WATER-SUPPLY POTENTIAL OF THE FLORIDAN AQUIFER SYSTEM IN THE COASTAL AREA OF GEORGIA--A DIGITAL MODEL APPROACH

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Department of Natural Resources
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ILLUSTRATIONS
[Plates are in pocket]

TABLES

CONVERSION FACTORS, ACRONYMS, AND VERTICAL DATUM

Multiply	*by*	*to obtain*
Length		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (L)
inch per square foot (in/ft^2)	273.3	millimeter per square meter (mm/m^2)
inch per acre (in/acre)	62.76	millimeter per hectare (mm/ha)
Flow		
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Transmissivity		
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/s)
Hydraulic Conductivity		
foot per day (ft/d)	0.03048	meter per day (m/d)

ACRONYMS

EPD, Environmental Protection Divison
GDNR, Georgia Department of Natural Resources
GGS, Georgia Geologic Survey
RASA, Regional Aquifer-System Analysis
RMSE, root-mean-square error
USGS, U.S. Geological Survey

VERTICAL DATUM

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)-- a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

A water-resources management tool has been developed that simulates the effects of ground-water withdrawal from the Floridan aquifer system in the coastal area of Georgia. The management tool consists of (1) a large-scale regional model; (2) a more detailed, subregional model that covers the coastal counties of Georgia; and (3) a highly detailed model that covers the Glynn County, Georgia area. These models were coupled into a multi-model management tool and used to identify areas where future water supplies can be developed in the Floridan aquifer system.

The multi-model management tool can be used as an aid in analyzing alternative plans for ground-water withdrawal such as increased pumpage based on projections of population growth and industrial water-use demands. Upward intrusion of saltwater and lateral encroachment of seawater locally constrain the ground-water availability of the aquifer system.

Saltwater intrusion is occurring in Brunswick, Georgia and seawater is encroaching at nearby Hilton Head Island, South Carolina. The Georgia Department of Natural Resources, Environmental Protection Division, intends to minimize these occurrences. To do so, additional head declines would need to be negligible in these areas.

An evaluation of the potential of the Floridan aquifer system (primarily the Upper Floridan aquifer) in the coastal area of Georgia to supply additional water indicates that under 1985 conditions and imposed constraints, the potential for increased ground-water withdrawal is limited. A map was constructed to delineate areas of ground-water-development potential for the Upper Floridan aquifer throughout the coastal area of Georgia. The procedure involved model simulations at various locations, independent of each other, and analysis of the effect on the head declines in the areas of interest. After each simulation, the rate of withdrawal was estimated and another site was tested. The development potential ranges from nearly zero to more than 5 million gallons per day.

The largest amount of water may be withdrawn from the aquifer in the areas of Charlton, western Brantley, and western Camden Counties. However, because the transmissivity is greater than 250,000 feet squared per day in that area, increased pumpage there probably would result in a shallow, but laterally extensive cone of depression. Even with small increases in pumpage, the cone of depression probably would extend to areas of saltwater intrusion in Brunswick. Only in the northern part of Bulloch and Screven Counties the Floridan may supply more than 5 million gallons per day without affecting those areas of saltwater intrusion and seawater encroachment. The areas of least development potential are Glynn and southern McIntosh Counties, because of the constraint related to saltwater intrusion in the Brunswick area, and Chatham and southern Effingham Counties, because of the constraint of seawater encroachment at Hilton Head Island.

INTRODUCTION

The Floridan aquifer system is the major source of water supply in the coastal area of Georgia. Withdrawal of water from the aquifer system began more than 100 years ago and by 1985, the aquifer system was supplying about 380 million gallons per day (Mgal/d) primarily to two major cities and to a number of large industries in the coastal area (Turlington and others, 1987). This growth in both industry and population, and the corresponding demand for large amounts of ground water from the Floridan aquifer system, has resulted in a general decline in the potentiometric surface of the Upper Floridan aquifer in the region and a substantial decline near some pumping centers. Ground-water withdrawal from the Upper Floridan aquifer in Georgia, as well as in adjacent parts of South Carolina and Florida, has resulted in both upward intrusion of saltwater and lateral encroachment of seawater locally.

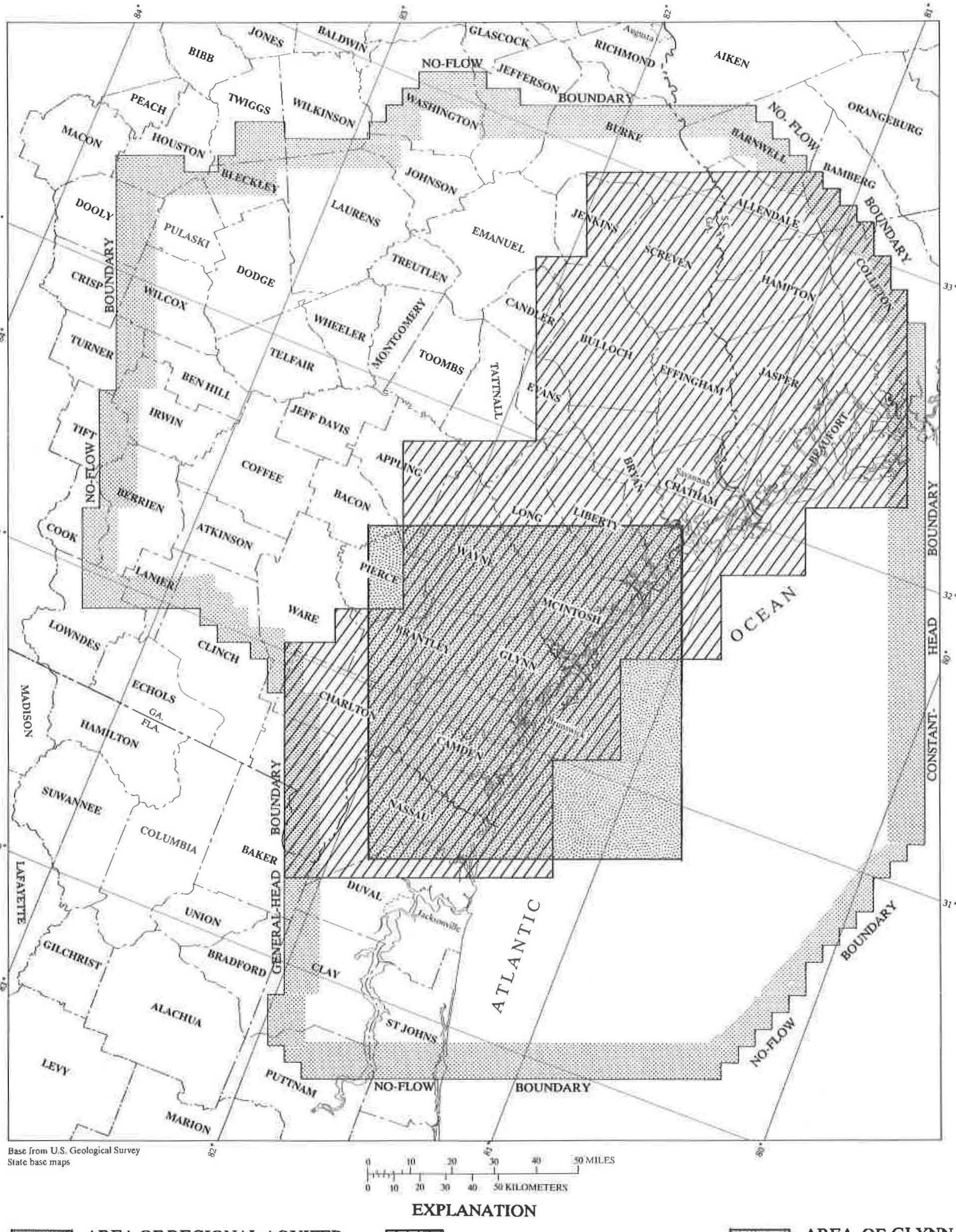
The concern by both State and local officials about potential decreases in the availability of ground water and further saltwater intrusion and seawater encroachment at places in the coastal area indicates the need for comprehensive management and protection of the aquifer. The Georgia Department of Natural Resources (GDNR), Environmental Protection Division (EPD), is the State agency having statutory authority to regulate water use through a permitting system. This system requires permits for all withdrawal of surface water or ground water that exceeds 100,000 gallons per day (gal/d). It became apparent that some limitations on additional withdrawal from the Floridan aquifer system were appropriate in some, but not all, parts of the coastal area in Georgia to protect the quality of public water supplies. The Georgia Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey (GGS), in cooperation with the U.S. Geological Survey (USGS), initiated a program for gathering additional hydrogeologic data as well as the development of digital simulation models to aid EPD in developing a state-of-the-art ground-water management system.

The U.S. Army Corps of Engineers, in cooperation with State, local and other Federal agencies, conducted water-resource management studies of the two largest metropolitan areas in the coastal area of Georgia. The study in the area of Glynn County (fig. 1), completed in January 1987 (U.S. Army Corps of Engineers, 1987), and the study in the area of Chatham County, completed in December 1983 (Bernard Johnson, Inc., 1983), were conducted to evaluate, among other things, the existing water-supply problems and to plan for future increases in water demands. Both studies utilized digital models to analyze various possibilities for future management of the local ground-water supply. The reader is referred to Randolph and Krause (1990) and Randolph and Krause (1984) for detailed discussions of these two studies.

The need for an areally extensive management model of the coastal area of Georgia became evident as the demand for ground water increased throughout the coastal area and the effects of pumping in the Savannah and Brunswick areas began to interact. A steady-state, ground-water flow model was designed as part of the Regional Aquifer-System Analysis (RASA) of the Floridan aquifer system (Krause and Randolph, 1989); and henceforth, is referred to as the RASA model (fig. 2). The RASA model covers the coastal area of Georgia and adjacent States, but the large scale of the grid blocks (16 mi^2) does not offer enough detail for use in comparing alternative water-use plans in areas of local interest.

A more site-specific model of the Floridan aquifer system in the coastal area was designed from the RASA model. This steady-state, finer-mesh model, which covers the entire coastal area (fig. 2), and henceforth, is referred to as the coastal model, was conceived for the current study. The coastal model is based on the RASA model and is dependent on that model for its boundaries. Development of the coastal model resulted in a coupled model that functions to simulate the flow system at the regional and subregional scale. A summary of the hydrogeologic setting of the Floridan aquifer system, and a discussion of the development of the coastal model and the

Figure 1.--Location of study area, model area, and structural features.



EXPLANATION

AREA OF REGIONAL AQUIFER-SYSTEM ANALYSIS MODEL

AREA OF COASTAL MODEL

AREA OF GLYNN COUNTY MODEL

Figure 2.--Model boundaries for the Regional Aquifer-System Analysis, coastal, and Glynn County models.

interaction of that model with existing models at other scales, are included as supplements I and II, respectively, at the end of this report.

Further, the subregional model developed as part of the U.S. Army Corps of Engineers' Brunswick Area Water Resources Management Study (U.S. Army Corps of Engineers, 1987), was similarly coupled with the large-scale, regional RASA model, which resulted in a multi-model-management tool. The large-scale, regional RASA model, the more detailed, subregional coastal model, and the highly detailed subregional model of Glynn County, Georgia area (henceforth, called the Glynn County model; fig. 2) interact to provide simulations of the aquifer system at the scales appropriate to address a wide range of management objectives.

Purpose and Scope

The purpose of this report is to evaluate the potential of the Floridan aquifer system in the coastal area of Georgia to meet future water-supply demands, and to assess four hypothetical ground-water-development alternatives.

This investigation includes the development of a multi-model management tool that simulates the effect of pumping on ground-water levels in the coastal area. The effects caused by various ground-water withdrawal scenarios are evaluated and the results presented in a map showing ground-water-development potential. The development potential was based on the constraint that water-level decline would be negligible in areas of known saltwater intrusion at Brunswick, Ga., and seawater encroachment at Hilton Head Island, S.C.

Study Area

The principal area of interest encompassed by the study includes all the major areas of ground-water development of the Floridan aquifer system in the coastal area of Georgia. This includes the six coastal counties and seven adjacent counties in Georgia (fig. 1). The model area, however, was extended beyond the study area to include the adjacent coastal counties of South Carolina and northeastern Florida, several counties west of the area of primary interest, and up to 20 mi offshore. This was done to simulate the effect on the ground-water flow system at natural hydrologic boundaries located outside the study area. The total area simulated by the coastal model is 14,016 mi^2. The areal extent of the study area is 7,243 mi^2 (fig. 2).

Previous Investigations

The hydrogeology of the Floridan aquifer system has been investigated extensively in the coastal area of Georgia and adjacent States. Among the more comprehensive investigations that include the area of interest are those by Hayes (1979) and Spigner and Ransom (1979) in the low country of South Carolina; Counts and Donsky (1963) in the Savannah area; Krause (1972) in the Liberty-McIntosh Counties, Ga., area; Maslia and Prowell (1990) in the Glynn County area; and Brown (1984) in the Nassau County, Fla.-Camden County, Ga., area. Krause and Randolph (1989) and Clarke and others (1990) describe the Floridan aquifer system and adjacent systems for the entire coastal area of Georgia.

Ground-water-flow models of the Floridan aquifer system have been devised for many areas along the coast of Georgia and adjacent States. A model of southeast Georgia and adjacent parts of Florida and South Carolina (the RASA model) was designed by Krause and Randolph (1989). The Savannah, Ga.-Hilton Head Island, S.C., area has been modeled by Randolph and Krause (1984) and Smith (1988) and a model of the Glynn County area was developed recently by Randolph and Krause (1990).

WATER-SUPPLY POTENTIAL

Although the Floridan aquifer system is being used extensively in places along the Georgia coast, in other areas, the aquifer system can support additional ground-water withdrawal without detrimental effects. The multi-model management tool, which consists of the coupled ground-water-flow models, was used to evaluate the potential of the Floridan aquifer system in the coastal area of Georgia to sustain additional ground-water development. The ability of the model package to simulate water-level changes that are likely to result from future withdrawal from the aquifer system enables State regulators to evaluate ground-water-use permit applications and decide whether such withdrawal, if permitted, will adversely affect the aquifer or other users. For a complete description of the multi-model management tool, see Supplement II.

Ground-water availability was evaluated to identify areas where additional ground-water withdrawal may be feasible and to estimate the maximum quantities of additional water available. Using the multi-model-management tool to evaluate the ground-water resource potential of the coastal area, the manager can obtain the information needed to help make appropriate decisions on management issues such as water-use permitting necessary for the effective management of ground-water resources in the area.

The results of the simulations were used to produce a map that delineates areas having potential for developing additional ground-water supplies from the Upper Floridan aquifer (fig. 3). The simulations of hypothetical pumping schemes were used as a guide for indicating, in general, the response of the Upper Floridan aquifer to such pumping. The Lower Floridan aquifer is not considered to be an alternative source of water in the coastal area because of its limited areal extent, its proximity to saline water, and because of the comparatively high cost of constructing wells in the deeper strata. The multi-model-management tool cannot be used to quantify the vertical and lateral movement of saline and brackish water; however, the results can be used to infer the potential for saltwater intrusion and seawater encroachment as a result of a particular pumping stress and its consequent water-level decline.

