

PRECIPITATION—THE SOURCE OF RECHARGE

The average annual precipitation for the study area ranges from 64 inches in the Florida Panhandle to 44 inches in the Savannah River basin near Augusta, Ga. Water-table records indicate that little, if any, recharge takes place to most of the aquifers during the warm growing season, because most of the precipitation is used to renew soil moisture, is transpired by vegetation, or is evaporated from the land surface. Except for recharge to some of the sand aquifers of Cretaceous age, practically all recharge takes place during the cool nongrowing season, when transpiration and evaporation losses are at a minimum. Therefore, in computations of how much precipitation is available for recharge the total average annual precipitation is not as important as the seasonal distribution of the precipitation.

In general, November through March constitutes the nongrowing, or recharge season. The average precipitation during this period is about 14 inches along the Atlantic Coast, 18–22 inches along the Fall Line, and 17–21 inches across southern Georgia, Alabama, and northern Florida. Expressed in relation to the recharge areas of the aquifer systems, precipitation ranges from about 18 to 22 inches on the Cretaceous sand aquifers, from about 14 to 22 inches on the principal artesian aquifer, from 16 to 22 inches on the lower Tertiary sand and limestone aquifers, and from 20 to 22 inches on the Miocene-post Miocene aquifers of the Florida Panhandle; it averages about 14 inches on the Miocene-Pliocene aquifers along the Atlantic coast.

The southern part of the study area has a subtropical climate in late summer; at times rainfall exceeds evaporation and the capacity of the soil to hold moisture, and substantial recharge may occur, particularly in areas of sand cover or limestone sinks. Also, tropical storms (hurricanes) may occur in late summer and fall; water levels often rise several feet in response to heavy rainfall associated with these storms.

The maximum quantity of water that can be pumped per year on a sustained basis is equal to the annual recharge. If an average of 10 inches of recharge could be obtained, this would amount to 0.737 cfs (cubic feet per second) per square mile, or 476,336 gpd per square mile. For the whole study area, 10 inches represents 32 billion gpd, or about 50,000 cfs.

Previous estimates of annual recharge to ground water have ranged from 1 to 11 inches. These represented the difference between rainfall and base flow, runoff, and estimated evaporation and transpiration losses. Actual recharge is much greater than previously suspected, but data are not available to make an exact computation of annual recharge to the aquifers. Streamgaging stations are not located at geologic boundaries, so they do not show net base-flow discharge from the aquifers; the water-level measuring network is inadequate to show changes in ground-water storage, and precipitation stations are too few. Base-flow data gathered during the drought years of 1954 and 1955, however, indicate that ground-water discharge in recharge areas of some of the aquifer systems is in excess of 3 inches per year per square mile, and for some parts of the Cretaceous sand aquifers, discharge may be as much as 40 inches per year per square mile. The lowest mean daily discharge of the streams was used at most places in computing the discharge of ground water from the aquifers to the streams. This method is not valid for determining the average conditions, but it was considered to be the best for indicating the minimum conditions that might occur only a few times in a century.

AQUIFER SYSTEMS

The Coastal Plain aquifers function as conduits or pipelines that transmit water from areas of recharge to areas of discharge. The determination of the volumes of water moving through the aquifer systems is possible to some extent, provided the basic data are available. As much of these data are lacking, the determinations must be made by the best of several methods, depending on the type of available data. For example, if one assumes that the hydraulic gradients in the systems are of the same magnitude as were the original gradients in the principal artesian aquifer, the volume of water movement can be approximated, provided the differences in lithology, permeability, and thickness of the aquifer systems are taken into account. For aquifers where few data are available, conditions must be assumed.

It is possible to learn about the yield of an aquifer from an analysis of the history of pumpage and the resultant drawdown and from the drawdown caused by a single pumping well or well field. Both of these techniques, however, provide information about segments of an aquifer rather than about the whole aquifer system.

The analysis of the network of flow lines across a piezometric map is helpful in obtaining quantitative information. So is the analysis of a flow network of a small part of an aquifer system. The information may be applied to the rest of the aquifer if conditions in the aquifer are the same everywhere or applied with qualifications if conditions are not the same.

The aquifer systems of the study area are not homogeneous, isotropic, or of constant thickness. Therefore, determinations of the volumes of water in and moving through the aquifers are subject to error.

SAND AQUIFERS OF CRETACEOUS AGE

The sand aquifers of Cretaceous age are several unconnected sand formations, only one of which, the Tuscaloosa Formation, is continuous as a formation and aquifer in the study area. The Tuscaloosa is the lowermost and deepest aquifer in the study area and the lowermost and deepest of the sand aquifers in this system. It yields more water to wells than any of the other sand aquifers, individually and collectively. For the purpose of this report, the Tuscaloosa Formation is assumed to contain twice as much available ground water as all the other sand aquifers of Cretaceous age combined.

The Tuscaloosa Formation contains fresh water in a belt about 60 miles wide from the Fall Line toward the coast, except in South Carolina, where water containing about 1,200 ppm (parts per million) dissolved solids flows from a well at Parris Island, a distance of about 110 miles southeast of the Fall Line. This system possibly contains usable fresh water for as much as 100 miles southeast of the Fall Line at other places in the study area, but the data are lacking that would substantiate this possibility.

The sand aquifers above the Tuscaloosa Formation are more irregular in extent and thickness, and their lithologies grade from sand into clay. Few data are available concerning the quantity of water that can be developed from them on a regional scale. Where these sands occur, however, they should contain fresh water for as far as 100 miles southeast of the Fall Line (fig. 2).

The only evaluation of the yield of the Cretaceous sand aquifers in the study area was made by Siple (1960, p. 165), who determined that the Tuscaloosa Formation has a transmissibility of 200,000 gpd per ft and that the aquifer was discharging about 170 mgd (million gallons per day) into the Savannah River along a 40-mile stretch of the river below Augusta, Ga.

The thickness of the Tuscaloosa Formation in its outcrop area ranges from a few feet to about 300 feet. Downdip, under cover of younger rocks it ranges from about 500 to 1,100 feet. The formation, however, probably averages about 600 feet in thickness where it contains fresh water.

The Chattahoochee River is approximately on the axis of a structural arch from which the Tuscaloosa dips to the southeast in Georgia and to the southwest in Alabama. From Augusta, Ga., to Savannah, Ga., and from Macon, Ga., to St. Marys, Ga., the formation slopes about 26 feet per mile; from Columbus, Ga., to Tallahassee, Fla., about 23 feet per mile; and from Grady, Ala., to Pensacola, Fla., about 22 feet per mile.

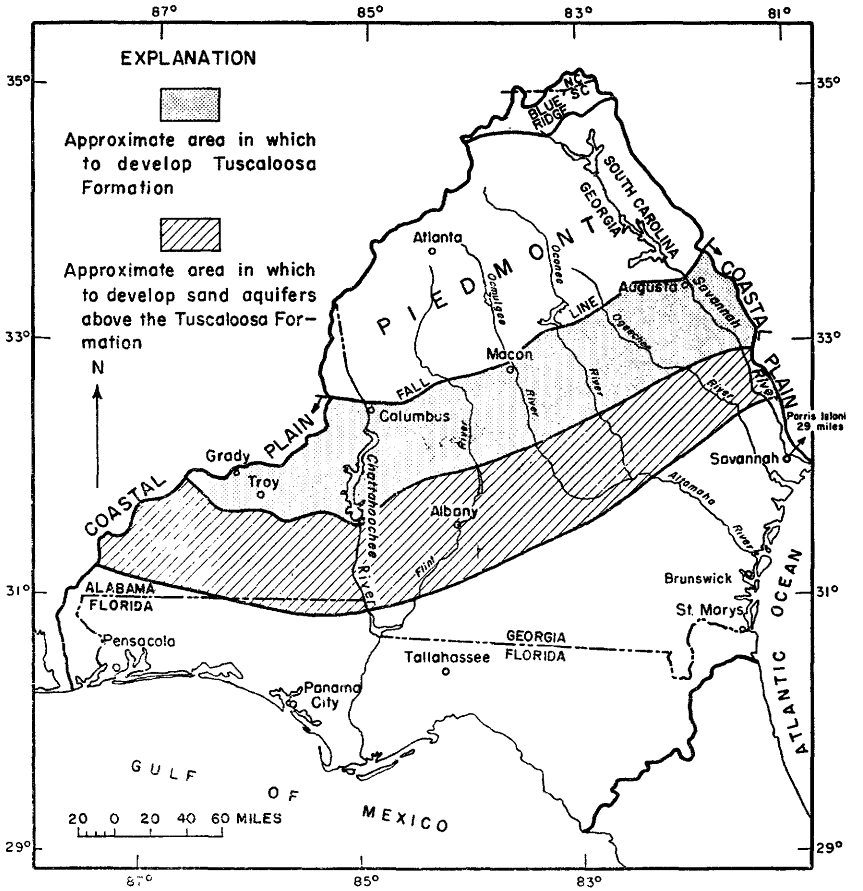


FIGURE 2.—Area of sand aquifers of Cretaceous age.

These slopes are the maximum hydraulic gradients that could be produced in the aquifers across these distances and along these lines. The hydraulic head in the aquifer at Parris Island, S.C., is about 150 feet above sea level. The known hydraulic gradients between the Fall Line and the Savannah area is about 2.5 feet per mile. If this value is an indication of the hydraulic gradient across other parts of the study area, the rate of ground-water movement is slow, but it could be increased by steepening the hydraulic gradients.

The Tuscaloosa Formation is an artesian sand aquifer. Artesian pressures in the Tuscaloosa are generally less than in the rocks below, but greater than in the rocks above.

RECHARGE

Precipitation on the recharge area of the sand aquifer of Cretaceous age averages about 48 inches, of which about 18–22 inches falls during the recharge season. Because of the great width and thickness of the sand beds, however, and because of their high permeability, recharge appears to take place in all seasons of the year. The fact that some streams in the sand belt have minimum flows that are not much less than their average flows (Thomson and Carter, 1955, p. 50) indicates a steady flow of water from the aquifers to the streams, very little storm runoff, and a high permeability of surface soils. Because of these conditions, the recharge potential of the aquifer system is high, especially that of the Tuscaloosa Formation.

As much as 40 inches per year is recharged to the sands in some places, although 10 inches of recharge per year probably is more common. However, most of it is discharged to nearby streams. Ten inches of recharge is roughly equivalent to about 500,000 gpd per sq mi, or 0.7 cfs per sq mi. On the approximately 10,000 square miles of Cretaceous recharge area, this recharge would be equivalent to about 5 billion gpd, or about 7,500 cfs.

Using base-flow measurements made in the fall of 1954 (Thomson and Carter, 1955), ground-water discharge from the Tuscaloosa Formation to the minor streams in Georgia was computed to range from 0.38 to 1.32 cfs per sq mi (equivalent to 5 to 18 inches of precipitation per year) and that from other Cretaceous sand aquifers, from 0.5 to 3.0 cfs per sq mi (6.8–40 inches per year). These measurements were made during September and October after a prolonged drought and reflect the high absorbtive capacity, storage capacity, and recharge potential of the sand aquifers. Drainage from the Tuscaloosa Formation to the Savannah River in 1954 was about 0.6 cfs per sq mi (8 inches per year) in the 10 miles south of Augusta, Ga. Drainage from the formation to the river in the same area was 0.4 cfs per sq mi (4.5 inches per year) in 1941. These figures reflect minimum rates of discharge.

The largest base flows to streams occur in western Georgia and eastern Alabama, where the formations are exposed over a much wider area, are not overlapped by younger rocks, and are therefore in a position to absorb larger amounts of rainfall. Thomson (1960, p. 13), in evaluating the major rivers of Georgia, showed graphically that the minimum monthly flows in 1954 were greater for west Georgia streams than for those in east Georgia. The flow of the Chattahoochee River below Columbus, Ga., was more than 0.1 cfs per sq mi; the flow of the Flint River below the Fall Line was more than 0.2 cfs per sq mi; and flows of the Ocmulgee River below Macon, Ga., and the

Oconee, Ogeechee, and Savannah Rivers below the Fall Line were less than 0.1 cfs per sq mi.

QUANTITATIVE DATA AVAILABLE

Siple (1960) determined from several pumping tests that the coefficient of transmissibility of the Tuscaloosa Formation about 10–40 miles below the Fall Line was as much as 450,000 gpd per ft but averaged about 200,000 gpd per ft. He computed a hydraulic gradient of 14 feet per mile from the recharge area at Aiken, S.C., to the discharge area in the Savannah River south of Augusta, Ga. The average hydraulic gradient from the Fall Line to the coast is 2.5 feet per mile, but in the last 80 miles, it appears to be less than 1 foot per mile.

Low-flow data indicate that the Tuscaloosa Formation and other Cretaceous sand aquifers are being drained of water in the valleys of the major rivers that cross the belt of exposed rocks. Drainage is also taking place in many of the tributary streams. Each of the other major rivers that cross the outcrops of the Cretaceous aquifers is probably draining at least as much water as the Savannah River. The Chattahoochee River probably drains much more because it crosses the widest parts of the outcrop areas.

The specific capacity of several wells tapping the Tuscaloosa Formation in east Georgia ranged from about 5 to 45 gpm per ft of drawdown. Probably the wells did not completely penetrate the aquifer or were screened in only a partial section of the aquifer. The transmissibility at the wells was estimated to range from 6,000 to 90,000 gpd per ft.

