HYDROLOGY OF THE FLORIDAN AQUIFER SYSTEM IN SOUTHEAST GEORGIA AND ADJACENT PARTS OF FLORIDA AND SOUTH CAROLINA

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403-D

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs **(see back inside cover)** but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

Alaska Distribution Section, U.S. Geological Survey,
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following Geological Survey Public Inquiries Offices, all of which are authorized agents of the Superintendent of Documents:

- **WASHINGTON, D.C.**--Main Interior Bldg., 2600 corridor, 18th and C Sts., NW.
- **DENVER, Colorado**--Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**--Federal Bldg., Rm. 7638, 300 N. Los Angeles St.
- **MENLO PARK, California**--Bldg. 3 (Stop 533), Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**--503 National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**--Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**--Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**--U.S. Courthouse, Rm. 678, West 920 Riverside Ave..
- **ANCHORAGE, Alaska**--Rm. 101, 4230 University Dr.
- **ANCHORAGE, Alaska**--Federal Bldg, Rm. E-146, 701 C St.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following Geological Survey offices:

- **ROLLA, Missouri**--1400 Independence Rd.
- **DENVER, Colorado**--Map Distribution, Bldg. 810, Federal Center
- **FAIRBANKS, Alaska**--New Federal Bldg., 101 Twelfth Ave.

Hydrology of the Floridan Aquifer System in Southeast Georgia and Adjacent Parts of Florida and South Carolina

By RICHARD E. KRAUSE *and* ROBERT B. RANDOLPH

REGIONAL AQUIFER-SYSTEM ANALYSIS—FLORIDAN AQUIFER SYSTEM

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403–D

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1989

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Any use of trade names in this publication is for description purposes only and does not imply endorsement by the U.S. Government

Library of Congress Cataloging in Publication Data

(Regional Aquifer-system analysis) (U.S. Geological Survey Professional Paper ; 1403–D)
Bibliography: p.
Supt. of Docs. no.: I, 19.16:1403–D
1. Aquifers—Georgia—Mathematical models. 2. Aquifers—Georgia—Data processing. 3. Aquifers—Florida—Mathematical models. 4. Aquifers—Florida—Data processing. 5. Aquifers—South Carolina—Mathematical models. 6. Aquifers—South Carolina—Data processing. I. Randolph, Robert B. II. Title. III. Series. IV. Series: U.S. Geological Survey Professional Paper ; 1403–D
GB1199.3.G4K73 1989 551.49′09758 85–600148

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,
Federal Center, Box 25425, Denver, CO 80225

FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

CONVERSION FACTORS

Factors for converting inch-pound units to the International System (SI) of units are given below:

Multiply	*By*	*To obtain*
	Length	
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	3.785×10^{-3}	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	6.309×10^{-5}	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second (m^3/s)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Leakance	
gallon per day per cubic foot [$(gal/d)/ft^3$]	0.1337	meter per day per meter [(m/d)/m]
foot per day per foot [(ft/d)/ft] (or in reduced form, day^{-1})	1.000	meter per day per meter [(m/d)/m]
	Gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Drawdown	
foot per year (ft/yr)	0.3048	meter per year (m/yr)

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 "Mean Sea Level of 1929."

HYDROLOGY OF THE FLORIDAN AQUIFER SYSTEM IN SOUTHEAST GEORGIA AND ADJACENT PARTS OF FLORIDA AND SOUTH CAROLINA

By Richard E. Krause and Robert B. Randolph

ABSTRACT

The ground-water flow of the Floridan aquifer system under predevelopment (about 1880) and present-day (1980) conditions in southeast Georgia and adjacent parts of Florida and South Carolina was simulated using a three-dimensional finite-difference digital model. The model was used to better define the hydrogeology and ground-water flow system in the Floridan aquifer system in that area.

The Floridan aquifer system, known as the principal artesian aquifer in Georgia, South Carolina, and Alabama, and as the Floridan aquifer in Florida, consists of interbedded clastics and marl in the updip area and massive limestone and dolomite more than 2,000 feet thick in the downdip area. The Floridan aquifer system, primarily of Eocene age, is hydraulically connected in varying degrees but has been divided into the Upper and Lower Floridan aquifers in most of the study area. In southeast Georgia and northeast Florida, the Lower Floridan includes a basal unit herein formally designated the "Fernandina permeable zone." The Floridan, in most of the area, is confined above by clay beds of the Miocene Hawthorn Formation. Low-permeability clastic, evaporitic, or carbonate rocks form the base of the aquifer system.

The Floridan is heterogeneous; transmissivity of the Upper Floridan ranges from nearly zero near the aquifer's updip extent to about 1 million feet squared per day in the cavernous thick carbonate sequence in south Georgia. Areally, the Floridan is traversed by the Gulf Trough, a structurally controlled, clastic-infilled series of grabens, approximately aligned along strike. This feature is an important control on the regional flow system; it impedes flow from the upgradient, primarily clastic part to the downgradient, massive carbonate part of the Floridan.

Simulation results indicate that a total of about 900 million gallons per day (1,400 cubic feet per second) of water flowed through the aquifer system prior to development. About two-thirds of this flow was in the area upgradient from the Gulf Trough. This flow consisted of recharge in areas between streams, lateral movement downgradient, and discharge to the major rivers. The flow system in most of the area downgradient from the Gulf Trough was characterized by slow lateral movement resulting from low diffuse recharge and discharge. Throughout the study area, almost all circulation was within the Upper Floridan.

Pumpage from the aquifer system, totaling about 625 million gallons per day (970 cubic feet per second) in 1980 and concentrated primarily in the areas downgradient from the Gulf Trough, changed the flow system markedly. The flow system was nearly unchanged upgradient from the Gulf Trough, where less than 5 percent of the pumpage occurred. Downgradient from the trough, large ground-water withdrawals concentrated along the coast, primarily from the Upper Floridan, caused significant head declines. These head declines caused lateral and vertical gradient changes and reversals, increased circulation in, and upward leakage from, the Lower Floridan and the Fernandina permeable zone, a local degradation in water quality, and land subsidence. Although not tapped by producing wells, the Fernandina permeable zone provided about 180 million gallons per day (280 cubic feet per second) of water to the coastal pumpage through solution-enlarged faults breaching the confining beds. The quality of the water in the Fernandina permeable zone ranged from fresh to brine, locally contaminating the Upper Floridan, most notably in Brunswick, Georgia. Model-simulated flow through the Floridan aquifer system under present-day (1980) conditions totaled about 1,350 million gallons per day (2,100 cubic feet per second).

Although heavily developed along the coast, the Floridan could withstand some additional development, especially inland, as indicated by simulations involving future hypothetical pumping schemes. The area around Waycross, Georgia, could probably undergo additional development of more than 26 million gallons per day (about 40 cubic feet per second), but in some places along the coast, where heavy withdrawals have already posed water-quality problems, additional development probably could not occur without detrimental effects to the system.

INTRODUCTION

The Floridan aquifer system, known as the principal artesian aquifer in Georgia, Alabama, and South Carolina and as the Floridan aquifer in Florida, is the major source of water in the area of its occurrence, except where it contains saline water. About 625 Mgal/d (970 ft^3/s) of water was withdrawn from the aquifer in 1980 for industrial, municipal, agricultural, and other uses in the eastern half of the Coastal Plain of Georgia, northeast Florida, and the southern part of South Carolina. Problems that have developed because of this heavy withdrawal are (1) decline in water levels, chiefly around pumping centers, but areawide as well, (2) highly mineralized water induced into the aquifer from underlying strata, (3) seawater moving toward pumping centers from offshore, and (4) land subsidence.

In 1978, the U.S. Geological Survey began a study of the Floridan aquifer system on a regional scale under its Regional Aquifer-System Analysis (RASA) program. The RASA program represents a systematic effort to study a number of regional aquifers which together cover much of the country and provide a significant part of the Nation's water supply. (See fig. 1 in chapter A of this Professional Paper series (Johnston and Bush, in press) for the location of these regional aquifers.) The overall objectives of the Floridan aquifer-system study include (1) a complete description of the hydrogeologic framework and geochemistry of the entire aquifer system, (2) an analysis of the ground-water flow through the aquifer system, (3) an assessment of the effects of large withdrawals of ground water on the aquifer, and (4) an appraisal of water-management alternatives. The study is regional in scope, and the aquifer system is defined in its entirety, without regard to political subdivisions.

Components of the Floridan aquifer-system analysis were divided on the basis of discipline, as well as areally. Areal subdivisions were based on the similarity of hydrologic features and problems and on the location of natural hydrologic boundaries within the aquifer system (fig. 1). Results of the study are being published as separate chapters in this Professional Paper series as follows:

A. Summary of the hydrology of the Floridan aquifer system
B. Hydrogeologic framework of the Floridan aquifer system
C. Regional hydrology and ground-water development of the Floridan aquifer system
D–H. Hydrology of the Floridan aquifer system:
  D. In southeast Georgia and adjacent parts of Florida and South Carolina (this report)
  E. In east-central Florida
  F. In west-central Florida
  G. In south Florida
  H. In southwest Georgia, northwest Florida, and extreme south Alabama
I. Geochemistry of the Floridan aquifer system.

Chapter A summarizes the hydrogeologic framework, hydraulic characteristics, and geochemistry of the aquifer system.

Chapter B describes the geologic framework and hydrogeologic characteristics of the aquifer system. Maps, sections, and fence diagrams show the relations of lithofacies, structure, thickness, and stratigraphy to aquifer and confining-unit geometry.

Chapter C presents a description of the regional flow system based on digital simulation and discusses ground-water development on a regional scale.

Chapters D–H present descriptions of the ground-water hydrology of the subregions emphasizing local hydrologic features and development.

Chapter I describes the natural geochemistry of the aquifer system. Maps, sections, phase diagrams, and tables are used to explain the occurrence of the hydrochemical facies, the relation between natural changes in water chemistry and the flow system, and geochemical changes induced by pumping and land development.

HISTORICAL TERMINOLOGY OF THE FLORIDAN AQUIFER SYSTEM

The existence of a regional flow system in what is herein called the Floridan aquifer system was first described in some detail in peninsular Florida by Stringfield (1936, p. 132, pl. 12). Warren (1944, p. 17) described the extension of this flow system in southeastern Georgia and applied the term "principal artesian aquifer" to the carbonate units involved (table 1). Stringfield (1966, p. 95) used the term "principal artesian aquifer" to describe the permeable carbonate rocks from the lower part of the Hawthorn Formation through the Oldsmar Limestone in Georgia and South Carolina, as well as in Florida and Alabama. The term "principal artesian aquifer" as defined by Stringfield has been used in Georgia and South Carolina.

Parker (in Parker and others, 1955, p. 188, 189) described the limestone units from the basal part of the Hawthorn Formation through middle Eocene (Lake City) limestone and named that sequence the "Floridan aquifer." The term "Floridan aquifer" is entrenched in the Florida ground-water literature and is also widely used in national and international publications.

Cederstrom and others (1979, p. 8, 14) referred to the aquifer as the "Tertiary limestone aquifer." Their designation of the aquifer includes rocks, primarily carbonates, of the Tampa Limestone through the Oldsmar Limestone.

During the regional study of the Floridan aquifer system, Miller used the term "Tertiary limestone aquifer system," which combined the age of the rocks and their general lithology, as the name of the aquifer system (Miller, 1982a, b, c, d, e). By the end of the study, the term "Floridan aquifer system" was formally applied to the aquifer system (Miller, 1985). The term "Floridan aquifer system" is uniformly used in all chapters of this Professional Paper series and is proposed

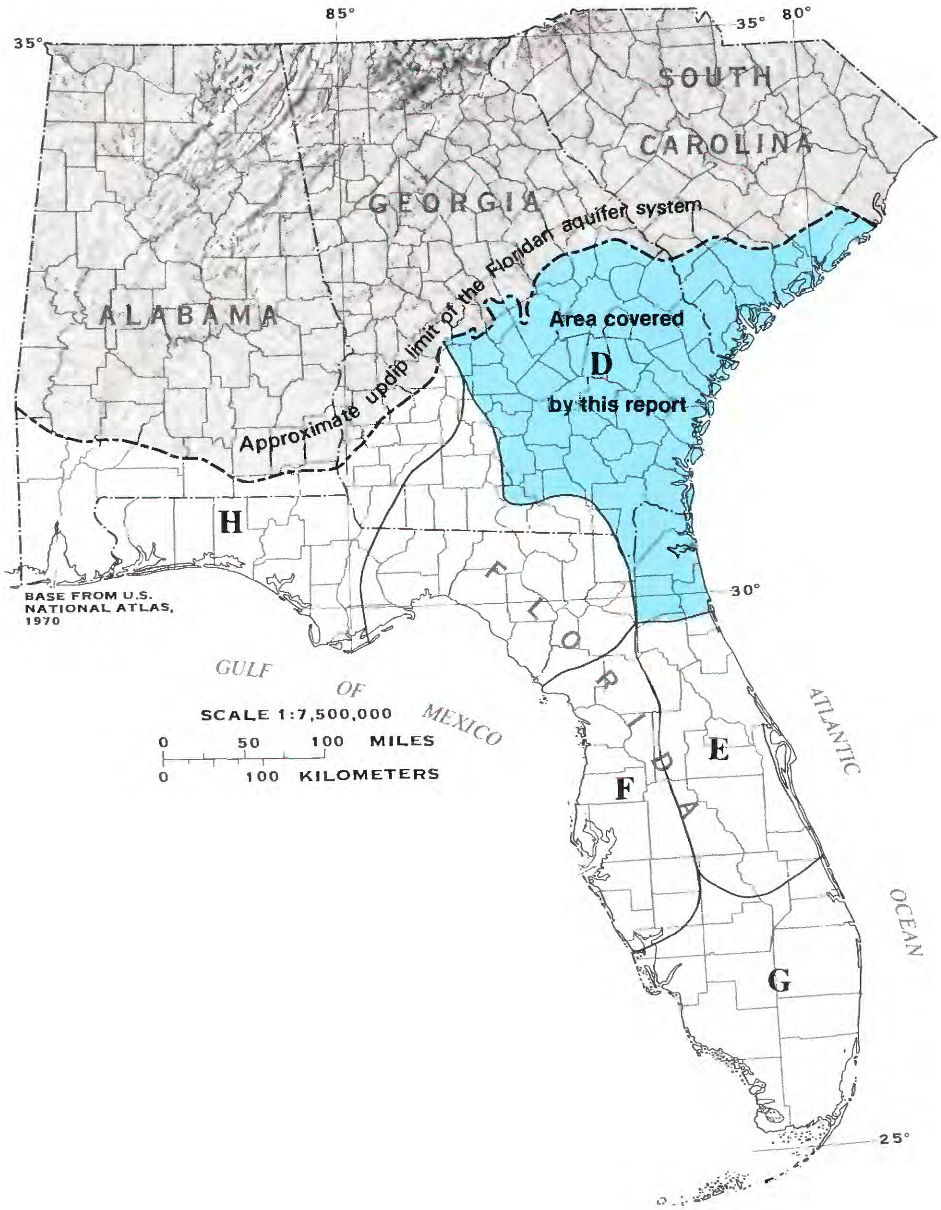


FIGURE 1.—Location of Floridan aquifer system study area, subregional project areas, and chapter designations in Professional Paper 1403.

for use in further investigations of the aquifer system. Because distinct, regionally mappable hydrogeologic units occur within the carbonate sequence, the term "aquifer system" is preferred to "aquifer." Use of "system" follows Poland and others (1972, p. 2), who stated that an aquifer system "* * * comprises two or more permeable beds separated at least locally by [confining beds] that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system." This definition applies to the Floridan aquifer system throughout most of its area of occurrence. (See table 1 for a summary of historical terminology and stratigraphy applied to the Floridan aquifer system.)

PURPOSE AND SCOPE

The overall purpose of this study was to describe the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina. Specifically, the objectives of the study were to (1) describe and

TABLE 1.—*Summary of historical terminology applied to the Floridan aquifer system*

<table>
<tr><th colspan="2">Series</th><th>Formation[1]</th><th>Warren (1944)</th><th>Parker and others (1955)</th><th>Stringfield (1966)</th><th>Cederstrom and others (1979)</th><th>Miller (1982b, 1982d)</th><th>This report[2]</th></tr>
<tr><td colspan="2" rowspan="2">Miocene</td><td>Hawthorn Formation</td><td rowspan="2"></td><td>Where permeable</td><td rowspan="6">Principal artesian aquifer</td><td></td><td></td><td rowspan="2"></td></tr>
<tr><td>Tampa Limestone</td><td rowspan="4">Floridan aquifer</td><td colspan="2">Where present and permeable</td></tr>
<tr><td colspan="2">Oligocene</td><td>Suwannee Limestone</td><td rowspan="2">Principal artesian aquifer</td><td rowspan="4">Tertiary limestone aquifer</td><td rowspan="5">Tertiary limestone aquifer system</td><td rowspan="5">Floridan aquifer system[3]</td></tr>
<tr><td rowspan="3">Eocene</td><td>Upper</td><td>Ocala Limestone</td></tr>
<tr><td>Middle</td><td>Avon Park Formation[2 4]</td><td rowspan="3"></td></tr>
<tr><td>Lower</td><td>Oldsmar Formation[2 5]</td><td rowspan="2"></td></tr>
<tr><td colspan="2">Paleocene</td><td>Cedar Keys Formation[2 6]</td><td></td><td></td></tr>
</table>

[1] Principal, most areally extensive formations representative of the downdip area.
[2] Based on Miller (1985), Professional Paper 1403-B.
[3] Tampa Limestone absent in the study area; rocks of Late Cretaceous age form the lowermost part of the aquifer system locally in the Brunswick, Ga., area.
[4] Formerly Avon Park Limestone and Lake City Limestone
[5] Formerly Oldsmar Limestone.
[6] Formerly Cedar Keys Limestone.

delineate the hydrogeologic framework of the aquifer system, (2) describe the flow system prior to development, (3) describe the present-day (1980) flow system and the changes that occurred as a result of development, (4) determine the potential for additional development, and (5) describe the quality of water in the aquifer system and its relation to present-day stresses.

This report describes the results of the study and relates to the other chapters of this Professional Paper series as stated below.

The hydrogeologic framework of the aquifer system as it relates to the ground-water-flow system in the study area is described and delineated in this report. A detailed description of the hydrogeologic framework on a regional scale is presented by Miller (1985) in chapter B of this Professional Paper series. The hydrogeologic framework described herein is largely that of Miller's chapter B; however, some differences exist because of the difference between the regional and the local scales. The local hydrogeologic units are subdivisions of larger units that make up the regional hydrogeologic framework.

The predevelopment and present-day flow systems of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina are described quantitatively in this report. In chapter C of this Professional Paper series, Bush and Johnston (in press) describe the flow system on a less detailed, regional scale. A one-to-one correlation of the quantitative results described in this report and in Bush and Johnston's report cannot be made because of the difference in simulation scale. However, the simulations described in both reports are based on the same set of data.

Determinations of the potential for additional ground-water development from the Floridan aquifer system in the study area are included in this report. Computer simulations, as well as existing information on the hydrology and water quality, provided the basis for the analysis. Bush and Johnston (in press) also include a section on development potential, but it is of lesser detail and is more general in scope.

Only a general description of the geochemistry of the Floridan aquifer system in the study area is included in this report. The quality of the water in areas where it is found to be locally of poor quality is described in greater detail. In these areas, the poor-water-quality features are related to the flow system as it existed prior to development, and as it exists as a result of ground-water development. A more detailed description of the geochemistry of the entire aquifer system is discussed in chapter I of this Professional Paper series (Sprinkle, in press). However, water-quality anomalies or local problems are discussed only in a general way in chapter I.

APPROACH AND METHODS

The hydrogeologic framework of the Floridan aquifer system was determined chiefly by Miller (1985), who delineated the aquifer system on the basis of lithologic, paleontologic, and hydrologic data determined from selected wells. These data were correlated with geophysical well-logs and were extrapolated throughout the study area.