The constraint or limitation to increased ground-water pumping primarily is the decline in water level caused by the increase in pumping in areas where saltwater intrusion and seawater encroachment have been documented or the potential is high. The two areas where these constraints exist are in the vicinities of Brunswick, Ga. and Hilton Head Island, S.C.

Vertical intrusion of saltwater from the Fernandina permeable zone through the rest of the Lower Floridan aquifer and into the Upper Floridan aquifer is thought to occur at two locations in Brunswick (fig. 4, and refer to discussion in Supplement I--Hydrogeologic Setting). Any additional water-level decline at these two locations would increase the rate of vertical intrusion of saltwater and lateral encroachment of seawater.

The lateral encroachment of seawater in the area of the north end of Hilton Head Island, S.C., was estimated (in 1984) to be occurring at the rate of approximately 50 to 80 ft/yr (Smith, 1988). Increased water-level decline in this area would increase the rate of lateral encroachment of seawater beneath Hilton Head Island, S.C.

The three sites corresponding to the two locations of saltwater intrusion in Brunswick and of seawater encroachment at Hilton Head Island were identified and assigned to nodes in the model (called indicator nodes). The locations of the indicator nodes are shown in figure 3. Because it is the intent of EPD to avoid any further increase in saltwater intrusion or seawater encroachment caused by increased pumping, water-level declines also would need to be avoided.

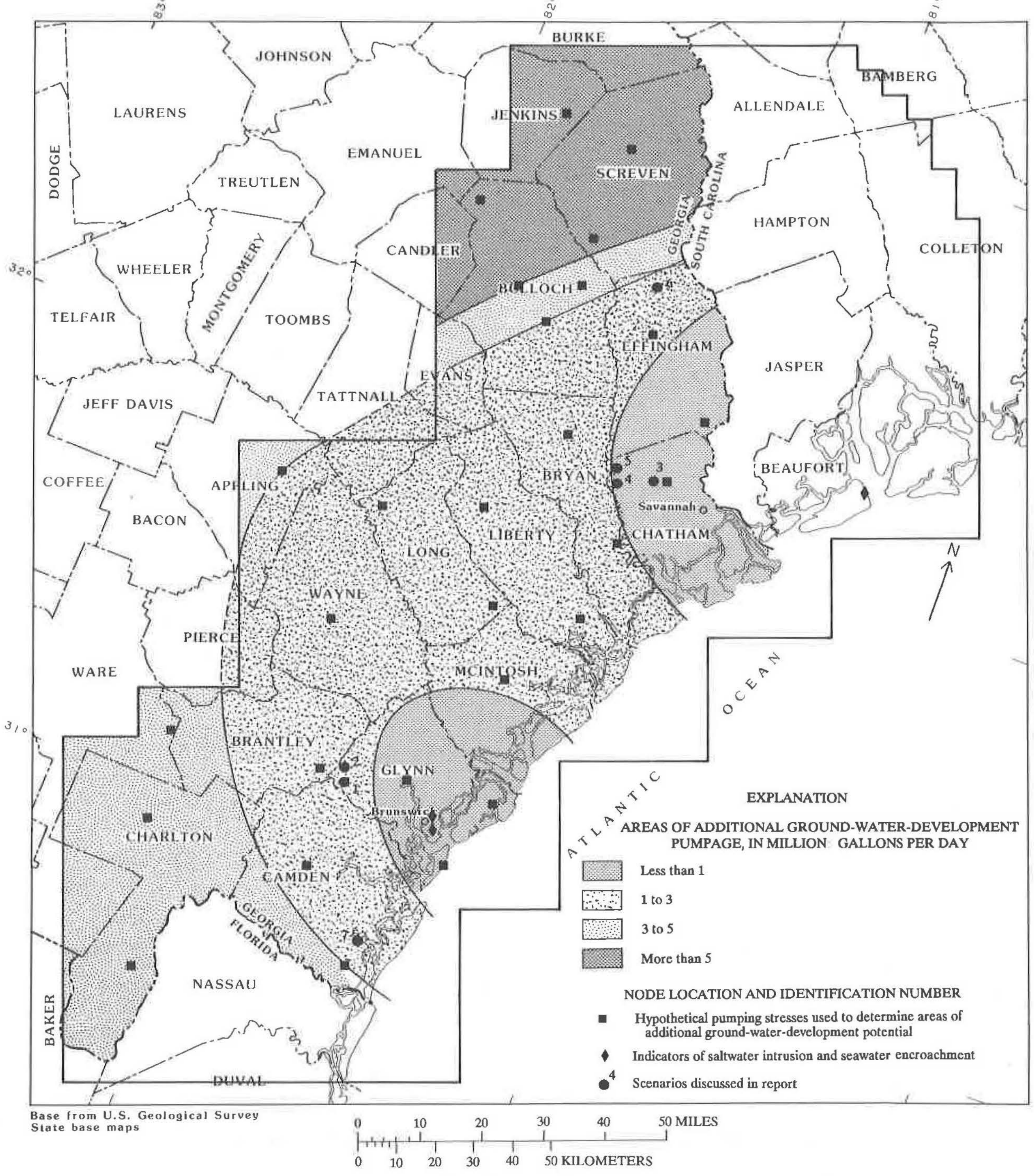


Figure 3.--Estimated water-supply potential of the Upper Floridan aquifer in coastal Georgia.

EXPLANATION

LOCATION AND ORIENTATION OF FAULTS ARE SPECULATIVE

U/D — INFERRED MAJOR FAULT--U, upthrown side; D, downthrown side

—— INFERRED ACCESSORY FAULT

—50— LINE OF EQUAL CHLORIDE CONCENTRATION--Interval in milligrams per liter

• INFERRED LOCATION OF POINT SOURCE OF SALTWATER INTRUSION

Figure 4.--Inferred faults and chloride concentrations in the Upper Floridan aquifer, Brunswick, Georgia area, 1985. Modified from Maslia and Prowell (1990)

Ground-water withdrawal was considered acceptable if the water-level decline was less than 0.05 ft at the three indicator sites. (Because there is some numerical error involved in any simulation, it is difficult to simulate an absolute zero decline; thus, the value of 0.05 ft was adopted as "no-change" or zero decline.) If a simulation resulted in "no change," then the pumping rate at that site was increased, another simulation was performed, and the results were analyzed.

The areas of ground-water availability in figure 3 were based on the results of single-node, independent simulations for 28 sites throughout the study area. Each simulation involves a single location where hypothetical pumping stress is tested. The effect of each withdrawal on the head declines at the indicator nodes is analyzed, and the development potential is estimated.

Evaluation of Ground-Water Availability

The water-supply potential of the Upper Floridan aquifer to meet future demands was arbitrarily divided into four ranges of acceptable increases in pumpage--areas where ground-water availability is represented by potential increases in pumpage of:

- o less than 1 Mgal/d,
- o 1 to 3 Mgal/d,
- o 3 to 5 Mgal/d, and
- o greater than 5 Mgal/d.

The maximum withdrawal rate was not estimated from the simulations, and therefore, is not shown on the map in figure 3.

The map showing ground-water availability (fig. 3) shows the estimated quantity of additional ground-water withdrawal that the Upper Floridan aquifer can reasonably support from pumping at a single site, or grid block of 4 mi^2 area. The actual potential for such a site may be more than the quantity expressed on the map if the water were derived from both the Upper and Lower Floridan aquifers. It is important to note that if any substantial change from the current hydrologic flow system occurs, the hydrologic regimen would change from that used to construct figure 3, and the availability of ground water could be different than that shown on the map. The new pumpage data would have to be incorporated into the model, the new steady-state condition would be simulated, and a new availability map then could be produced. Although 1985 conditions were used to construct the map, ground-water-level and limited pumpage data on file for 1990 indicate that since 1985 the change in the flow system has been negligible.

Also, the ground-water availability, or the maximum development potential of each area, is that quantity of pumpage from a single well, or more than one well in a single node. It does not represent the total quantity of water that could be withdrawn from that area. For example, in the area where ground-water availability ranges from 1 to 3 Mgal/d, the maximum increased pumpage from a single well, or from more than one well in a single node, is 3 Mgal/d. However, it may be possible to develop more than 3 Mgal/d if the wells are optimally located with regard to the hydraulic conditions and water-quality constraints as discussed in previous sections. Thus, a total of 4 Mgal/d may be developed from within the area--for example 2 Mgal/d from Camden County and 2 Mgal/d from northern Effingham County--both within the area of 1 to 3 Mgal/d development potential. Similarly, the total maximum development potential in the area of less than 1 Mgal/d may be greater than 1 Mgal/d if more than one well is used and the wells are optimally located.

The area where ground-water availability is greater than 5 Mgal/d as depicted on figure 3 lies in the northern part of the study area away from the constrained sites and where transmissivity is comparatively low. This area is located above the Gulf Trough, where aquifer heads are the highest, and where water-quality problems are not known to exist.

The area where ground-water availability ranges from 3 to 5 Mgal/d includes the counties of Charlton, western Brantley, and western Camden, in the southwestern part of the study area. Here, additional ground-water withdrawal of as much as 5 Mgal/d probably could be developed without detrimental effects to the aquifer or the water quality. Based on the aquifer characteristics in this area and on simulation, this area would extend north and westward beyond the limits of the model area. The ground-water-development potential of this area was expected to be higher than 5 Mgal/d. However, this is an area where the transmissivity is the largest and, therefore, the cone of depression caused by additional pumpage would be shallow and laterally extensive. Even small increases in pumpage could result in water-level declines that would extend to the areas of saltwater intrusion at Brunswick. Another area where ground-water availability ranges from 3 to 5 Mgal/d is in central Bulloch and southern Screven Counties in the northern part of the study area.

The area where ground-water availability ranges from 1 to 3 Mgal/d is in the area surrounding Glynn and Chatham Counties, where the major pumping centers are located.

The two areas where ground-water availability is less than 1 Mgal/d are in and adjacent to the cities of Brunswick and Savannah. The Brunswick area includes all of Glynn County and the southern part of McIntosh County, and the Savannah area includes Chatham County extending to the southern part of Effingham County. Increased ground-water withdrawal in this area, could lower ground-water levels and possibly could accelerate existing saltwater intrusion or seawater encroachment, or both.

Results of Hypothetical Simulations

Results of four simulations made to evaluate possible alternative management schemes are described below.

Glynn County

This simulation addresses a site in western Glynn County, which is a possible location for providing additional water supply to meet water-supply demands, primarily for the city of Brunswick.

According to the map shown in figure 3, it would not be possible to withdraw much additional water in the Brunswick area; thus, one possibility might be the redistribution of pumpage in this area.

A simulation was made to evaluate the effects of moving 20 Mgal/d (about 40 percent of the total 1985 pumpage from the areas of heaviest industrial pumpage in Brunswick) to a new well field (two sites, each supplying 50 percent of the total pumpage) about 10 mi west of the city of Brunswick (locations 1 and 2, figure 3). Simultaneously, at the same locations, the simulation included an additional withdrawal of 10 Mgal/d to satisfy future demands in the Brunswick area. The effect of the redistribution and addition of pumpage on the water levels at the indicator nodes (locations of saltwater intrusion and seawater encroachment) was evaluated. The results of this pumping scheme in the area of saltwater intrusion indicate that there would be about a 6-ft water-level rise at the northerly indicator node, and a 4-ft water-level rise at the southerly indicator node. The water-level decline at the proposed wells is about 14 ft. The higher water levels in the Brunswick area most likely would reduce the saltwater intrusion in Brunswick. In addition, the effect on the water-level at the north end of Hilton Head Island is negligible; thus, there probably would be no change in the seawater encroachment with this pumping scheme (see figure 5).

Chatham County

A similar simulation was made for the Chatham County area in which there also was a redistribution and addition of pumpage. In this case, it was assumed that 10 Mgal/d (about 40 percent of the 1985 total pumpage in the areas of heaviest industrial pumpage in Savannah) were moved to a new well field approximately 10 mi northwest of the city of Savannah (location 3, figure 3). This new site was to produce an additional 5 Mgal/d. The hypothetical increase in pumpage of 15 Mgal/d at the new well field and decrease in

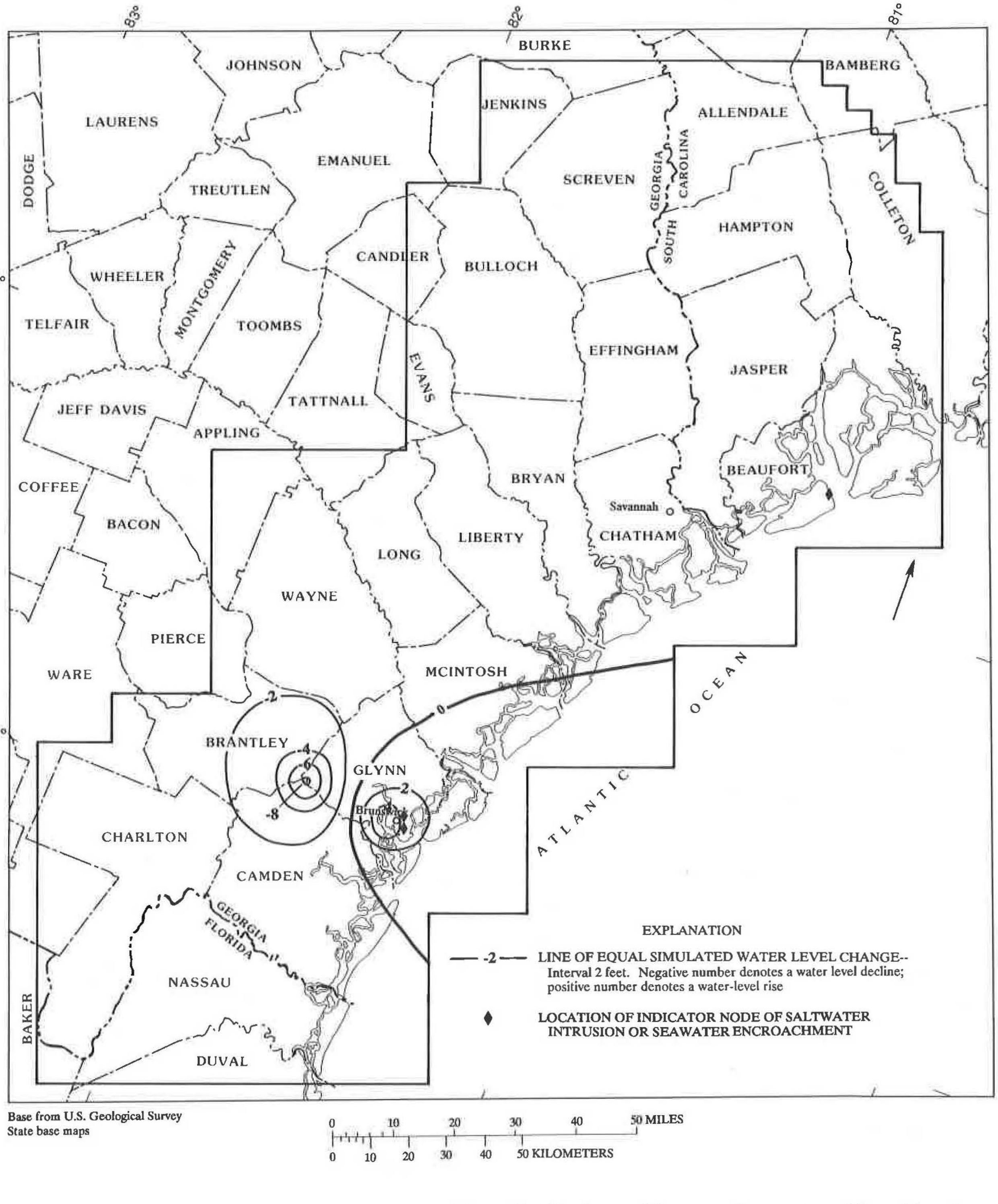


Figure 5.--Simulated water-level change caused by redistribution and increased pumpage, Glynn County.