If the Tuscaloosa Formation has a transmissibility of 200,000 gpd per ft and the average hydraulic gradient is 2.5 feet per mile, then about 0.5 mgd moves southward through the aquifer across each mile of the approximately 400-mile width of the study area. This amount is equivalent to 200 mgd across the entire aquifer. If the gradient were increased to the maximum slope of the beds, it would range from 20 to 25 feet per mile. At this gradient, the southward flow would increase to 4–5 mgd per mile, or a total of about 2 billion gallons. Siple (1960) estimated that 2.8 mgd per mile was discharging into the Savannah River. If another 0.5 mgd moves downdip in the aquifer, the total of 3.3 mgd per mile represents a recharge to the area of about 1.3 billion gpd.

If we assume that all other Cretaceous sand aquifers combined will yield about half as much water as the Tuscaloosa Formation and that the hydraulic gradients are virtually the same, their combined flow in 1960 was about 0.25 mgd per mile, a total of about 100 mgd, and the ultimate flow under increased hydraulic gradients would be from 2 to 2.5 mgd per mile, a total of about 1 billion gpd.

DEVELOPMENT OF AQUIFERS BY PUMPING

In view of the depth of the Tuscaloosa Formation in the area where it is considered to contain fresh water, the best area in which to develop the aquifer extends from just below the Fall Line to the southern edge of a belt about 40–50 miles south of the Fall Line. In this area the top of the aquifer lies within 100–1,800 feet of the land surface. The greatest depths are in Alabama and western Georgia. Maximum gradients of about 20 feet per mile could be induced east of the Ocmulgee River, and gradients ranging from 25 to 55 feet per mile west of the river. The steepest gradients would be induced west of the Chattahoochee River. The increased gradients would induce a recharge of 4–5 mgd per lineal mile across the area in eastern Georgia and of as much as 8–10 mgd per mile in western Georgia and Alabama.

If the recharge belt of the Tuscaloosa Formation is assumed to average 10 miles in width and 400 miles in length, then the aquifer has a recharge area of 4,000 square miles. A mile-wide band across the recharge area contains 10 square miles. If the average existing hydraulic gradient is assumed to be 2.5 feet per mile, 0.5 mgd flows through each 1-mile segment normal to the gradient, and each square mile contributes 0.05 mgd, 0.077 cfs, or the equivalent of about 1 inch of precipitation per year. With the gradients increased to 25 feet per mile, each square mile would contribute 0.5 mgd, 0.77 cfs, or the equivalent of about 10 inches of precipitation per year.

The induced recharge to the aquifers under these conditions would stop the base flow of many streams crossing or draining the outcropping Tuscaloosa Formation.

Ground water moves slowly through aquifers. The velocity of water movement is computed by the formula

$$v=\frac{PI}{395\,p},$$

where v= velocity, in feet per day;
P= permeability, in gallons per day per square foot;
I= hydraulic gradient, in feet per mile;
p= porosity, as a percent of volume; and
395= conversion factor.

If one assumes a hydraulic gradient of 2.5 feet per mile, a permeability of 500, and a porosity of 30 percent, the velocity of groundwater movement downdip is 0.105 feet per day. If the hydraulic gradient were increased to 25 feet per mile, the velocity of the water would be 1 foot per day.

WATER MANAGEMENT

The management of all the sand aquifers will require a great deal more knowledge of their capability to store and transmit water than is presently known. From what is known, the most feasible method of management in the present century would be to develop properly spaced well fields across the study area and into the adjoining areas. The well fields should be spaced across the recharge area and also downdip so as to lower the water table to create steep hydraulic gradients and to increase recharge from the present 0.05 mgd per sq mi to at least 0.5 mgd per sq mi. The well fields may be spread across the study area in a belt extending about 50 miles south of the Fall Line. In the vicinity of major rivers, wells could be more concentrated. The Savannah River valley is an example where well fields might be developed about 1–3 miles from the river and parallel to it along both sides from the southern part of Augusta, Ga., to a point about 15 miles downstream. A hydraulic gradient of 50 feet per mile could be created that would induce 10 mgd per lineal mile to flow from the river to the aquifer on each side of the river. This method would decrease the flow to the river by 300 mgd, or 465 cfs. If this development were integrated with postulated well fields to the south, which would decrease discharge to the river by about 200 to 300 cfs, the total decrease of flow to the Savannah River would be about 600–750 cfs.

The same method of development could be used along the other major rivers on any of the sand aquifers of Cretaceous age that have a hydraulic connection with the rivers.

Depending on the use made of the water, varying volumes of water would be returned to the streams with the waste products.

Intense development of ground water close to the rivers would not have as great an effect on salt-water encroachment as would development 50 miles or more to the south.

The southward limit to which development could take place is conjectural at the present time. More data are needed concerning the depth to water, the yield of wells, and the chemical quality of the water. Development as far updip as possible will generally make available a better chemical-quality water.

SUMMARY

An analysis of data available indicates that at least 7.5 mgd per lineal mile across the study area could be developed from the sand aquifers of Cretaceous age without danger of the deterioration of the chemical quality of the water. This amount is equivalent to about 3 billion gpd. Probably as much as 5 billion gpd could be developed from these aquifers by widespread pumping of the aquifer area and by concentrations of well fields near the major rivers.

Induced recharge will prevent the immediate loss of the water to the sea and will reduce losses by evaporation and transpiration.

The use of well fields will provide a dependable water supply of nearly constant chemical quality and temperature.

LIMESTONE AND SAND AQUIFERS OF EARLY TERTIARY AGE

The limestone and sand aquifers of early Tertiary age are an important source of ground-water supplies in a continuous belt across the study area but are most important from the Ocmulgee River westward to the edge of the study area in Alabama (fig. 3). This aquifer system is underlain by the sand aquifers of Cretaceous age, which dip under it on the north, and is overlain by the principal artesian aquifer system on the south. In southeastern Georgia and northeastern Florida, thick limestone and thin sand beds of the uppermost part of this aquifer system are considered to be a part of the principal artesian aquifer system and will not be discussed further in this section.

In the parts of the study area where this system is a source of ground water, it consists of from one to six different water-bearing formations, and one or more of them occur within the area shown on the map (fig. 3).

In the shaded area shown on the map, the aquifer system contains fresh water. Along the southern edge of the shaded area and in most of western Florida along the Gulf of Mexico, some or all of the aquifers of the system contain salty water.

At Savannah, Ga., the upper beds of the system contain salty water; at Brunswick, Ga., the uppermost bed contains salty water, whereas lower beds contain fresh water. In spite of the widespread occurrence of the aquifer system in the study area, few data pertaining to the limit of fresh water downdip have been obtained, mostly because of the availability of large supplies of fresh water in the overlying principal artesian aquifer.

The aquifer system consists of rocks of three groups of early Tertiary age (table 1). The rocks wedge out along the north and thicken to the south. They are exposed across the study area in a band that is relatively narrow because they have been overlapped by younger rocks. They yield ground water in a belt having a width of about 40 miles in South Carolina and east Georgia, 50 miles along Chattahoochee River, and 60 miles at the edge of the study area in Alabama.

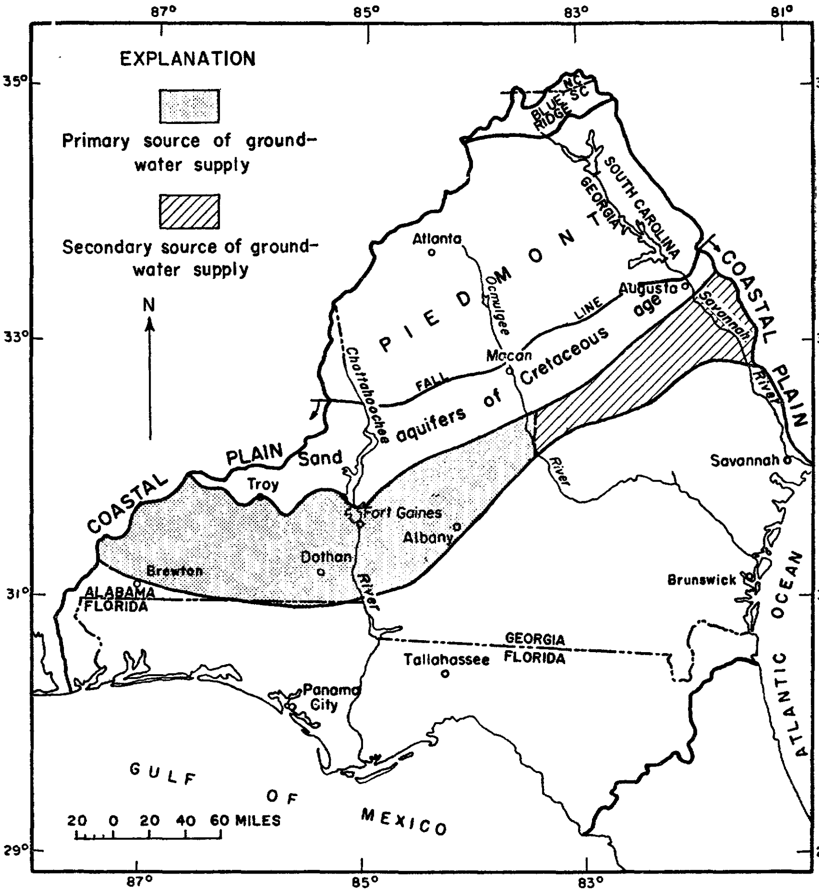


FIGURE 3.—Area of limestone and sand aquifiers of early Tertiary age.

All the formations are characterized by the changes in their lithologic character and thickness from place to place. Sand grades into silt and clay; limestone grades into clay and marl. As the lithology and thickness change, the permeability, porosity, and transmissibility change also. Thus, a formation that is an aquifer at one place is a confining bed at another. The lithology is better known than the water-bearing character of the formations. Only a few determinations of transmissibility have been made. In relation to the yield of wells, only qualitative data are available.

RECHARGE

Recharge to this aquifer system takes place mostly where the rocks are exposed across the study area, although some recharge from other rocks occurs.

East of the Ocmulgee River most recharge takes place through overlying rocks, because the early Tertiary rocks are exposed only in small areas along major streams. West of the Ocmulgee River in Georgia the aquifers are exposed in wider bands, but the total exposed area probably does not exceed 1,000 square miles. In Alabama, these aquifers are exposed over a broad area of about 6,000 square miles.

TABLE 1.—*Geologic formations of the aquifer system of early Tertiary age in the Southeast River Basins*

	Alabama	Georgia		South Carolina
		West	East	
Claiborne Group	Gosport Sand	Gosport Sand		Castle Hayne Limestone
	Lisbon Formation	Lisbon Formation	McBean Formation	McBean Formation
	Tallahatta Formation	Tallahatta Formation	Tallahatta Formation	Santee Limestone Congaree Formation
Wilcox Group	Hatchetigbee Formation			Black Mingo Formation
	Tuscahoma Sand	Tuscahoma Formation	Not differentiated	
	Nanafalia Formation	Nanafalia Formation	Not differentiated	
Midway Group	Clayton Formation	Clayton Formation	Clayton Formation	Rocks of Midway age

The recharge potential of the aquifer system ranges from good to poor, depending on the lithology that is exposed, the width of the outcrop, and the relation of the individual aquifers to rocks overlying and underlying them.

East of the Ocmulgee River the recharge potential is relatively poor. The exposed rocks are mostly clay and silt of Claiborne age, and the belt of outcrop is relatively narrow. No data are available pertaining to ground-water discharge from these rocks in this area.

West of the Ocmulgee River in Georgia the recharge potential for the Clayton Formation is fair, and for the few other aquifers exposed, it is fair to poor.

In Alabama the recharge potential is fair to good. The aquifers are exposed over a much wider area, and more of them are sand and limestone, rather than silt and clay.

Ground-water discharge to the Escambia and Choctawhatchee River basins from this aquifer system in the fall of 1954, based on the mean monthly discharge of several streams, ranged from 0.01 to 0.6 cfs per sq mi (0.1–8 inches per year per square mile).

About half the flows represented more than 1 inch of precipitation per year, and these probably were discharged from rocks of Claiborne age.

The Clayton is the only predominately limestone formation of this system; all others are sand or sand and clay. Sand and limestone in the aquifer system are exposed to recharge in about 50 percent of the outcrop area in Alabama, in about 25 percent in west Georgia, and in a few percent in east Georgia and South Carolina.

QUANTITATIVE DATA

In South Carolina, rocks of Claiborne age have a coefficient of transmissibility ranging from 7,000 to 100,000 gpd per ft (table 2). In west Georgia, computed coefficients of transmissibility range from 1,000 to 150,000 gpd per ft. In Alabama, the only value available is about 13,000 gpd per ft. At Fort Gaines, Ga., the transmissibility of the Clayton Formation is 60,000 and 75,000 gpd per ft. The coefficient of transmissibility of other parts of the aquifer system is not known.

Individual wells in these formations yield as much as 2,000 gpm. Most municipal and industrial wells yield from 250 to 1,200 gpm.

Data are not available on which to predict the ultimate yield of the several aquifers in this system. Limestone of the Clayton Formation yielded from 5 to 15 mgd for more than 2 years at Fort Gaines; drawdown was only about 40 feet near the pumped wells. This formation probably would yield a like amount of water to well fields for at least 50 miles east and west of the Chattahoochee River. At Albany, Ga., at least 4 mgd has been pumped from the whole aquifer system for several years without appreciable drawdown. The aquifer system as a whole contains water-bearing beds that are the equivalent of the Tuscaloosa Formation of Cretaceous age in total thickness. Because of the similarity in the thickness of the aquifers and extent of their outcrop areas, it should be possible to develop water supplies from this aquifer system as large as those from the sand aquifers of Cretaceous age in the area from the Ocmulgee River westward to the edge of the study area in Alabama. East of the Ocmulgee, smaller supplies could be developed. In about 9,000 square miles of the western area, development should be possible at a rate of at least 0.5 mgd per sq mi, or 4,500 mgd (7,000 cfs) for the area. For about 3,000 square miles in east Georgia and western South Carolina, perhaps 0.25 mgd per sq mi could be developed, which is equivalent to 750 mgd (1,200 cfs).