Most of the hydrologic data used in this study were available from previous investigations and ground-water monitoring programs. Sources of the data, some of which dated back to the late 1800's, were the published literature, files containing unpublished data in the form of tables, maps, graphs, and logs, and the more recent computer data bases.

The types of data assembled and used in the analysis and simulation of the flow system included the following: (1) precipitation, streamflow, evapotranspiration (derived from rainfall, pan-evaporation, and temperature data), used for determining recharge and discharge rates; (2) aquifer characteristics, including thickness, specific capacity, hydraulic conductivity, and transmissivity; (3) hydraulic head; (4) confining-unit characteristics, including thickness, vertical hydraulic conductivity, and leakage coefficients; and (5) water use.

Most of the water-quality data used in the description of the geochemistry of, and quality of water from, the aquifer system were collected and published as part of previous investigations and water-quality monitoring programs. Interpretations of water quality were focused primarily on local anomalies, such as concentration of chloride in the areas of saltwater encroachment.

The gathering of new field data was limited to selected areas and activities to fill specific data voids, as follows:

1. Two wells penetrating the entire Floridan aquifer system were drilled near Waycross, Ga. Geologic, geophysical, hydrologic, and water-quality data were collected from coring, logging, packer testing, aquifer testing, and water sampling. Results are reported by Matthews and Krause (1984).
2. An offshore oil-test well abandoned in 1979 was used for data collection, including drill-stem testing. Geologic, geophysical, hydrologic, and water-quality data were collected and analyzed, and were reported by Johnston and others (1982).
3. In May 1980, synoptic water-level measurements were made in approximately 500 wells tapping the Floridan aquifer system in the study area. The resulting potentiometric surface provided information on the present-day (1980) flow system and was used for model calibration. The map and the related information were reported by Johnston and others (1981).
4. Geophysical logging was done in selected wells where data were lacking to provide better definition of the hydrogeologic framework.

The principal method of analysis of the Floridan aquifer system was computer simulation. Computer simulation was used to (1) identify the types of data that are needed to understand the flow system, and to indicate what data were lacking, (2) provide a working hypothesis for testing and evaluating various concepts of the flow system, and (3) provide a tool that can be used to evaluate alternative methods of resource management and to estimate the development potential of the aquifer system.

The computer model used in this analysis is a quasi-three-dimensional, finite-difference code that simulates lateral flow within aquifers and leakage vertically across confining units. All components of the flow system within the Floridan aquifer system, as well as hydrologic units that are adjacent to it and that affect it hydrologically, are part of the simulation.

LOCATION AND EXTENT OF STUDY AREA

The hydrogeologic investigation covers an area of about 30,000 mi^2 in southeast Georgia and adjacent parts of Florida and South Carolina, of which 10,000 mi^2 is offshore (fig. 1).

The extent of the study area is based on natural hydrologic boundaries. The western and southern boundaries were delineated on the basis of ground-water divides. The northern boundary is the outcrop area and updip limit of the aquifer system. The eastern boundary is the easternmost limit of the aquifer system in South Carolina or the freshwater–saltwater interface offshore in Georgia and part of South Carolina.

PREVIOUS INVESTIGATIONS

The hydrogeology of the Floridan aquifer system in southeast Georgia and in parts of Florida and South Carolina has been investigated extensively in the areas of greatest development. However, these studies are restricted almost entirely to a narrow band between the coastal cities of Savannah, Ga., and Jacksonville, Fla., which represents less than 15 percent of the area included in this study. Among the more recent and comprehensive hydrogeologic investigations in this coastal area are those by Hayes (1979) and Spigner and Ransom (1979) in the Low Country (southern part) of South Carolina, Counts and Donsky (1963) in the area of Savannah, Ga., Dyar, Tasker, and Wait (1972) and Krause (1972) in parts of Liberty and McIntosh Counties, Ga., Wait and Gregg (1973) and Gregg and Zimmerman (1974) in the area of Brunswick, Ga., and Bermes, Leve, and Tarver (1963), Leve (1966) and Snell and Anderson (1970) in the northeast Florida area. Paull and Dillon (1979) provide a description of the geology and hydrogeology of the offshore area, the Florida–Hatteras Shelf and Slope, and the Inner Blake Plateau.

Inland from the coastal area, almost no hydrogeologic investigations have been conducted and data are lacking. One exception was an investigation by Krause (1979) of the hydrogeology of the area of Valdosta, Ga., on the western limit of this study.

Callahan (1964), using existing data, included most of the study area in a report on the Coastal Plain aquifers in Georgia and parts of northeast Florida and southern South Carolina. Stringfield (1966) is the most comprehensive reference on the water from Tertiary limestone in the Southeastern States.

Only in two areas has the ground-water-flow system been studied by using computer simulations. The studies were in Georgia, in the areas of Brunswick (Krause and Counts, 1975) and Savannah (Counts and Krause, 1976; Randolph and Krause, 1984). The simulation models, although only two-dimensional in scope, serve as management tools for evaluating declines in the water level and deterioration of water quality due to heavy pumping.

The regional aquifer-system study of the Floridan aquifer system has generated several reports in addition to those in this Professional Paper series. These reports, all covering the Floridan aquifer system on a regional scale, describe the hydrogeologic framework of the aquifer system (Miller, 1982a, b, c, d, e); the geochemistry and ground-water quality (Sprinkle, 1982a, b, c, d); the estimated potentiometric surface prior to development (Johnston and others, 1980); and the potentiometric surface for present-day (May 1980) conditions (Johnston and others, 1981).

Results of test drilling and aquifer testing conducted during this investigation have been reported. Included are (1) results of hydrologic testing in an abandoned oil exploratory hole on the Atlantic Outer Continental Shelf (Johnston and others, 1982), (2) geologic and hydrologic data from a test-monitor well at Fernandina Beach, Fla. (Brown, 1980), (3) geologic and hydrologic results of test drilling and aquifer testing near Waycross, Ga. (Matthews and Krause, 1984), and (4) geologic and hydrologic data gathered from test drilling at Jacksonville Beach, Fla. (Brown and others, 1984).

The predevelopment flow system in the study area was described by Krause (1982) as part of this study. The report documents the initial phase of this study: model design, calibration, and results of computer simulation of the aquifer flow system prior to development. Because the report was preliminary in scope, conceptualization of the aquifer system was more general than that reported herein. In effect, the preliminary report describes a working conceptual model and consequent simulation of the predevelopment flow system in the Floridan. However, simulation of the present-day (1980) flow system under stressed conditions brought about a somewhat different conceptual model of that flow system.

GEOGRAPHIC AND TOPOGRAPHIC SETTING

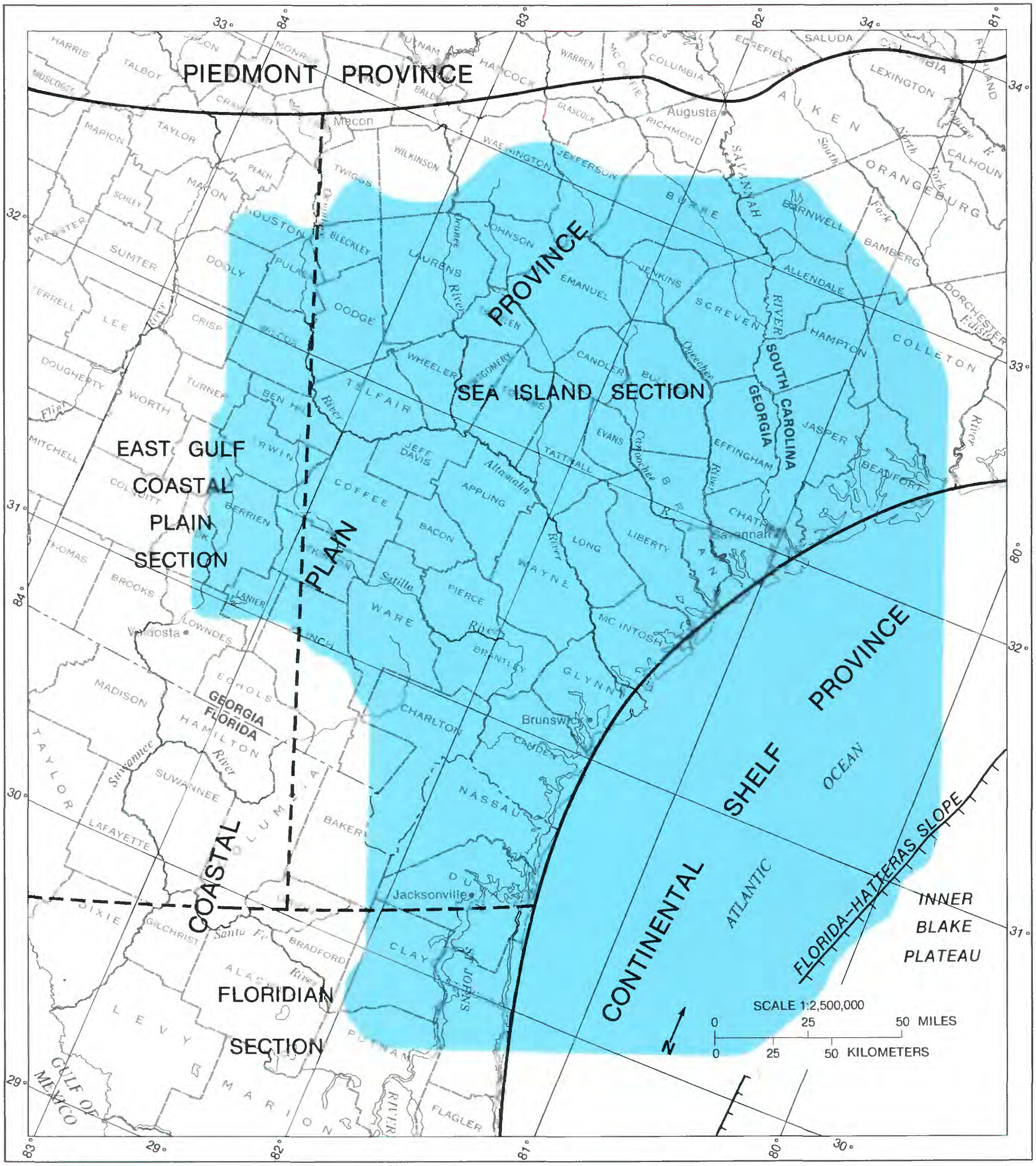
The study area lies entirely within the Coastal Plain and Continental Shelf provinces of the Atlantic Plain (Fenneman, 1938, pl. 3). The onshore Coastal Plain province accounts for about 20,000 mi^2 of the study area and the offshore Continental Shelf province, about 10,000 mi^2. Of the Coastal Plain province, about 75 percent of the area is within the Sea Island section, 16 percent within the East Gulf Coastal Plain section, and 9 percent within the Floridan section (fig. 2).

The topographic divisions shown in figure 3 are chiefly those of Cooke (in LaForge and others, 1925, p. 17, for Georgia; Cooke, 1936, p. 3, for South Carolina; and Cooke, 1939, p. 14, for Florida). Stringfield (1966, fig. 2) modified the divisions somewhat to conform along State lines.

The Coastal Lowlands range in altitude from sea level to about 100 ft. The region typically consists of barrier islands, marshes, level plains, and a series of five terraces resulting from the most recent advances and retreats of the sea during the late Pleistocene, which left shorelines and sea floors along the Coastal Lowlands.

The Central Highlands of Florida include all of north-central Florida inland of the Coastal Lowlands and range in altitude from about 40 to 250 ft in the study area. The Central Highlands area includes lakes, swampy plains, terraces, ridges, and hills. The central part of the Central Highlands is marked by karst topography—characterized by numerous sinks, sinkhole lakes, sinking streams, and springs—that extends into the Valdosta area of south Georgia. The karst topography in this area is a result of uplifting of the carbonate rocks during post-Oligocene time which locally exposed the rocks and facilitated erosion of the overburden (Stringfield, 1966, p. 73). This part of the study area, because of its karst features, is one of the most hydrologically dynamic areas, having large quantities of recharge through swallow holes, sinkholes, and sinkhole lakes, and discharge from springs.

The Coastal Terraces of Georgia and South Carolina range in altitude from about 100 to 270 ft. The area's topography is chiefly an inland continuation of the terraces deposited along the Coastal Lowlands and is represented by similar shorelines and sea bottoms left by early Pleistocene advances and retreats of the sea.



Base from U.S. National Atlas, 1970

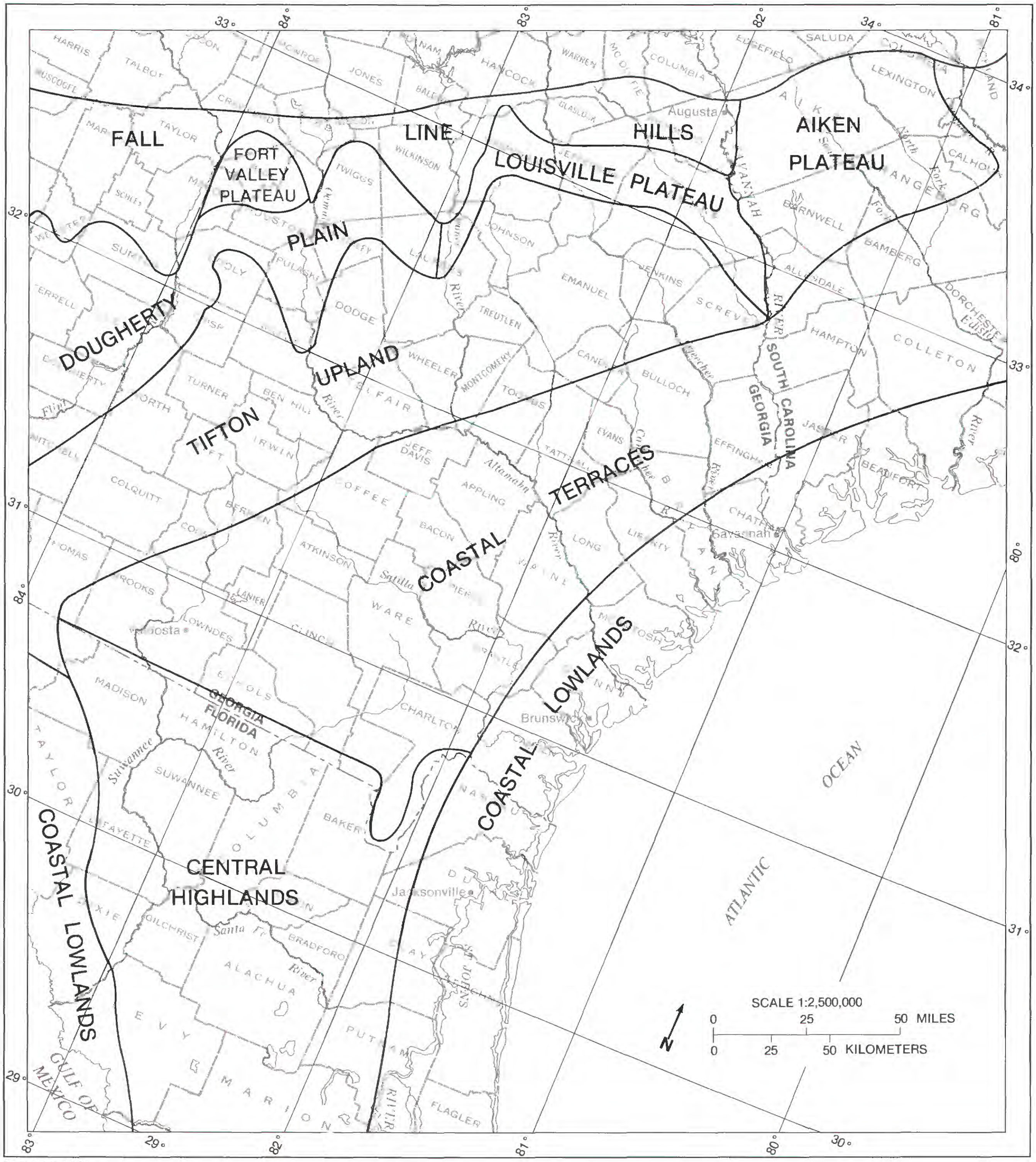
EXPLANATION

Province boundary

Section boundary

Study area

FIGURE 2.—Location of study area and physiographic subdivisions. From Fenneman (1938).



Base from U.S.
National Atlas, 1970

FIGURE 3.—Generalized topographic divisions of the Coastal Plain province. From LaForge and others (1925), Cooke (1936; 1939), and Stringfield (1966).

The Tifton Upland ranges in altitude from about 120 to 400 ft in the study area and is characterized by rolling hills and both gentle and deeply incised valleys. The Hawthorn Formation of Miocene age (table 1) underlies the Tifton Upland and extends downdip toward the coast, becoming more deeply buried under the Coastal Terraces. The upland is terminated to the northwest by a scarp and to the southeast by the Coastal Terraces. The Coastal Terraces boundary of the Tifton Upland is the approximate downdip edge of the Gulf Trough, a series of clastic-filled basins formed by high-angle faults (D.C. Prowell, U.S. Geological Survey, written commun., March 1982; Miller, 1985). The trough is narrow, generally less than 5 mi wide but as much as 10 mi wide in central Georgia and near the Florida–Georgia State line. The trough has a pronounced effect on the hydrology of the aquifer system, as ground-water flow is impeded by the fine clastic material in the trough, and on water quality, as mineralized water is associated with evaporites downgradient from the trough.

The Dougherty Plain ranges in altitude from about 200 to about 600 ft in the study area. The Dougherty Plain is typical of a karst topography, especially in the southwestern part of Georgia where limestone is covered by only a thin residuum. The northwestern part of the plain is characterized by subtle hills and valleys. Here the Hawthorn Formation is missing and the aquifer grades into sands.

The Louisville Plateau and Fort Valley Plateau are similar to the northeastern part of the Dougherty Plain. The plateaus range in altitude from about 300 to 600 ft and are characterized by broad, flat uplands. The area of the Louisville Plateau is roughly the same as the areal extent of sand and calcareous sand (Barnwell Formation) that is equivalent in age to the Upper Floridan aquifer. The Fort Valley Plateau is also underlain by this sand.

The Aiken Plateau is similar to the Louisville Plateau, having about the same altitude range and being underlain by similar material. Undrained depressions and Carolina Bays are common in the Aiken and Louisville Plateaus.

The Fall Line Hills area ranges in altitude from about 300 to 800 ft and is characterized by rolling hills and valleys. The area corresponds roughly with the outcrop area of Cretaceous material that extends from the Piedmont province at the Fall Line to the plains and plateaus coastward.

GENERAL HYDROLOGY

PRECIPITATION

Average annual precipitation based on the records for 1941–70 ranges from less than 44 in/yr south of Augusta, Ga., to more than 58 in/yr in a small area west of Jacksonville, Fla. (fig. 4). Each area of extreme range is represented by only one climatological station. In most of the study area, the average annual precipitation ranges from 46 to 56 in/yr. Precipitation is generally lowest in the east-central part of the Coastal Plain of Georgia and along the South Carolina coast and greatest in northern Florida.

Rainfall is unevenly distributed throughout the year. Within the study area, maximum rainfall, mainly from thunderstorms, occurs during the summer months of July and August in most of Georgia and in South Carolina. Maximum rainfall occurs in June, July, and August in south Georgia, and in July, August, and September in northeast Florida. Minimum rainfall occurs during October and November over most of the area and extends through December in south Georgia and northeast Florida, and through January farther south in Florida. Seasonal variation is greater in the coastal area than inland.