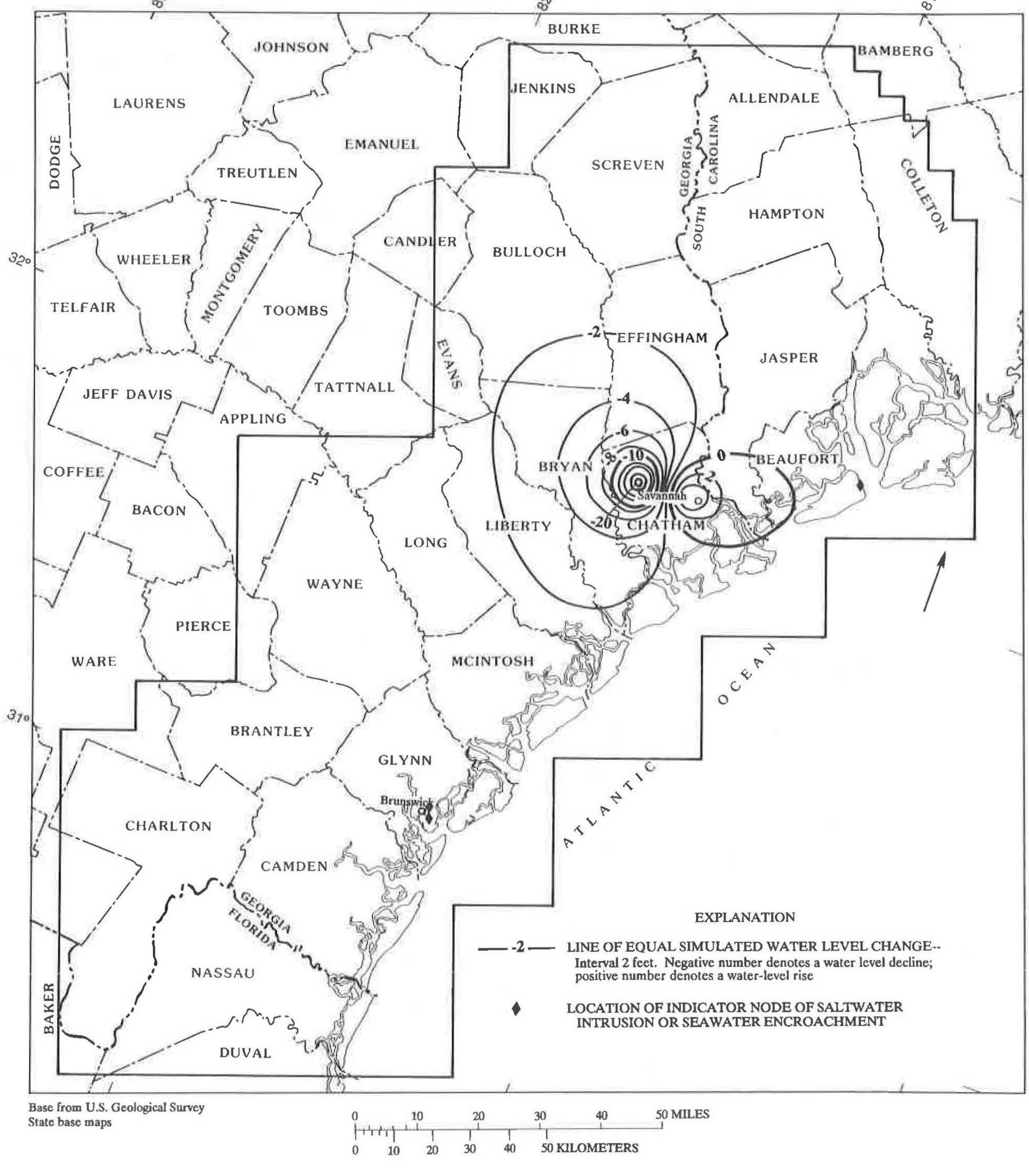


Figure 6.--Simulated water-level change caused by redistribution and increased pumpage, Chatham County.

10 Mgal/d in Savannah was simulated and resulted in a water-level decline for both saltwater-intrusion indicator nodes of about 0.1 ft in Brunswick. The water-level decline at the seawater-encroachment indicator node was 0.03 ft and at the proposed well field, about 37 ft (fig. 6).

Glynn and Chatham Counties

The third simulation was a combined strategy for Chatham and Glynn Counties in which there was redistribution and addition of pumpage in both counties.

This scenario considered simultaneously (1) moving 20 Mgal/d from Brunswick to a new well field 10 mi west of the city (location 1, figure 3), and additional pumpage of 10 Mgal/d; and (2) moving 10 Mgal/d from Savannah to a new well field (two wells, each pumping 50 percent of the total) 10 mi northwest of the city (locations 4 and 5, figure 3), and additional pumpage of 10 Mgal/d. This hypothetical pumping scheme resulted in water-level rises at the indicator nodes for saltwater intrusion in Brunswick, of about 5 ft at the northerly node and 3 ft at the southerly node. The effect on the water level at the north end of Hilton Head Island was negligible, and the water-level decline at the proposed well fields were about 37 ft for Chatham County and 21 ft for Glynn County (fig. 7).

Because the constraints are inflexible, and are applied in two widely-spaced locations, the redistribution and addition of pumpage in both critical areas seems to be a possible approach to meet future water demands in the coastal area, without further increases in saltwater intrusion and seawater encroachment.

Effingham and Camden Counties

The potential-development areas shown in figure 3 were drawn based on single well locations. If the wells are optimally spaced, the potential of development may increase, as discussed in the "Ground-Water Availability" section.

This simulation was made for two sites located in the 1 to 3 Mgal/d area and 4 Mgal/d of total pumpage. One well is located in northern Effingham County (location 6, figure 3) with a pumpage rate of 2 Mgal/d; and the other at southern Camden County (location 7, figure 3) also pumping 2 Mgal/d.

Results from the simulation indicate that the effect in the water-level decline at any of the indicator nodes--saltwater intrusion or seawater encroachment--is negligible (less than 0.05 ft). On the other hand, the effect of the pumpage on the proposed wells is about 10 ft at Effingham County and 2 ft at Camden County (fig. 8.) Thus, it may be feasible to increase the total pumpage to 4 Mgal/d (fig. 3), if the location and pumpage of each well is the one mentioned above.

SUMMARY AND CONCLUSIONS

A multi-model-management tool was developed by coupling three ground-water-flow models that covers part or all of the study area in coastal Georgia. The use of the multi-model results in simulations that are more site-specific and address the flow system changes at the scale of interest.

The purpose of developing such a tool is to provide assistance in the evaluation of future ground-water development involving withdrawal from the Floridan aquifer system in the Coastal area of Georgia.

Sites were chosen in the coastal area of Georgia and hypothetical withdrawals from the Upper Floridan aquifer were simulated at each site to evaluate the potential for increased development in the area, based on the effects that pumpage might have on water levels at known areas of saltwater intrusion in the vicinity of the city of Brunswick, Ga., and on areas of seawater encroachment at the north end of Hilton Head Island, S.C.

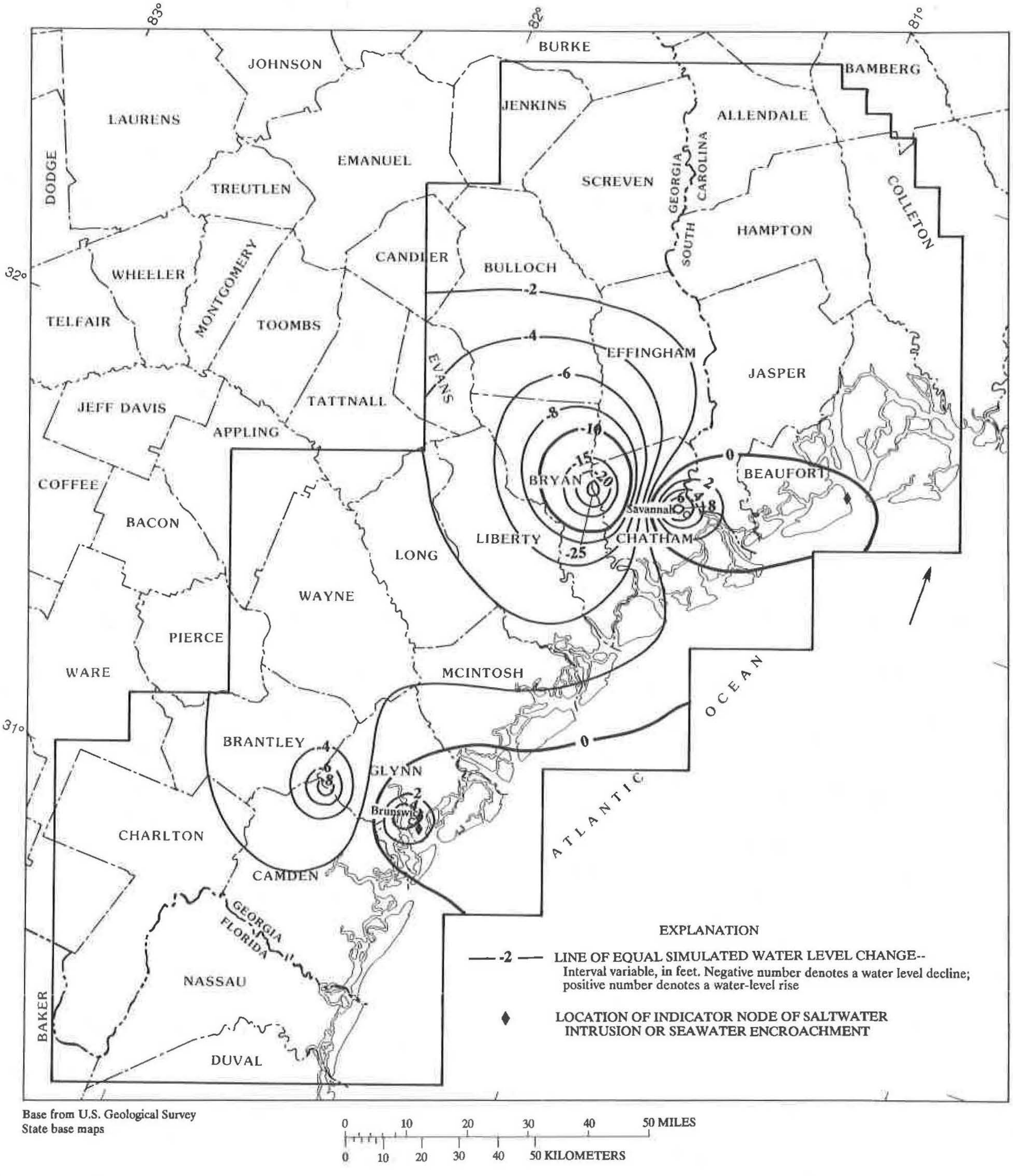


Figure 7.--Simulated water-level change caused by redistribution and increased pumpage, Chatham and Glynn Counties.

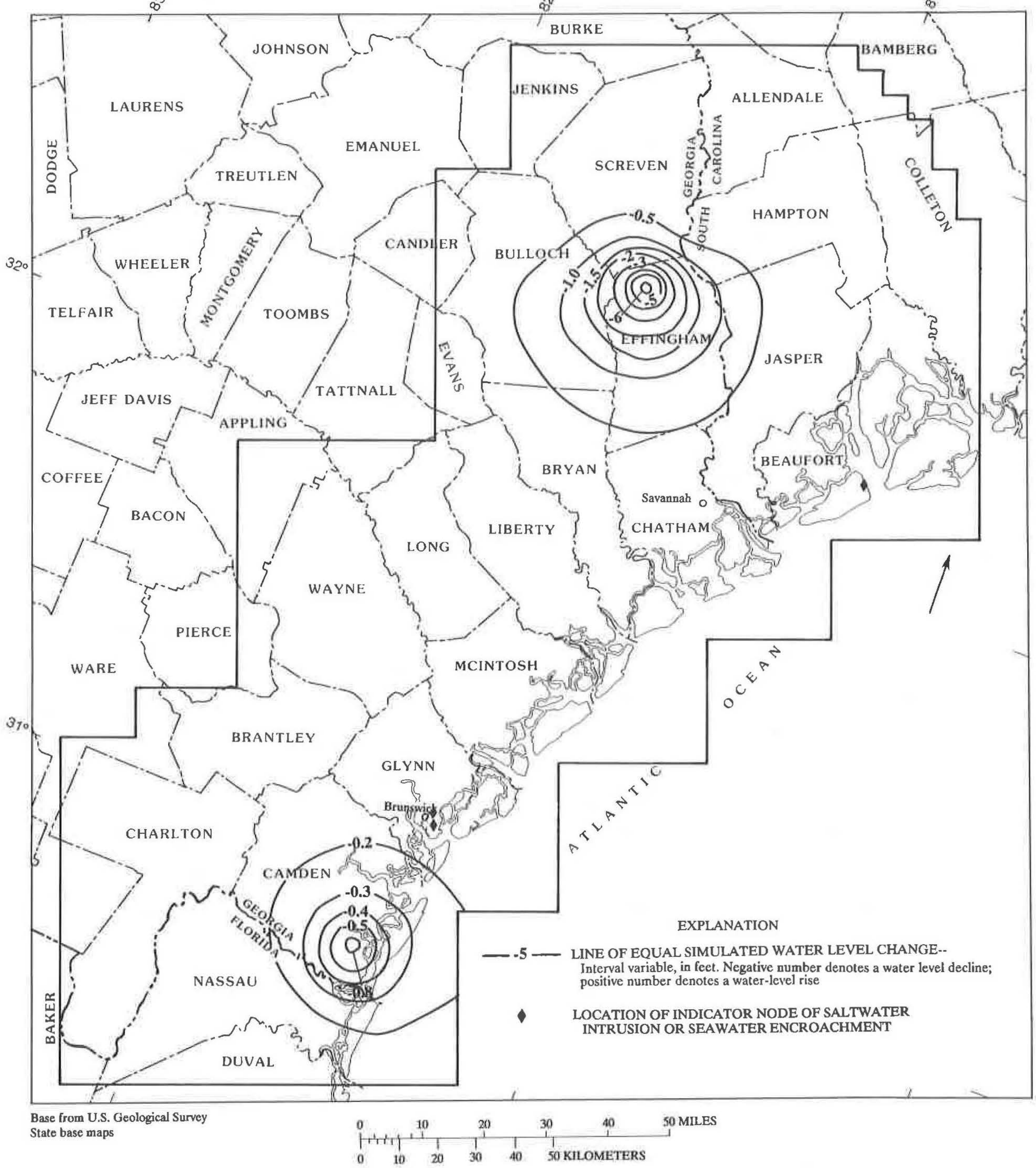


Figure 8.--Simulated water-level change caused by redistribution and increased pumpage, Effingham and Camden Counties.