Development could be accomplished by widespread pumping to lower the water levels in the various formations so that additional recharge could take place. Hydraulic gradients in 1960 appear to be from 2 to 3 feet per mile from the outcrop area to the coast across Georgia and are probably of the same magnitude elsewhere. The gradients could be steepened by pumping to increase recharge to the aquifers.

TABLE 2.—*Coefficients of transmissibility of aquifers of early Tertiary age determined from pumping tests*

County location	Coefficient of transmissibility	Pumping rate (gpm)
Claiborne age		
Aiken, S.C.[1]	60, 000	480
Barnwell, S.C	7, 000	175
Do	100, 000	410
Early, Ga	6, 000	18
Do	1, 000	46
Lowndes, Ga	40, 000	140
Early, Ga	20, 000	50
Baker, Ga	100, 000	250
Worth, Ga	150, 000	200
Crisp, Ga	60, 000	1, 230
Do	2, 000	30
Dooley, Ga	120, 000	1, 000
Burke, Ga	13, 000	50
Do	1, 000	30
Escambia, Ala	13, 000	----------
Midway age		
Clay, Ga	60, 000	690
Do	75, 000	910

[1] Coefficient of storage, 0.0002.

WATER MANAGEMENT

The most likely area for development of this aquifer system extends from the western boundary of the study area in Alabama to the Ocmulgee River in Georgia and to the Savannah River Basin in South Carolina. As the individual aquifers of the system are separated by confining beds and increase in number from north to south, they could be developed singly in the outcrop areas or collectively downdip if a single aquifer did not yield sufficient water. Wells could be developed as they have been at Albany, Ga. (fig. 4), where several different water-bearing zones contribute water to a well (Wait, 1957).

The aquifers could be developed along the same pattern as any other aquifer in the study area—that is, across a broad area but with concentrations of wells where the aquifer is exposed along the major rivers. Salty water occurs in rocks of Wilcox age at Brewton, Ala., at a depth of about 1,000 feet and in rocks of Claiborne age at Savannah, Ga., at a depth of 900 feet. The possibility of salt-water encroachment would have to be considered in development downdip along the southern limits of the aquifer area. Too little data are available about the hydrologic characteristics of the limestone and sand aquifers of early Tertiary age.

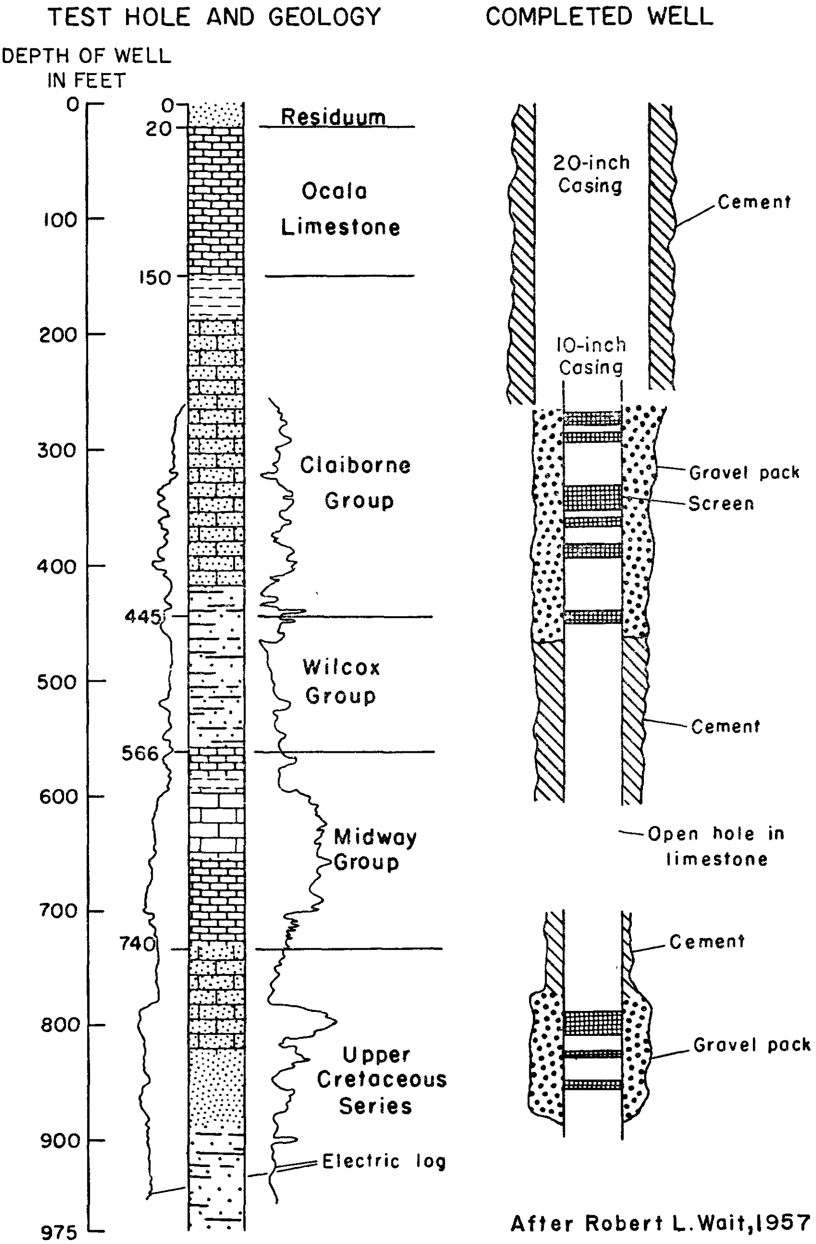


FIGURE 4.—Sketch of city well 15, Albany, Ga., showing development of several water-bearing zones.

SUMMARY

About 5.0 billion gpd probably could be developed from the aquifers of early Tertiary age in the study area. Development along the major river valleys could induce large amounts of recharge from the rivers. Data are not available to refine this prediction of the amount of water that is available nor of the effect of development on the aquifers, confining beds, the flow of rivers, and salt-water encroachment.

PRINCIPAL ARTESIAN AQUIFER

The principal artesian aquifer is the most extensively used aquifer system in the study area. In the study area, it underlies two-thirds of Georgia, all of Florida, and small parts of southwestern South Carolina and southeastern Alabama (fig. 5). It is predominantly a limestone aquifer, although it contains beds of dolomite, sand, silt, clay, and marl. It consists of several formations, and their terminology varies from one State to another. The Ocala Limestone of late Eocene age occurs in all four States, and it and the upper and lower contiguous formations, which are hydraulically connected, make up the aquifer system.

Where the aquifer is a source of ground-water supplies, it ranges in thickness from about 50 to as much as 1,500 feet. It thins out along its edge exposed updip across Georgia and southeastern Alabama. It appears to have three important recharge areas: the main area exposed updip, which lies across Georgia; an area centered near Valdosta, Ga.; and an area in and to the south of the Okefenokee Swamp in Georgia and Florida.

Wherever the entire thickness of the aquifer has been penetrated, it has one or more water-bearing zones, which are connected hydraulically to some degree. In the Savannah area the aquifer contains at least three different water-bearing zones, separated by virtually impermeable limestone, but most of the water appears to flow from two zones in the upper part of the aquifer. In the Brunswick area it contains two main water-bearing zones—one at the top of the aquifer and another about 500 feet lower. Relatively small amounts of water flow from the intervening rocks. At Valdosta, the aquifer contains at least two high-yielding zones, but the lower zone has yielded a poor quality water to at least one well.

The upper part of the aquifer system contains fresh water everywhere in the study area except in the extreme western part of the Florida Panhandle in a narrow strip adjacent to the gulf coast.

In the Savannah, Ga., area adjacent to the Atlantic coast, the bottom of the aquifer contains salty water. The underlying tight siltstone and limestone also contain salty water.

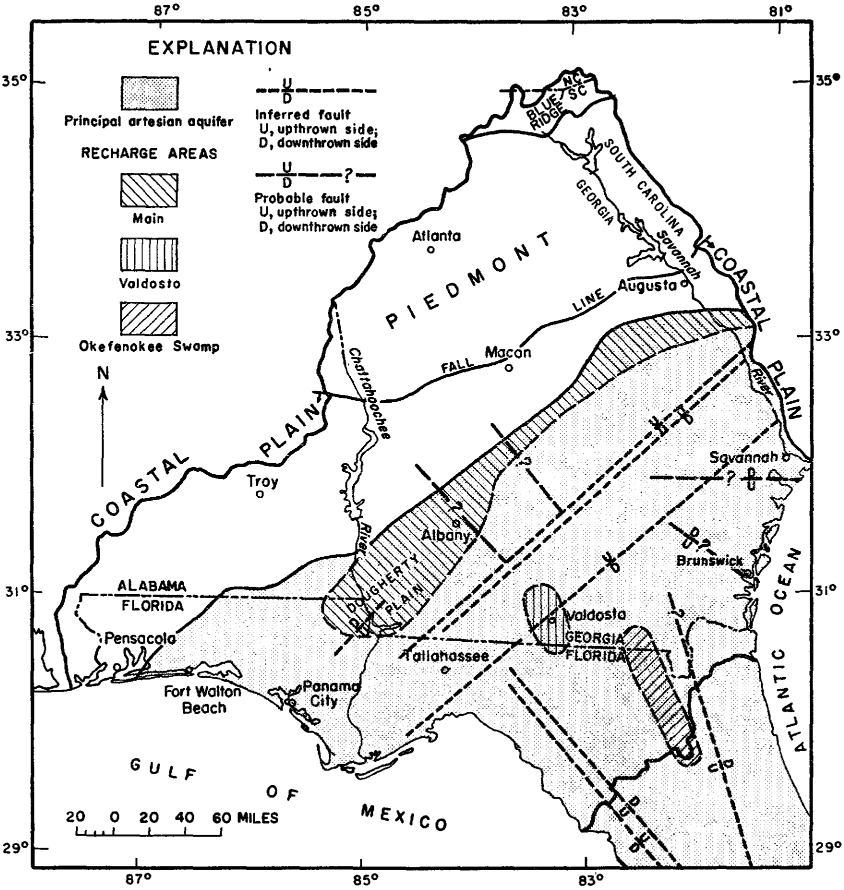


FIGURE 5.—Area of principal artesian aquifer, showing approximate extent of recharge areas and length of faults.

In the Brunswick, Ga., area the aquifer contains salty water in a confined and separated zone at a depth between 1,050 feet and 1,400 feet. The underlying limestone contains fresh water to a depth of at least 1,700 feet.

At Fernandina, Fla., the aquifer contains fresh water to a depth of about 1,800 feet.

At Valdosta, Ga., the aquifer contains fresh water in the top zone but salty water in a lower zone at some places. The exact distribution of the salty water is not known. In parts of Grady, Thomas, and Colquitt Counties, Ga., the aquifer yields water of poor quality from a lower zone at depths of about 1,000 feet.

At Fort Walton Beach, Fla., the top of the aquifer is 500 feet below sea level and dips westward along the coast to 1,200 feet below sea level at Pensacola, Fla. The upper part of the aquifer contains salty water in a narrow strip adjacent to the Gulf Coast that extends from Santa Rosa County, Fla., westward.

The increased use of ground water in the past 15 years has lowered the piezometric surface of the aquifer system to below sea level in the Savannah area, and salt-water encroachment is taking place slowly. Counts (1960, p. 47) estimated that at a pumping rate of 125 mgd (twice the rate of pumping in 1960) it would be a century or more before salt water reached the city. If the pattern of pumping wells was changed, the depth and extent of the cone of depression could be changed, and the rate of salt-water encroachment would be slowed.

Piezometric levels south of Savannah, Ga., along the Atlantic coast are still above sea level, except at the centers of cones of depression (pl. 1). In addition, the formation is exposed on the ocean floor at a greater distance to the east than at Savannah. The piezometric surface still is above sea level on the seaward side of the pumping centers, although the position of the salt-water wedge offshore is not known. Existing data indicate, however, that lateral salt-water encroachment from the ocean should occur much later than at Savannah and might be prevented if the aquifer were developed properly. Salt-water encroachment, however, could take place vertically from underlying rocks when the piezometric surface is lowered below about 25 feet, if salt water is present in the underlying rocks, because the bottom of the aquifer along the Atlantic coast lies at a depth of about 1,000 feet below sea level. As previously pointed out, salt water occurs in rocks below the aquifer at Savannah, and both salty and fresh water occur in it at Brunswick, Ga. At Fernandina, Ga., water in the lower part of the aquifer has increased in chloride content during the past 10 years. The extent and limits of salty-water zones is not known in most of the area. Nevertheless, upward salt-water encroachment is a possibility along the Atlantic coast, and probably is of greater importance along the southern half of the coast in the study area.

RECHARGE

Recharge to an aquifer takes place wherever the piezometric surface is lower than an overlying water table and the aquifers are connected hydraulically to some degree. Under these conditions, almost the whole area of occurrence of the principal artesian aquifer is a recharge area. Certain areas, however, are more important as recharge areas, and these consist of about 10,000 square miles within the study area. The delineation of these areas is somewhat arbitrary. About 1,000 square miles are in and to the south of the Okefenokee Swamp; about 500 square miles are in the Valdosta area; and about 8,500 square miles are in the main outcrop area of the aquifer. In the Okefenokee Swamp area, recharge takes place through overlying thin sand, limestone, and clay beds, and the quantity is limited by the thickness and permeability of the rocks through which the water moves and by the difference in head between the water table in the shallow sand, or the water surface in the swamp and the bottom of the confining layer.