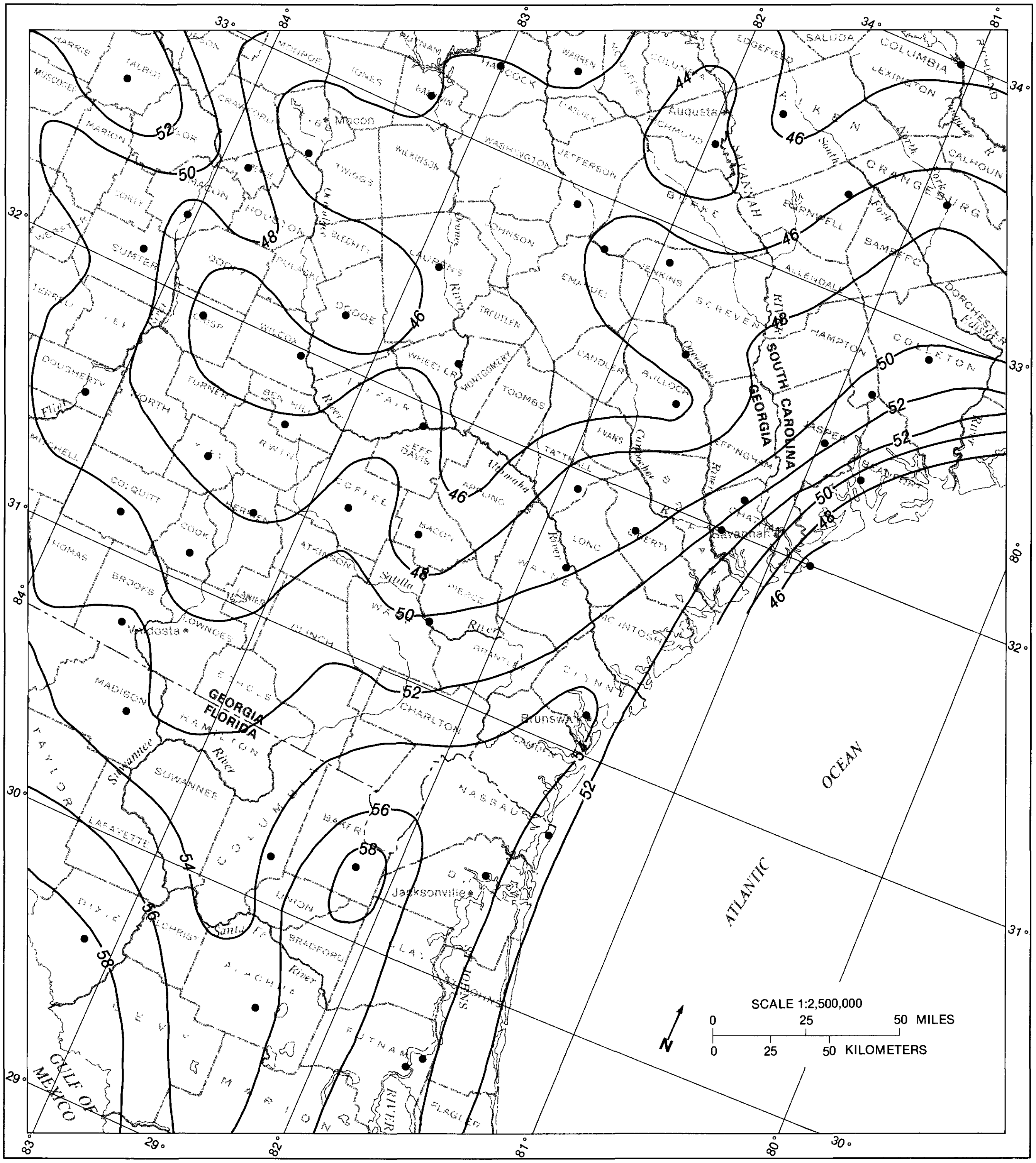
Rainfall as a source of recharge to aquifers is most important during the nongrowing season, when evapotranspiration is lowest. Generally, October through March constitutes the nongrowing season in the study area. During this period, average precipitation ranges from about 15 in/yr along the coast to almost 25 in/yr immediately below the Fall Line.

RUNOFF

Average annual runoff, based primarily on records for the period 1941–70, ranges from about 10 to 15 in/yr in most of the study area (fig. 5). Runoff is generally lowest along the coast and highest immediately below the Fall Line, corresponding to a similar distribution of precipitation.

Runoff is anomalously high in the Suwannee River basin, where average annual runoff for the period of record was greater than 35 in/yr. Rainfall is also high in this area (fig. 4), but the primary cause of the high runoff is interbasin transfer of water. In this area, water derived from rainfall in adjacent basins moves through the Floridan aquifer system and discharges as springs or seeps into the downgradient part of the Suwannee River basin. Conversely, the upgradient part of this basin loses significant quantities of water to sinking streams, thereby anomalously reducing runoff. Therefore, in the karst areas of north-central Florida and extreme south-central Georgia, basin runoff is not a simple function of the rainfall less evapotranspiration and infiltration, but also is related to karst topography.

Lines of equal runoff in figure 5 are drawn on the basis of average annual runoff at the centroid of the drainage area above the corresponding stream gages. Ad-



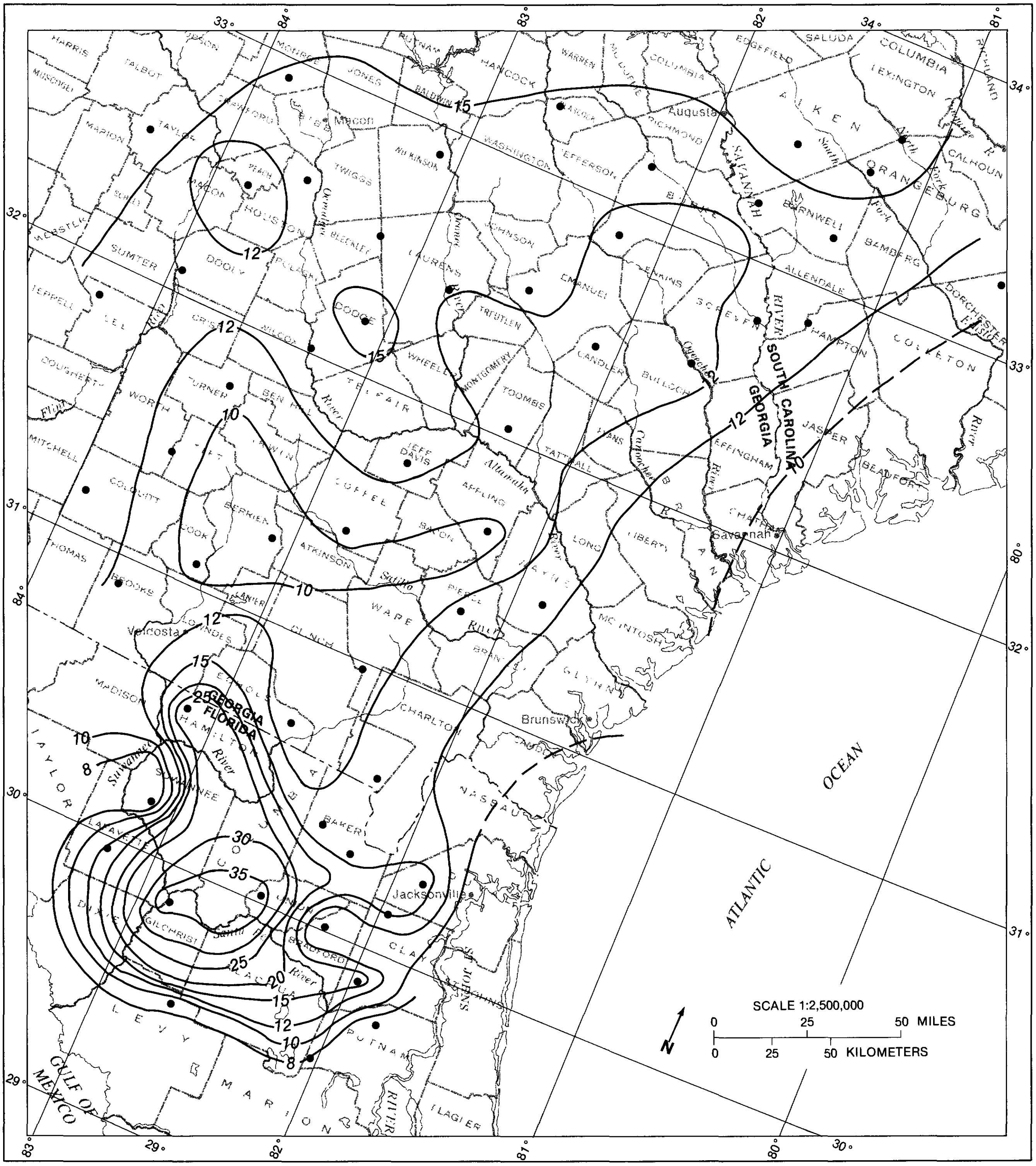
Base from U.S. National Atlas, 1970

EXPLANATION

—52— **Line of equal precipitation**—Interval 2 inches

● **Data point**

FIGURE 4.—Average annual precipitation, 1941–70.



Base from U.S. National Atlas, 1970

EXPLANATION

—*10*— **Line of equal runoff**—Interval 2 inches below 12, 3 inches to 15, and 5 inches above 15. Dashed where approximately located

● **Data point**

FIGURE 5.—Average annual runoff, 1941–70.

justments were made to discharge at gages where diversions, regulations, or consumptive uses were significant. Data were omitted for sites where satisfactory adjustments could not be made. Data for the period 1941–70 were used except for a few sites in South Carolina and Florida, where the only data available were for periods of record: from the forties or early fifties through 1978. Comparison of runoff at several nearby sites for all periods indicated an acceptable correlation. The period 1941–70, rather than the period 1951–80 (both conforming to the 30-year climatological summary period used by the U.S. National Weather Service), was used because more stream-discharge data from gaging stations were available in the earlier period, as several stations were discontinued between 1970 and 1980.

The average annual runoff for Florida shown in figure 5 may differ from that delineated for Florida by Hughes (1978) for several reasons: (1) the method of determining runoff herein, and depicting it with lines of equal runoff, is unlike the method used by Hughes, who merely showed ranges of runoff within major basin boundaries, and (2) data coverage for the method used herein was considerably greater; data from several subbasins, each having a unique runoff, were included herein, but were averaged and lumped into the larger hydrologic units of Hughes.

EVAPOTRANSPIRATION

Evapotranspiration ranges from about 30 to 40 in/yr over the study area (fig. 6). Areal distribution of evapotranspiration rates indicates that evapotranspiration increases from north to south and from inland toward the coast. An exception occurs in southeast Georgia, where the Okefenokee Swamp accounts for the highest rate of evapotranspiration in the State.

Evapotranspiration rates used to construct figure 6 were chiefly those determined by Bush (1982), who used the values to make initial estimates of recharge and discharge rates for the regional flow model. The lines of equal evapotranspiration rates shown in figure 6 were based on 25 data stations located at the centroids of areas that were subdivided on the basis of drainage area and Thiessen polygons of rainfall distribution. Bush (1982) estimated total evapotranspiration rates within each basin from weighted averages of evaporation rates from open-water areas, such as swamps and marshes, and evapotranspiration rates from land areas. He estimated open-water evaporation rates from a map of average annual lake evaporation for the period 1946–55 (Kohler and others, 1959, pl. 2). Evaporation rates from swamp and marsh areas were assumed to be 90 percent of the open-water rate (Bush, 1982).

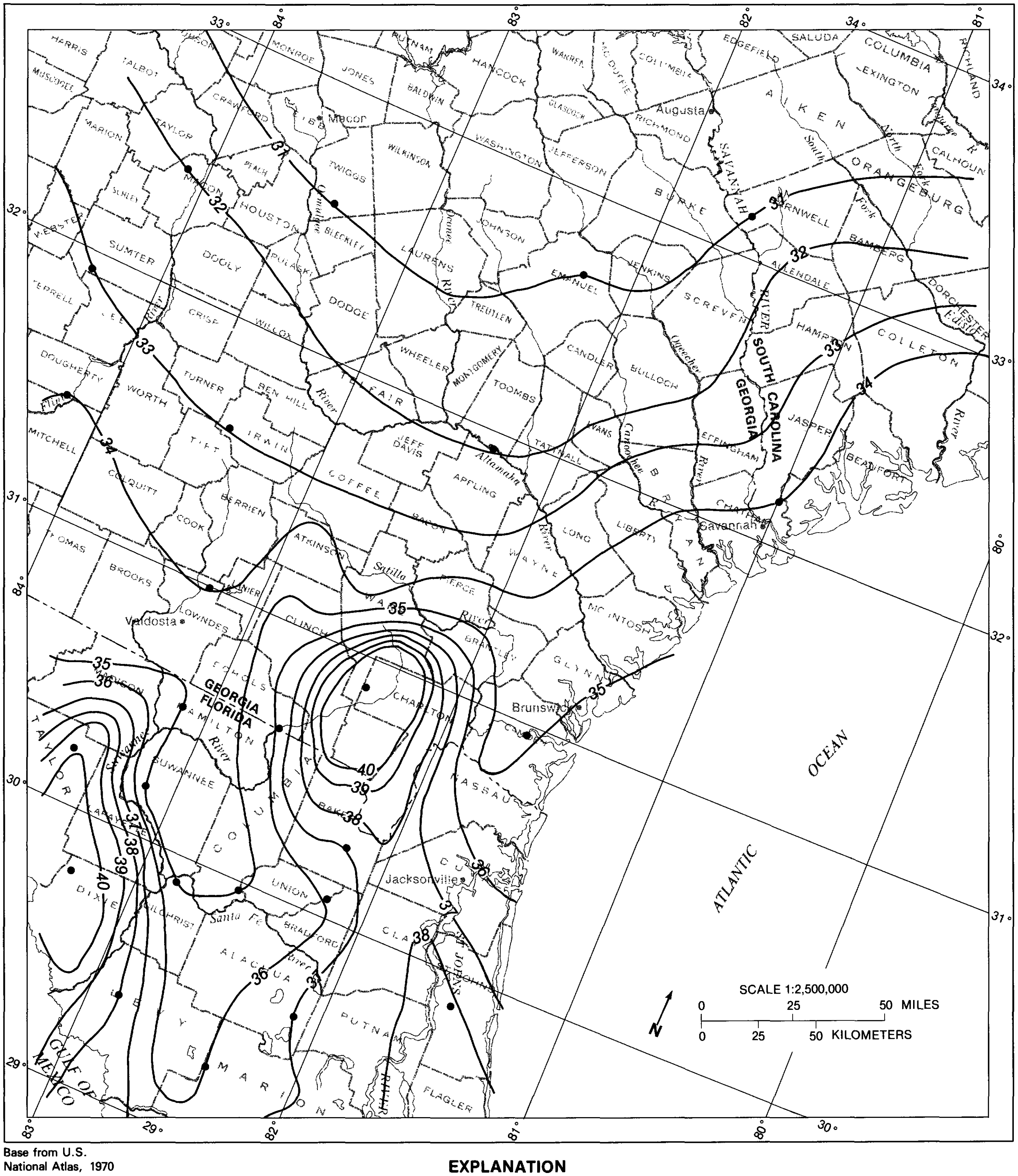
Bush (1982) estimated rates of evapotranspiration from land areas by using a method developed by Holdridge (1967) and later described and used in Florida by Dohrenwend (1977, p. 185). The method uses Holdridge's (1967) "life-zone" bioclimatic classification system, based on latitudinal and altitudinal regions, humidity provinces, soil and vegetative types, and precipitation. The important variable in the method is biotemperature, defined by Holdridge (1967) as the sum of hourly temperatures between 0° and 30°C divided by the number of hours in the year. For a complete discussion of the methodology, see Bush (1982).

HYDROGEOLOGIC SETTING

In general, the Floridan aquifer system is made up of consolidated marine and marginal marine limestone and dolomite and lesser amounts of evaporites, clay, sand, and marl (table 2, in pocket). In the study area, the aquifer system consists of several formations that range in age from early Eocene to Oligocene (table 2). Principal units making up the system are the Oldsmar and Avon Park Formations and the Ocala, Santee, and Suwannee Limestones. Locally, in the Brunswick, Ga., area, rocks of Paleocene age (the Cedar Keys Formation) and the Lawson Limestone of Late Cretaceous age are also part of the aquifer system. In the northern part of the study area, updip clastic facies of the carbonates, although not considered by Miller (1985) to be part of the Floridan aquifer system, are hydraulically connected with it and are thus part of its regional flow system. The aquifer system forms a nearly vertically continuous carbonate sequence that is hydraulically connected in varying degrees. Zones of low permeability and areal continuity exist within the Floridan throughout most of the area and separate the aquifer system into two permeable, water-bearing zones, the Upper Floridan aquifer and the Lower Floridan aquifer, and locally into a third zone, the Fernandina permeable zone, which is part of the Lower Floridan aquifer. The Floridan is confined below by low-permeablity beds of clastic or evaporitic material, and in most of the area is confined above by clayey strata primarily of Miocene age (table 2).

HYDROGEOLOGIC FRAMEWORK OF THE FLORIDAN AQUIFER SYSTEM

The hydrogeologic framework of the Floridan aquifer system in southeast Georgia and parts of Florida and South Carolina described in this report chiefly follows the regional definition of the aquifer system described by Miller (1982a, b, c, d, e; 1985, chapter B of this Professional Paper series). Miller's framework of the aquifer system is restricted to the predominantly carbonate sequence. However, the hydrogeologic framework described herein also includes updip, largely clastic beds



EXPLANATION

—37— **Line of equal evapotranspiration**—Interval 1 inch

● **Data point**

FIGURE 6.—Average annual evapotranspiration. Adapted from Bush (1982).

that are chronostratigraphic equivalents of the carbonate sequence and can be shown by simulation to be part of the Floridan's flow system.

The Floridan aquifer system thickens from a featheredge in the northern outcrop area to more than 2,000 ft downdip in coastal Georgia and to more than 2,600 ft locally in the area of Brunswick, Ga. (pl. 1). The system includes all strata that lie between the top of the uppermost continuous high-permeability carbonate sequence (top of the Floridan) and the top of highly clastic or evaporitic rocks having low permeability (base of the Floridan).

Plate 1 and the other hydrogeologic framework maps in this report are modified from Miller (1982a, b, c, d, e). Miller mapped the areal extent of the top, base, and thickness of the aquifer system and separated the component aquifers and confining units on the basis of permeability contrasts. These permeability contrasts may exist anywhere within a rock unit (stratigraphic horizon or stage equivalent). Therefore, these maps may differ from previously published maps that portray the extent of carbonate sequences or particular geologic units that are not classified on the basis of permeability contrast.

Various geologic and time-stratigraphic units in different combinations make up the aquifer system in different places. The thickness of the aquifer system is represented by the composite thickness of several units having similar permeability characteristics, yet the number of units that make up the system, and their ages, may differ from place to place.

Miller (1982d) arbitrarily placed the updip limit of the aquifer system along a line where the aquifer system is generally less than 100 ft thick and where clastic units, which are facies of the limestone units, make up more than 50 percent of the section. In the updip part of the aquifer system, limestone becomes a small part of the section, being interbedded with calcareous sand and clay. Still farther updip, these units grade into units that are mostly clastic, are stratigraphic equivalents of the limestone, and have hydrologic properties somewhat similar to the limestone. In this updip area north and west of the line shown on plate 1 as the approximate updip limit of the aquifer system, there are thin beds and lenses of limestone that may be either connected to the main limestone body or isolated from it because of postdepositional erosion. Although these thin beds locally yield small to moderate amounts of water, they are not considered part of the Floridan aquifer system of Miller (1985). However, the thin limestone units and the clastic units in this updip area are included in the flow simulation in this study because of their local hydrologic significance.