Results of the simulated hypothetical pumping increases are presented on a map showing ground-water development potential for the coastal area of Georgia. The range of development potential varied from less than 1- to more than 5-million gallons per day. The two areas where withdrawal is limited to less than 1-million gallons per day are Glynn County, the southern part of McIntosh County, and Chatham County and the southern part of Effingham County.

To illustrate the capacity of the multi-model package to be used to evaluate management alternatives, four selected hypothetical simulations within the coastal area are discussed. Hypothetical withdrawal alternatives tested by simulation included redistributing and adding pumpage in (1) Glynn County; (2) Chatham County; (3) in Glynn and Chatham Counties; and (4) increasing pumpage in northern Effingham and southern Camden Counties.

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SUPPLEMENT I -- HYDROGEOLOGIC SETTING

The hydrogeologic framework of the Floridan aquifer system in coastal Georgia and adjacent parts of northeastern Florida and southern South Carolina described in this report is based on a more areally extensive definition of the aquifer system that was developed by Krause and Randolph (1989). Only those parts of the hydrogeologic framework that affect the flow system of the Upper Floridan aquifer are discussed in this report. A discussion of the hydrogeologic setting in adjacent northeast Florida and southern South Carolina is included herein because data and information in those areas are included in the ground-water-flow model, discussed in Supplement II.

The Floridan aquifer system is composed of a predominately carbonate rock sequence that includes limestone and dolomite, and smaller amounts of evaporite, clay, sand, and marl. The aquifer system thickens from less than 100 ft at the northern extent of the study area to more than 2,000 ft downdip in Glynn and Camden Counties, Ga., and in Nassau County, Fla. The aquifer system is more than 2,600 ft thick in the southeastern part of Glynn County, Ga. (Krause and Randolph, 1989).

The Floridan aquifer system is composed of several lithostratigraphic and chronostratigraphic units (fig. 9). However, the aquifers and confining units comprising the Floridan do not necessarily correspond to specific stratigraphic units (Krause and Randolph, 1989).

The Floridan aquifer system is separated into two permeable, water-bearing units throughout most of the study area---the Upper and the Lower Floridan aquifers. In the southern part of the study area, a third permeable unit has been identified as the Fernandina permeable zone (Krause and Randolph, 1989), that is in the lower part of the Lower Floridan aquifer.

Aquifers and Confining Units

Hydrogeologic units of interest are, in descending order (1) the surficial aquifer, (2) the upper confining unit, (3) the Upper Floridan aquifer, (4) the middle semiconfining unit, (5) the Lower Floridan aquifer, (6) the lower semiconfining unit, (7) the Fernandina permeable zone, and (8) the lower confining unit. The confining units within the Floridan aquifer system are termed "semiconfining" to indicate that they are internal to the aquifer system (Miller, 1986).

Surficial Aquifer

The surficial aquifer is present throughout the study area and consists of unconsolidated, well-sorted post-Miocene sand. In some areas, these sands are interbedded with layers of poorly sorted sand, clayey sandy silt, and, at depth, argillaceous limestone. Post-Miocene sediments range in thickness from less than 10 ft to more than 100 ft in the study area (Krause and Randolph, 1989).

Water in the surficial aquifer is unconfined. Generally, the configuration of the water table is a subdued replica of the land surface. The water table is near land surface in low-lying areas, along streams, in marshes and swamps, and generally, in areas along the coast. The water table is deeper in areas beneath topographic highs and where thick deposits of permeable material are found. Water-table gradients are relatively steep along major streams and relatively flat in interstream areas. The surficial aquifer has the potential to recharge the Upper Floridan aquifer where the hydraulic gradient is downward, and is recharged by the Upper Floridan where the hydraulic gradient is upward.

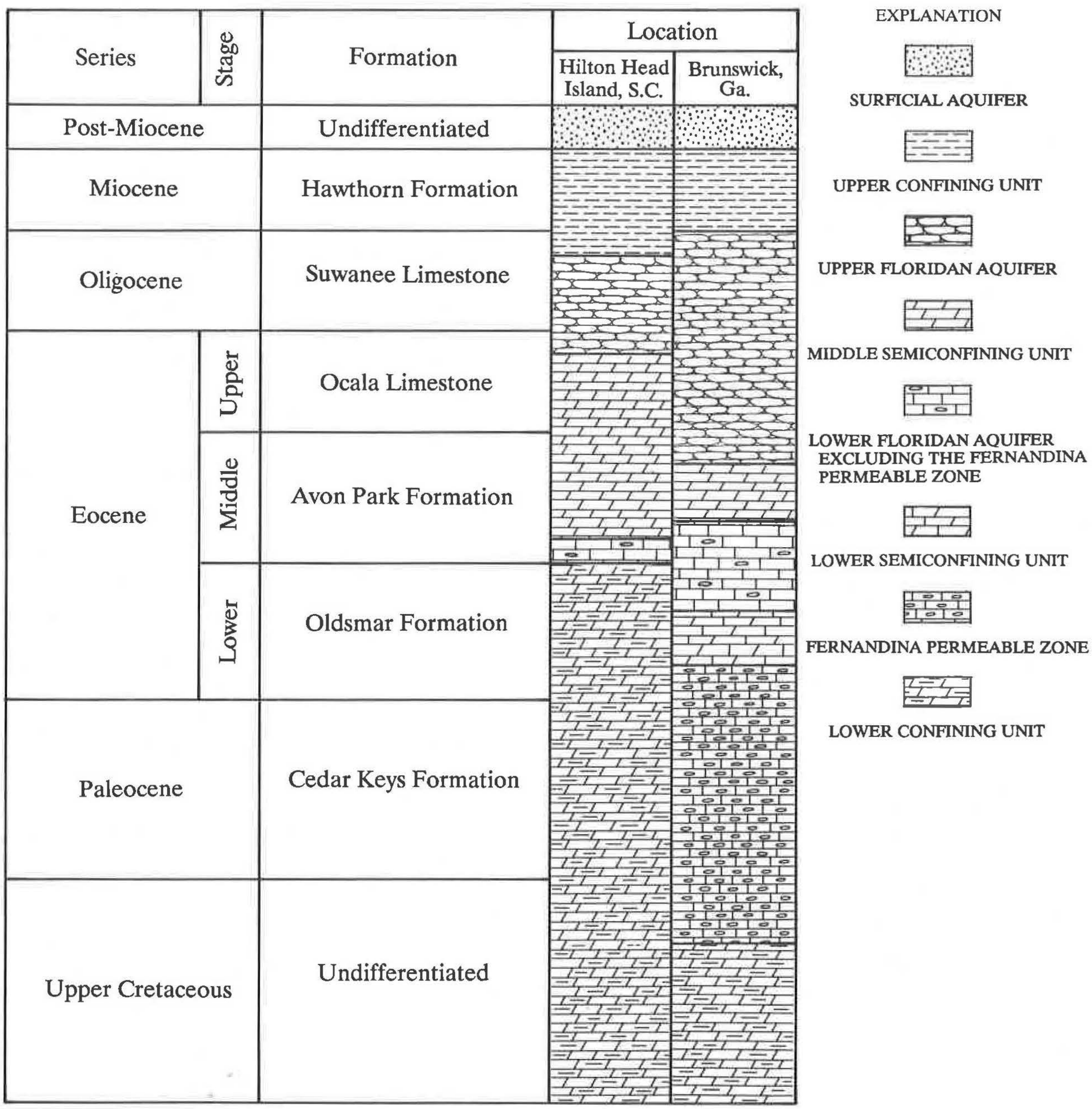


Figure 9.--Relation of geologic and hydrogeologic units , coastal Georgia.

Upper Confining Unit

The upper confining unit underlies the surficial aquifer, and consists of strata between the surficial aquifer and the Upper Floridan aquifer. These strata include not only clay of extremely low permeability, but also interbedded, locally highly phosphatic beds of sand, silt, clay, and sandy clay of moderate permeability from the upper and middle Miocene Hawthorn Formation. (Although this sequence locally includes important aquifers, for the purpose of the evaluation and simulation of the Floridan aquifer system, it is treated as the confining unit overlying the Upper Floridan aquifer). The reader is referred to Clarke and others (1990) for a complete description of the locally occurring aquifers and confining units that occur within the upper confining unit.

The thickness of the upper confining unit ranges from less than 50 ft in northern Screven County and in coastal South Carolina to about 600 ft in Brantley County, Ga., (Krause and Randolph, 1989, plate 6). Scouring action of creeks and estuaries, as well as the additional removal of material by dredging operations, has breached the upper confining unit and has allowed seawater encroachment in the area of Hilton Head Island, S.C., (Duncan, 1972, p. 103; Randolph and Krause, 1984, p. 5).

Data on the vertical hydraulic conductivity of the upper confining unit are not widely available. Vertical hydraulic conductivity of the upper confining unit, as determined by laboratory analyses of geologic cores, ranged from 5 x 10^{-5} ft/d (Wait, 1965, p. 48) to 1.1 ft/d (Wait and Gregg, 1973, table 9) in the Brunswick area. An average vertical hydraulic conductivity of 1.3 x 10^{-3} ft/d was calculated from laboratory analyses of 52 core samples in the Savannah area (Furlow, 1969, p. 23).

Materials that comprise the upper confining unit differ greatly in lithology and permeability throughout the study area, and are complexly interlayered throughout the vertical section. The vertical hydraulic conductivity of these separate layers within the vertical sequence differ by several orders of magnitude. The major controlling factor for the vertical hydraulic conductivity of the sequence as a whole seems to be the thickness of the unit. The hydraulic conductivity is lowest where the unit is thickest (such as in Brantley County), and highest where the unit is thinnest (such as in northern Screven County and in the area of Hilton Head Island, S.C.).

Upper Floridan Aquifer

The Upper Floridan aquifer primarily consists of the Oligocene Suwannee Limestone and the upper Eocene Ocala Limestone and their equivalents (fig. 9). The upper part of the Ocala is fossiliferous and has high effective porosity and permeability. Secondary permeability has developed along bedding planes, joints, fractures, and other zones of weakness, that has made the Ocala Limestone extremely permeable.

Throughout the study area, the Upper Floridan aquifer generally consists of one vertically continuous permeable unit, except in the Brunswick area where two permeable zones exist -- the upper and the lower water-bearing zones (Wait and Gregg, 1973; Gregg and Zimmerman, 1974). These two zones are treated as a single unit (the Upper Floridan aquifer) for this study because of their limited areal extent and the hydraulic connection between them.

The Upper Floridan aquifer ranges in thickness from less than 100 ft in Screven County, Ga., to more than 700 ft in southeastern Camden County, Ga. The aquifer is most productive where it is thickest and where secondary permeability is most developed. Transmissivity values derived from aquifer tests of the Upper Floridan aquifer in the coastal model area range from 4,000 ft^2/d at Hunting Island, S.C. to about 240,000 ft^2/d near Jesup, Ga. (plate 1). Reported well yields of 5,000 to 10,000 gal/min are common in Camden, Wayne, and Glynn Counties, Ga. A more complete discussion of the hydraulic properties of the Upper Floridan aquifer can be found in Krause and Randolph (1989) and Clarke and others (1990).

Middle Semiconfining Unit

The Upper and the Lower Floridan aquifers are separated by the middle semiconfining unit. This unit consists of dense, low permeability, recrystallized limestone and dolomite of the upper part of the middle Eocene Avon Park Formation (Miller, 1986) and the upper Eocene Ocala Limestone. The thickness of the middle semiconfining unit in coastal Georgia ranges from 100 to 300 ft. The permeability of this unit is sufficiently low to effect confinement between the two aquifers and to cause a vertical head gradient. However, the unit is breached locally by fractures and faults in the Brunswick, Ga., area, which enhances the vertical exchange of water between the aquifers (Krause and Randolph, 1989).

The vertical hydraulic conductivity of the middle semiconfining unit is known only from laboratory analyses of five cores obtained from a 100-ft section of dense dolomitic limestone in the Brunswick area. Results of the analyses indicate that the vertical hydraulic conductivity ranged between 4.0×10^{-6} and 5.4×10^{-5} ft/d (Wait, 1965). The hydraulic conductivity is substantially greater where fractures and faults occur.

Lower Floridan Aquifer

The Lower Floridan aquifer is a permeable unit occurring chiefly in the middle Eocene Avon Park and Lower Eocene Oldsmar Formation (fig. 9). These units are less fossiliferous and more dolomitic than those rocks comprising the overlying Upper Floridan aquifer. Permeability in the Lower Floridan aquifer has developed along bedding planes and other zones of weakness. This aquifer is not a substantial contributor of water to wells in Georgia that tap the entire thickness of the Floridan aquifer system. Data on the Lower Floridan are limited because few wells penetrate this aquifer.

The thickness of the Lower Floridan aquifer in the coastal area ranges from less than 100 ft in coastal South Carolina to more than 2,000 ft in southern Glynn County, Ga., where the aquifer contains two permeable zones (Miller, 1986). The depth to the Lower Floridan aquifer below land-surface ranges from less than 500 ft in coastal South Carolina to greater than 1,400 ft in Glynn County, Ga. Transmissivity generally decreases westward and northward based on thickness data and qualitative estimates of porosity and permeability made from geophysical well logs.

The lower part of the Lower Floridan aquifer in Glynn and Camden Counties, and southwestern McIntosh County, Ga., and in adjacent Nassau and Duval Counties, Fla., contains a highly permeable, cavernous zone called the Fernandina permeable zone (Krause and Randolph, 1989). The thickness of the zone ranges from about 100 ft in the Duval County, Fla., area to more than 500 ft in the Brunswick, Ga., area. The approximate northern extent of the zone is shown in figure 1. The Fernandina permeable zone occurs mainly in the Paleocene Cedar Keys Formation and is separated from the rest of the Lower Floridan aquifer by low permeability rocks of early Eocene age composed of microcrystalline, locally gypsiferous dolomite, and finely pelletal micritic limestone. The vertical hydraulic conductivity of this semiconfining unit is low, except where it has been breached by fractures and faults (Krause and Randolph, 1989).

Little data are available on the water-bearing properties of the Lower Floridan aquifer. The transmissivity of the Lower Floridan aquifer, exclusive of the Fernandina permeable zone, generally decreases from south to north, and is highest in the area of Duval County, Fla., where it is estimated from aquifer tests to be about 300,000 ft^2/d (G.W. Leve, U.S. Geological Survey, written commun., 1979). In the Savannah area, transmissivity probably is less than 10,000 ft^2/d (Krause and Randolph, 1989). Transmissivity of the Fernandina permeable zone is sparse compared to that of the rest of the Lower Floridan aquifer. The relative transmissivity of the zone has been estimated through the use of borehole geophysical logs, that indicate that the Fernandina permeable zone locally is cavernous and has high permeability.

Field data for the lower semiconfining unit between the Lower Floridan aquifer and the Fernandina permeable zone are unavailable. However, an acoustic televiewer log for a well in Glynn County indicates that the unit is fractured, which could provide conduits for the vertical movement of water (Clarke and others, 1990).