In the Valdosta, Ga., area, recharge is mostly through sinkholes in the limestone and through the sand and clay on top of the limestone. In the main recharge area, recharge takes place mostly through cavernous limestone to the west and through both sand and cavernous limestone to the east.

The average annual precipitation on the recharge areas generally ranges from 44 to 55 inches. Precipitation during the recharge season (November through March) is about 18 inches south of Augusta, Ga., 22 inches in Florida, 14 inches in the Okefenokee Swamp area, and 17 inches in the Valdosta area.

Some parts of the recharge area function somewhat similarly to the Cretaceous sand-aquifer area, in that a cavernous limestone region, like a sandy region, is open to recharge in any season. Transpiration and evaporation losses, however, appear to be greater in a limestone region, because the limestone is overlain by a sandy clay soil or because water diverted into some sinkholes remains as lakes that evaporate slowly.

The main recharge area (fig. 5) is one of high base flows along the downdip edge of the exposed rocks and low base flows along the updip edge. The widest exposures of the aquifer are in the Dougherty Plain in southwest Georgia, and the least extensive are in eastern Georgia and western South Carolina.

In the main recharge area to the east, from the Savannah River to the Ocmulgee River, low flows in 1954 ranged from 0.17 to 0.30 cfs per sq mi (2.3 to 4.1 inches per year) in the upper reaches of tributary streams where the aquifer was the only contributor to flow. In the northern part of the Dougherty Plain in Macon County, Ga., low flows ranged from 0.35 cfs to 1.07 cfs per sq mi (4.7 to 14.5 inches per year). In the southern and western part of the Dougherty Plain in Georgia, the main stem of the Flint River appears to drain about 0.43 cfs per sq mi (5.8 inches per year) at low flow. Tributary streams, where not dry, yielded from 0.002 to 0.30 cfs per sq mi (0.03 to 4.1 inches per year). The lowest yields were updip at higher altitudes; the higher yields were closer to the main stem of the Flint River.

On the basis of these measurements it is not possible to arrive at an accurate average yield of the aquifer to the stream. For estimating the total yield, however, a yield of 0.25 cfs per sq mi was assumed for 3,500 square miles on the east, and a yield of 0.43 cfs per sq mi was assumed for 5,000 square miles on the west. These amount to 875 cfs for the east and 2,150 cfs for the west, or about 3,000 cfs for the main recharge area, and convert to 3.4 inches per year on the east, 5.8 inches per year on the west, and 4.8 inches per year for the average of the main recharge area. These figures represent natural ground-water discharge to the streams, water that the aquifer could not transmit downdip under existing gradients. They indicate that the initial recharge to the ground is somewhat greater and that at least 1 inch more moves through the aquifer.

Natural ground-water discharge in the Valdosta, Ga., area in the form of base flow to streams was relatively low in the fall of 1954. Most of the tributary streams had zero flow, but a few had a yield of 0.014–0.054 cfs per sq mi (0.19–0.73 inches per year). A short reach of the Withlacoochee River, where the river is incised into the top of the limestone, yielded about 0.1 cfs per sq mi (1.3 inches per year). The limestone in this area is cavernous, the terrane is a solution type, and recharge to the aquifer is relatively rapid. The area receives about 17 inches of precipitation during the recharge season. Possibly, most of this precipitation recharges the aquifer. The low base flows during the 1954 drought may have resulted from a low water level caused by relatively rapid ground-water flow away from the area. The quantity of recharge based on 17 inches of precipitation per year is equivalent to 1.25 cfs, or 0.8 mgd per sq mi.

The Okefenokee Swamp region and adjoining areas in Florida appear to constitute a recharge area to the principal artesian aquifer over an area whose extent is undetermined at the present time. For convenience, the swamp region was assumed to contain 1,000 square miles. Data indicate that the piezometric contours close in this area. In order to determine the contribution of water from the swamp to the aquifer, several assumptions and averages were made for the permeability and thickness of the confining layer and for the altitude of the water table in the swamp, which usually is at land surface. The computation of recharge is based on the formula

$$Q=PIA,$$

where

Q=discharge, in gallons per day per unit area;
P=permeability of the confining layer, in gallons per day per square foot;
I=hydraulic gradient, in feet per foot; and
A=cross sectional area, in square feet.

The confining layer is thickest and least permeable, and the aquifer is deepest, in the northern part of the area in Georgia. It is less thick and more permeable, and the aquifer is shallower, in the area in Florida. Figure 6 illustrates a problem in which are assumed the least favorable conditions of recharge and a permeability of the confining layer that is similar to a laboratory computation of permeability of the same rocks near Savannah, Ga. Using these assumptions, the problem is solved mathematically as follows:

$$Q=PIA,$$

where

$$P=0.001\frac{\text{gpd}}{\text{sq ft}};$$

$$I=\frac{\text{Water table, or hydraulic head at top of confining bed} - \text{piezometric surface or head at bottom of confining bed}}{\text{thickness of confining bed}}, \text{ or}$$

$$\frac{120-80}{200}=0.2\frac{\text{ft}}{\text{ft}};$$

$A=1{,}000 \text{ sq mi}=27{,}878{,}400{,}000 \text{ sq ft}$; and

$$Q=0.001\times0.2\times27{,}878{,}400{,}000$$
$$=5.6 \text{ mgd}$$
$$=8.7\text{cfs}.$$

Generally, the upper limit of the water table in the swamp is about at the land surface, although it declines in times of drought. At such times, recharge to the underlying aquifer would be reduced. However, if the piezometric level in the aquifer can be lowered by pumping along the adjacent coastline, recharge from the swamp to the aquifer will increase. If the piezometric surface were lowered to the bottom of the confining bed, and the foregoing basic assumptions are made, losses from the swamp to the aquifer would increase to 34.8 mgd, or 53.9 cfs. This is equivalent to only 0.73 inches of precipitation per square mile per year.

These estimates are extremely conservative. The assumed conditions regarding the confining layers may apply only to 20 percent of the area. The average permeability of the confining layer may be more than 10 times larger than the figure assumed. The confining bed is not of uniform thickness and is probably breached by sinkholes or not present at many places. Also, the analysis of the piezometric map indicates that underflow from this area may be as much as 30 times greater than underflow computed in this example.

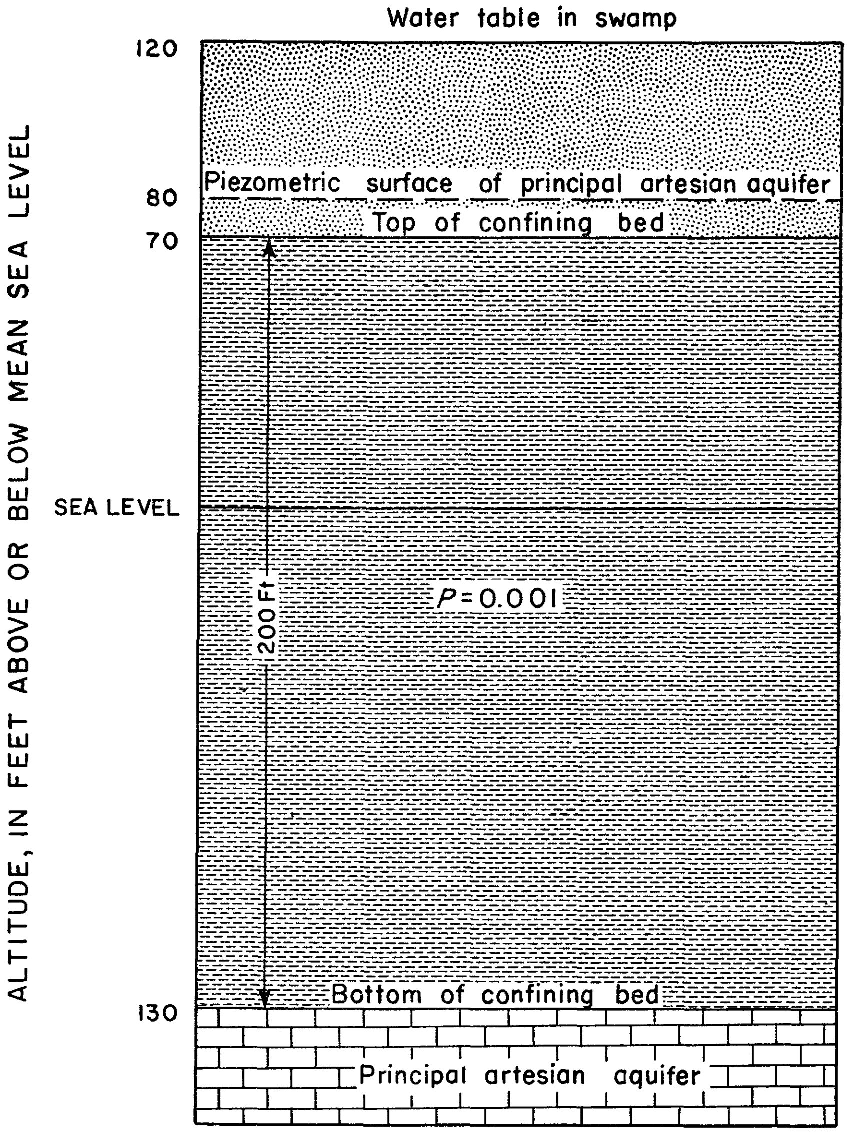


FIGURE 6.—Assumed conditions for recharge from Okefenokee Swamp to principal artesian aquifer.

In general, precipitation during the drought of 1954–55 was less than sufficient to sustain the swamp and the streams that drained it, but recharge continued at virtually a constant rate to the aquifer beneath it. Minor tributaries to the St. Marys River below Moniac, Ga., flowed at the rate of 3.11 cfs in October 1954. Of 11 streams, only 2 had flow. The St. Marys had no flow at Moniac. Its mean discharge during October 1954 was 61.1 cfs near MacClenny, Fla. For about the same period, the Suwannee had no flow at Fargo, Ga., for more than 30 consecutive days.

In October 1954, the Suwannee River near Wilcox, Fla., had an average flow of 4,263 cfs. This represents a discharge of 0.449 cfs per sq mi, or a rate of about 5.5 inches per year of precipitation. The river drains an area of about 9,500 square miles, in which many springs discharge from the principal artesian aquifer into the river or its tributaries. October 1954 was part of the drought period during which only minor precipitation fell. Probably most of the streamflow was discharge from the aquifer.

SPRINGS

Large springs discharge hundreds of millions of gallons of water daily from the principal artesian aquifer in the study area. (See table 3 and fig. 7.) Springs occur where the piezometric surface in the aquifer is above land surface and the overlying rock is breached to allow water to flow. Large springs commonly flow from sinkholes or solution openings that are connected to the rocks at depth by other solution openings. The volume of flow is related to the size and interconnection of the solution openings, the permeability of the aquifer, and the hydrostatic pressure—or height of the piezometric surface—at that place.

The total minimum measured flow of most of the larger springs is at least 1.5 billion gpd (2,600 cfs). The total maximum flow from these springs is probably 3 billion gpd, but not included in this compilation are the flow from hundreds of small springs, the discharge of several relatively large springs, and the discharge from springs in the many river beds.

The flow of most springs varies seasonally and with the recency of precipitation, and—generally—the nearer a spring is to the recharge area the more pronounced is the flow. The flow of some springs varies with the stage of nearby rivers, probably as the result of a back-water effect.

Some large springs are the source of rivers, especially in Florida. Nearly all large springs are in or adjacent to the rivers. The bed of the Flint River in southwest Georgia contains many large springs in the limestone from which water flows, and these create "boils" in the river. Wakulla Springs in Florida, the head of Wakulla River, discharges an average of 181 mgd and is the second largest spring in the study area. The largest is Ichatucknee Spring, which has a measured flow ranging from 157 to 302 mgd.

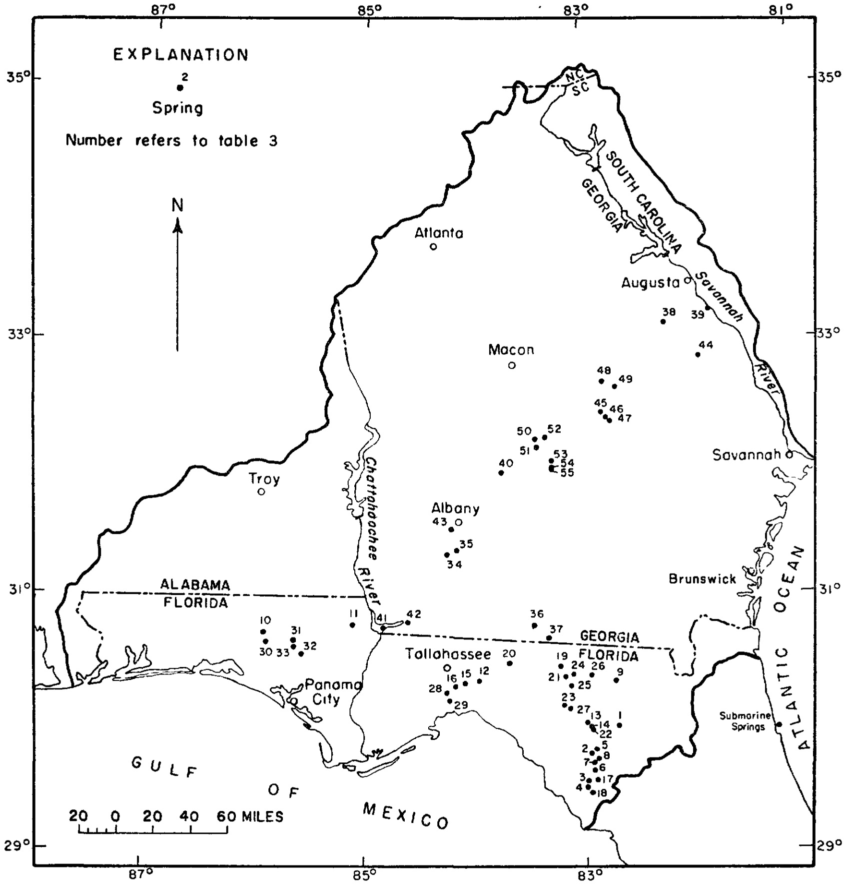


FIGURE 7.—Location of springs in the principal artesian aquifer.