Generally, in northeast Florida and southeast Georgia, rocks of the aquifer system consist of limestone and dolomite, having very little organic or argillaceous material (Chen, 1965, p. 75). In the northern part of the study area, the rocks of the lower part of the aquifer system are terrigenous clastics. In a northerly direction from a line trending east-northeast through Echols County, Ga., the limestone and dolomite become more argillaceous, then arenaceous, grading to calcareous clastics and finally to noncalcareous clastics at the outcrop belt along the Fall Line. The transition zone between the carbonate and clastic facies is the approximate northern extent of the thick carbonate platform that existed in the Florida peninsula during early Tertiary time. Between the predominantly terrigenous clastic and the predominantly carbonate areas and trending east-northeast through Echols County, Ga., is a thick sequence of Tertiary material, chiefly fine calcareous clastics and carbonates, that probably represents the Suwannee Strait described by Ewing and others (1966, p. 1969) and Husted (1972, p. 1558) or the Suwannee Channel described by Chen (1965, p. 10). The channel or strait was a factor influencing the distribution of these depositional facies. The effect of the channel or strait was most pronounced in Late Cretaceous time, and its effect decreased with time until it finally disappeared near the end of Eocene time. The transition zone between carbonate facies to the south and clastic facies to the north migrated northward from extreme southeast Georgia during Paleocene and Eocene time (Chen, 1965, p. 8, 9). The carbonate platform subsequently enlarged toward the north until finally, in late Eocene time, the carbonate facies had extended to a line approximated by the 100-foot aquifer-system thickness line (pl. 1).

The central part of the coastal area of Georgia, where the aquifer system is thick (pl. 1), lies in a depositional basin called the Southeast Georgia embayment. The altitude of basement rock is lower and all time-stratigraphic units in the Tertiary System are thicker in the embayment than in surrounding areas. Within this embayment, in the area of Brunswick, Ga., rocks of Paleocene and Late Cretaceous age are part of the Floridan aquifer system, resulting in a great thickness of the system in that area.

A significant feature affecting the thickness of the aquifer system is the Gulf Trough, first defined by Herrick and Vorhis (1963, p. 55) and later described by Gelbaum (1978, p. 39). The Gulf Trough trends northeastward within the study area from Colquitt County to Effingham County, Ga., and extends southwestward out of the study area to the panhandle of Florida. Simulation of the flow system indicates that the trough probably extends northeastward into South Carolina.

The Gulf Trough is a graben system caused by high-angle faulting that was active during much of the time of deposition of the rocks that make up the Floridan aquifer system (Gelbaum, 1978). Within the grabens are thick accumulations of low-permeability, clastic sediments and argillaceous carbonate rocks. Permeable, water-bearing units of the aquifer system are thus thinner within these grabens. (See pl. 1.)

Ground-water flow in the Floridan aquifer system is partially impeded by the Gulf Trough as a result of two mechanisms. First, near-vertical displacement of rocks along the faults of the graben system has juxtaposed rocks of lower permeability against the more permeable rocks of the aquifer system. Second, within the grabens the aquifer system consists of relatively low permeability material, which decreases the aquifer system's effective thickness.

Immediately downdip from the Gulf Trough, in the western part of the study area, the aquifer system is thin, ranging in thickness from about 400 to 900 ft (pl. 1). In this area the limestone of the lower part of the aquifer system contains evaporites, chiefly gypsum, that occur as nodules and lenses infilling the otherwise porous limestone (Krause, 1979). In this area, ground-water flow downgradient from the Gulf Trough was restricted and probably was not sufficient to produce the secondary porosity and permeability of the aquifer system as in other parts of the study area.

The limestone making up the Floridan aquifer system is thin in part of South Carolina, ranging in thickness from about 20 to 80 ft (pl. 1). In this area, the Upper Floridan aquifer is largely absent (Hayes, 1979, p. 28–30) and the Lower Floridan makes up the aquifer system. In a northeasterly direction from the extreme southern part of South Carolina, the Upper Floridan aquifer becomes thin and undergoes a facies change to low-permeability clastic rocks; the effect is that of a pinch-out of the Upper Floridan (Miller, 1985). Also, nearly all wells drilled in this part of South Carolina for water supply pass through the Upper Floridan and tap the Lower Floridan, where water is readily available. The northeasterly extent of the Upper Floridan (pl. 1) is marked arbitrarily by the reduction of the aquifer system's permeability and is shown on plate 1 by a dashed northwest-trending line whose location is based on widely scattered well control. In this area, the Lower Floridan aquifer consists of a thin permeable section at the base of the middle Eocene Santee Limestone.

An indication that the middle Eocene Santee Limestone is a significant aquifer in Orangeburg County, S.C., northeast of the Floridan aquifer system's extent as defined by this study, is documented by Siple (1975, p. 30). Siple (1975, p. 36) states that the Santee is the lithostratigraphic equivalent of the "Principal Limestone Aquifer" of Stringfield (1966, p. 95), which is basically equivalent to the Floridan aquifer system herein described. Siple (1975, p. 30, 36, 37) also states that the Santee is permeable and locally karstic, containing caves and springs near Lake Marion (located along the eastern county lines of Calhoun and Orangeburg Counties) and having transmissivity (estimated from specific-capacity data) as high as 5,000 ft^2/d. One well tapping the Santee was reportedly pumped at a rate of 600 gal/min with no appreciable drawdown (Siple, 1975, p. 40). In Colleton County, between the Orangeburg County area and the limit of the Floridan aquifer system defined in this report, Hayes (1979, p. 38–42) considers the upper permeable zone (Upper Floridan) to be thin and of low yield (less than 250 gal/min with more than 25 ft of drawdown). The lower permeable zone of Hayes (1979), equivalent to the Lower Floridan aquifer of this report, also yields small quantities of water. The specific capacities of eight wells tapping the Floridan aquifer system in Colleton County (Hayes, 1979, table 10) are less than 5 (gal/min)/ft. Thus, although rocks of the Santee Limestone in Orangeburg County northeast of the study area are probably stratigraphically equivalent to the Floridan aquifer system of the study area, and constitute a significant aquifer in both areas, they are not continuous and the Floridan probably extends only to its limit delineated in this study (pls. 1–4).

TOP OF THE AQUIFER SYSTEM

The top of the aquifer system as defined and mapped by Miller (1982d) represents the top of the highly permeable carbonate rock that is overlain by low-permeability material, either clastic or carbonate, which makes up the upper confining unit. Rocks of Oligocene age (Suwannee Limestone or equivalent) make up the top of the aquifer system over most of the central part of the study area. Rocks of late Eocene age represent the top of the aquifer system in most of northeast Florida and extreme southeast Georgia, and in small areas of Georgia and adjacent South Carolina where the Oligocene rocks have been stripped away by post-Oligocene erosion. Locally, in northeast Florida, small outliers of Oligocene rocks that were not eroded constitute the top of the aquifer system. Rocks of late Eocene age also make up the top of the aquifer system in east-central Georgia and adjacent South Carolina (pl. 2). Here, Oligocene rocks were not deposited, or were thin and readily eroded, or both. In part of the extreme updip Coastal Plain in Georgia and South Carolina, calcareous clastic rocks of late Eocene age make up the top of the aquifer system (pl. 2). Here, the rocks consist of fossiliferous, argillaceous, glauconitic, calcareous clay and are part of the Barnwell Formation. Hydraulically, these beds, which are clastic facies of downdip carbonate rocks, do not represent a significant, corresponding change in permeability. Instead, these permeable clastic beds are hydraulically connected with the downdip carbonate rocks of the Upper Floridan aquifer.

In the extreme northeast part of the study area in South Carolina, the lower part of the Santee Limestone of middle Eocene age forms the top of the aquifer system (pl. 2). The Lower Floridan constitutes the permeable part of the aquifer system here.

BASE OF THE AQUIFER SYSTEM

In general, the base of the aquifer system is youngest in the updip part of the study area and is successively older downdip. The base of the aquifer system is oldest in the area of Brunswick, Ga., where it consists of evaporite beds and low-permeability dolomite of Late Cretaceous age. The altitude, configuration, and stratigraphy of the base of the aquifer system, chiefly as defined by Miller (1985), are shown on plate 3. In places, the base of the flow system differs slightly from the hydrogeologic base of the aquifer system as defined by Miller (1985). The predominantly clastic units, which lie both updip and below the predominantly carbonate rocks, are not a part of the Floridan aquifer system as defined by Miller (1985). They are hydraulically connected with the aquifer system, however, and thus were simulated during this study.

Rocks primarily of late Eocene age form the base of the aquifer system in the area downdip from the Gulf Trough in the western part of the study area (pl. 3). There, deposition of secondary gypsum has filled most of the pore space in the lower part of the Ocala Limestone and locally in the upper part of the Avon Park Formation. The Ocala is normally a highly permeable rock unit, and is the most productive of any of the formations in the Floridan aquifer system in the study area. Owing to the gypsum mineralization and the general lack of high secondary permeability, the lower part of the Ocala is a low-permeability unit to the southeast of the western part of the Gulf Trough within the study area. In that part of the area, the Ocala grades downward into low-permeability clastic rocks of the Lisbon Formation, and no Lower Floridan aquifer is present.

The base of the aquifer system near its updip limit in the northwestern part of the study area (pl. 3) is composed of fine-grained, calcareous, glauconitic sand interbedded with clay and argillaceous sand. These strata are part of the Lisbon Formation of middle Eocene age. Still farther downdip, the thickness of permeable material in the aquifer system increases and its base becomes progressively lower toward the southeast with respect to altitude and stratigraphic position. In a narrow northeast-trending strip across the central Georgia Coastal Plain, clastic rocks of the Lisbon Formation have graded by facies change into permeable limestone, which continues downdip. The base of the aquifer system in this transition zone consists of fine-grained, highly glauconitic sand, argillaceous sand, and clay, all of which are part of the Tallahatta Formation (pl. 3).

In the area along the Savannah River in Georgia and South Carolina (pl. 3), the base of the aquifer system is composed of highly sandy, calcareous clay interbedded with soft, sandy, argillaceous limestone and fine, calcareous sand. These rocks are time-equivalent to the Santee Limestone of South Carolina. Both the updip Lisbon and the downdip Tallahatta grade laterally into the Santee equivalent by facies change.

In these aforementioned areas where the base of the aquifer system is composed of middle Eocene rocks, permeable clastic units lying below the predominantly carbonate rocks are not a part of the aquifer system of Miller (1985) and are thus not shown on plate 3. They are, however, hydraulically connected with the downdip and the overlying carbonate facies of the Lower Floridan. Where such sands are present, the base of the Floridan aquifer system, for purposes of this study, lies within the Huber Formation in updip areas, and within either the Gosport equivalent, the Lisbon Formation, or the Tallahatta Formation in downdip areas.

Clastic rocks of early Eocene age form the base of the aquifer system in east-central coastal Georgia. These low-permeability rocks consist of silty, highly glauconitic, micaceous fine sand interbedded with lignitic clay. They are undifferentiated at present, but they are stratigraphic equivalents of the Tuscahoma and Nanafalia Formations of western Georgia and eastern Alabama. In the northern part of this area, permeable, clastic material of early Eocene age is hydraulically connected with the carbonate facies of the Lower Floridan.

The base of the aquifer system in south-central Georgia and adjacent counties in north Florida is represented by chalky, glauconitic, gypsiferous limestone and dolomite that are part of the Oldsmar Formation. Part of the Oldsmar grades northward and westward into equivalents of the Tuscahoma and Nanafalia Formations.

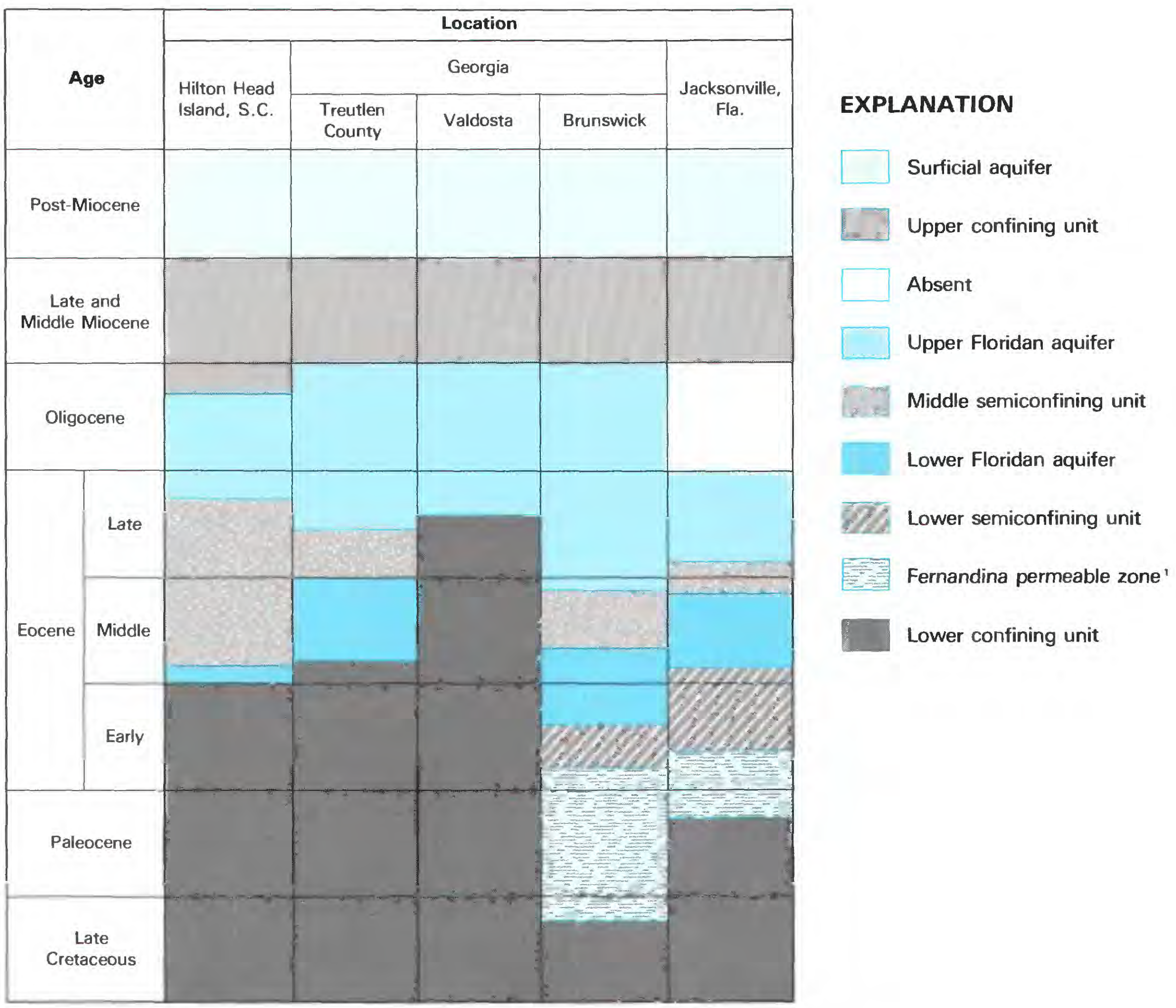
The Cedar Keys Formation of Paleocene age constitutes the base of the aquifer system in northeast Florida and extreme southeast Georgia. Rocks of the Cedar Keys Formation are dolomitic limestone and dolomite, having regionally extensive interbedded anhydrite layers that mark the base of the system. In the extreme northeast part of the study area in South Carolina, the base consists of fine-grained, argillaceous, calcareous sand of the Black Mingo Formation.

Locally, in the area of Brunswick, Ga., the base of the aquifer system consists of soft, argillaceous, chalky limestone of Late Cretaceous (probably Tayloran) age. Younger, highly permeable, Late Cretaceous (Navarroan) calcarenite overlies the chalk and is part of the aquifer system.

AQUIFER-SYSTEM LAYERING

The Floridan aquifer system can generally be divided into upper and lower major permeable zones, called the Upper Floridan and the Lower Floridan aquifers, respectively. These aquifers are separated by what is termed the "middle semiconfining unit," whose age and lithologic character vary. In part of the study area, there is an extensive high-permeability zone within the Lower Floridan aquifer, herein formally designated the "Fernandina permeable zone" (pl. 3). The Fernandina permeable zone is everywhere overlain by a low-permeability confining unit of subregional extent. Although this confining unit is known to leak along local fractures, it otherwise effectively separates the Fernandina permeable zone from the overlying permeable beds within the rest of the Lower Floridan aquifer. Throughout most of the study area, the Floridan aquifer system is confined above by low-permeability clastic rocks of Miocene age. The system is everywhere underlain by a lower confining unit, which consists of low-permeability materials that may be evaporites, clastic rocks, or carbonate rocks. The age of the lower confining unit ranges from late Eocene to Late Cretaceous. (See table 3 and pl. 3.) The individual

TABLE 3.—*Aquifer-system layering*



[1] Part of Lower Floridan aquifer.

aquifers and confining units are shown on plates 4 and 5 and described below.

SURFICIAL AQUIFER

In most of the area where the Floridan aquifer system is confined, a surficial aquifer overlies the upper confining unit. The surficial aquifer consists of post-Miocene age, unconsolidated fine to very coarse, well-sorted sand, at depth commonly phosphatic and calcareous. In some areas, grain size is as large as fine gravel. Interbedded with these beds are layers of poorly sorted sand, clayey silt and sand, and, at depth, argillaceous limestone. In the extreme updip part of the study area, the upper confining unit is absent and the calcareous, clastic facies of the Floridan are largely unconfined. In this area, the Upper Floridan is under water-table conditions and supplants the surficial aquifer.

Water in the surficial aquifer is unconfined or under water-table conditions. The configuration of the water table is generally 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 also is near land surface in areas where the aquifer contains beds of low-permeability material. Generally, the water table is lower beneath topographic highs in areas of moderate to comparatively high relief. It is also lower where thick deposits of permeable material are present, such as along the Pleistocene shoreline ridges paralleling the coast. Relatively steep gradients in the water table adjoin the major stream courses, and relatively gentle gradients exist in the broad interstream areas.

In some areas where the clastic material overlying the Floridan aquifer system is thick, such as in the Southeast Georgia embayment, additional, partially confined permeable zones of clastic material are present within the upper confining unit and between the surficial aquifer and the Upper Floridan. Heads in these water-bearing zones may be higher or lower than heads in the surficial aquifer, depending on the degree of confinement, proximity of aquifers, withdrawal of water from the aquifers, and head gradient between the surficial aquifer and the Upper Floridan aquifer.

Precipitation infiltrates the surficial aquifer and moves down to the water table, providing the prime source of recharge to the aquifer. Water moves laterally downgradient and discharges into streams, ponds, and other surface-water bodies. Some water is lost to evaporation and transpiration, and some leaks downward into the Upper Floridan. The water level in the surficial aquifer responds rapidly to rainfall and shows seasonal variations corresponding to similar variations in rainfall and evapotranspiration. Seasonal fluctuations in the water level may be as great as 15 to 20 ft in areas of high topographic relief and where the aquifer is composed chiefly of coarse clastic, high-permeability material. Seasonal fluctuations are more commonly less than 10 ft in flat-lying areas and where low-permeability material is within, and especially near the top of, the surficial aquifer (fig. 7). Long-term climatic fluctuations in the water level in the surficial aquifer are probably negligible. Marked departures from normal precipitation (based on the period 1943–81) typically cause only a few feet of change in the water level (fig. 8).

The surficial aquifer functions as a source or sink to the underlying Floridan aquifer system, receiving water from or giving water to the Floridan. In areas where the water table in the surficial aquifer is above the potentiometric surface of the Floridan, the surficial aquifer recharges the Floridan by downward leakage through the upper confining unit. Where the head gradient between the surficial aquifer and the Floridan is in the opposite direction, the surficial aquifer receives upward leakage from the Floridan.

UPPER CONFINING UNIT

The upper confining unit consists primarily of the Hawthorn Formation of late and middle Miocene age, where present. It is composed of all strata between the surficial aquifer and the Upper Floridan aquifer, and thus includes not only clay of extremely low permeability but also, locally, sand beds of moderate permeability. In some areas, low-permeability beds of post-Miocene age are part of the upper confining unit. Over most of the study area, the unit is of middle Miocene age and consists of interbedded, locally highly phosphatic sand, silt, clay, and sandy clay beds of low permeability. The maximum thickness of the unit is about 600 ft in the Southeast Georgia embayment near Brunswick, Ga. (pl. 4).