The Floridan aquifer system is underlain by the lower confining unit, which consists chiefly of Upper Cretaceous to lower Eocene sediments composed of highly glauconitic, silty, often micaceous sand interbedded with brown lignitic clay (Miller, 1986; Krause and Randolph, 1989). Vertical hydraulic-conductivity data for this unit also are unavailable but are assumed to be low.

Geologic Features Affecting the Flow System

The Gulf Trough is a northeast-trending geologic feature that consists of thick accumulations of clastic sediments and argillaceous carbonate rocks. Within the study area, the Trough traverses Bulloch, Screven, and Effingham Counties, Ga., and probably extends into South Carolina (fig. 1). The Gulf Trough impedes the natural downgradient flow of ground water and locally results in low well yields, low transmissivities, and steep gradients in the potentiometric surface (Krause and Randolph, 1989).

The Southeast Georgia embayment is an east- to northeast-plunging synclinal geologic feature centered in northeastern Florida and southeastern Georgia and extending offshore (fig. 1) (Miller, 1986). Units comprising the Floridan aquifer system are thicker and more deeply buried within the embayment than in surrounding areas, which results in greater thicknesses of the water-bearing zones and thicker confining units.

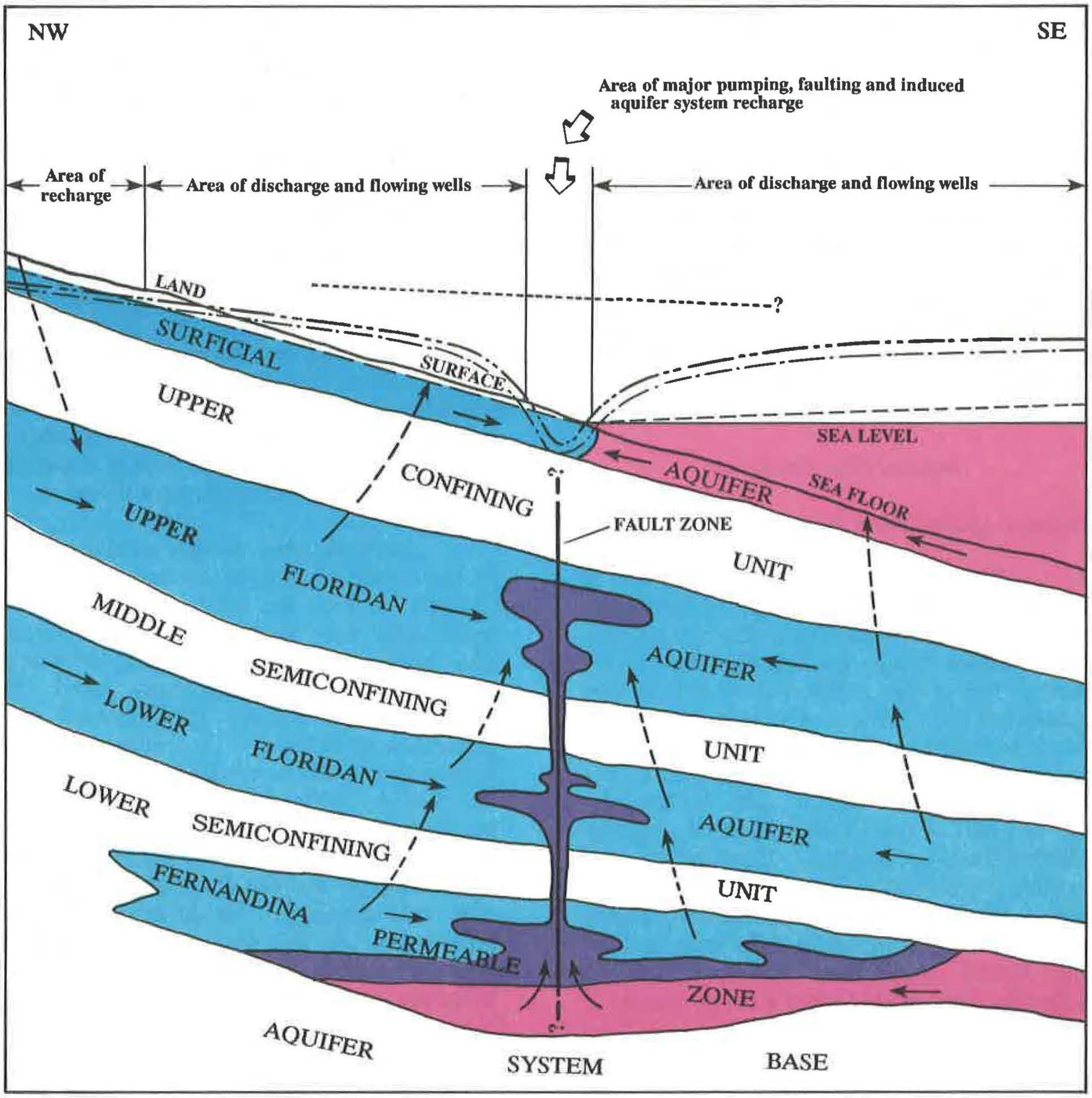
Fracture zones attributed to major inferred northeast-striking faults in the Glynn County area affect the flow system on a more local basis. These inferred faults and their related smaller accessory faults are the most probable vertical conduits through the semiconfining units for vertical migration of saltwater from the Fernandina permeable zone (figs. 4, 10).

SUPPLEMENT II-- DIGITAL MODEL PACKAGE

The technique of coupling two or more ground-water-flow models to simulate an aquifer at different scales is valuable in predicting aquifer response to changing stresses. The multiple scales permit simulation of the flow system with the detail necessary to evaluate the effects of a particular change in stress. The integrity of the prediction is maintained through the simulation of a large part of the flow system that extends well beyond the area of influence of the added stresses.

The multi-model management tool package was developed to simulate the effects of ground-water withdrawal from the Floridan aquifer system in the coastal area of Georgia. The management tool was developed by coupling three ground-water-flow models that cover the Floridan aquifer system in the coastal area of Georgia. The management tool consists of (1) a large-scale regional (RASA) model; (2) a more detailed, subregional (coastal) model that covers the coastal counties of Georgia; and (3) a highly-detailed (Glynn County) model that covers the Glynn County, Georgia area. These models were coupled into a multi-model-management tool and used to identify areas where future water supplies can be developed in the Floridan aquifer system.

The coastal and Glynn County models are aligned with the RASA model, and each grid block is a fraction of the 16 mi^2 grid blocks in the RASA model. This allows for the direct transfer of simulated flows from the RASA model to the coastal and Glynn County models. These simulated flows, internal to the RASA model, function as the specified boundary conditions of the coastal and Glynn County models, and allow these models to function as if they were simulating the flow through the entire area of the large RASA model. The detail of the coastal and Glynn County models, coupled



EXPLANATION

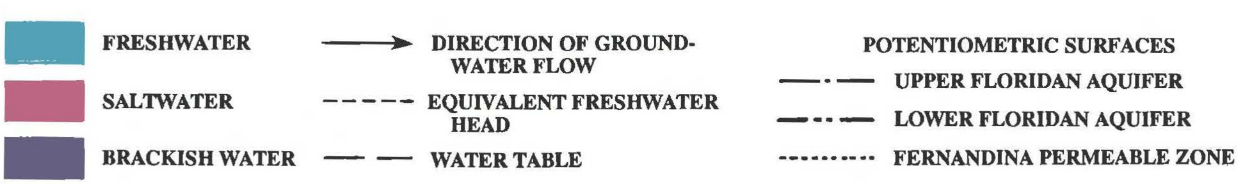


Figure 10.--Idealized section of the Floridan aquifer system under 1985 conditions showing the effects of faulting on the ground-water-flow system. Modified from Krause and Randolph (1989).

with the boundary conditions provided by the large-scale RASA model, results in simulations that are more site-specific and address the flow-system changes at the scale of interest.

Model Design

The numerical models were designed within the structure of a quasi-three-dimensional, finite-difference computer code documented by McDonald and Harbaugh (1984). The following section gives a description of the three flow models, including boundary conditions, aquifer layering, finite-difference grids, calibration, validation, and sensitivity analysis.

Regional Flow Simulation

Regional Aquifer-System Analysis Model

The multi-model-management tool is based on a three-dimensional, coarse-grid, steady-state model of the aquifer system that was developed as part of the Floridan RASA study. The reader is referred to Krause and Randolph (1989) for a complete description of this model. The large-scale, regional model simulates the northeastern part of the Floridan aquifer system that covers the eastern half of the Coastal Plain of Georgia, southeastern South Carolina and northeastern Florida (fig. 2). The total area covered by the model is approximately 53,250 mi^2. The uniform, finite-difference grid of the RASA model has 52 rows and 64 columns. Each grid block is 4 mi on a side, 16 mi^2 in area.

The RASA model simulates lateral flow and water-level change in the Upper and the Lower Floridan aquifers. The Upper Floridan aquifer is overlain by the upper confining unit, through which water is simulated as leaking vertically in either direction. The upper confining unit is overlain by the water-table or surficial aquifer, where the water level is variable areally, but does not fluctuate significantly with time and functions as a source or sink to the Upper Floridan aquifer. Thus, in the RASA model, the surficial aquifer is simulated as a constant-head boundary condition.

The middle semiconfining unit between the Upper and the Lower Floridan aquifers is simulated as leaking water vertically in either direction between the two aquifers. The lower semiconfining unit, where present, functions similarly between the Fernandina permeable zone and the rest of the Lower Floridan aquifer.

The Floridan aquifer system is underlain by the lower confining unit, which does not allow flow across it. In the RASA model, the lower confining unit is simulated as a no-flow boundary condition. Where present, the Fernandina permeable zone functions as a source of water to the rest of the Lower Floridan aquifer and is simulated as a constant-head boundary condition.

Laterally, the RASA model extends to the outcrop area in southeastern South Carolina and to the offshore extent of the fresh-water flow system to the east (fig. 2). The southern boundary is simulated by using a constant-head designation, and the southwestern boundary is simulated as a general-head boundary. A general-head-type boundary condition calculates the flow into the RASA model based on the hydraulic gradient from an arbitrary distance outside the model to the first active grid block inside the boundary, and the average transmissivity over that distance. These artificial lateral boundaries are far enough away from the coastal counties of Georgia so that their influence on the areas of interest is minimal.

The RASA model simulates the 1985 conditions as steady state rather than transient. This was based on the observation that no long-term water-level decline is occurring; and thus, no substantial contribution of water to the flow system presently is derived from storage in the aquifer (Krause and Randolph, 1989). Development and simulation of the 1985 conditions using the Glynn County model also indicate that, on a subregional scale, the flow system is in a steady-state condition (Randolph and Krause, 1990).

Subregional Flow Simulations

Coastal Model

The subregional coastal model covers the coastal counties of Georgia and extends into adjacent parts of Florida and South Carolina (fig. 2). The steady-state model simulates an area of about 14,000 mi^2. The model grid is uniformly divided into 84 rows and 74 columns. Each grid block is 2 mi on a side and corresponds to one-fourth of an original RASA model grid block.

The coastal model boundaries coincide with the RASA model boundaries in some areas (fig. 2). Laterally, the outcrop area in southeastern South Carolina and the general-head boundary along the southwestern boundary of both models are coincident. Otherwise, the lateral boundaries are internal to the RASA model and are derived as node-to-node flow during simulations by the RASA model. This type of boundary is referred to herein as the calculated-flow boundary condition. Vertically, the coastal-model boundaries are identical to those of the RASA model.

Glynn County Model

The Glynn County model was designed to gain the greatest resolution in the areas of largest pumping and saltwater intrusion. This required a variable finite-difference grid that had detailed discretization in the Brunswick area to allow for simulation of local flow anomalies, yet of a limited areal extent to keep the size of the model manageable. A detailed description of the Glynn County model design and development is given in Randolph and Krause (1990).

The lateral boundaries of the Glynn County model are completely within the RASA model boundaries, and rely on the RASA model for calculated boundary flows derived during simulation (fig. 2). The Glynn County model grid is variable, but is aligned with the RASA model so that each boundary grid block is a fraction of the original 4-mi face of a RASA grid block. The Glynn County model grid blocks range in area from 16 mi^2 on the four corners of the grid to 0.0625 mi^2 at the center of the grid in the pumping center at Brunswick. The vertical boundaries are the same as those of the RASA and coastal models. The total model area is 6,080 mi^2; about 2,000 mi^2 is offshore (fig. 2).

Model Calibration

The hydraulic characteristics and constraints of the aquifer system were adjusted during the calibration process by addressing the flow system at the scale simulated by the RASA, coastal and Glynn County models. Distributed values of transmissivity and vertical hydraulic conductivity of the coastal model were obtained by transferring calibrated values directly from the Glynn County model, where available, and the RASA model in the other areas. In the final calibration process, the hydraulic parameters were adjusted in the coastal and Glynn County models first, and averaged over equivalent model areas to obtain values for the RASA model. Because the RASA and Glynn County models were calibrated previously, by using predevelopment (1880) and 1980 conditions, their physical characteristics were in agreement. The calibration process ensures that the physical characteristics and flows of the coastal model agree with those of the RASA and Glynn County models in areas where the three models coincide or overlap. This required only slight adjustments to the calibrated physical parameters of the RASA and Glynn County models. All three simulation periods--predevelopment (1880), 1980, and 1985 conditions--were included in the calibration process.

In areas outside the Glynn County model, the RASA and coastal models had to agree in areas of known hydraulic constraints or local flow anomalies of the aquifer system. The hydraulic constraints of the Floridan aquifer system include the Gulf Trough in the northern part of the RASA and coastal models, rivers that drain the aquifer above the Trough, pumping, and some local conduit flow in the Brunswick area.

The Gulf Trough restricts lateral flow across the northern part of the Floridan aquifer system. The hydraulic characteristics of this constraint were controlled with transmissivity in both the RASA and coastal models. Calibrated transmissivity values of the Upper Floridan aquifer in this area are less than 20,000 ft^2/d, which result in a simulated lateral flow of approximately (1) 16 Mgal/d predevelopment (1880) conditions, and (2) 26 Mgal/d in 1985 conditions. This small change in flow across the Trough indicates that large withdrawal in the coastal area tends to have little effect upgradient of the Trough.

Rivers drain the Upper Floridan aquifer primarily north of the Gulf Trough where the aquifer is thinly confined. In the RASA and coastal models, the rivers were conceptualized as a string of grid blocks where the upper confining unit has been partially eroded, and was simulated with high vertical hydraulic conductivities, resulting in vertical discharge from the Floridan aquifer system to the surficial aquifer. The interstream areas updip of the Gulf Trough were treated as high recharge areas that provide the necessary ground-water flow to the streams. Plate 1 shows the simulated vertical flow through the upper confining unit for 1985 conditions, and shows large vertical flow along the rivers updip of the Gulf Trough. Krause and Randolph (1989) discuss the conceptualization and simulation of these rivers, and the comparison with estimated streamflow.

For pumpage input, wells were located by using the most detailed model covering the area, and pumping rates were summed over equivalent model areas to obtain the rate for the larger models. This ensured that equal areas received identical stress. The distribution of pumpage within 4 mi^2 areas (grid blocks) throughout the coastal model is presented for 1980 and 1985 conditions on plate 1.