Magnolia Springs in Jenkins County, Ga., a large but unmeasured spring, reflected the heavier-than-average precipitation in the winter of 1960 by an increase in flow that reportedly caused it to disgorge large quantities of sand, wood, and leaves. Radium Springs near Albany, Ga., discharges from 2.6 to 87 mgd and probably averages about 35 mgd. Its flow varies with the stage of nearby Flint River. Springs along the Santa Fe River near High Springs, Fla., discharge an average of 930 mgd into the river.

The large springs in the study area occur in two general areas: (1) the main recharge area, extending from the Savannah River Basin on the east to the De Funiak Springs, Fla., on the west and (2) in central north Florida in the Suwannee River Basin, including parts of the recharge areas of Valdosta, Ga., and the Okefenokee Swamp.

TABLE 3.—*The flow of springs from the principal artesian aquifer*

Spring (Fig. 7)	County	Spring name	Flow Mgd	Flow Cfs
		Florida		
1	Columia	Ichatucknee [1]	157–302	243–467
2	Dixie	Big Cypress	8	12. 4
3	do	Cooper	12	18. 8
4	do	Little Cooper	1. 3	2
5	Gilcrist	Hart	38–40	58. 6–62. 1
6	do	Lumber Camp	1. 9	3
7	do	Otter	3. 5	5. 4
8	do	Rock Bluff	27	42. 1
9	Hamilton	White	23–46	36. 2–72
10	Holmes	Ponce de Leon	12–13	18. 1–20. 7
11	Jackson	Blue	56–179	86. 4–277
12	Jefferson	Wacissa	65+	100. 8+
13	LaFayette	Morrison	33	51. 6
14	do	Troy	36–96	55. 2–149
15	Leon	Natural Bridge	74–85	115–132
16	do	Rhode	45	67
17	Levy	Fannin	70–88	109–137
18	do	Manatee	88–141	137–218
19	Madison	Blue	94	145
20	do	Pettis	. 1	. 15
21	do	Swanacoochee	19	29. 6
22	Suwannee	Branford	6. 8	10. 6
23	do	Charles	6. 1–24	9. 4–36. 8
24	do	Ellaville	27	41. 2
25	do	Falmouth	36–236	59. 6–365
26	do	Suwannee	3. 9–28	6. 1–44
27	do	Telford	24	37
28	Wakulla	River Sink	115	178
29	do	Wakulla	181	283
30	Walton	Morrison	57–78	89–121
31	Washington	Beckton	32	49
32	do	Blue	20–34	31. 6–52. 5
33	do	Cypress	55	84. 9
		Georgia		
34	Baker	Blue		
35	do	Lester		
36	Brooks	Blue or Wade	15	23. 21
37	do	McIntyre	30	46. 42
38	Burke	Davis		
39	do	Cox		
40	Crisp	Cordele Town		
41	Decatur	Russell		
42	do	Blue		
43	Dougherty	Radium (Blue)	2. 6–87	4–135
44	Jenkins	Magnolia	Several	
45	Laurens	Well		
46	do	Rock		
47	do	Wilkes		
48	do	Thundering		
49	do	Lovett		
50	Pulaski	Mock	6	9. 28
51	do	Blue	3	4. 64
52	do	Hawkinsville(?)	3	4. 64
53	Wilcox	Poor Robin	. 4	. 62
54	do	Abbeville Mineral		
55	do	Osewichee	12	18. 57

[1] Third largest in Florida, largest in study area.

Spring flow in the main recharge area is natural ground-water discharge that cannot flow downdip through the aquifer under existing gradients. Spring flow in Florida is partly natural discharge in a recharge area and partly discharge through breaches in the overlying confining beds. Geologic conditions in Florida are somewhat different than in Georgia. In Florida a much larger area is underlain by limestone that is at, or closer to, the land surface than in Georgia; the rocks and, consequently, the movement of ground water appear to have been affected by geologic structures to a greater extent. Northwest-trending faults (fig. 5) in the Suwannee River basin appear to have influenced the course of the Suwannee River channel and to have created more permeable zones for the drainage of ground water to the river (pl. 1) and springs (fig. 7). In parts of the Suwannee River basin, ground water emerges from the riverbed at one place, only to return to the rocks at another. The detailed studies that would lead to a determination of the water budget in this basin have not yet been made. The area, however, has a great potential for ground-water development. The basin could support large ground-water withdrawals merely by the capture of spring discharge.

Submarine springs discharge ground water where the aquifer crops out on the ocean bottom and where old sinkholes and other openings have breached the overlying confining bed. The northern area of submarine discharge is within a few miles east of Chatham County, Ga., and Beaufort, S.C. Off southern Georgia the aquifer crops out much farther to the east on the ocean floor. Off northern Florida, the top of the aquifer is exposed or breached a few miles off St. Johns County, Fla., east of the southern boundary of the study area (see fig. 7), where a submarine spring flows sufficiently to cause a slight boil on the ocean surface (Stringfield and Cooper, 1951, p. 62.). Submarine springs occur in the Gulf of Mexico south of the study area.

Spring discharge in the study area represents a significant amount of water that could be diverted to well discharge, if it were more desirable to utilize the water in this manner or at some place other than at the spring.

EVALUATION OF PIEZOMETRIC MAPS

The piezometric map published in 1949 (pl. 1) was made by combining several maps made between 1936 and 1943. As such, the map is a picture, rather than an engineering diagram. It is useful, however, in that it indicates areas of apparent recharge and discharge, possible differences in the transmissibility of the aquifer, and the direction of flow of ground water.

The piezometric contours are highest along the northern side of the mapped area and lowest along the coasts. The northeast trend of the contours across the northern part of the mapped area indicates the southeastward movement of ground water. The closeness of the contours above the 80-foot line indicate a decrease in the transmissibility of the aquifer, especially in the area to the southeast. Subsurface geologic data indicate northeast-trending fault zones in the region to the north of the 80-foot contour that extends across Georgia; the downthrown side of the faults is on the southeast. The faults could cause the permeable zones in the limestone to be offset or constricted. Groundwater would tend to be held back by the constriction, and the hydraulic gradient would be steepened as water moves from the high- to the low-faulted block through a smaller cross section.

The sinuous pattern of contours in the Florida peninsula appears to be related to the location of major streams in the Suwannee River basin. The pattern indicates discharge from the aquifer to the rivers. The location of the rivers may have been directed by northwest-trending faults that appear to extend from the Florida peninsula into southern Georgia. The low hydraulic gradients in southeast Georgia and on the Atlantic side of northeastern Florida are the result of relatively high transmissibility, and some of the eastern protuberances may be caused by water movement along eastward-trending fault zones or by the retardation of movement of ground water by block faults, one of which probably is just south of Brunswick, Ga.

By using values of transmissibility that were determined by different methods during the past 20 years, an attempt was made to determine if the known discharge of water from the aquifer could be balanced by the computed flow of water across certain areas measured normal to the piezometric contours. The flow was computed by the formula

$$Q=TIL,$$

where

Q=volume of flow, in million gallons per day;

T=transmissibility of the aquifer, expressed as flow through a 1-mile-wide strip of the aquifer under a gradient of 1 foot per mile;

I=hydraulic gradient in feet per mile; and

L=distance along a given contour line, in miles.

It can be seen that if the quantity Q and the distance L remain constant the transmissibility will vary inversely with the hydraulic gradient. On the basis of the computed values of transmissibility, the volume of flow computed for several areas did not agree with the known discharge by wells located along the Atlantic coast. The volume was most nearly correct for flow into the cone of depression at Savannah, Ga., if one allows for a contribution from the South Carolina side of the cone outside the study area.

The flow through the aquifer computed for the area from the Altamaha River basin to the southern boundary of the study area was based on coefficients of transmissibility determined previously. The coefficients ranged from 0.7 to about 2 mgd per ft. Most were about 1 mgd per ft; the highest computed value was at Brunswick, Ga. At an average value of 1 mgd, the computed flow amounted to about half of the known discharge from wells. Thus, either most coefficients of transmissibility determined previously are lower than average or possibly the hydraulic gradients as mapped were in error. Some downward leakage takes place from the upper confining bed, and some upward leakage may take place from the underlying limestone, but the volume of leakage probably does not equal the volume flowing through the aquifer. The transmissibility of the aquifer along the Atlantic coast from middle Georgia to northern Florida is probably on the order of 2 mgd per ft, and this value was used in computing the flow in this area (table 4).

A few values of transmissibility across southern Georgia and northern Florida have been computed, and these were used as the basis of the computation of flow. The computed flow through certain segments of the aquifer, however, generally was less than the discharge of springs. For example, the Santa Fe River near High Springs, Fla., discharges more than 600 cfs, but the computed underflow to that area is only 65 cfs. The discrepancy may be due to solution channels in the aquifer, whose effect was not accounted for in the results of pumping tests. The computed flow from the Okefenokee Swamp piezometric high to the Fernandina-St. Marys cone of depression was only about 26 cfs (17 mgd), and pumpage was about 62 cfs (40 mgd). Under conditions assumed in figure 5, recharge to the whole swamp area was computed as about 9 cfs, but total underflow computed from the piezometric map was 253 cfs (163 mgd).

The assumed permeability and thickness of the rocks overlying the aquifer in the swamp recharge area were obviously not applicable to the entire recharge area.

Flow across the 90-foot contour line from the piezometric high centered at Valdosta, Ga., was computed to be about 43 mgd on the basis of an average transmissibility of 300,000 gpd per ft. For 500 square miles of recharge area, this flow is equivalent to about 85,000 gpd per sq mi—the equivalent of about 0.132 cfs, or 1.8 inches of precipitation per year—and is about the same as the low-flow discharge to a part of the Withlacoochee River in 1954.

TABLE 4.—*Coefficients of transmissibility used to determine ground-water flow through principal artesian aquifer*

No. on pl. 1	Transmissibility	Flow (mgd)	No. on pl. 1	Tranmissibility	Flow (mgd)
Flow from main recharge area					
1	216, 000	21. 7	7	130, 000	8. 1
2	72, 000	9. 3	8	176, 000	10. 1
3	87, 000	16. 9	9	360, 000	16. 8
4	87, 000	279. 6	10	244, 000	53. 1
5	90, 000	5. 8			
6	90, 000	3. 6	Total		425. 0
Flow to east, south, and west periphery of study area					
11	300, 000	21. 7	25	270, 000	4. 0
12	450, 000	9. 3	26	250, 000	7. 2
13	1, 000, 000	16. 9	27	250, 000	6. 8
14	2, 000, 000	38. 0	28	250, 000	4. 9
15	2, 000, 000	13. 0	29	250, 000	19. 7
16	2, 000, 000	24. 0	30	300, 000	24. 6
17	1, 000, 000	20	31	300, 000	42. 1
18	1, 000, 000	36	32	600, 000	22. 6
19	250, 000	11. 3	33	300, 000	8. 1
20	250, 000	7. 8	34	300, 000	10. 1
21	250, 000	8. 6	35	300, 000	16. 8
22	280, 000	13. 2	36	300, 000	53. 1
23	270, 000	28. 2			
24	270, 000	2. 8	Total		470. 8
Flow from Valdosta, Ga., recharge area					
37				300, 000	42. 6

The total flow within the aquifer from the Savannah, Ga., area on the northeast and around the southern edge of the study area to the Pensacola Bay, Fla., area on the west, through intervals of 10–20 feet reduction in head and across the 80- to 50-foot contour lines, was computed to be 471 mgd, or 730 cfs. If this recharge took place over 10,000 square miles, it is the equivalent of 0.073 cfs per sq mi, or about 1 inch of precipitation per year. Flow to the Atlantic side was 198 mgd (307 cfs) and to the gulf side was 273 mgd (423 cfs).

The total flow across the 100- and 90-foot contours from the Savannah River on the northeast to the Pensacola Bay area on the southwest and upgradient from the Valdosta and swamp recharge areas was computed as 452 mgd (700 cfs). If this recharge took place on about 8,500 square miles of recharge area, it is equivalent to 0.082 cfs per sq mi, or about 1.1 inches of precipitation per year.

Generally, the area between the 120- and 80-foot contour is the part of the aquifer having the lowest transmissibility, especially in the eastern half of Georgia, and is the limiting factor to the amount of water than can be induced to flow to the coastal areas from the main recharge area. The coefficient of transmissibility in this zone was computed by extending the segments already measured upgradient, by assuming that Q remained constant, and by solving the equation for T.

The computed flow through the aquifer as a whole is considered to be a conservative estimate. It may be as much as 100 percent greater.

It is concluded that the available data cannot be used to make an accurate estimate of the amount of flow of water through the aquifer. In each estimate, the computed flow through the aquifer was less than the known discharge to wells and springs. The data necessary to make better estimates of recharge are also not available.