The upper confining unit overlies all of the Floridan aquifer system except in the extreme updip part of the study area and in small areas where the confining unit has been breached or removed by erosion (pl. 4). These areas are not completely delineated by the lines of thickness of the upper confining unit shown on plate 4 because of the low density of control-well data. The thickness of the confining unit in the area of Brooks and Lowndes Counties, Ga., shown on plate 4 has been depicted with somewhat greater detail on the basis of work by Krause (1979, pl. 1). In Lowndes County, within the channel of the Withlacoochee River, the confining unit has been stripped away (pl. 4). In addition, some of the deeper sinkholes in the areas of thin confinement in the area of Lowndes County, as well as in the area of Keystone Heights, Fla., probably also breach the confining unit.

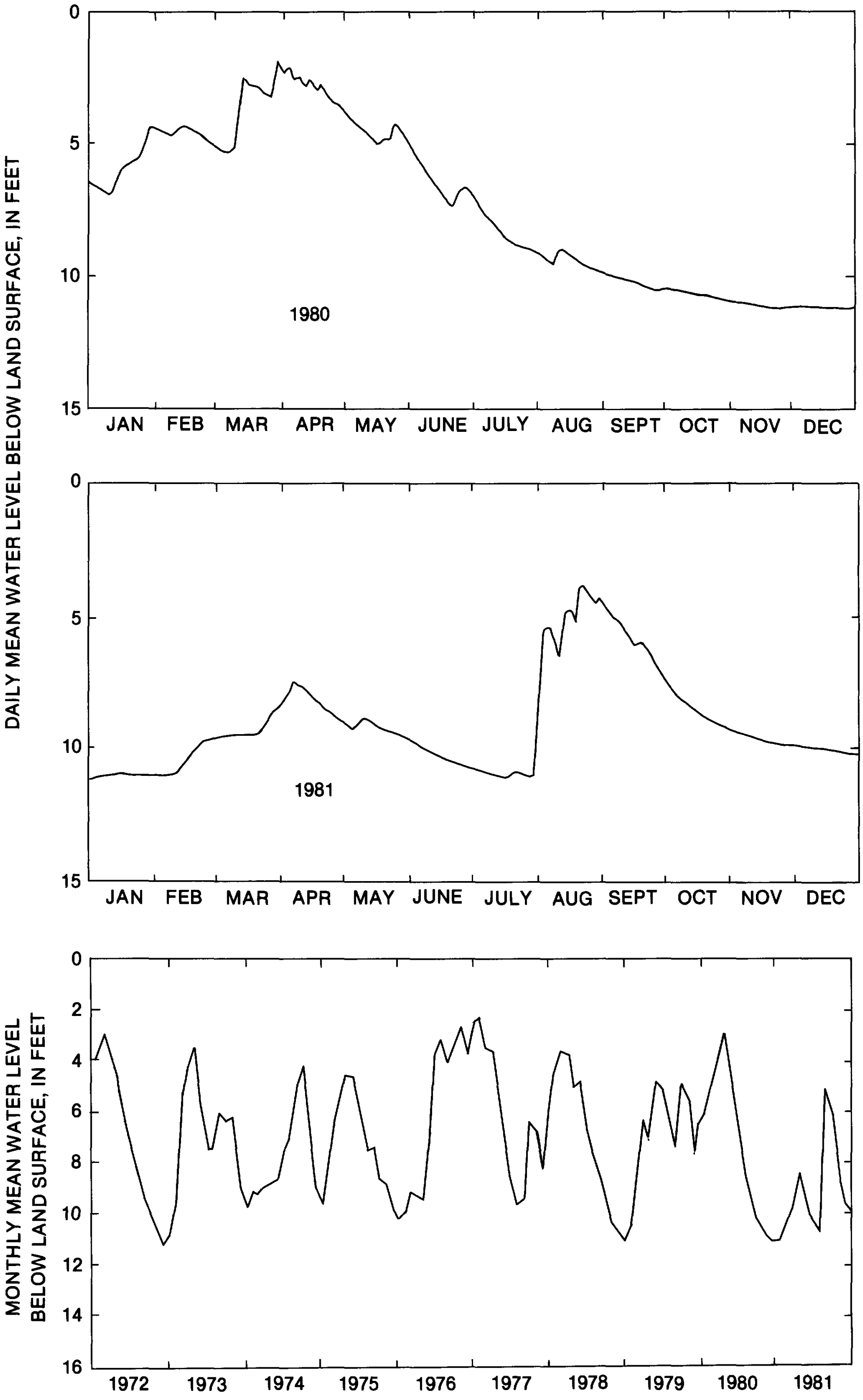


FIGURE 7.—Water-level fluctuations in the surficial aquifer, well 35P94, near Savannah, Ga.

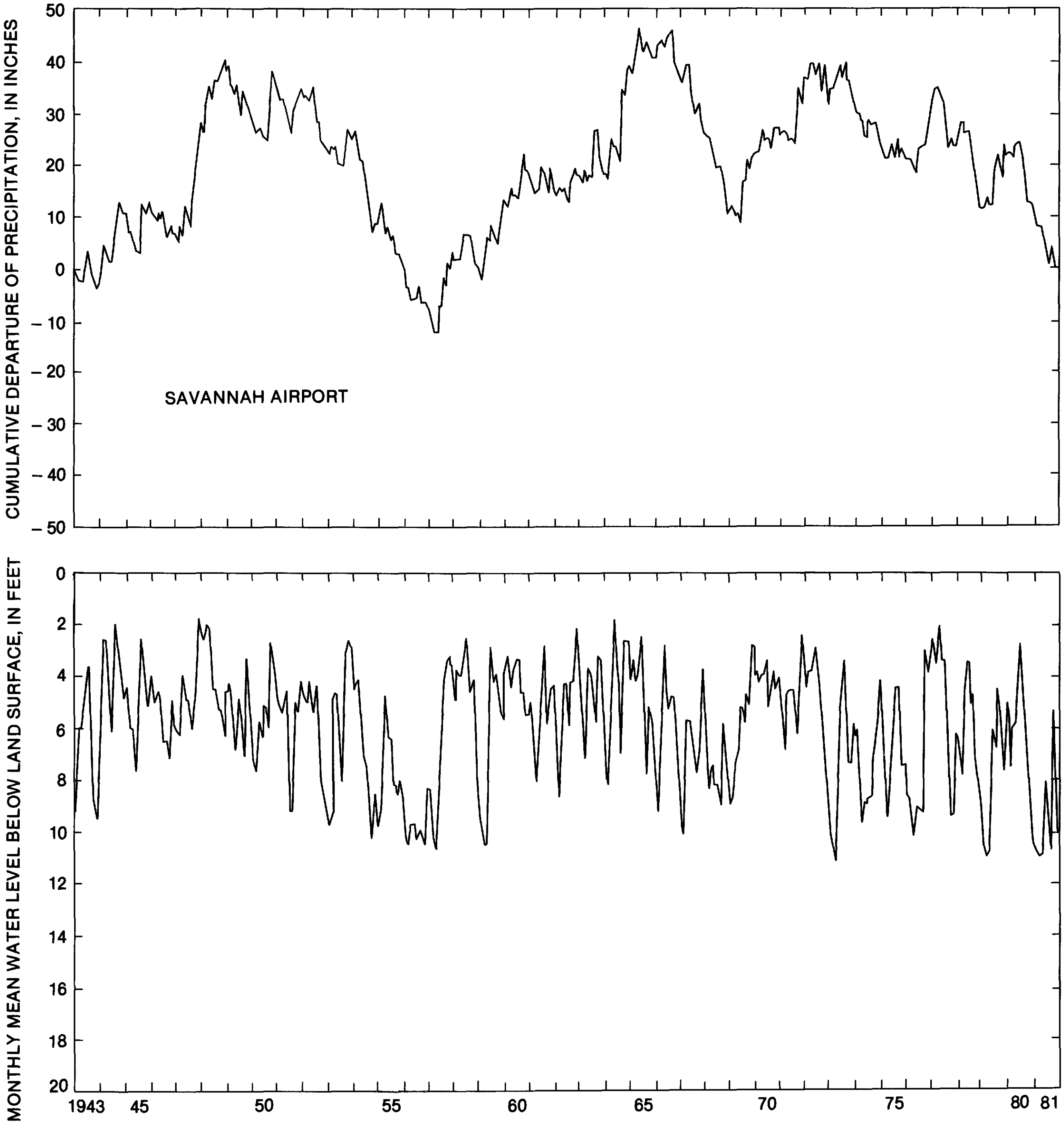


FIGURE 8.—Water-level fluctuations in the surficial aquifer, well 35P94, and cumulative departure of precipitation, Savannah, Ga., area, 1943–81.

In the area of Savannah, Ga., and Hilton Head Island, S.C., where the upper confining unit is thin, scouring action of creeks and estuaries, as well as the additional removal of material by dredging, has breached the upper confining unit (pl. 4) (Duncan, 1972, p. 103; Hayes, 1979, p. 30, 50; Randolph and Krause, 1984, p. 5).

In the part of South Carolina where the Upper Floridan aquifer is absent, the upper confining unit is mapped as an extension of the same late and middle Miocene and part of Oligocene strata that elsewhere compose the upper confining unit. Therefore, the thickness of the upper confining unit shown on plate 4 does not represent the entire thickness of the material overlying the Lower Floridan, but includes only the rocks that are chronostratigraphic equivalents of the upper confining unit.

The major updip rivers—Ocmulgee, Oconee, and Ogeechee in Georgia, the Savannah on the Georgia-South Carolina State line, and the Salkehatchee in South Carolina—also probably breach the confining unit, but the extent is largely unknown.

UPPER FLORIDAN AQUIFER

The Upper Floridan aquifer of the Floridan aquifer system consists chiefly of the Ocala Limestone and equivalents of late Eocene age. The Ocala, especially the upper part, is a very fossiliferous limestone having high effective porosity and permeability. Secondary permeability, which was developed by the migration of ground water along bedding planes, joints, fractures, and other zones of weakness, has made the Ocala extremely permeable.

In the area of Brunswick, Ga., the Upper Floridan consists of two permeable zones—the "upper and lower water-bearing zones" described by Wait and Gregg (1973, p. 16) and by Gregg and Zimmerman (1974, p. D17). The upper water-bearing zone includes the uppermost part of the Ocala and ranges in thickness from about 75 to 150 ft. It is a very fossiliferous, permeable limestone that contributes about 70 percent of the water to wells that tap both zones. The lower water-bearing zone includes the basal Ocala and the uppermost part of middle Eocene rocks, and ranges in thickness from about 15 to 110 ft. It is a recrystallized dolomitic limestone, less permeable than the upper water-bearing zone, and contributes about 30 percent of the water to wells that tap both zones. The two zones are treated as a single aquifer (Upper Floridan) in this study. Water-supply wells in the area of Brunswick generally do not tap water-bearing units beneath the Upper Floridan.

Although Miller (1985) included the Oligocene Suwannee Limestone, which overlies the Ocala, in the Upper Floridan in the area of Brunswick, the Suwannee is thin and yields insignificant quantities of water when compared with the upper and lower water-bearing zones.

In the area of Savannah, Ga., the Upper Floridan consists chiefly of two permeable zones—"zones 1 and 2" described by McCollum and Counts (1964, p. D9). These permeable zones were delineated on the basis of current-meter tests made in open holes in the Savannah area. Zone 1 is in the basal part of the Suwannee Limestone and the top part of the Ocala and is generally less than 50 ft thick. Zone 2 is near the middle of the Ocala and ranges from 25 to 75 ft in thickness. Zones 1 and 2 generally yield more than 70 percent of the water pumped from open holes tapping the entire aquifer system (McCollum and Counts, 1964). The two zones are treated together as the Upper Floridan aquifer in this study. Water-supply wells in the area of Savannah generally do not tap water-bearing zones beneath the Upper Floridan.

In the southern tip of South Carolina, the Upper Floridan is the "upper permeable zone" described by Hayes (1979) and Spigner and Ransom (1979). There, the Upper Floridan consists of the basal part (late Eocene age) of the Cooper Formation and the upper part of the Santee Limestone of middle Eocene age. The Upper Floridan is more than 200 ft thick in the extreme southern part of the area and thins toward the north until it pinches out near the Combahee River (pls. 1, 2, 5). The Upper Floridan is the primary source of ground water in most of the southern part of South Carolina.

In the northeast Florida area, the Upper Floridan consists of the Ocala Limestone (the "Ocala Group" of the Florida Geological Survey) (Leve, 1966, p. 11, 24). The Ocala is a sequence of permeable, hydraulically connected marine limestone that contains few low-permeability carbonate beds to restrict vertical movement of water (Leve, 1966, p. 24). The Upper Floridan contributes about one-half of the water pumped from wells tapping the entire Floridan aquifer system in the Jacksonville area. Head difference between the Upper Floridan and the underlying Lower Floridan is generally less than 2 ft in that area (Leve, 1966, p. 25). However, head differences between the Upper Floridan and the Lower Floridan may be as much as 20 ft in areas of large withdrawals from the Upper Floridan, such as that in the area of Fernandina Beach, Fla. (Fairchild and Bentley, 1977, p. 13).

In the western part of the study area, the Suwannee Limestone of Oligocene age forms the major part of the Upper Floridan aquifer. The Suwannee Limestone is similar in character to the Ocala but is more fossiliferous and somewhat sandy and phosphatic. The development of secondary permeability was similar to that in the

Ocala, making the Suwannee highly permeable. Secondary permeability is greatest at the erosional unconformity between the Ocala and the overlying Suwannee Limestone. The permeable zone at the Suwannee–Ocala unconformity is a major source of water in the Upper Floridan aquifer, especially in the area of Valdosta, Ga. (Krause, 1979, p. 10). An erosional unconformity containing highly developed secondary permeability is also present between the Suwannee and the overlying sandy limestones of early Miocene age in the Valdosta area. This zone is also a significant part of the Upper Floridan in that area (Krause, 1979, p. 10). In the Valdosta area, the Upper Floridan aquifer is the sole producing zone in the Floridan aquifer system. There, the Lower Floridan has low permeability and a sluggish, nearly static flow system that is isolated from the rest of the aquifer system, contains mineralized water, and herein is not considered part of the aquifer flow system.

In the extreme updip part of Georgia, the Upper Floridan aquifer consists chiefly of the Barnwell Formation of late Eocene age, which grades by facies change to the Ocala Limestone. The Upper Floridan extends updip to the late Eocene facies that consists of less than 50 percent carbonate (Miller, 1982d). The Oligocene Suwannee Limestone is a minor part of the Upper Floridan in all but the extreme updip area.

LOWER FLORIDAN AQUIFER AND MIDDLE SEMICONFINING UNIT

The Lower Floridan over most of the study area consists chiefly of middle to lower Eocene carbonate rocks, less fossiliferous and more dolomitic than the overlying Upper Floridan. Permeability is primarily secondary and is developed along bedding planes and other zones of weakness. The Lower Floridan is an insignificant contributor to wells tapping the entire Floridan aquifer system except in the area of Jacksonville, Fla., and east of the Combahee River in South Carolina. In extreme southeast Georgia and northeast Florida, the Lower Floridan includes a mappable water-bearing zone, formally designated the "Fernandina permeable zone." This zone, lying at the base of the Lower Floridan aquifer, is distinctive in its flow characteristics in this study area and is considered a separate water-bearing unit. Discussions of the Lower Floridan in this section exclude the Fernandina permeable zone, which is discussed in the following section.

In the updip part of the study area, the Lower Floridan as defined by Miller (1982b; 1985) does not exist. In parts of the updip area, Miller combined the Upper and Lower Floridan and termed them the "Upper Floridan." In other parts of the updip area, he excluded the Lower Floridan from the aquifer system because rocks that make up the water-bearing zone consist chiefly of clastic material. For this study, the Lower Floridan is considered a separate unit and, even where clastic, a part of the active flow system.

In the area of Jacksonville, Fla., the Lower Floridan (exclusive of the Fernandina permeable zone) consists chiefly of the middle Eocene Lake City Limestone of former usage (Leve, 1966, p. 29). The Lake City, as formerly used, was not differentiated stratigraphically from the overlying Avon Park Formation (also of middle Eocene age) in this report or in Miller (1985). However, Leve (1966, p. 14) made the distinction between the Lake City and the Avon Park on the basis of foraminifera. Miller (1985) abandoned the name Lake City Limestone and included the entire middle Eocene section in the Avon Park Formation—"formation" rather than "limestone" because the Avon Park contains significant amounts of dolomite. This report follows that usage. Lithologically, the entire middle Eocene section consists of alternating beds of limestone and dolomite, the lower part having well-developed secondary permeability.

The Lower Floridan is about 500 ft thick in the Jacksonville area, lying about 950 to 1,400 ft below land surface (Leve, 1966, p. 29). Within the Lower Floridan are zones of high and low permeability. Leve (1966, p. 29) reported that two permeable zones exist in this sequence—an upper zone between about 950 and 1,200 ft below land surface and a lower zone between about 1,250 and 1,400 ft. As described by Leve (1966), the two zones are separated by hard limestone and dolomite in the Lake City (of former usage) and have somewhat different head and yield characteristics.

The Lower Floridan is confined above by hard, low-permeability limestone and dolomite of the upper part of the middle Eocene Avon Park Formation (Miller, 1985) and the basal part of the upper Eocene Ocala Limestone (Leve, 1966). This hard, low-permeability limestone, called the middle semiconfining unit, is of sufficiently low permeability to cause some head difference between the Upper and Lower Floridan. (See discussion of Jacksonville area in earlier section on the "Upper Floridan Aquifer.") This semiconfining unit locally is breached by faults or fractures that facilitate leakage, generally from the Lower to the Upper Floridan, where the head difference is sufficient. (Leakage is discussed in a later section.) About one-half of the water pumped by large municipal and industrial wells in the Jacksonville area is withdrawn from the Lower Floridan.

The Lower Floridan in the area of Fernandina Beach, Fla., is similar to that in the Jacksonville area, except there is no confinement within the Lake City Limestone (of former usage; Leve, 1966, p. 30) and the Lower Floridan is more deeply buried. Almost no water is withdrawn from the Lower Floridan in the Fernandina area; however, the zone leaks water to the Upper Floridan where the Upper Floridan is heavily pumped.

The Lower Floridan in the area of Brunswick, Ga., consists of interbedded limestone and dolomite of the lower two-thirds of the middle Eocene, and the upper part of the lower Eocene. The Lower Floridan in this area includes the "brackish-water zone" and the "deep freshwater" described by Gregg and Zimmerman (1974, pl. 1). Neither of these zones is tapped by supply wells in the Brunswick area, but water from the zones leaks upward through faults or fractures in the middle semiconfining unit into the Upper Floridan. The middle semiconfining unit consists of dense, low-permeability, recrystallized limestone and dolomite near the top of the middle Eocene section.

In the area of Savannah, Ga., and Hilton Head Island, S.C., the Lower Floridan consists of dolomitic limestone of middle Eocene age. In the Savannah area, the Lower Floridan represents permeable zones 3, 4, and 5 described by McCollum and Counts (1964, p. D9), as determined from current-meter tests made in wells. The Lower Floridan is not tapped for water supply in the Savannah area. However, it responds to pumping from the Upper Floridan, as indicated by the similarity of water levels observed in the Upper and Lower Floridan aquifers (fig. 9). This suggests that the Lower Floridan is hydraulically connected with the Upper Floridan.

In the area of Hilton Head Island, S.C., the Lower Floridan is similar to that at Savannah, but individual permeable zones have not been reported. The Lower Floridan in this area is the "lower permeable zone" described by Hayes (1979) and Spigner and Ransom (1979), which is the Santee Limestone of the basal middle Eocene. The lower permeable zone consists of a siliceous, glauconitic limestone having secondary permeability. It is less than 100 ft thick in this area. In the extreme northeastern part of the study area in South Carolina, the Upper Floridan is not present (pls. 1, 5) and the Lower Floridan is the primary source of ground water. The middle semiconfining unit there is a soft, siliceous, argillaceous, marly limestone of low permeability that ranges in thickness from about 200 to 900 ft.