Comparison between the RASA, coastal, and Glynn County models for the three simulation periods focused on matching ground-water levels, and lateral and vertical flows for similar areas. Some subjectivity in evaluating calibration exists. The simulated head represents the value at the center of the grid block, and this can be considerably different than the measured water levels used to construct potentiometric surfaces, especially in areas of steep hydraulic gradients such as within deep cones of depression. Also, inherent scale differences between the three models introduce numerous problems in comparing simulated heads between the models. Therefore, matching heads alone would not ensure agreement between the RASA, coastal, and Glynn County model. However, the comparison of lateral and vertical flows between the models ensured that each model was simulating the same response to given hydraulic conditions and constraints.

The RASA, coastal, and Glynn County models were considered calibrated when vertical flows between similar model areas matched within 10 percent, and the mean error between simulated and observed heads was less than 10 ft. The mean error between the simulated and measured heads for the coastal model for all active grid blocks was 4 ft for the Upper Floridan and 5 ft for the Lower Floridan for 1985 conditions (table 1). Calibration of the Lower Floridan aquifer and middle semiconfining unit was limited to matching those few data available for defining aquifer transmissivity and flow across the confining unit. Problems in matching observed heads updip of the Gulf Trough were encountered for 1985 conditions in both the RASA and coastal models due to the lack of control points and the inability to compare water levels obtained from the same wells. A comparison of estimated and simulated predevelopment (1880) potentiometric surfaces for the coastal model is shown on plate 2. A comparison of observed and simulated potentiometric surfaces for 1980 and 1985 conditions, is shown on plate 2.

Water budgets derived from simulation of the three steady-state flow models indicate changes in the ground-water-flow system from predevelopment (1880) to 1985 conditions (fig. 11). Ground-water pumpage through 1985 caused increased vertical inflow to the Upper Floridan aquifer (about 310 ft^3/s) and a corresponding decrease in vertical outflow (about 80 ft^3/s)

Table 1. -- *Statistical summary of differences between measured and simulated water levels in the Floridan aquifer system using the coastal model under 1985 conditions*

Model layer	Absolute mean error (feet)	Standard deviation (feet)	Root-mean-square error (feet)
Upper Floridan aquifer	4.0	5.2	6.6
Lower Floridan aquifer	5.0	6.4	8.2

than occurred during predevelopment (1880) conditions. Lateral inflow into the Upper Floridan aquifer is more than twice that occurring during predevelopment (1880) conditions, further indicating the effects of pumping on the ground-water-flow system.

Sensitivity Analysis

A sensitivity analysis was conducted on the stressed steady-state coastal model. The analysis measured the confidence in the calibrated model parameters to duplicate properties found in the physical system, and to assess the model calibration. The sensitivity analysis was conducted on those parameters that were adjusted in the calibration procedure and include (1) the transmissivity of the Upper and the Lower Floridan aquifers, (2) the vertical leakance between the two aquifers and the Fernandina permeable zone, and (3) the general-head-boundary condition used to regulate flow along the western edge of the coastal model. The sensitivity of the calculated-flow boundary condition to steep hydraulic gradients also was tested.

The coastal model was considered to be sensitive to a parameter when a substantial change in that parameter resulted in a comparatively significant deviation of simulated water level from the calibrated value. Similarly, the coastal model was considered to be insensitive to a parameter when a change in that parameter resulted in little or no change in simulated water level from the calibrated value. There is higher confidence in the accuracy of estimated aquifer and confining-unit properties used in the calibrated coastal model when the sensitivity analysis indicates a greater sensitivity to that parameter value, whereas less confidence exists when the model is insensitive to a particular parameter. The coastal model sensitivity was evaluated by comparing the calibrated water levels with those simulated during the parameter testing of the sensitivity analysis. The 1985 calibrated simulation was used for this comparison.

Sensitivity was determined quantitatively in terms of the absolute mean error between simulated and measured water levels; the standard deviation, a measure of the dispersion of simulated water-level residuals about the mean; and the root-mean-square error (RMSE), which is similar to the standard deviation, but measures the correlation between water-level residuals (tables 2, 3). Mathematically, these parameters are defined

$$\mu = \left(\sum_{i=1}^{n} (h_s - h_o)\right)/n$$

where μ = the mean head residual, h_s the simulated head, h_o the measured head, and n is the number of measurements (or active grid blocks).

$$SD = \sqrt{\sum_{i=1}^{n} (h_s - \mu)^2 / (n-1)}$$

where SD = the standard deviation, and h_s is the simulated head.

$$RMSE = \sqrt{\sum_{i=1}^{n} (h_s - h_o)^2 / n}$$

where RMSE = the root-mean-square error.

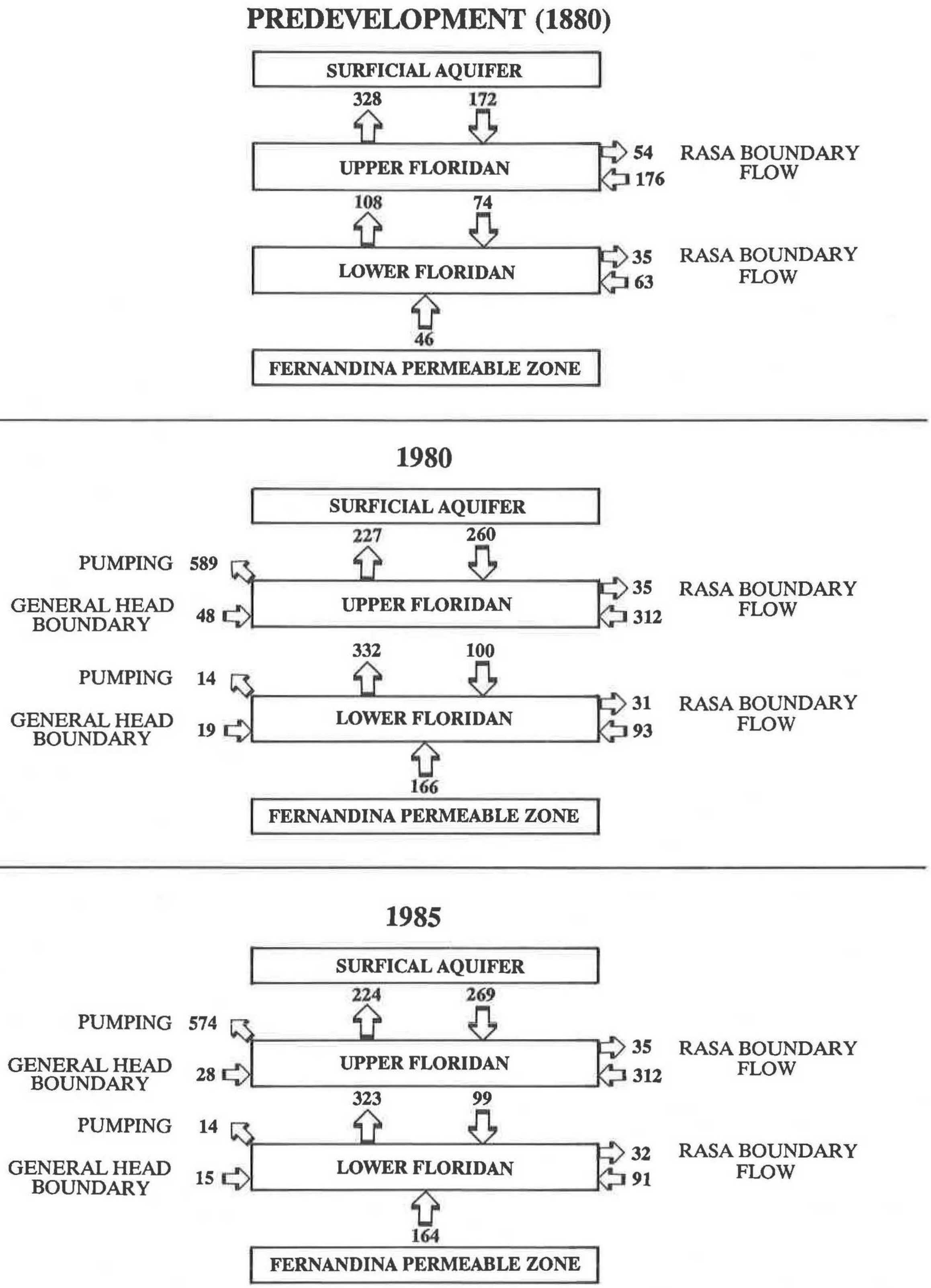


Figure 11.--Simulated water budgets for predevelopment (1880), 1980, and 1985 conditions. Arrows indicate direction of flow; numbers indicate flow rate, in cubic feet per second.

The values of transmissivities and leakances were increased and decreased by a factor of two. These parameters were varied independently in all layers to isolate the model response to changes in that parameter in each aquifer (tables 2 and 3).

Table 2.--*Statistical results of the sensitivity analysis of the Upper Floridan aquifer in the coastal model under 1985 conditions*

Parameter varied	Multiplier	Water-level changes: Absolute mean error (feet)	Standard deviation (feet)	Root-mean-square error (feet)
Transmissivity of the Upper Floridan aquifer	0.5	10.5	10.2	14.7
	2.0	10.5	8.9	13.8
Transmissivity of the Lower Floridan aquifer	.5	4.1	4.8	6.3
	2.0	6.2	6.5	9.0
Vertical leakance between the surficial and the Upper Floridan aquifers	.5	4.9	5.1	7.1
	2.0	6.7	6.4	9.3
Vertical leakance between the Upper and Lower Floridan aquifers	.5	4.0	7.0	6.7
	2.0	4.1	5.2	6.6
Vertical leakance between the Lower Floridan aquifer and the Fernandina permeable zone	.5	5.8	5.3	7.8
	2.0	6.4	5.3	8.3

Table 3.--*Statistical results of the sensitivity analysis of the Lower Floridan aquifer in the coastal model under 1985 conditions*

Parameter varied	Multiplier	Water-level changes: Absolute mean error (feet)	Standard deviation (feet)	Root-mean-square error (feet)
Transmissivity of the Upper Floridan aquifer	0.5	9.0	7.2	11.6
	2.0	11.5	10.1	15.3
Transmissivity of the Lower Floridan aquifer	.5	4.3	5.4	6.9
	2.0	8.1	8.4	11.6
Vertical leakance between the surficial and the Upper Floridan aquifers	.5	5.3	6.1	8.1
	2.0	7.8	7.4	10.7
Vertical leakance between the Upper and Lower Floridan aquifers	.5	5.6	7.0	9.0
	2.0	4.7	6.0	7.6
Vertical leakance between the Lower Floridan aquifer and the Fernandina permeable zone	.5	6.0	6.0	6.1
	2.0	7.8	7.8	6.9

Comparison of the statistics, tables 1 to 3, indicates that the Upper and Lower Floridan aquifers are more sensitive to changes in the transmissivity of the Upper Floridan aquifer than to the changes in any of the other parameters. For example, a decrease or increase of the transmissivity of the Upper Floridan aquifer increases the absolute mean error from 4 ft to 10.5 ft. Whereas, for a similar change of the other parameters, the mean absolute error remains almost the same.

A decrease in the transmissivity of the Upper Floridan aquifer resulted in a 30-percent reduction in lateral flow across the coastal model boundary. The reduced lateral flow caused more water to flow into the Upper Floridan vertically from the surficial and the Lower Floridan aquifers to satisfy the water budget. In areas upgradient of the influence of pumping, the water levels increased because lateral flow to the downdip areas was restricted.

An increase in the leakance between the Upper Floridan and the surficial aquifers increased the water levels in the updip areas of the Upper Floridan aquifer, as vertical flow between the aquifers increased. The RMSE increased approximately 30 percent over the calibrated value of 6.6 ft to 9.3 ft. The increased vertical flow across the upper confining unit increased the water levels updip, which caused more water to flow downgradient. The net effect of the increased vertical flow caused increased water levels in the Upper Floridan aquifer throughout most of the model area.

An increase in the leakance of the upper confining unit also caused increased water levels in the Lower Floridan aquifer over much of the area, because the Upper Floridan discharged the excess inflow from the surficial aquifer in both lateral and vertical directions. Lateral inflow across the aquifer layer of the coastal model boundary was reduced by 3 percent, and lateral outflow was increased by 26 percent. In addition, water that normally is discharged from the Upper Floridan aquifer to the Lower Floridan aquifer increased by 31 percent. The increased flow across the middle semiconfining unit reduced the vertical leakance of water from the Fernandina permeable zone by 5 percent.

The sensitivity of the coastal model to its boundary conditions was tested only in the Upper Floridan as the water-level surface is better defined in this aquifer, and the model showed a greater sensitivity to the transmissivities of the Upper Floridan aquifer than to the Lower Floridan aquifer. The results showed that the boundary flow that resulted from the general-head type boundary was most sensitive to changes in water level in areas where the hydraulic gradient was steep. In areas where the gradient was comparatively flat, the boundary flow was more sensitive to the transmissivity outside the boundary. A greater flow enters the coastal model when the gradient between the water level at an arbitrary point outside the model and the water level at the model boundary is steep, and where transmissivities of the aquifer are higher. The opposite occurs where the gradient is flattened or transmissivities are lowered.

The sensitivity of the calculated-flow boundary condition of the coastal model (boundary flows calculated internally to the RASA model) to steep gradients was tested for the area around the steep cone of depression at Savannah, Ga. The boundary was extended seaward beyond the steep contours of the cone of depression, but the boundary was still internal to the RASA model. The flows at the new boundary were calculated by the RASA model and input to the coastal model as boundary wells. A comparison was made between the flows calculated by the RASA model at the original boundary location and the internal flows calculated by the coastal model at the same location under the new boundary condition. It was determined that the boundary flows calculated by the RASA model and the internal flow of the coastal model agree within 3 percent, having flows of 13.84 ft^3/s and 14.20 ft^3/s, respectively. This indicates that the model is relatively insensitive to the location of the calculated-flow boundary. The simulated flows indicate that the steep gradients at the boundary in the Savannah area are acceptable. This also is evidenced by the match between measured and simulated water levels on plate 2.