The piezometric map (pl. 2) is the only one of the whole aquifer area. Several piezometric maps have been made of smaller areas at different times, especially along the Atlantic coast of Georgia. The piezometric map of 1960 shows the well-defined cones of depression at Savannah and Brunswick, Ga., and Fernandina, Fla. (pl. 1). Data are lacking to define the cone near Jesup, Ga., that has been created by pumping 45 mgd.

An analysis of the discharge of ground water in 1960 was made using the same values of transmissibility that were used for the earlier map. The eastward discharge through the aquifer was 320 mgd. For the same area in early 1940's it was 143 mgd. The increased volume indicates approximately the increased pumpage in the past decade.

Known discharge in 1943 was about 170 mgd, and computed flow through the aquifer was only 143 mgd. Some of the underflow, however, was from South Carolina, which had not been evaluated for the computation. Pumpage in 1960 was about 240 mgd along the coast, whereas discharge through the aquifer was computed as 320 mgd. The difference of 80 mgd represents water flowing past the coastline to submarine springs from the area south of Liberty County, Ga. Apparently all flow north of Liberty County is diverted into the cone of depression at Savannah, Ga.

Additional pumping in the southern part of the coastal area, at Brunswick and Fernandina, for example, will lower the piezometric level, steepen the hydraulic gradients, and make the cones of depression more extensive, thereby inducing more water to move in from the recharge areas to the west, lessening the flow to discharge areas to the east, and lowering the piezometric surface on the coastward sides of the cones. Some of the increase will be balanced by downward leakage through the confining bed.

In relation to safe yield, the lowered piezometric surface and lessened discharge to the east will, in time, result in lateral salt-water encroachment if the piezometric surface on the coastward side of the cones is lowered to about 25 feet above sea level or lower.

PUMPAGE AND WATER-LEVEL DECLINE

Warren (1944, p. 134, 135) estimated that the water level in the Brunswick, Ga., area would decline 0.6 ft per 1 mgd of pumpage 1½ miles from a pumped well. This value was based on a decline of 25 feet caused by 37 mgd discharge. In 1960, about 90 mgd of pumpage had caused 45 feet of decline, or a decline of about 0.5 ft per 1 mgd at the same distance. Closer to the center of pumping, the decline is greater; farther away, it is less. Pumping at Brunswick has lowered the water level as much as 25 feet about 10 miles away at Jekyll Island, or about 0.28 ft per 1 mgd. The island is to the southeast where the piezometric level has continued to remain higher than might be expected. About 14 miles northeast of Brunswick at St. Simons Island, the pumping has caused a decline of 30 feet, or 0.33 ft per 1 mgd. This decline means that an increase of pumpage of 100 mgd at Brunswick would cause the water level to decline as follows: About 50 feet 1½ miles from the pumped wells or to 30 feet below sea level; 25 feet on Jekyll Island, or to 25 feet above sea level; and 33 feet on St. Simons Island, or to 3 feet below sea level. Thus, the piezometric surface would be below sea level from Brunswick to at least 14 miles northeastward to the coastline and in some areas beyond the coastline. The pumpage would also cause a deepening of the Savannah, Ga., cone, because water would be diverted from it. Thus, any large-scale development of ground water at Brunswick would increase the rate of salt-water encroachment at Savannah. With the cone at this depth at Brunswick, salt water would be free to move upward from deeper limestone beds unless a tight, confining layer is present. Also, the salt-water front in the aquifer to the east would begin to move toward the land.

The protuberance in the piezometric surface to the south of Brunswick, Ga., would also decline but would be at least 25 feet above sea level. The probable direction of lateral salt-water encroachment would be from the east.

At Fernandina, Fla., and at nearby St. Marys, Ga., a cone of depression has been created. Pumpage increased from less than 0.5 mgd prior to 1938 to about 78 mgd in 1959, and the center of the cone is below sea level (Leve, 1961). Total decline has been about 70 feet, indicating a decline of 0.9 ft per 1 mgd. An increase in pumpage to 160 mgd at St. Marys and Fernandina would result in a deepening of the cone by about 70 feet, and the surface would be 80 feet below sea level. About 7 miles from the cone, the decline would be about 45 feet; to the west, the surface would decline to 25 feet below sea level; to the east, the surface would decline to about 15 feet below sea level.

East of Fernandina the piezometric levels in 1960 were still above sea level, but salt-water encroachment may be taking place from the deeper limestone. The chloride content of water from some wells in Fernandina has increased. Since 1940, the chloride content of water in wells less than 1,400 feet deep has increased less than 10 ppm. Since 1952, however, the chloride content of water in wells more than 1,400 feet deep has increased 20–640 ppm (Leve, 1961, p. 2), and some 1,800-foot wells have water containing more than 1,000 ppm chloride.

The greatest danger of salt-water encroachment at Fernandina appears to be from vertical upward movement rather than from the ocean to the east. In order to determine the probable rate of salt-water encroachment from the east, the position of the salt-water wedge in the aquifer by offshore test drilling must be known.

As of 1958, pumpage at Savannah, Ga., was 60 mgd, and it remained fairly steady through 1960. Water-level declines from the time pumping from the aquifer began until 1958 (Counts and Donsky, 1959, p. 96) were more than 145 feet near the center of pumping, about 54 feet 8 miles southwest from the center, 25 feet 23 miles west of the center, and about 20 feet 20 miles east of the center. For every 1 mgd, these values represent approximate declines of 2.4 feet at the center, 0.9 foot 8 miles to the southwest, 0.37 foot 23 miles to the west, and 0.33 foot 20 miles to the east. (See fig. 8 for graph from which to predict drawdown.) The decline apparently has nearly stabilized at Hilton Head Island, 25 miles from the center of pumping. This evidence indicates that a hydraulic boundary has been met, which is probably the aquifer top exposed on the ocean floor. Salt-water encroachment is taking place at Savannah, but Counts and Donsky (1959) estimated that if the water is moving uniformly through all parts of the aquifer and is not restricted to a few permeable zones, salt water would not reach the center of pumping for more than 100 years even if the pumpage at Savannah was more than doubled. Warren (1944, p. 126) estimated that a pumpage of 25 mgd is about the maximum amount of water that could be pumped at Savannah and still maintain a divide in the piezometric surface between Savannah and the natural discharge area in the sea that would prevent the lateral encroachment of salt water. The safe yield of the aquifer, however, has been exceeded at Savannah, and salt-water encroachment has begun. The rate of encroachment and methods of development to slow down the rate of encroachment, or possibly to stop it completely, are still to be determined more precisely. Surface water might be diverted into the aquifer through recharge wells along the coast to maintain an artificial barrier of fresh water to prevent salt water from moving inland.

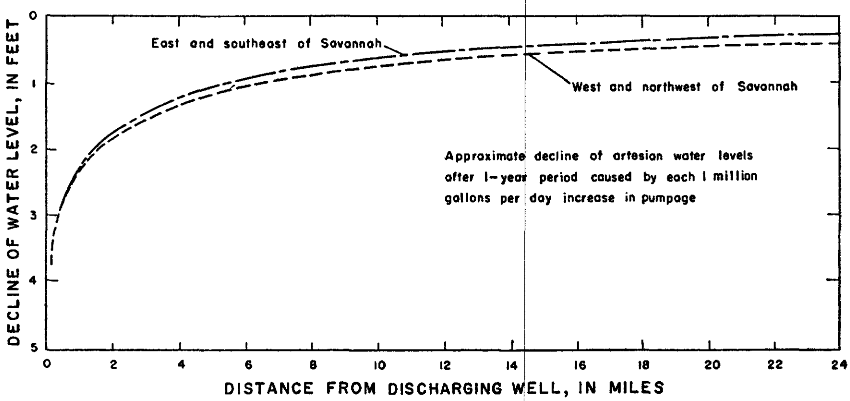


FIGURE 8.—Relation between an increase in pumping of artesian ground water and the decline of artesian water levels in Savannah, Ga., area (from Warren, 1944).

WATER MANAGEMENT

The principal artesian aquifer is the source of water to more wells and water systems than any other aquifer system in the study area. Withdrawal from the aquifer has caused the lowering of the piezometric surface mostly in localized areas along the Atlantic coast. Salt-water encroachment is probable in a little more than 100 years at Savannah, Ga., and in areas to the south if present pumping patterns are maintained.

Proper management methods should allow the maximum development of the aquifer system. The management must be based on a knowledge of the capability of the aquifer to transmit and store water. The vertical limits, lateral extent, and permeability of the water-bearing zones must be known in adequate detail. The physical boundaries that have an effect on the recharge and movement of water must be determined. For example, a river may act as a line source of water to the aquifer, or it may be a line of discharge from the aquifer. Faults may act as physical boundaries; they may increase, decrease, or stop the flow of water; they may divert the flow, or they may be a line source of discharge or recharge. The volume of leakage from the confining beds as the piezometric surface in the aquifer is lowered should be determined because it will be significant.

As an aid to the overall management of the water resources of the principal artesian aquifer, the following paragraphs discuss the probable results for a variety of procedures for development. They serve to emphasize that the potential yield of this aquifer is very large and that with good management this yield can be sustained almost indefintely. It should be reemphasized, however, that none of these developments can be undertaken with assurance without vastly greater knowledge of the aquifer and of the hydrology of the area than is currently available.

If the necessary data about the aquifer are available, the method of management becomes a choice for those who utilize the water. They may choose to spread the pumping evenly over the aquifer in order to utilize more land area, or they may choose to concentrate the pumpage along the coastlines and pump the aquifer at whatever rate is necessary, with the full knowledge that salt-water encroachment will eventually take place. At the time of encroachment the area of heavy pumping could be shifted a certain number of miles inland and a new line of well fields developed. These would be pumped until the salt water made the aquifer unusable, and another shift would follow. This procedure could be followed as many times as necessary, until the line of development was immediately downdip from the recharge area. Then, the maximum amount of water that could be pumped would be limited by the annual recharge that could be induced.

The volume of water that may be pumped from the aquifer will be limited by the volume of recharge although ground water may be mined for extended periods on a planned basis. In the early 1940's, about 198 mgd was flowing to the Atlantic coast. In 1960, the flow was 320 mgd, an increase of about 120 mgd. The increased flow was caused by a steepening of the hydraulic gradient. A further increase of discharge by pumping along the coast will increase the hydraulic gradient from the outcrop area on the west and induce additional recharge from the recharge areas. However, it will also decrease discharge to the ocean, steepen the gradient from the ocean on the east, and induce salt water to move toward the pumpage centers.

The fault zones in the aquifer will act as hydrologic boundaries. They will retard the southeastward movement of water from the main recharge area. The fault south of Brunswick, Ga., may act as a barrier retarding the southward extent of the cone of depression and modifying the effect of pumping on the well fields at St. Marys, Ga., and Fernandina, Fla., but, if it does, the cones must steepen in other directions.

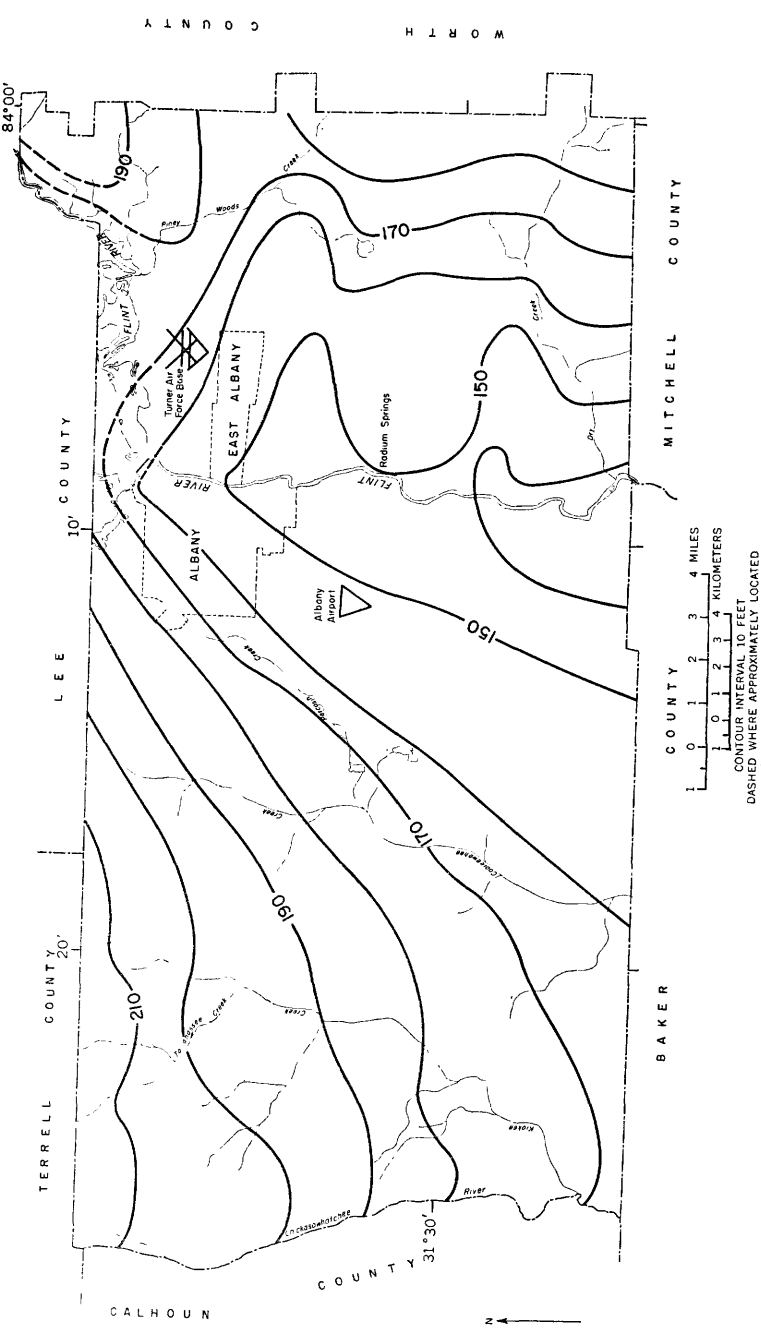
If pumpage at Savannah, Ga., were doubled to 125 mgd, at Brunswick to 180 mgd, and at St. Marys and Fernandina to 160 mgd, discharge of fresh water to the ocean would virtually cease, and salt water would begin to move toward the centers of pumping all along the Atlantic coast.