Downdip from the Gulf Trough in middle Georgia, the Lower Floridan consists chiefly of siliceous, argillaceous limestone of middle Eocene age. The Lower Floridan, as a permeable carbonate facies within the entire Floridan aquifer system, extends only to about the Gulf Trough. Updip from the Gulf Trough, the character of rocks stratigraphically equivalent to the downdip carbonate facies changes considerably. In the updip area, the aquifer grades northward from a carbonate facies along the trough to clastic facies along the updip extent of the aquifer system.

Updip from the Gulf Trough, the Lower Floridan, according to Miller's (1985) framework of the aquifer system, does not exist. In that area, Miller limited the Floridan aquifer system to strata that are more than 50 percent carbonate. Although the units in this area are predominantly noncarbonate and are designated by different formation names, they are the clastic equivalents of Miller's Lower Floridan, differing only in lithology. The units are hydraulically part of the Lower Floridan flow system and therefore are treated as part of the Lower Floridan in this study. The clastic units consist of calcareous silt and sand, fossiliferous, glauconitic, sandy limestone, and clean quartz sand and gravel having high porosity and permeability. The units are chiefly part of the Huber Formation (Buie, 1978), the exact age of which is unknown, which occurs between two recognizable unconformities—one at the end of the Cretaceous and one at the end of the middle Eocene.

The middle semiconfining unit overlying the Lower Floridan is made up of low-permeability clay, siltstone, and argillaceous limestone of the basal part of upper Eocene strata. The unit grades into the adjacent Upper and Lower Floridan, and in places has moderate permeability and effective vertical hydraulic conductivity, in effect providing little separation between the aquifers.

Little is known of the extent, thickness, and character of similar facies of the Lower Floridan and the middle semiconfining unit in the inland part of the study area. Few data are available for the Lower Floridan and middle semiconfining unit, as only a few wells tap the Lower Floridan, especially in this inland area. Sufficient water supplies are generally obtained from the Upper Floridan, making drilling into the Lower Floridan unnecessary. Some oil-test wells have been drilled through the Lower Floridan; however, only geologic and geophysical data were obtained.

Fernandina Permeable Zone

The Fernandina permeable zone of the Lower Floridan aquifer was first tapped in 1945 by a 2,130-ft test well at Fernandina Beach, Fla., and that name is used herein. The zone consists of pelletal, recrystallized limestone and finely crystallized dolomite that has extremely high permeability and is locally cavernous. In the areas of Fernandina Beach and Jacksonville, the zone is in the basal lower Eocene and Paleocene—the Oldsmar and Cedar Keys Formations, respectively. In the area of Brunswick, Ga., the zone is lower stratigraphically and lies at a greater depth in rocks of Paleocene and latest Cretaceous age. Thickness of the zone ranges from about 100 ft in the Jacksonville area to more than 500 ft at Brunswick. The zone's approximate extent is shown on plate 3. The offshore extent

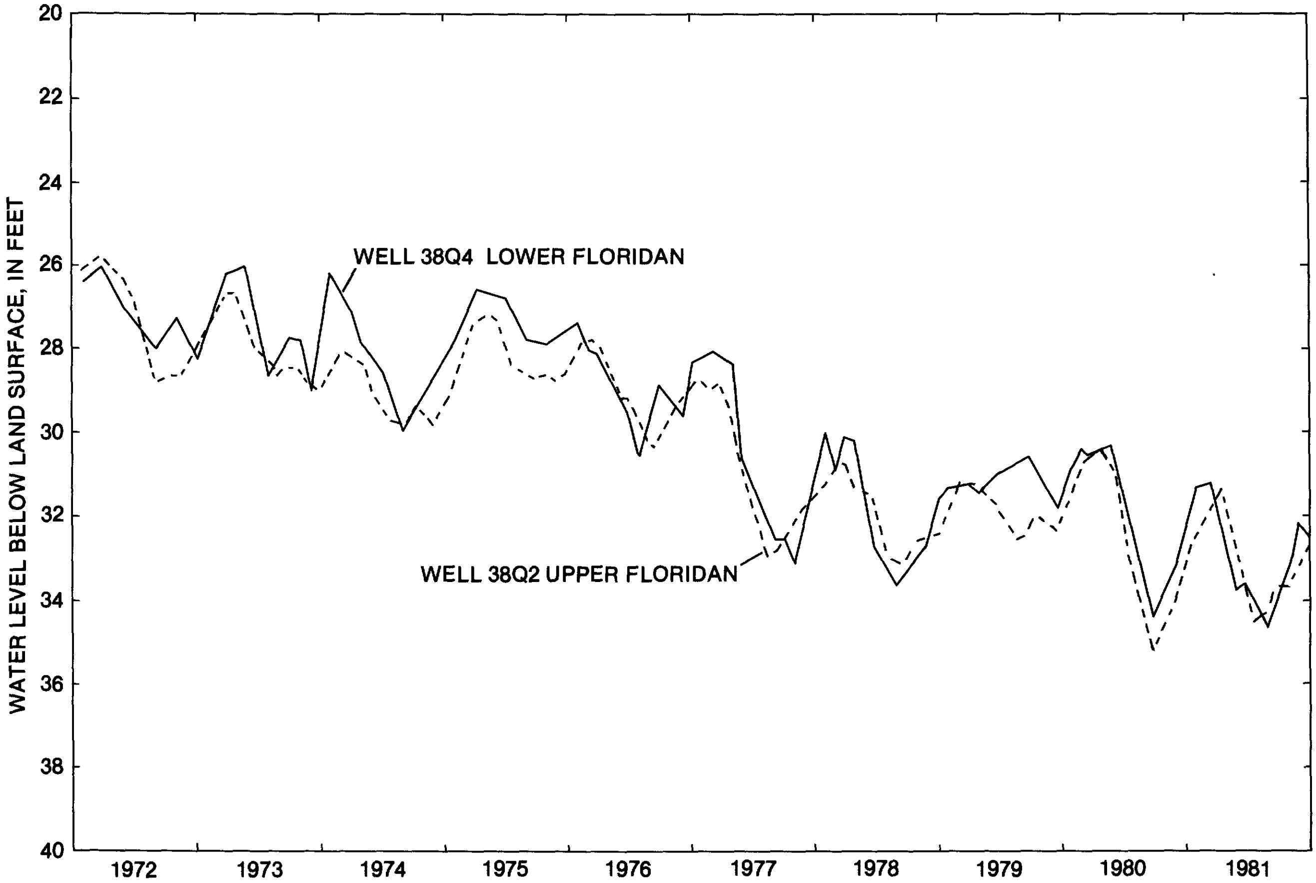


FIGURE 9.—Comparison of water levels in the Upper and Lower Floridan aquifers, Savannah, Ga.

of the zone is unknown, but it undoubtedly extends some distance offshore and may crop out on the ocean floor. Miller (1985) states that the semiconfining unit overlying the Fernandina permeable zone pinches out toward the south and southwest in Florida, and that the zone merges with the rest of the Lower Floridan aquifer.

Because few wells tap the Fernandina permeable zone, very little is known about its extent, thickness, and characteristics. Definition of the zone on the basis of geophysical logs is also made difficult because of the varying and largely unknown quality of its water and occurrence of cavernous zones.

The Fernandina permeable zone is confined above by low-permeability rocks of lower-middle to early Eocene age consisting chiefly of limestone and dolomite, nearly the same as the permeable zones adjacent to it. Vertical hydraulic conductivity of the lower semiconfining unit overlying the Fernandina permeable zone is low, except where it has been breached by faulting.

HYDRAULIC CHARACTERISTICS

Like the geologic data, the hydraulic characteristics of the Floridan aquifer system are primarily known for the Upper Floridan aquifer and the upper confining unit. Very few data are available for the middle and lower semiconfining units and the Lower Floridan aquifer. Almost all aquifer tests conducted in the Floridan in the study area have been of the Upper Floridan. Of these tests, most were made in wells penetrating the upper part of the Upper Floridan. No aquifer tests have been made exclusively in the Lower Floridan. Only one aquifer test, conducted near Waycross, Ga., as part of this study, has been made in wells that tap the entire thickness of the Floridan aquifer system.

Hydraulic characteristics of the Floridan aquifer system vary greatly within the study area, owing to the heterogeneity (and locally to the anisotropy) of the aquifers and to the confinement (or lack of confinement) provided by the confining units.

AQUIFERS

Hydraulic conductivity and transmissivity of the Upper and Lower Floridan aquifers are generally lowest in the areas of outcrop, along the extent of the aquifers in South Carolina and probably offshore and along the Gulf Trough. Hydraulic conductivity and transmissivity generally increase downdip and downgradient from the Gulf Trough throughout Georgia, then decrease near the Florida–Georgia State line, and finally increase farther south in northeast Florida.

The heterogeneity of the aquifer system is chiefly related to the development of secondary porosity and permeability in the carbonate rocks. Secondary porosity and permeability are developed by circulating ground water as it flows through bedding-plane separations, faults, joints, fractures, and other zones of weakness in the carbonate and enlarges them by solution. Anisotropy of the aquifer is, in places, enhanced by the preferential orientation of structural features along which ground water flows. In the area of Valdosta, Ga., Krause (1979, p. 9) concluded that uplift during the Miocene produced northwest–southeast- and northeast–southwest-trending joints along which preferential ground-water flow developed. The directions of preferential flow are indicated by trends in surface drainages, alignments of karst physiographic features, and areal variations in water quality.

Cavities, cavernous zones, and solution channels tens of feet in vertical and horizontal dimensions have been tapped by wells throughout the downgradient part of the Floridan aquifer system in southeast Georgia and northeast Florida. These zones are chiefly in the Upper Floridan, but some of the largest are in the Lower Floridan and its Fernandina permeable zone in extreme southeast Georgia and northeast Florida. Most of the cavernous zones and solution channels are oriented in the horizontal plane, enhancing lateral permeabilities. However, some solution channels are oriented along nearly vertical planes and probably formed along zones of weakness caused by high-angle fractures and faults. These nearly vertical conduits locally connect permeable zones within the entire Floridan aquifer system along the coast in extreme southeast Georgia and in northeast Florida. Although faults are believed to be present along the southeast Georgia coast (D.C. Prowell and H.E. Gill, U.S. Geological Survey, written commun., 1983), they have not been mapped by Miller (1985) and are not shown on the structure maps in this report.

Conversely, structure in the form of nearly vertical faulting has locally decreased the lateral permeability of the aquifer system. The most pronounced effects of faulting and lateral permeability reduction in the aquifer system are in the area of the Gulf Trough. There, high-angle faults probably have juxtaposed permeable zones nearly opposite to zones of low permeability, markedly decreasing what probably had been continuous lateral permeability. Infilling of low-permeability clastic material in the grabens further decreased permeability. Even in the downgradient area along the southeast Georgia–northeast Florida coast, where only carbonate rocks of the aquifer system were faulted, some of the high-angle faulting has probably decreased lateral permeability.

Hydrogeologic differences within the Upper and Lower Floridan aquifers result in large variations in hydraulic properties within short distances. Estimated hydraulic conductivity increases from less than 5 ft/d in the western part of the Gulf Trough to greater than 500 ft/d less than 10 mi downdip from the trough (pl. 7). Hydraulic properties vary in even shorter distances because of the extreme areal variability of secondary porosity and permeability. The transmissivity values derived from some of the aquifer tests did not approximate the regional transmissivity values simulated during this study. Some values obtained from aquifer tests are considerably lower than those simulated. Probable causes of this discrepancy are that these aquifer tests were too short, or were conducted on wells that partially penetrated the aquifer or that tapped parts of the aquifer lacking fractures or solution conduits that control flow on the regional scale.

The transmissivities shown on plate 7 are from a variety of sources. In order of descending reliability, those sources are (1) multiwell aquifer tests using the Theis analysis, (2) single-well aquifer tests using the Cooper-Jacob approximation, and (3) estimation from specific-capacity data. Bush and Johnston (in press) used a statistical analysis of transmissivity values of the Floridan aquifer system and concluded that the relation between transmissivity values estimated from specific-capacity data and those obtained from simulation was minimal, and that the transmissivity estimated from specific capacity is almost always less than that from simulation. They also concluded that transmissivity values derived from aquifer tests were slightly less than those simulated, but that they were in better agreement with simulated values than were those estimated from specific-capacity data. Specific capacity is thus not a particularly good basis from which to estimate transmissivity in most parts of the Floridan aquifer system. Transmissivities obtained from multiwell aquifer tests (where pumping and observation wells are hundreds of feet apart) more nearly equal the simulated transmissivity values, which represent the regional flow system.

Hydraulic conductivity of the Upper Floridan shown on plate 7 was estimated from aquifer tests and ranges from less than 5 ft/d to more than 1,000 ft/d. Transmissivity ranges from less than 1,000 ft^2/d to nearly 1,000,000 ft^2/d (pl. 7). Actual ranges of hydraulic conductivity and transmissivity, which control ground-water flow on a regional scale, are probably greater. Hydraulic conductivity and transmissivity approach zero at the outcrop limit of the aquifer, where thickness approaches zero, and become extremely large near springs and swallow holes, where water moves through solution channels as much as tens of feet in diameter.

Most of the data on plate 7 are from aquifer tests made along the heavily developed and intensively studied coast. Because of the paucity of data on hydraulic properties of the aquifer system in the inland area, an aquifer test was conducted during this investigation at an area of suspected high transmissivity near Waycross, Ga. The two wells constructed for the test penetrated the entire Floridan aquifer system. However, all of the flow was derived from the Upper Floridan aquifer. Matthews and Krause (1984) describe the test drilling and aquifer testing in detail. Only a brief summary of the aquifer test follows.

The aquifer test was conducted June 16–19, 1981, at a site about 9 mi southeast of Waycross, Ga. (pl. 7), where the Floridan aquifer system is moderately thick and the transmissivity was believed to be very large. The aquifer system is about 1,250 ft thick, extending from about 600 to 1,900 ft below land surface, which has an altitude of about 150 ft.

A nearly constant rate of 2,040 gal/min was maintained in the pumped well for 47 h. Water-level measurements were made in the observation well, 154 ft away, throughout the pumping and recovery periods. The orifice method was used to measure the pumping rate. Electric and wetted-tape methods and water-level recorders were used for water-level measurements.

Complicating factors during the test included (1) minimal water-level decline of less than 0.5 ft in the observation well, (2) cyclic fluctuations in the water level (probably the result of earth tides) nearly as great as the decline induced by pumping, and (3) a seasonal water-level decline that encompassed the test period. These factors precluded the determination of definitive values of the aquifer properties.

Figure 10 is a plot of the drawdown adjusted for the regional water-level decline versus time for the observation well. The cyclic water-level fluctuations were not the result of barometric fluctuations (Matthews and Krause, 1984, p. 13, fig. 3) but, as stated, were probably caused by earth tides. These fluctuations were ignored and the Theis-type curve was superposed through a graphic median of the data as shown in figure 10.

Using the match points for the Theis curve and associated parameters shown in figure 10, the transmissivity was calculated to be about 1,000,000 ft^2/d. A storage coefficient of 0.0001 was calculated, but its accuracy is questionable. It is, however, similar to values reported elsewhere in the thickly confined area. Although the aquifer test was conducted using wells that fully penetrated the Floridan aquifer system, a borehole-flowmeter survey taken when the pumping well discharged 1,900 gal/min indicated negligible (unmeasurable) flow from depth below about 1,100 ft. This indicates that the discharge is entirely from the Upper Floridan aquifer.

The transmissivity determined from this aquifer test is the largest ever derived from a pumping test for the freshwater interval of the Floridan aquifer system. Higher values have been determined by areal, flow-net methods in the area of springs in north-central Florida. Faulkner (1973, p. 93–96) determined transmissivity by flow-net analysis to be an average of more than 2,000,000 ft^2/d around Silver Springs. One segment of the flow net had an estimated transmissivity of more than 25,000,000 ft^2/d.

Although undetermined to date, higher transmissivity also probably exists along the coast in southeast Georgia. Highest hydraulic conductivities in the study area are recorded there (pl. 7) and the Floridan aquifer system, which includes rocks of Late Cretaceous age, is thickest there (pl. 1). Caliper and sonic televiewer logs and borehole television traverses made in a test well near Brunswick, Ga., showed extensive caverns throughout the Floridan aquifer system.

In contrast to these extremely large transmissivities, values of less than 1,000 ft^2/d in the area along the Gulf Trough have been determined by estimates from specific-capacity data. Low values are expected there because of faulting, juxtaposition of permeable and nonpermeable zones, and clastic infilling. Low transmissivity also occurs in the outcrop areas and at the physical limits of the aquifer due to thinning of the aquifer system. The areal distribution of transmissivity of the Upper Floridan aquifer as simulated by the flow model is shown on plate 8. The transmissivity distribution is in good agreement with those derived from field data (pl. 7).

Transmissivity data for the Lower Floridan aquifer are nearly nonexistent. Estimates of transmissivity were based primarily on thickness and qualitative estimates of permeability made from geophysical well logs. Transmissivity of the Lower Floridan aquifer probably ranges from about 2,000 ft^2/d to nearly 400,000 ft^2/d.

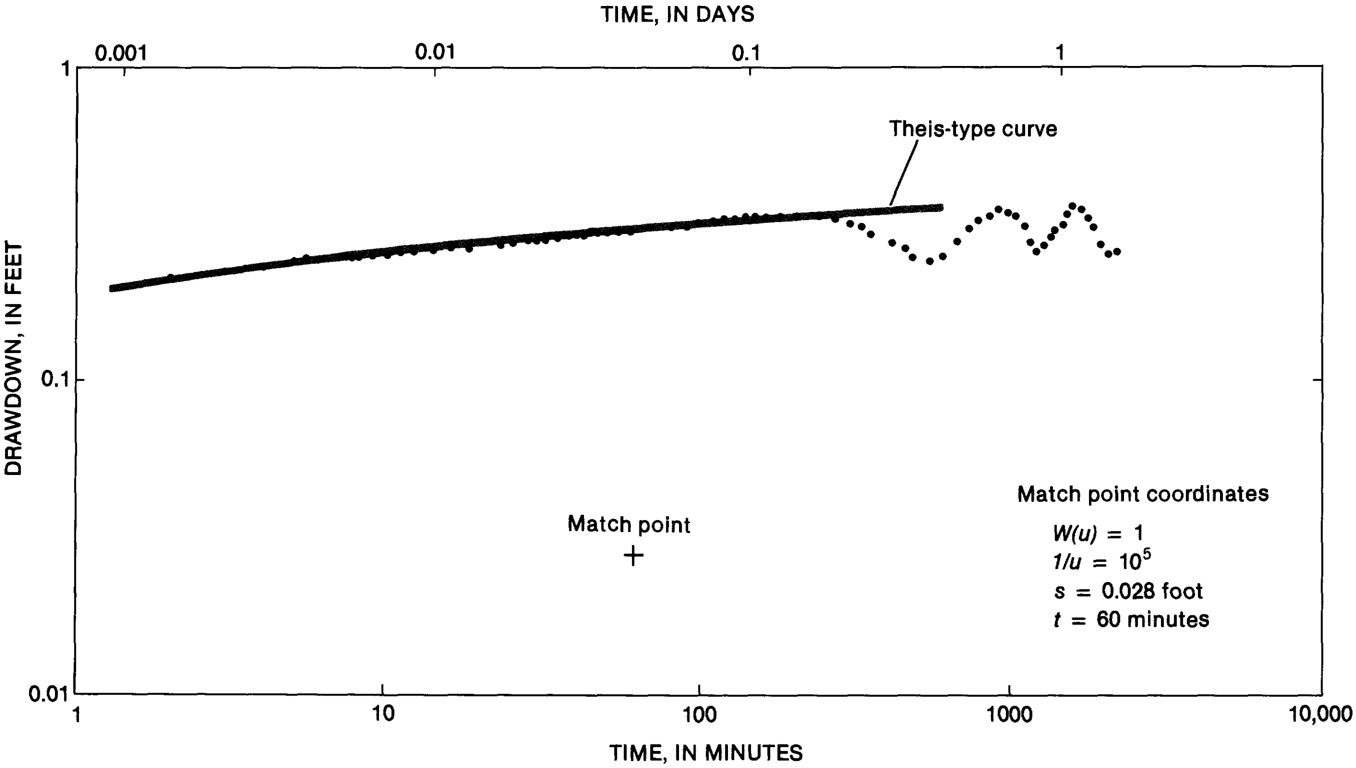


FIGURE 10.—Logarithmic plot of drawdown (s) in the observation well versus time (t) from the Waycross aquifer test, superposed on the Theis type curve (nonleaky, artesian). From Matthews and Krause (1984).