GEORGIA DEPARTMENT OF NATURAL RESOURCES
ENVIRONMENTAL PROTECTION DIVISION
GEORGIA GEOLOGIC SURVEY

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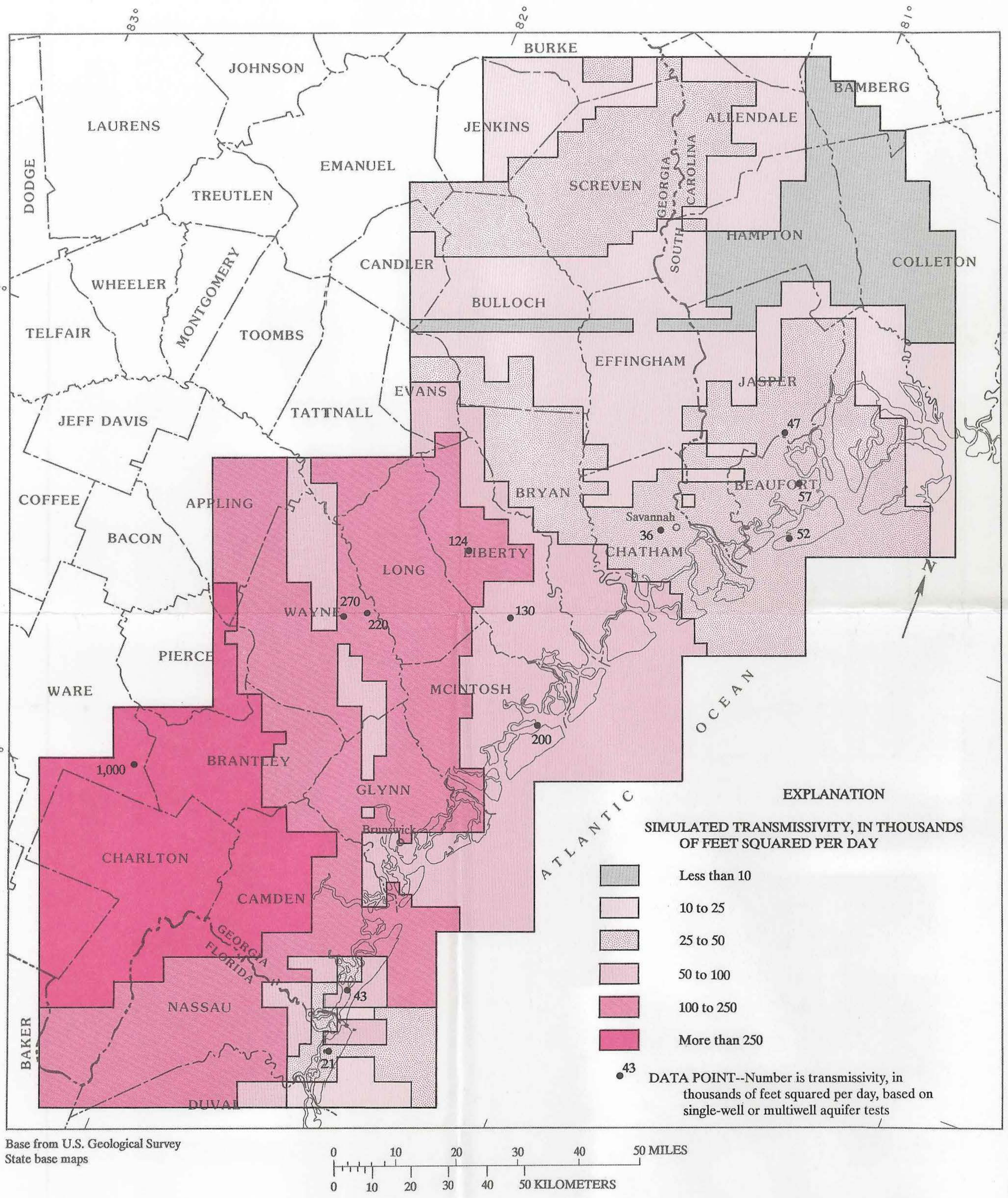
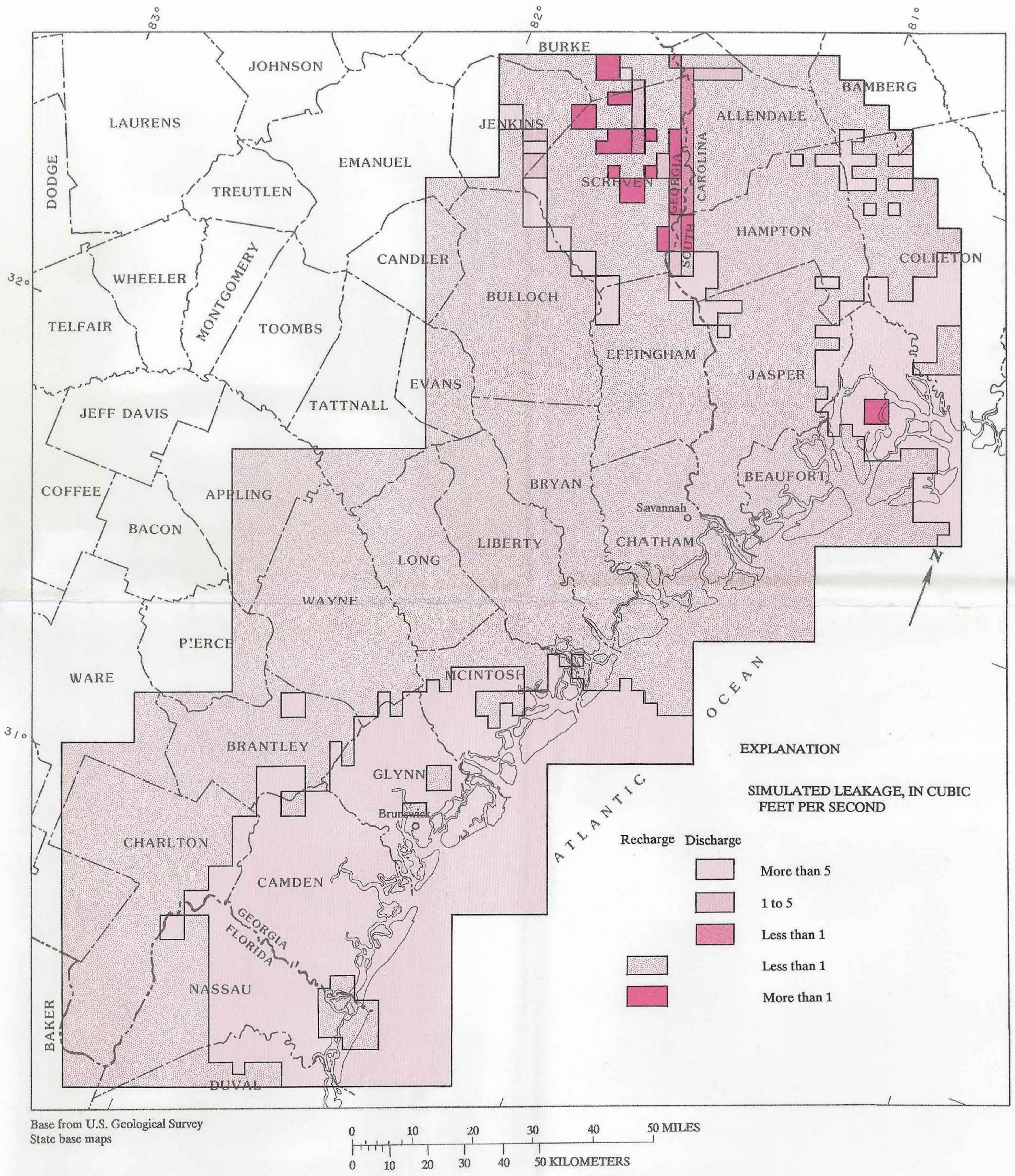
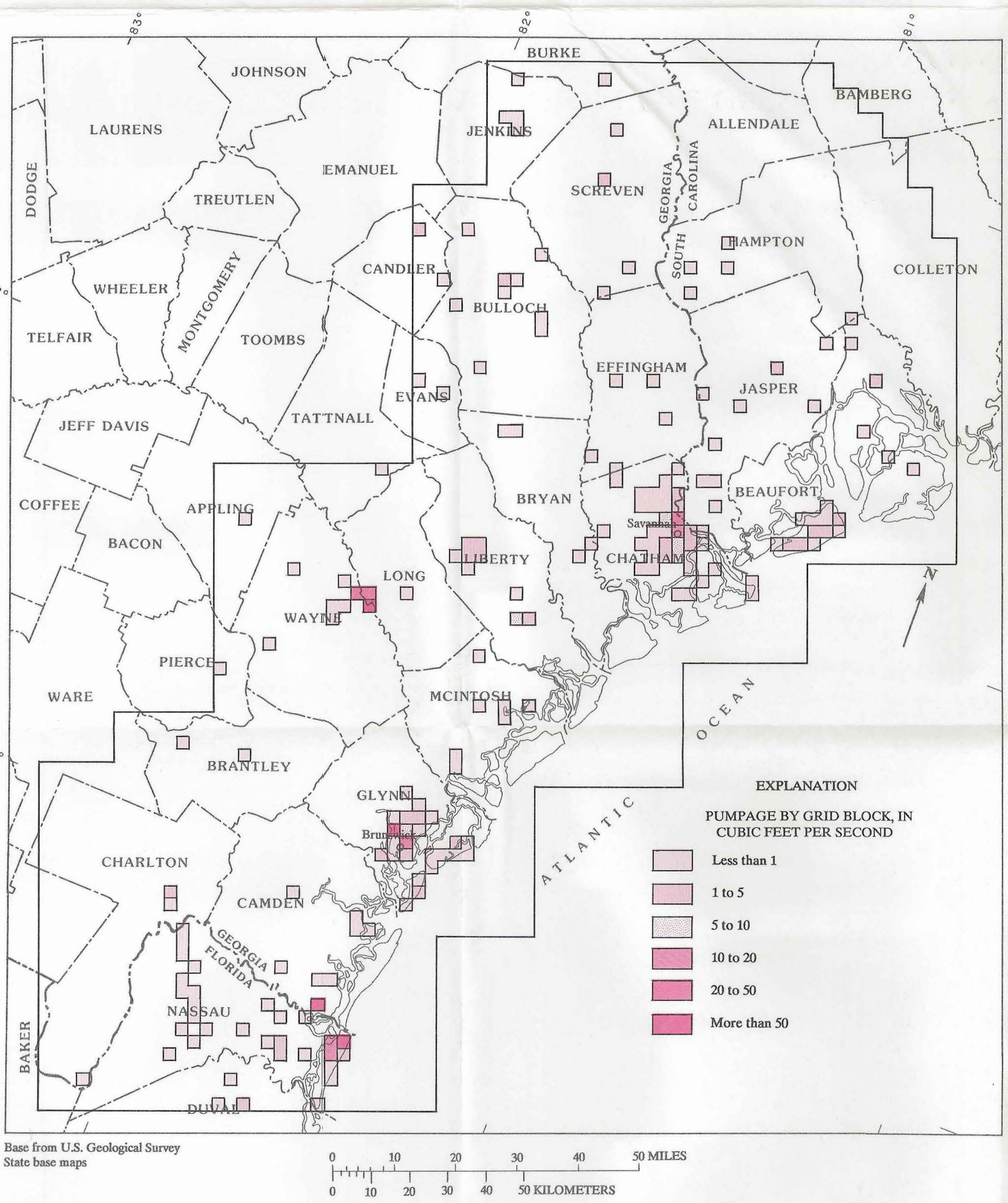
BULLETIN 116
PLATE 1



FIELD-DERIVED AND SIMULATED VALUES OF TRANSMISSIVITY OF THE UPPER FLORIDAN AQUIFER



SIMULATED LEAKAGE THROUGH THE UPPER CONFINING BED, 1985



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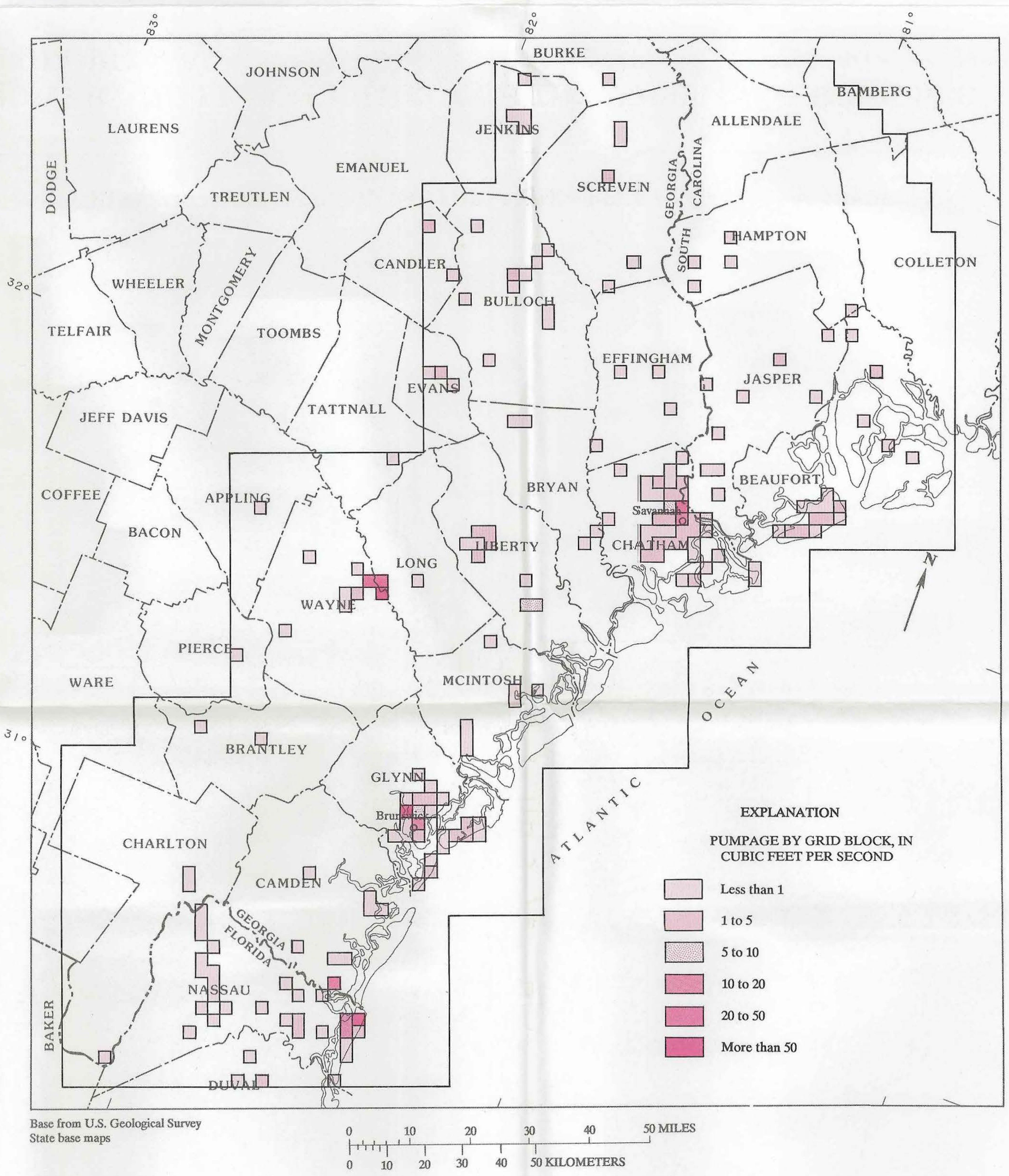