The water supplies of coastal areas of both the Atlantic and the gulf are the most vulnerable to the effect of aquifer development. If the aquifer is overpumped at the coast, salt-water encroachment from the sea or adjoining rocks will be caused. Development of the aquifer upgradient from the coast, however, will also lower the water level at the coast. It would be possible to develop large ground-water supplies 20 miles inland from the coastal cities, divert a large percentage of the ground-water flow, lower the piezometric levels at the coast, and cause salt-water encroachment. The maintenance of an artificial fresh-water barrier along the coast by diversion of surface water through recharge wells would help to prevent encroachment.

The existing data indicate that the aquifer should be developed over a broader area, with a minimum concentration of pumping if the advance of salt water is to be checked. In this way, the water level would be lowered more evenly over wider areas, and cones of depression would be less deep. Further development along both coasts should be spread over a wider area and in an inland direction. For example, if the pumping pattern at Savannah, Ga., were modified and new well fields were located west of the city, the depth of the cone of depression would be lessened, thus decreasing the negative hydraulic gradient to the east and slowing the rate of salt-water encroachment.

Widespread development of the aquifer in the study area should be in and downgradient from the recharge areas to produce the maximum long-term yield. This will increase the hydraulic gradients in that area and salvage much of the loss to springs and to the base flow of the streams. It should also induce recharge from major lakes, such as Lake Seminole.

The major development of the main recharge area in Georgia could take place in the recharge area itself and for a distance of about 25 miles southeast of its southern limit. The development would be upgradient from the northeast fault zone. If the hydraulic gradients were doubled across this area, the quantity of water moving southeastward would be doubled, and about 1 inch per year of additional precipitation would be induced to recharge. Additional development could also be parallel to the course of the major rivers, where the aquifer is exposed in the riverbeds. For example, development of the east side of the Flint River from Cordele to the State line would induce additional recharge from the river. In Dougherty County, Ga., the aquifer is drained by the Flint River (fig. 9). At Albany, Ga., the 150-foot contour line of land surface is at river level. The aquifer is exposed on the banks and in the bed of the river. The



After Robert L. Wait, 1957

FIGURE 9.—Piezometric surface in principal artesian aquifer, August 1957, Dougherty County, Ga.

piezometric surface also is at river level. The 170-foot contour of the piezometric surface runs northward, parallel to and about 6 miles east of the river. It crosses the river in the vicinity of the lake north of Albany and then trends southwestward across the county. If a line of wells were developed 6 miles east of and parallel to the river, the piezometric surface could be lowered about 40 feet to reverse the hydraulic gradient to 3–4 feet per mile to the east. This lowering would stop the drainage of the aquifer from the east and induce recharge from the river.

As of 1957, the hydraulic gradient on the east side of the river near Albany was 3–4 feet per mile to the west. The transmissibility of the aquifer, determined from one test, is about 1 mgd per ft. On this basis, approximately 3–4 mgd per lineal mile (4.65–6.2 cfs) was draining into the river. If this hydraulic gradient were reversed and the piezometric level were lowered to 130 feet above sea level along the present 170-foot contour, 3–4 mgd would recharge the aquifer. Although figures are not available for the yield of the aquifer per foot of drawdown, it is probably on the order of 1 foot of drawdown per 1 mgd. Therefore, 40 feet of drawdown might yield 40 mgd at any one place. The pumping centers might be located 10 miles apart from the vicinity of Cordele to the State line. Induced recharge of 3 mgd per mile across this area would be 240 mgd (372 cfs), and an equal amount would move to the wells from the east.

The minimum daily flow of Flint River at Albany, Ga., in 1954 was 645 cfs. If the aquifer had been developed to prevent the flow of ground water to the river, the flow of Flint River at Albany would probably have been reduced by about 100 cfs; and the flow at the State line, by an additional 140 cfs.

In the Florida Panhandle south of the main recharge area, development could take place north of a line from Tallahassee to east of Niceville. This would place the developed area from about 15 to almost 50 miles north of the Gulf of Mexico. Hydraulic gradients across this line in the early 1940's were about 2–3 feet per mile. Under these gradients, some 600,000–900,000 gpd per lineal mile were flowing southward from the recharge area. If the piezometric level were lowered to approximately sea level along this line, gradients would be increased to 4–6 feet per mile, and the flow would be increased to 1.2–1.8 mgd per lineal mile. At the same time, the piezometric level at the coast would remain above sea level and hold back the landward movement of salt water. Across approximately 130 miles, this lowering would allow the development of at least 150 mgd (232 cfs). If the development took place by a somewhat even distribution of pumpage from a line 20 miles north of the gulf to the recharge area, at least 300 mgd could probably be developed in this area.

Recharge could be induced in the Valdosta, Ga., recharge area by distributing wells in a circular area having a 25-mile radius from Valdosta. This area would merge on the north with the development of the main recharge area and on the southeast with the Okefenokee Swamp recharge area. If hydraulic gradients could be doubled, recharge of about 1.5 inches per year (0.11 cfs) of additional precipitation would be induced. This is equivalent to 0.7 mgd per sq mi, or about 350 mgd for the recharge area. In addition, the lower water level in the aquifer would create conditions that would be more favorable for recharge during the recharge season.

Warren (1944, p. 60–66) discussed the possible effect of heavy rainfall on fluctuations of the piezometric surface in the Valdosta area from January through March 1942. He theorized that, with a 5-foot rise in the water level in the Valdosta area, the average rate of recharge in a 30-day period would average 65 mgd (100 cfs), if the aquifer had a coefficient of storage of 0.0003. The rate of recharge would be proportionally greater with a larger coefficient of storage.

The development of the aquifer in the Florida peninsula from Tallahassee eastward to the Okefenokee Swamp recharge area will intercept ground-water flow enroute to the gulf from the swamp area on the east, from the main area and the Valdosta area on the north, and from smaller local recharge areas not delineated. In the early 1940's, underflow to the west from the swamp area was computed as about 33 mgd (51 cfs), and that to the south from the Valdosta and the main area, as 132 mgd (204 cfs). A total of 165 mgd (255 cfs), therefore, was moving under hydraulic gradients of 1–3 feet per mile. About 120 mgd (198 cfs) of this underflow was in the Suwannee River basin. These totals are at variance with spring flow in the same area, which is at least 1,100 mgd (1,800 cfs). If the well fields were concentrated downgradient from the piezometric highs, they would, in general, parallel the course of the main streams. Most of the development should take place upgradient from the 20-foot piezometric contour line to create steepened gradients from recharge areas and at the same time to maintain a head above sea level on the gulf side. It appears that a minimum of 1,100 mgd (1,800 cfs) could be developed by diverting spring discharge to the well fields. With the proper distribution of pumping in the Suwannee River basin, most of the base flow of the stream could be diverted. In September 1954, the flow was 2,500 mgd (3,860 cfs). Data are insufficient to make a better estimate.

SUMMARY

It is not possible to add the various totals of base flow, spring flow, and underflow through the aquifer and arrive at a total volume of water that might be pumped on a sustained basis. A total of 7.5 billion gpd (11,600 cfs), apparently, could be pumped from the principal artesian aquifer in the study area, provided that the pattern of well fields were a proper distribution with respect to recharge areas and other hydrologic boundaries. This total is probably conservative. More water can be developed if artificial recharge is done. Consideration was not given to leakage that would take place from the confining beds, and in much of Georgia the overlying beds might contribute 0.5 inch of water per year per square mile. This amount would be equivalent to about 0.04 cfs, or 0.026 mgd per sq mi. An area of about 30,000 square miles would contribute about 1,200 cfs, or 780 mgd. Some of this water would come from overlying sands of Miocene and post-Miocene age, but its removal probably would induce additional recharge at the surface.

The development of the principal artesian aquifer would divert discharge from springs and streams, but much of it would probably be introduced to the same or other streams after use.

Further development of the aquifer along the coasts should proceed with great caution and more planning. Studies have been made in greater detail along the Atlantic coast than in any other part of the study area, but none of these have yet been completed in the necessary detail.

The subsurface structural features and changes in the lithology of the aquifer are not well enough known.

The position and rate of movement of salt water is known for only a few places, and this knowledge is wholly inadequate.

At the present intensity and rate of completion of studies of this and other aquifers in the study area, the rate of acquisition of knowledge about ground-water resources will continue to fall behind the rate of ground-water development.

SAND AND GRAVEL AQUIFERS OF MIOCENE AND POST-MIOCENE AGE OF THE SOUTHWESTERN AREA

In the western Florida Panhandle and adjoining Alabama (fig. 10) is an area in which water supplies are obtained from beds of sand and gravel of Miocene and post-Miocene age. These beds are the primary source of ground-water supplies in most of the mapped area and contain fresh water from their updip edge to the gulf coast to an approximate depth of 1,000 feet. They begin along the northern and eastern edge of the area shown on the map and dip to the southwest as much as 30 feet per mile, increasing in thickness downdip.

The sand and gravel beds are interbedded with and underlain by beds of clay and silt that act as confining beds.

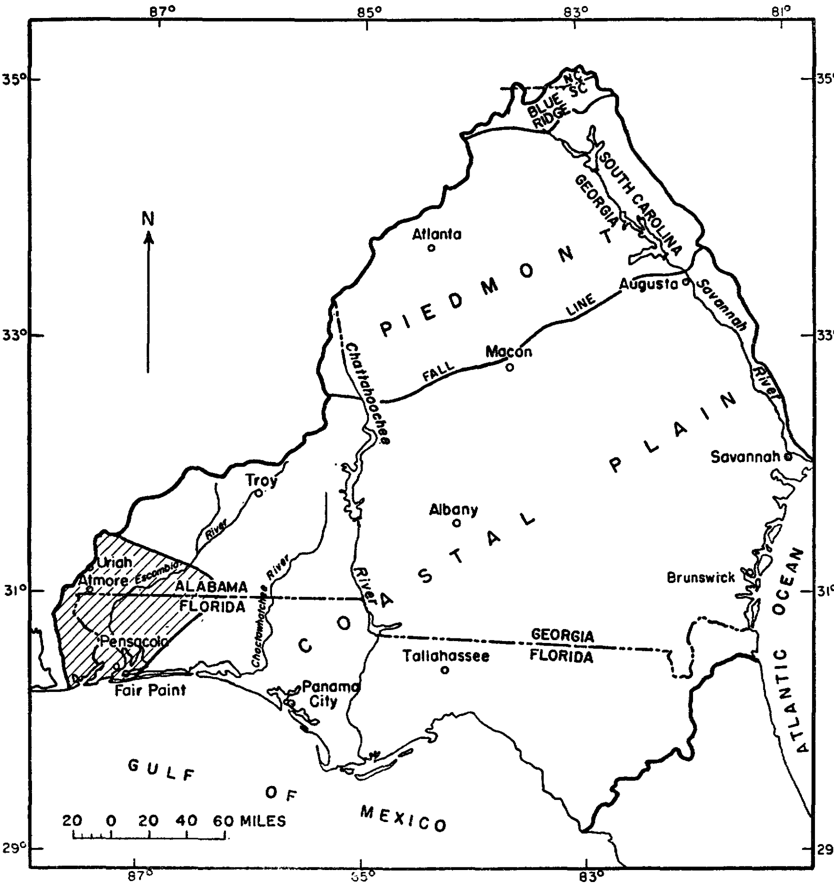


FIGURE 10.—Area of sand and gravel aquifers of Miocene and post-Miocene age.

These aquifers are a source of large supplies of water, but because the upper sands are connected hydraulically to the gulf and salt-water estuaries, a great deal of detailed information will be necessary before they can be developed fully, especially along the coast. Lateral salt-water encroachment of the shallowest sands has occurred at several places along the gulf. The widespread occurrence of clay beds has protected some of the sand aquifers from lateral encroachment, but the possibility of upward encroachment from deeper lying salt water remains.

RECHARGE

The aquifers of sand and gravel underlie an area of about 4,500 square miles in the study area. The area is one of low relief that receives more than 60 inches of precipitation per year. The potential of this area for recharge is relatively high because of the high permeability of the surface and the large volume of precipitation.

Tributaries and the main stem of the Escambia and Choctawhatchee Rivers yielded from 0.68 to 0.95 cfs per sq mi as a mean monthly flow during September 1954. This flow is the equivalent of about 9–13 inches of precipitation per year as the minimum of ground-water discharge. Characteristically, the water table in these aquifers is close to land surface.

Overland runoff is retarded somewhat by the high permeability of the soil. Streamflow is greatest in the late winter when the water table is at the seasonal high. Although not known precisely, the porosity of the sand and gravel beds probably is from 25 to 30 percent, and the permeability is high. Thus the physical characteristics of the aquifer system and the climate favor recharge.