Transmissivity of the Lower Floridan generally decreases from south to north within the carbonate sequence downdip from the Gulf Trough. It is highest in northeast Florida, especially in the area of Jacksonville, where it is nearly 400,000 ft^2/d and the Lower Floridan yields about half the water withdrawn there from the Floridan aquifer system. The transmissivity of the Lower Floridan is probably less than 100,000 ft^2/d everywhere except in northeast Florida and extreme southeast Georgia. In the Savannah, Ga., area, the transmissivity of the Lower Floridan is probably less than 10,000 ft^2/d. Because the Lower Floridan includes thick sequences of permeable clastic material near the outcrop area of the aquifer system, transmissivity of the Lower Floridan is higher there than it is downdip in most of central Georgia. Transmissivity values there range from about 10,000 to 40,000 ft^2/d, based on simulation.

Transmissivity of the Fernandina permeable zone is less well known than that of the rest of the Lower Floridan. The hydrogeology of the Fernandina permeable zone based on borehole geophysical data gives some indication of the relative transmissivity of the zone. Borehole television and caliper logs of a test well 3 mi southwest of Brunswick, Glynn County, Ga., showed cavities, or conduits, in the Fernandina permeable zone that were tens of feet in height and of undetermined lateral extent. A similar cavernous zone in the Lower Floridan in South Florida has a transmissivity greater than 3,000,000 ft^2/d (Meyer, 1974). Borehole geophysical logs indicate that the Fernandina permeable zone is cavernous and has high permeability in northeast Florida, although somewhat less than at Brunswick. Transmissivity probably decreases markedly from those areas and approaches zero at the limit of the zone's extent. Also, if the zone extends toward the south and southwest in Florida and merges with the rest of the Lower Floridan aquifer (Miller, 1985), its transmissivity would not, of course, approach zero in that area.

CONFINING UNITS

Hydraulic data for the confining units are more sparse than those for the aquifers. Except for laboratory analyses of the vertical hydraulic conductivity of cores from the middle semiconfining unit at Brunswick, Ga. (Wait and Gregg, 1973, p. 42), the only data available are for the upper confining unit.

In Brunswick, Ga., vertical hydraulic conductivity of the upper confining unit, as determined by laboratory analyses of cores, ranged from 5×10^{-5} ft/d (Wait, 1965, p. 48) to 1.1 ft/d (Wait and Gregg, 1973, table 9). Vertical hydraulic conductivity suggested by simulation is about 1×10^{-5} to 1×10^{-3} ft/d. A hydraulic conductivity of 1×10^{-4} ft/d for a 475-ft confining-unit thickness results in a leakance of 2.1×10^{-7} d^{-1}. A 25-ft head difference between the surficial and the Upper Floridan aquifers would effect leakage of about 0.02 in/yr through the upper confining unit.

An average vertical hydraulic conductivity of 1.3×10^{-3} ft/d was determined by laboratory analyses of 52 cores taken from the upper confining unit (Miocene Hawthorn Formation) at various locations in Chatham County, Ga. (Furlow, 1969, p. 23). The cores were taken from within a 40-ft sequence of a fuller's earth type of clay that probably represents the least permeable part of the upper confining unit. The average hydraulic conductivity of the entire upper confining unit is undoubtedly greater than the laboratory-determined values because of the presence of more permeable strata in the unit. Leakance of the 40-ft sequence having a vertical hydraulic conductivity of 1.3×10^{-3} ft/d would be 3.2×10^{-5} d^{-1}. Leakage through the sequence under the prevailing vertical head difference of 15 ft would be 2.1 in/yr.

In the area of Baker and Columbia Counties, Fla., just southwest of the study area, vertical hydraulic conductivity of the upper confining unit (Hawthorn Formation) was determined by laboratory analyses of cores to range from 1.5×10^{-2} to 7.8×10^{-7} ft/d, and by extensometer analysis to be about 2×10^{-4} ft/d (Miller and others, 1978, table 17).

An estimated conductivity of 1×10^{-4} ft/d for the 10-ft "D member" of the Hawthorn Formation (Miller and others, 1978) results in a leakance of 1×10^{-5} d^{-1}. Leakage through that unit would be 0.04 in/yr under the prevailing vertical head difference of 1 ft. The hydraulic conductivity of 2×10^{-4} ft/d from the extensometer analysis, for the 14-ft "Lower B member" of the Hawthorn results in a leakance of 1.4×10^{-5} d^{-1} (Miller and others, 1978). Leakage through that unit would be about 0.06 in/yr under the 1-ft head difference.

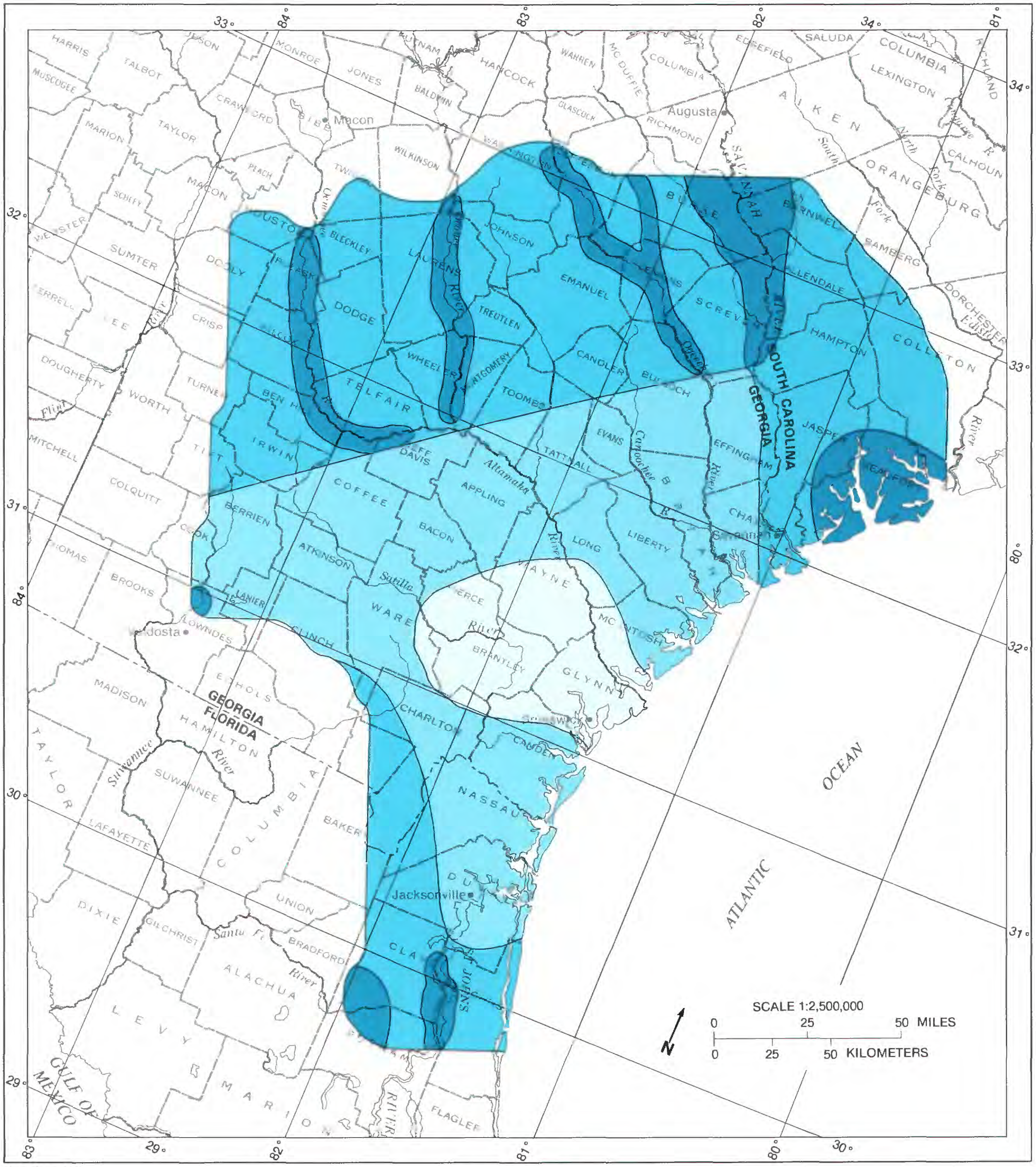
In the southern part of St. Johns County, Fla., just south of the study area, a vertical hydraulic conductivity of the upper confining unit of 1.1×10^{-2} ft/d and a leakance of 3.8×10^{-4} d^{-1} were determined by using a geometric analysis of the potentiometric surface (Bermes and others, 1963, fig. 26). For the analysis, the assumption was made that flow conditions were at steady state; transmissivity was known from aquifer-test analyses, and the water-table altitude was known. Leakage through the unit under the prevailing vertical head difference of 2.5 ft would be 4.2 in/yr.

The materials that make up the upper confining unit vary greatly in lithology and permeability and are complexly interlayered throughout a vertical section. Although values of the vertical hydraulic conductivity of the upper confining unit vary by orders of magnitude within a vertical section, a composite or average value for the full section probably does not vary much areally. Thus, the leakance of the upper confining unit would vary inversely with its thickness (pl. 4).

Under these conditions, leakances would be lowest in the Southeast Georgia embayment where the upper confining unit is thickest, and highest where the unit is thinner, as in the area updip from the Gulf Trough. Leakance is greatest in areas where the upper confining unit is largely absent, as along the major rivers updip from the Gulf Trough, and in the areas of Valdosta, Ga., Keystone Heights and Green Cove Springs, Fla., and Beaufort County, S.C. (fig. 11). Leakance of the upper confining unit shown in figure 11 is based on the thickness of the unit and the results from the simulation of the flow system (discussed in Supplement I).

The vertical hydraulic conductivity of the middle semiconfining unit is known only from laboratory analysis of five cores of two wells in Brunswick, Ga. The vertical hydraulic conductivity of the dolomitic limestone making up the middle semiconfining unit ranged from 4.0×10^{-6} to 5.4×10^{-5} ft/d. Leakance of the unit, which is about 100 ft thick and has an estimated vertical hydraulic conductivity of 1×10^{-5} ft/d, would be extremely low—about 1×10^{-7} d^{-1}. Leakage through that unit under a 7-ft head difference would be only 0.003 in/yr. The low vertical hydraulic conductivity and leakance is understandable for the dense dolomitic 100-ft-thick limestone. However, fractures and faults are known to be present in the Jacksonville, Fla., and Brunswick, Ga., areas and probably along the entire coast, and such fractures and faults would markedly increase the vertical hydraulic conductivity and leakance of this unit.

Field data for the lower semiconfining unit are unavailable. The hydraulic properties of the unit are known only from simulation.



Base from U.S.
National Atlas, 1970

EXPLANATION
Leakance, in feet per day per foot

	Less than 10^{-6}
	10^{-6} to 10^{-5}
	10^{-5} to 10^{-4}
	More than 10^{-4}

FIGURE 11.—Estimated leakance distribution of the upper confining unit of the Floridan aquifer system.

PREDEVELOPMENT GROUND-WATER-FLOW SYSTEM

Ground-water flow in the Floridan aquifer system is controlled chiefly by rates and distribution of recharge to and discharge from the system, the extent and effects of confinement, and the ability of the aquifers to transmit and store water. Prior to development, the flow system is considered to have been at dynamic equilibrium and the potentiometric surfaces nearly unchanged from year to year. Recharge to the aquifers was balanced by natural discharge, resulting in no change in storage in the aquifer system on a long-term-average basis. Only seasonal and short-term climatic fluctuations affected the altitude of the potentiometric surface.

Dynamic changes to the flow system resulting from post-Pleistocene sea-level changes probably occurred prior to development. These changes would have altered all components of the predevelopment flow system—recharge and discharge, heads, flows, and the location of the freshwater-saltwater interfaces. However, sufficient time probably has elapsed for the flow system to reach equilibrium, and, therefore, steady-state conditions were assumed for this study.

POTENTIOMETRIC SURFACE

The estimated predevelopment potentiometric surface of the Upper Floridan aquifer in the study area is shown on plate 9 and is based on those by Johnston and others (1980) and by Krause (1982, pl. 2). Data used to construct these maps were (1) historic data gathered prior to development in areas that later had significant ground-water development, and (2) recent data from areas where development has had an insignificant effect on the potentiometric surface. Although the predevelopment potentiometric surface shown on plate 9 is that of the Upper Floridan aquifer, some data used in its construction were from wells that probably tap water-bearing zones in the lower part of the overlying Hawthorn Formation that are not considered part of the Upper Floridan aquifer. The water level in these wells would be slightly higher or lower than that in the Upper Floridan, depending on the vertical head gradient. Therefore, plate 9 shows the general configuration of the predevelopment potentiometric surface of the Upper Floridan aquifer in the study area and is not an accurate representation of site-specific water levels.

In the upgradient areas along the major rivers, especially the Savannah River, contours of the potentiometric surface on plate 9 differ slightly from those of Johnston and others (1980) and Krause (1982, pl. 2) because of the inclusion of more recent data. A recent investigation by Faye and Prowell (1982, fig. 8) indicates that a greater relation exists between the aquifer and the Savannah River than previously thought. The head in the aquifer is significantly lower near the river than away from the river, indicating that the aquifer discharges into the river. For that reason, the potentiometric contours in the vicinity of the river are markedly bent upgradient.

Although the relation between the aquifer and the other major upgradient rivers has not been documented, a similar steep gradient and discharge relation undoubtedly exists. These rivers exert more influence on the aquifer, as manifested in the potentiometric contours, than is shown on plate 9. The amount of influence would be related to the degree of river entrenchment, the thickness and leakance of material separating the aquifer and the riverbed, and the resistance to downgradient ground-water flow caused by the Gulf Trough, as well as to the head in the aquifer and the stage in the river.

COMPONENTS OF THE PREDEVELOPMENT GROUND-WATER-FLOW SYSTEM

Under predevelopment, steady-state conditions, recharge was equal to discharge and no change in aquifer storage took place. Recharge generally occurred in upgradient areas, producing high head. Water then flowed downgradient toward the coast and discharged in areas of lower head (pl. 9). The simulation indicates that total flow through the Floridan aquifer system in the study area prior to development was about 1,400 ft^3/s. Table 4 shows the simulated components and distribution of flow through the aquifer system prior to development.

The simulated distribution of vertical flow, or leakage, under predevelopment, steady-state conditions through the upper confining unit is shown on plate 10. The leakage is expressed in inches per year.

The area of highest recharge to the aquifer system prior to development was chiefly updip and upgradient from the Gulf Trough, where the aquifer system is exposed or thinly covered and least confined. In this area, recharge occurred in the topographically high areas, either directly into the exposed or thinly covered Upper Floridan or through the upper confining unit where the head in the surficial aquifer was higher than the head in the Upper Floridan. Flow through the Upper Floridan aquifer in this updip area was chiefly toward the major rivers, where the water was discharged. The components and areal distribution of simulated flow through the aquifer system prior to development are shown in figure 12.

In the area updip from the Gulf Trough, about 750 ft^3/s was recharged to the Upper Floridan from the surficial

TABLE 4.—*Simulated water budget for predevelopment (1880) and present-day (1980) flow systems*

[Negative number denotes opposite flow direction; values are rounded off only enough to maintain the numerical balance of the water budget; implication of accuracy to the degree shown is not intended]

	Simulated flow, in cubic feet per second													Pumpage, in cubic feet per second	
	Total flow		Net vertical leakage			Lateral boundary flow									
						Lower Floridan					Upper Floridan				
	In	Out	Surficial aquifer to Upper Floridan	Lower Floridan to Upper Floridan	Fernandina permeable zone to Lower Floridan	Northern inflow	Southern outflow	Eastern outflow	North-western inflow	South-western inflow	Southern outflow	Eastern outflow	South-western inflow	Upper Floridan	Lower Floridan
Predevelop-ment	1,400	1,400	-329	383	40	338	47	2	60	0	51	2	0	0	0
Present-day	2,100	2,100	92	612	282	338	47	-2	60	70	34	-6	201	878	93

aquifer and 990 ft³/s was discharged from the Upper Floridan, primarily to the major rivers. About 90 ft³/s infiltrated to the Lower Floridan, 456 ft³/s migrated from the Lower Floridan to the Upper Floridan, and 126 ft³/s migrated downgradient in the Upper Floridan through the Gulf Trough.

Circulation within the Lower Floridan in the area upgradient from the Gulf Trough was similar to that in the Upper Floridan, but of a smaller magnitude. In addition, because the Lower Floridan here is composed chiefly of clastic material, most of the flow occurred within these clastics, which are not a part of the (predominantly carbonate) Floridan aquifer system as defined by Miller (1985). The Lower Floridan was recharged with about 90 ft³/s from the Upper Floridan through the middle semiconfining unit. Because the clastic facies of the Lower Floridan aquifer extend farther updip and upgradient than shown and simulated herein, flow occurred from the clastics across the upgradient boundary of the model. This boundary flow was simulated to be about 338 ft³/s from the north and about 60 ft³/s from the northwest (fig. 12). The Lower Floridan discharged about 456 ft³/s through the middle semiconfining unit into the Upper Floridan. About 32 ft³/s remained in the Lower Floridan as downgradient flow through the Gulf Trough (fig. 12).

The small quantity of flow passing downgradient through the Upper and Lower Floridan aquifers across the Gulf Trough, compared with the total flow in the area upgradient from the trough, further supports the existence of an active but nearly isolated flow system in the Floridan upgradient from the Gulf Trough.

Ground-water contribution from the Floridan aquifer system to the major rivers and their tributaries in the area upgradient from the Gulf Trough was estimated from field data and subsequently simulated by the model. The estimates of the ground-water contribution were based largely on streamflow records from 13 gaging stations on the four major rivers: Ocmulgee, Oconee, Ogeechee, and Savannah. Summaries of 1-day, 7-day, and monthly minimum average flows made during the 1954 drought (Thomson and Carter, 1955, 1963) and annual low-flow data for periods of record were used. In addition, total discharge determined from instantaneous low-flow measurements made in tributaries to the major rivers was considered to be ground-water contribution to the streamflow.

The ground-water contribution of the Floridan aquifer system to the major rivers and their tributaries in the area upgradient from the Gulf Trough is considerably less than the observed base flow. A large part of the base flow is contributed by sources other than the Floridan aquifer system (most of which was not simulated by the model). These sources are the surficial aquifer and the updip clastic equivalents of the Floridan aquifer system. Stricker (1983) calculated the base flow to unregulated streams in selected basins in the Cretaceous-Tertiary outcrop area, which included part of this study area. Stricker used the method of hydrograph separation and concluded that discharges at the 65-percent duration point of flow-duration curves were good estimates of mean annual base flow. Using this criterion, an estimate of the base flow in most of the area upgradient from the Gulf Trough could be about 8 in/yr (Bush and Johnston, 1986). In this area, the local flow system (surficial aquifer) contributes most of the water to the base flow. Water in this local flow system either does not reach the Upper Floridan or, where it does and the Upper Floridan is the surficial aquifer, circulates on a scale that is smaller than that herein considered and simulated as part of the Floridan aquifer system. The Floridan aquifer system in this area probably contributes only about 1,000 ft³/s, or about 2 in/yr, to the base flow of the major rivers and their tributaries.