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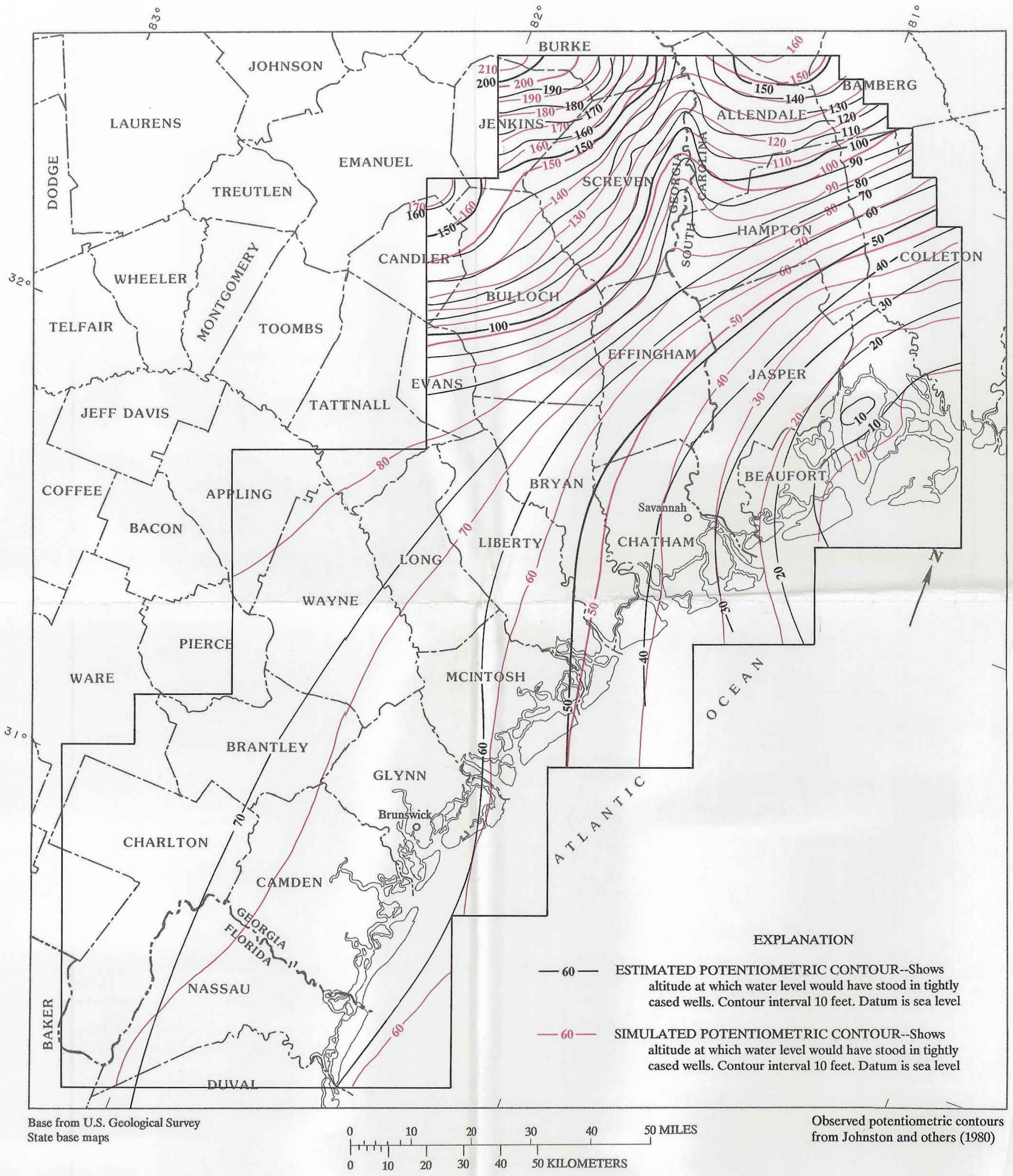
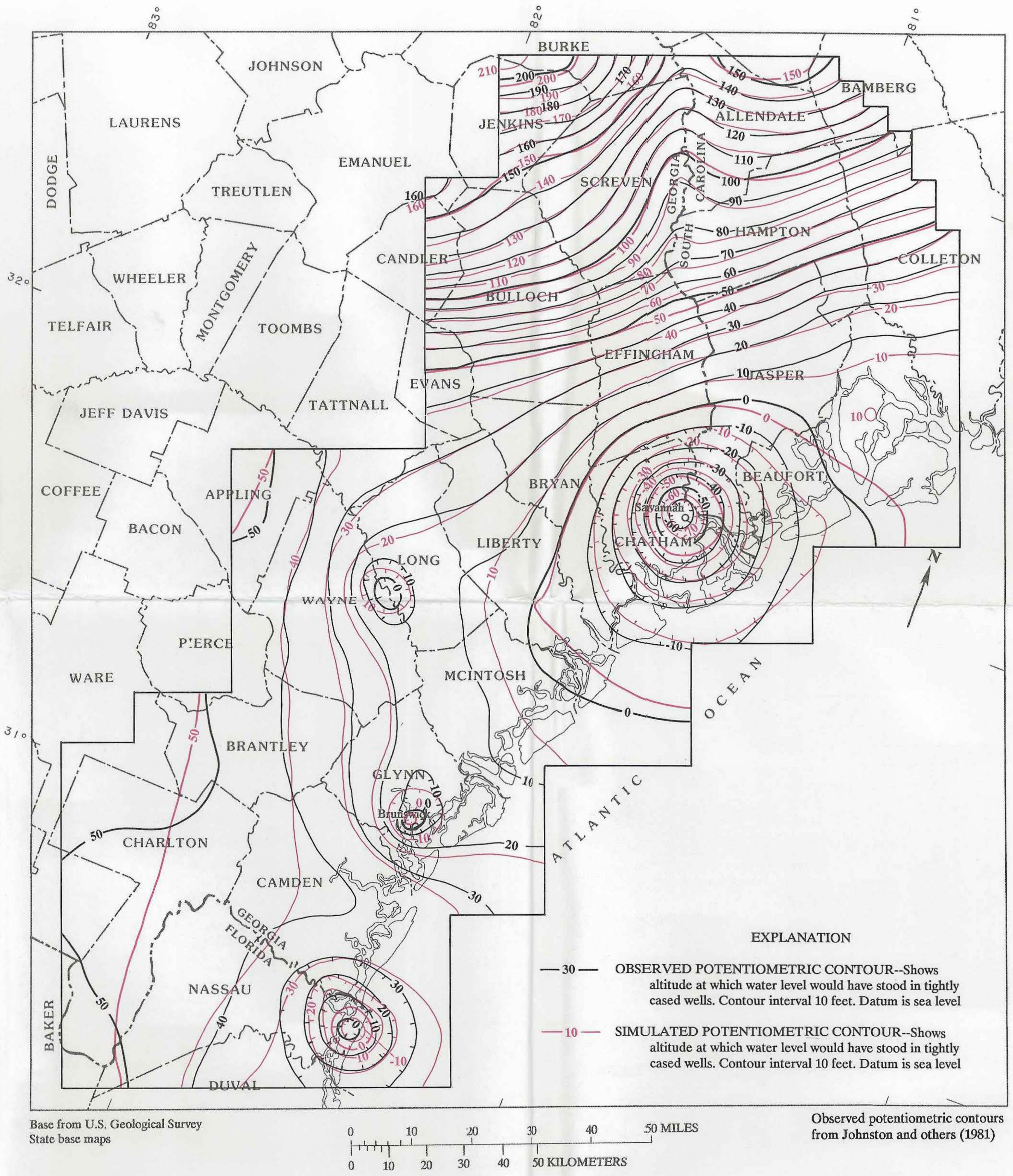
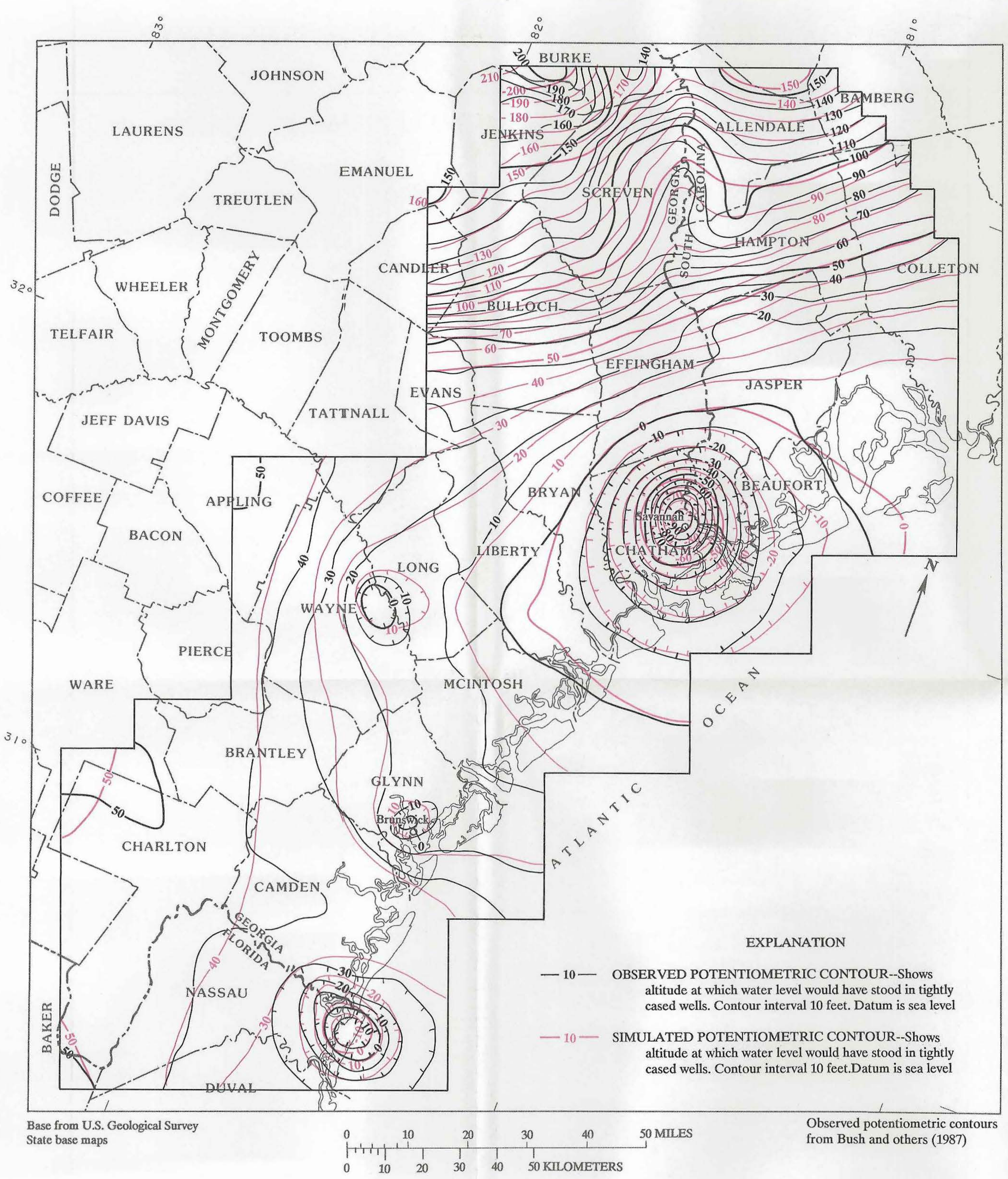
TRANSMISSIVITY AND PUMPAGE FROM THE UPPER FLORIDAN AQUIFER AND LEAKAGE THROUGH THE UPPER CONFINING BED IN COASTAL GEORGIA



ESTIMATED AND SIMULATED POTENTIOMETRIC SURFACES OF THE UPPER FLORIDAN AQUIFER, 1880



OBSERVED AND SIMULATED POTENTIOMETRIC SURFACES OF THE UPPER FLORIDAN AQUIFER, 1980



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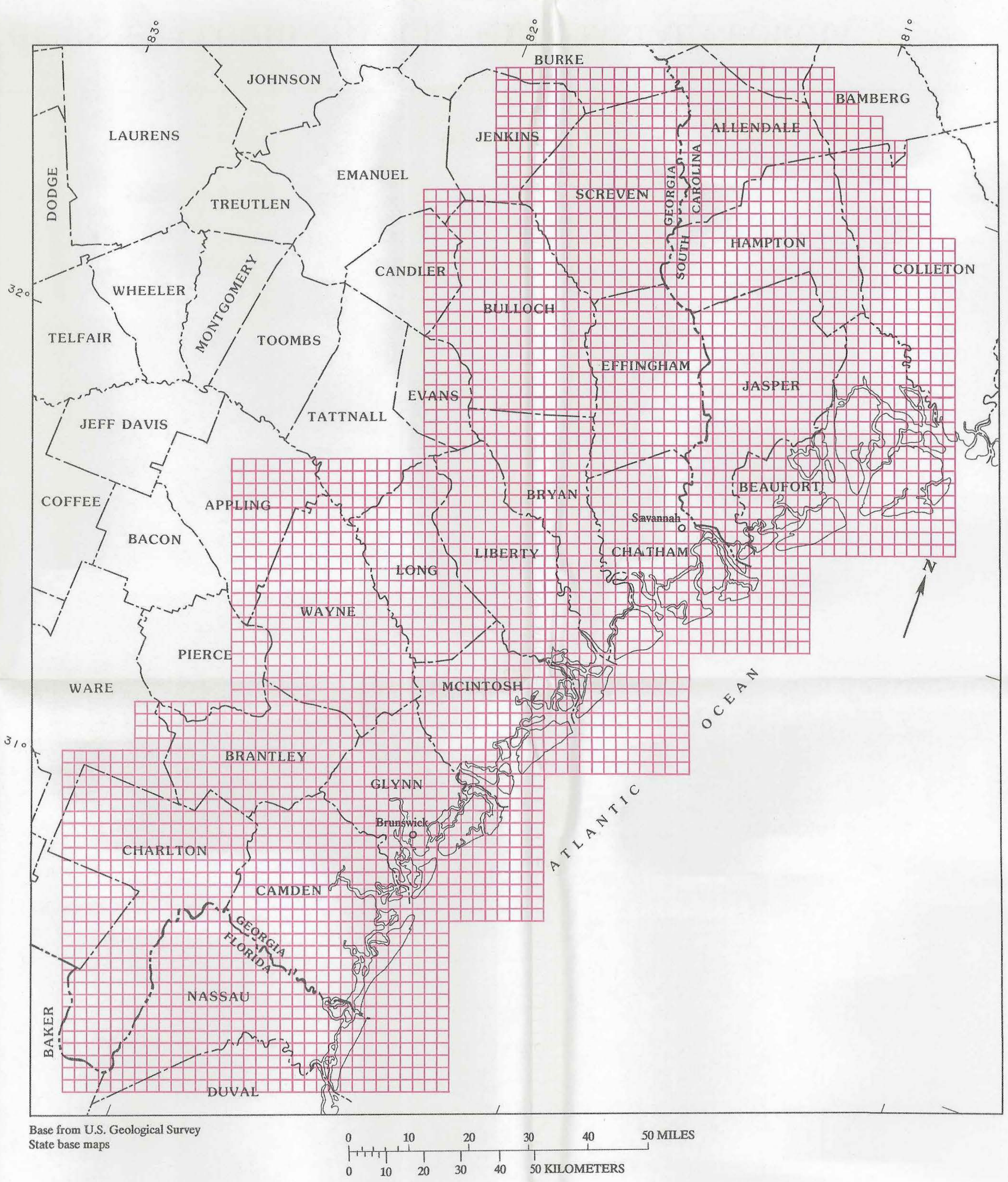

MODEL GRID

COMPARISON OF THE POTENTIOMETRIC SURFACES OF THE UPPER FLORIDAN AQUIFER IN COASTAL GEORGIA

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