QUANTITATIVE DATA

Wells which penetrate the sand and gravel aquifers yield more than 1,000 gpm. The coefficient of transmissibility of a deep artesian sand aquifer at Pensacola, Fla., is 500,000 gpd per ft (table 5). At Pensacola, and at other places, coefficients of transmissibility of shallow water-table aquifers range from about 34,000 to 78,000 gpd per ft. If one considers that the individual aquifers tested were no more than 100 feet thick, the permeability of the sands is on the order of 350–5,000 gpd per sq ft. These aquifers are capable of storing and transmitting large volumes of water. Hydraulic gradients within the different water-bearing zones are relatively low regionally but may be high in the vicinity of the rivers.

TABLE 5.—*Coefficient of transmissibility of sand and gravel aquifers of Miocene and post-Miocene age*

Location	Coefficient of transmissibility (gpd per ft)	Aquifer
Uriah, Ala	74, 800	Miocene deposits.
Atmore, Ala	77, 600	Citronelle Formation.
Pensacola, Fla	500, 000	Deep artesian sand.
Do	75, 000	Shallow nonartesian sand and gravel.
Fair Point, Fla	34, 000	Shallow nonartesian sand.

WATER MANAGEMENT

The sand aquifers lend themselves rather well to widespread development. The sands crop out at land surface, are highly permeable, and drain to the streams. Widespread pumping could lower the water table sufficiently to allow increased recharge to the aquifers and deceased ground-water discharge to the streams. Ground water could be mined in certain seasons of the year to dewater the aquifers so that additional recharge could take place. The lowered water table would lessen evaporation and transpiration. The concentration of pumping centers along the gulf coast and along tidal streams should be avoided to safeguard the aquifers from salt-water encroachment.

Salt-water encroachment of the shallow sand aquifers has occurred in some of the well fields in the Pensacola, Fla., area, and this will limit development. Heath and Clark (1951) determined that the safe yield of the shallow sand at the center of the Fair Point Peninsula was about 100,000 gpd per ft because of salt-water encroachment from both sides of the peninsula. Pumpage would have to be regulated carefully along the coast and estuaries so as to prevent any further salt-water encroachment of either shallow or deep aquifers. Greater concentrations of pumpage could take place a safe distance inland from the salt-water estuaries.

SUMMARY

A minimum of 1 mgd (1.55 cfs) per sq mi could probably be developed safely over the 4,500 square miles of this area. This is the equivalent of about 21 inches of precipitation per year. Most of the precipitation could possibly be captured in parts of this aquifer area by mining ground water during parts of every year or during dry years so that the ultimate safe yield of this aquifer system might exceed 4.5 billion gpd by a factor of two.

AQUIFERS OF THE ATLANTIC COAST OF MIOCENE AND PLIOCENE TO RECENT AGE

Along the Atlantic coast in the study area, and for as much as 100 miles inland, is an area underlain by a blanket of sand and clay beds of Pliocene to Recent age (fig. 11). These beds are underlain by a much more extensive and thicker series of beds of clay, silt, sand, limestone, and dolomite of Miocene age that form the upper confining layer of the principal artesian aquifer. Few quantitative data are available concerning the water-bearing character of any of these rocks. Streams flowing across the sand frequently go dry. The sands provide water for domestic use in some parts of the area, but the yields of wells are not known. Water is pumped from water-table ponds constructed for irrigation. A few water supplies are obtained from the deeper beds of Miocene age.

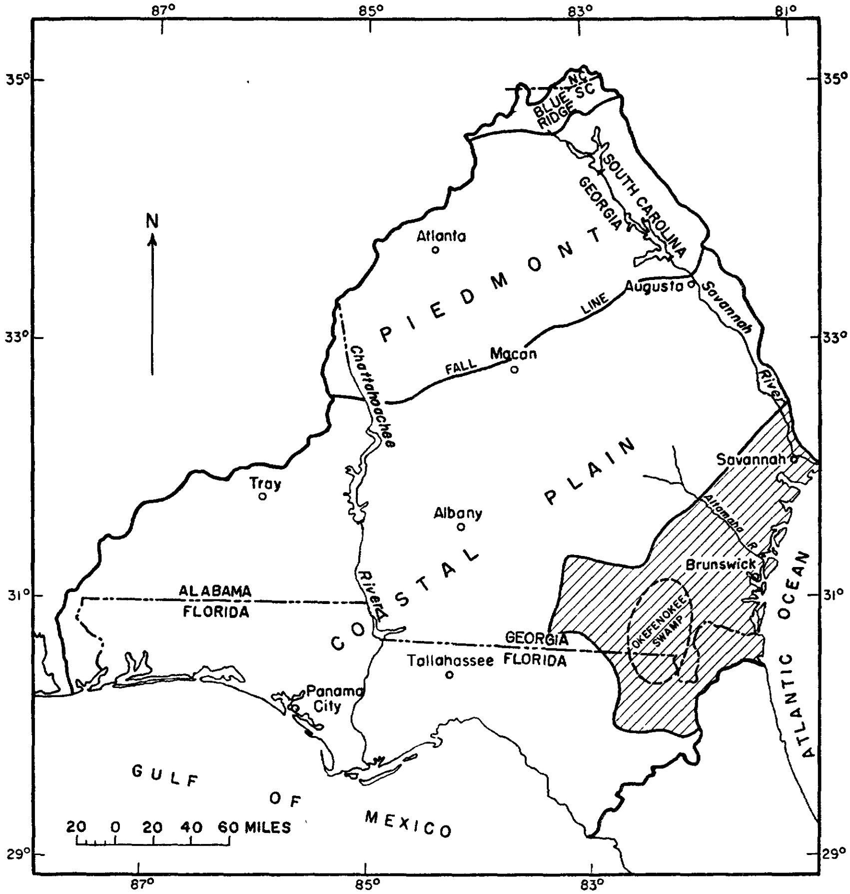


FIGURE 11.—Aquifers of the Atlantic coast of Miocene and Pliocene to Recent age.

MIOCENE ROCKS

Rocks of Miocene age, known as the Hawthorn Formation, underlie much of the Coastal Plain. The rocks consist of clay, silt, sand, limestone, and dolomite. Some of the limestone and dolomite beds are aquifers of minor importance, furnishing water for domestic supplies and a few small municipal supplies. Individually, the aquifers are thin, discontinuous, and constitute a small percentage of the total volume of the rocks. The most important function of the Hawthorn Formation is to confine water in the underlying principal artesian aquifer.

The Hawthorn Formation is generally not particularly open to recharge, and the permeability of some of the rocks, as determined in the laboratory, ranges from 0.001 to 0.0004 gpd per sq ft. The formation may be breached by sinkholes, however, and the permeability of some rocks may be higher than that listed.

Not enough is known about the capability of the water-bearing zones to estimate a safe yield to wells. As the piezometric level in the principal artesian aquifer is lowered, however, downward leakage from the Hawthorn Formation will recharge the deeper aquifer. On the basis of a coefficient of permeability of 0.0004 gpd per sq ft, downward leakage might some day be about 11,000 gpd per sq mi. If this occurred over 5,000 square miles, it would total 55 mgd. Probably, the Hawthorn Formation is breached by sinkholes at many places and the permeability value used is lower than the average for the formation everywhere; therefore, downward leakage may be greater and may be a significant contribution to the water resources of the study area.

PLIOCENE TO RECENT SANDS

About 5,000 square miles of the study area, including the offshore islands, are underlain by the sand blanket. The sands are interbedded with clay beds, and they are as much as 100 feet thick. The water table is close to land surface during wet seasons but declines below the bottoms of tributary streams in the dry seasons.

The major rivers crossing the sands contain brackish or salt water for as much as 40 miles upstream from the coast, and salt marshes extend several miles inland. In about 25 percent of the area, salt water is in direct contact with the upper sand beds.

RECHARGE

The recharge potential of the sand aquifers is high in at least 50 percent of the area. It is limited in tidal marshes along the coast by muck and periodic salt-water inundation. Where the potential is high, as much as 1 mgd could be induced to recharge by maintaining a low water table.

QUANTITATIVE DATA

Quantitative data for this aquifer are scarce. During the irrigation season a few million gallons per day are pumped from several water-table ponds. The high yield of the ponds indicates a relatively high coefficient of transmissibility, which in some places is probably as much as 500,000 gpd per ft.

On the basis of an estimated recharge potential of 1 mgd per sq mi for 50 percent of the area, about 2.5 billion gpd could be pumped from this aquifer.

WATER MANAGEMENT

In future years this sand aquifer is expected to be utilized more fully, especially in areas where the principal artesian aquifer becomes completely developed. The sand aquifer can be developed for irrigation and special industrial uses. The water generally is soft and slightly acidic.

Much more data will be needed before this aquifer system can be fully developed. The areal extent of the sand is incompletely known, as are the thickness and permeability of the beds.

SUMMARY

On the basis of what is known about the extent and thickness of the aquifer, the estimated yield should be about 1 mgd per sq mi in about 2,500 square miles of the area of occurrence.

Salt-water encroachment will be a problem along the entire coast and adjacent to the major rivers and tidal estuaries.

The sand aquifer should provide large volumes of water for supplemental irrigation, domestic, and some industrial uses.

SUMMARY AND CONCLUSIONS

The safe yield of the sedimentary aquifers of the Coastal Plain of the study area is estimated at about 24 billion gallons per day. The aquifer systems and their safe yields are listed in table 6. The volume of fresh water in storage in the aquifers is estimated at about 21 billion acre feet. This is a ratio of about 1-acre foot of ground water in storage for every 1 gallon per day of safe yield. Such a large volume of water in storage would make it feasible to exceed the safe yield of the aquifers for long periods of time, for years or even centuries. The safe yield of 24 billion gallons per day might be exceeded by an equal withdrawal from storage, at which rate the water in storage would be depleted in some 800 years.

The availability of data about the aquifer systems in the study area is related to the amount of development that has taken place from the aquifer systems and to the degree and extent that ground-water studies have been made. The availability of data is given in order of abundance, as follows: (1) The principal artesian aquifer, the most fully developed aquifer system; (2) the sand aquifers of Cretaceous age; (3) the limestone and sand aquifers of early Tertiary age; (4) the sand and gravel aquifers of the southwestern area; and (5) the sand aquifers of the Atlantic coast.

The estimates of safe yield were based on incomplete data by making broad assumptions that are probably valid but conservative and do not allow for storage depletion. The scope of this report could not include the determination of the effect of ground-water withdrawal on the flow of all the streams or the effect of drainage to the aquifers from confining beds. The report does not describe the exact degree of salt-water encroachment that might result from a given overpumping at a specific place. It does point out that, if certain conditions are exceeded, salt-water encroachment will take place.

TABLE 6.—*Safe yield, in billion gallons per day, of sedimentary aquifers of the Coastal Plain*

Aquifer system	*Yield*
Aquifers of the Atlantic coast of Miocene and Pliocene to Recent age	2.5
Sand and gravel aquifers of southwestern area	4.5
Principal artesian aquifer	7.5
Limestone and sand aquifers of early Tertiary age	5.0
Sand aquifers of Cretaceous age	5.0
Total	24.5

On the average, the aquifers receive more recharge during the winter season (November through March) than during the rest of the year. The recharge areas generally are areas of high ground-water discharge to streams. Although as much as 40 inches of precipitation recharges some aquifers, most of the water discharges to streams in short distances, and only 1–2 inches moves downdip through each of the aquifers.

The ultimate yield assumes that some development will decrease the base flow to large streams and stop the base flow to some minor streams. On the assumption that the water use will not be entirely consumptive, however, a certain percentage of the ground water withdrawn will be returned to surface streams.

Artificial recharge of some of the aquifers will be one way of conserving water, especially in areas threatened by salt-water encroachment. Fresh-water mounds can be created by artificial recharge through wells on the seaward side of cones of depression to prevent salt-water encroachment. This might be one way of alleviating the problem at Savannah, Ga. Artificial recharge might also be made possible by the construction of dams or spreading structures in recharge areas that would hold back or divert the floodflow of rivers and allow time for the water to recharge the aquifers. This might be done in the Valdosta, Ga., area to recharge the principle artesian aquifer. Geologic conditions appear to favor this possibility. This same principle might be applied to other parts of the study area.

The search for and analysis of data that preceded the writing of this report showed the critical need of adequate data. Topographic maps are needed for land-form and geologic analysis, determination of depth to aquifers and water, and locating precisely points of interest. Stream-gaging stations should be located only after proper consideration of the geology so that the data provide not only the information needed about the flow of the rivers but also indicate the relationship of the streams to the aquifers that they cross. More tests of all the aquifers are needed at more places in order to determine the ability of the aquifers to store and transmit ground water. Additional geologic data are needed to locate precisely the faults and other structural features not readily apparent at land surface that affect the occurrence and movement of ground water.

Sufficient data are lacking on which to make a more precise estimate of the safe yield of any of the aquifer systems. Ground-water use in some parts of the study area has increased at a greater rate than the national increase and will probably continue to do so. The rate at which use is increasing is greater than the rate at which knowledge is accumulating. If this trend continues, some areas may be confronted with problems before the data necessary to solve them have been obtained.

Although water law has not been considered in this report, it must be considered before the water resources can be managed properly and legally. For example, in the Beaufort area of South Carolina, just outside the study area near Savannah, Ga., it has been proposed that a water shortage be alleviated by importing water from the Savannah River into an adjacent river basin. The problem is typical of what might be expected along the Atlantic coast of the study area in future years. The transfer of river water to Beaufort would not be legal under common law. On the other hand, however, pumpage at Savannah has diverted ground water that formerly flowed to the Beaufort area and has aggravated the water shortage at Beaufort. The States have no laws to cover this situation.

The proper management of water resources in the study area will permit the maximum use of the total available water. It will result in the diversion of water from one river basin to another. The lowering of water levels in aquifers can divert the flow of ground-water discharge from the streams and induce additional recharge to the ground from the streams. Only with adequate knowledge can we control water resources wisely.

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