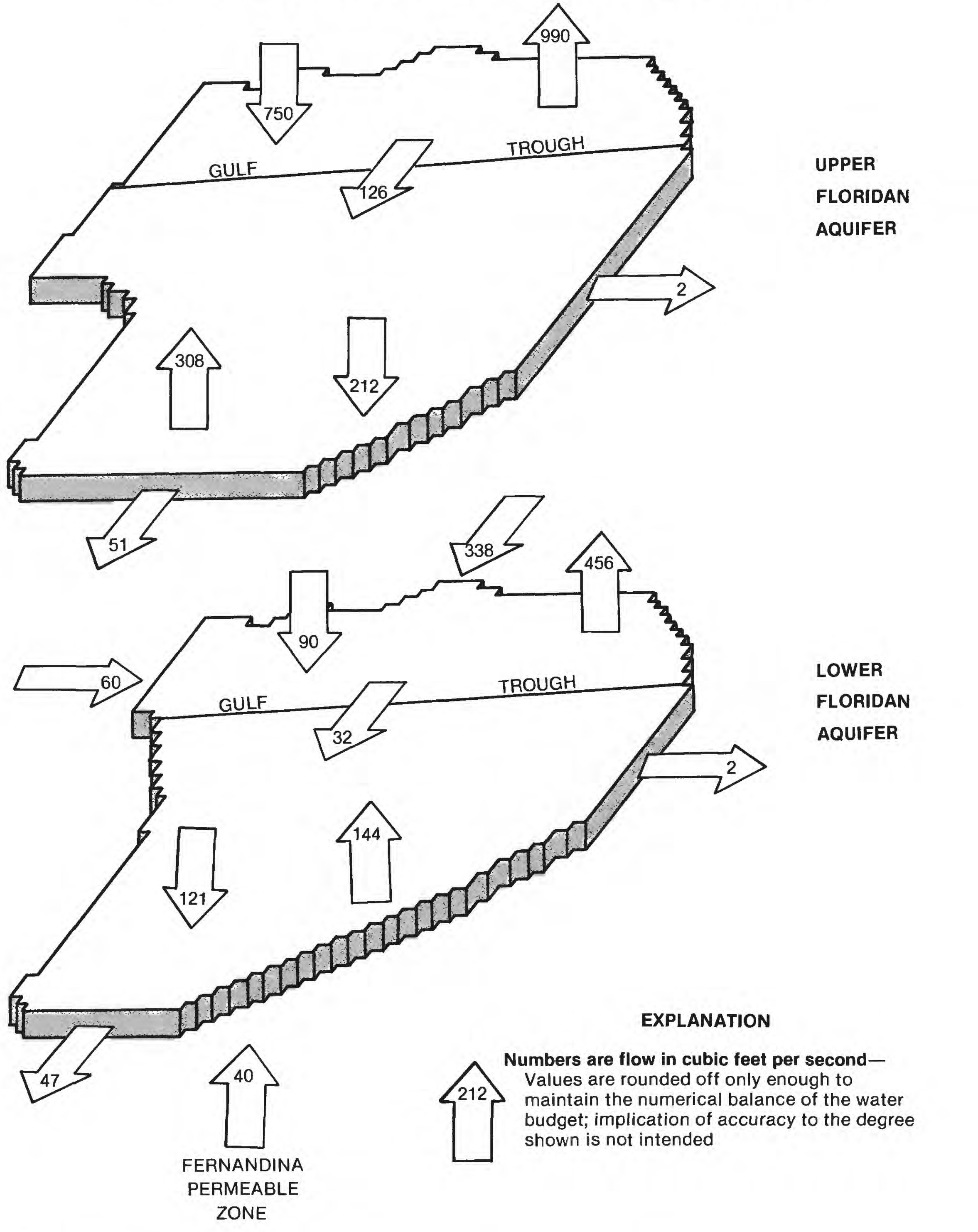


FIGURE 12.—Simulated components and areal distribution of flow through the Floridan aquifer system prior to development.

Total ground-water contribution to the major rivers was apportioned among the three aquifers: surficial (where different from the Upper Floridan aquifer), Upper Floridan, and Lower Floridan (which, in this area, is composed predominantly of clastic beds) on the basis of hydrogeologic framework and hydraulic characteristics of the aquifers. Estimated and simulated values are listed below.

Aquifer		Ground-water contribution to streamflow, in ft^3/s — River: Ocmulgee	Oconee	Ogeechee	Savannah
Surficial[1]	Estimated	50	25	25	50
Upper Floridan	Estimated	220	80	70	190
	Simulated	247	83	68	200
Lower Floridan	Estimated	120	30	10	240
	Simulated	99	34	14	260
Total Floridan aquifer system	Estimated	340	110	80	430
	Simulated	346	117	82	460
Total	Estimated	390	135	105	480

[1]Surficial aquifer was not simulated.

Downgradient from the Gulf Trough, the flow system was more sluggish, characterized by flat gradients, high aquifer transmissivities, low velocities, and, with some exceptions, low recharge and discharge rates. Recharge and discharge over most of the downgradient area were chiefly low rates of diffuse infiltration or leakage. It is doubtful that the highly transmissive, cavernous nature of the aquifer system was developed under these conditions; it probably developed in the geologic past, as a result of either Pleistocene sea-level fluctuations, or, more likely, karstification during exposure of the Floridan carbonates shortly after deposition during Tertiary time. (See Miller, 1985, chapter B of this Professional Paper series, for a complete discussion of cavernous permeability development.)

The Upper Floridan aquifer in the area downgradient from the Gulf Trough received about 126 ft^3/s as lateral downgradient flow through the trough (fig. 12). Recharge from the surficial aquifer to the Upper Floridan aquifer was about 212 ft^3/s, and discharge from the Upper Floridan to the surficial aquifer was about 308 ft^3/s, resulting in a net discharge of 96 ft^3/s. Most of the recharge from the surficial aquifer to the Upper Floridan occurred as diffuse infiltration where the hydraulic gradient was downward in the large inland area away from the coast. Most of the discharge from the Upper Floridan to the surficial aquifer was diffuse upward leakage where the hydraulic gradient was upward, primarily in the coastal area. Discharge was concentrated in the Savannah, Ga., area, and along the St. Johns River, including Green Cove Springs, in Florida, where the upper confining unit is thin and locally absent.

Northeast Florida had the most active part of the predevelopment flow system downgradient from the Gulf Trough. There, the Upper Floridan aquifer is near land surface, and in places the upper confining unit is breached. Sinkholes, sinkhole lakes, sinking streams, and springs make this area typically karst. Recharge to the Upper Floridan, based on simulation, was about 60 ft^3/s in the area near Keystone Heights in western Clay County, Fla. (pl. 10). Much of the water that recharged the aquifer near Keystone Heights was discharged in springs such as Green Cove Springs near the St. Johns River and unnamed springs along that river. Discharge also occurred as diffuse upward leakage from the Upper Floridan where leakance and head differences were favorable along the St. Johns River, totaling about 50 ft^3/s.

Significant recharge to the Upper Floridan also occurred near Valdosta, Ga., where about 100 ft^3/s enters the aquifer (Krause, 1979, p. 26), about 17 ft^3/s of which enters the study area from the southwest. North of Valdosta, part and sometimes all of the Withlacoochee River flows into swallow holes that are interconnected with the aquifer (Krause, 1979, p. 11).

Recharge to the Upper Floridan aquifer of about 8 ft^3/s occurred near Beaufort, S.C., where the aquifer is thinly covered. Discharge occurred nearby in deeply scoured reaches of creeks and estuaries near Hilton Head Island, S.C. (pl. 10).

In the area downgradient from the Gulf Trough, the Upper Floridan discharged about 51 ft^3/s across the southern boundary into Florida and offshore and about 2 ft^3/s into South Carolina and offshore across the eastern boundary. The Lower Floridan discharged about 144 ft^3/s to the Upper Floridan aquifer, largely as diffuse upward leakage in the downgradient area along the coast where the vertical hydraulic gradient was upward. The Upper Floridan recharged the Lower Floridan at a rate of about 121 ft^3/s, chiefly in the upgradient area near the Gulf Trough where the hydraulic gradient was downward (fig. 12).

The Lower Floridan aquifer in the area downgradient from the Gulf Trough received about 32 ft^3/s as downgradient flow through the trough and discharged about 47 ft^3/s and 2 ft^3/s across the southern and eastern boundaries, respectively. The Lower Floridan had a net discharge of about 23 ft^3/s to the Upper Floridan and received about 40 ft^3/s from the Fernandina permeable zone (fig. 12). Because the hydraulic characteristics of the Fernandina permeable zone are poorly known and only roughly estimated, the simulated flux of 40 ft^3/s may be in significant error.

The Fernandina permeable zone was fairly inactive prior to development. The approximately 40 ft^3/s that discharged from the zone into the rest of the Lower Floridan aquifer occurred chiefly along the northeast Florida–southeast Georgia coast where the lower semiconfining unit is breached by faults (Leve, 1966; Gregg and Zimmerman, 1974). It is thought that water in the Fernandina permeable zone is, in part, relict or partially flushed connate water, probably having a nearly horizontal freshwater–saltwater interface. If the small quantity of water that leaked from the Fernandina permeable zone along the coast is approximately the same as the simulated quantity, that leakage probably did not significantly move the freshwater–saltwater interface within the zone. Although not known, the source of water that replaced the water lost by the zone may have been the Lower Floridan aquifer in central Florida, where the Fernandina permeable zone may merge with the rest of the Lower Floridan aquifer, or it may be modern seawater from the offshore area, or a combination of the two.

Downgradient from the Gulf Trough, for example in Jeff Davis County, Ga., where the head in the surficial aquifer was higher than the head in the Upper Floridan, circulation included diffuse recharge and downgradient flow (pls. 9, 10; fig. 13). Figure 13 is a schematic showing the predevelopment flow system in the Floridan aquifer system in the study area along a hypothetical flow line. Farther downgradient toward the southeast, the gradient between the surficial and Upper Floridan aquifers changed direction and discharge occurred. Still farther downgradient, near the coast, the head in the Upper Floridan exceeded land surface altitude and flowing wells were obtainable; diffuse upward discharge and downgradient flow still occurred (pls. 9, 10; fig. 13). Similar flow circulation of lesser quantities existed in the Lower Floridan aquifer.

The downgradient limit to the predevelopment freshwater flow system in the Upper Floridan was estimated to be near and approximately parallel to the Florida-Hatteras Slope (pl. 9). This limit for the aquifer flow system corresponds to the freshwater–saltwater interfaces within the aquifers (fig. 13).

The position of the freshwater-saltwater interface was estimated on the basis of an equation described by Hubbert (1940, p. 872). The assumption of the equation is that at the interface, pressure created by the freshwater head is balanced by pressure created by the saltwater head. The interface equation assuming flowing freshwater, static saltwater, and a sea-level datum is

$$Z=\left[\frac{p_f}{p_s-p_f}\right]\bullet h_f,$$

where

Z = altitude of the interface above a datum,
p_f = density of freshwater,
p_s = density of saltwater, and
h_f = freshwater head at the interface.

If p_f is assumed to be 1.000 g/cm^3 for freshwater and p_s to be 1.025 g/cm^3 for seawater, then

$$Z=40h_f.$$

This relation indicates that the depth below sea level to the base of freshwater is 40 times the altitude of the freshwater head at the interface. To estimate the interface position, it was assumed that the head at the interface was equal to the head of the potentiometric surface of the Upper Floridan as measured or estimated vertically above the interface. This condition is not precisely met because freshwater flow above the interface necessitates lines of equal head that are curved, not vertical. However, Johnston and others (1982, fig. 7) have shown that the interface offshore of southeast Georgia, which constitutes the limiting flow line of the freshwater flow system, has a very low slope. Therefore, freshwater flow lines near the interface must be nearly horizontal. This in turn suggests that the lines of equal head near the interface are nearly vertical. Thus, an estimate of the interface position based on heads higher in the section is probably acceptable.

PRESENT-DAY GROUND-WATER-FLOW SYSTEM

The present-day (1980) flow system reflects the changes that have occurred as a result of ground-water development. The flow system has undergone changes that involve water levels, rates and distribution of recharge and discharge, ground-water flow, and the quality of the water. Ground-water withdrawals primarily have lowered water levels, induced additional recharge and reduced natural discharge, and increased total flow through the system, and, to a lesser extent, have reduced aquifer storage, caused land subsidence (at Savannah), and degraded the quality of the water in places on the coast.

GROUND-WATER WITHDRAWAL

The first well drilled into the Floridan aquifer system in the study area was in Savannah, Ga., in 1885 (McCallie, 1898, p. 64). The city of Savannah began using ground water from the Upper Floridan in 1886, and by 1900 more than 10 Mgal/d (15 ft^3/s) was withdrawn for municipal supply. Since then, development of ground water has spread throughout the area, chiefly along the coast, where flowing wells supplied suf-

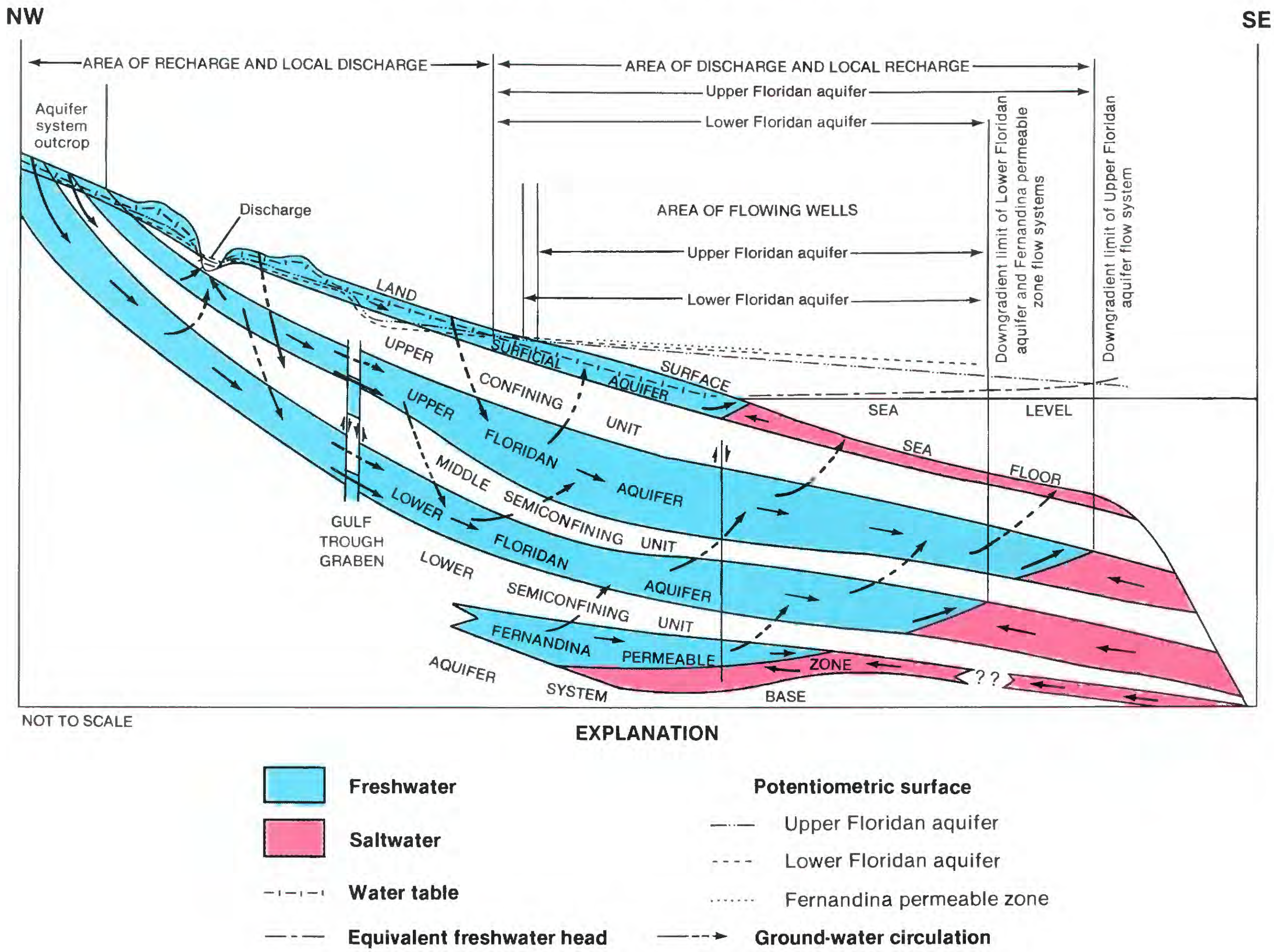


FIGURE 13.—Conceptual model of the predevelopment flow system for the Floridan aquifer system from the outcrop area in the northwest to the offshore area in the southeast.

ficient water to most users. Development continued to increase gradually, initially for municipal, domestic, and small commercial supplies. Large industries, chiefly paper manufacturers, located plants in the area and began to withdraw increasingly large quantities of water from the Upper Floridan, primarily along the coast. With the exception of the city of Jacksonville, Fla., the largest users of ground water are industries, and the major pumping centers are those that include ground water withdrawn by the pulp and paper industry.

In 1980, the total estimated ground-water withdrawal from the Floridan aquifer system in the study area was approximately 625 Mgal/d (970 ft^3/s). The distribution of pumpage for the study area by aquifer is shown on plate 11. The pumpage data were largely derived from Pierce and others (1982) for Georgia, Hayes (1979, p. 51, fig. 20) for South Carolina, and unpublished records (E.C. Hayes, U.S. Geological Survey, written commun., May 1981) for Florida. About 90 percent of the withdrawal was from the Upper Floridan. The 10 percent withdrawn from the Lower Floridan (about 93 ft^3/s) was chiefly in the Jacksonville area, where deep municipal and industrial wells tap both aquifers. A small quantity was withdrawn from the Lower Floridan in the outcrop area in Georgia, where neither aquifer is very productive, and in the area of South Carolina, where the Upper Floridan yields little water (pl. 11; table 4).

POTENTIOMETRIC SURFACE AND WATER-LEVEL DECLINE

The most obvious impact of ground-water withdrawal on the flow system has been the lowering of water levels. Large withdrawal of ground water along the coast has produced large cones of depression, which in places have overlapped, and generally has lowered potentiometric surfaces as far upgradient as the Gulf Trough (pl. 12). The potentiometric surface for May 1980 shown on plate 12 is that of the Upper Floridan aquifer in the study area, and is based on a similar map covering the entire Floridan aquifer system described by Johnston and others (1981). Although the potentiometric surface in the area upgradient from the Gulf Trough is believed to have been unaffected by ground-water development, the potentiometric surfaces for predevelopment (pl. 9) and present-day conditions (pl. 12), differ in that area. The present-day (1980) potentiometric surface is based on nearly synchronous measurements made during May 1980, whereas the predevelopment potentiometric surface is a general configuration, as previously discussed.

The potentiometric surface of the Lower Floridan is about the same as that of the Upper Floridan shown on plate 12. Sufficient data are not available to construct a 1980 potentiometric surface for the Lower Floridan. However, downgradient from the Gulf Trough, limited head data from both aquifers indicate that the head in the Lower Floridan is only slightly higher than that in the Upper Floridan. Maximum differences in heads between the Upper and Lower Floridan probably occur in the area of the deeper cones of depression and in areas where confinement is greatest and hence leakage is least. Fairchild and Bentley (1977, p. 13) indicated that at Fernandina Beach, Fla., the head in the Lower Floridan is as much as 20 ft higher than that in the Upper Floridan. This head difference probably represents a maximum; generally, head differences are less than 5 ft (fig. 9). However, locally in recharge areas upgradient from the Gulf Trough, where little withdrawal from the Upper Floridan has occurred since predevelopment, the head probably remains lower in the Lower Floridan. Similarly, head in the Lower Floridan is lower than in the Upper Floridan in the recharge areas near Keystone Heights, Fla., and Beaufort, S.C.

The deeper cones of depression of the potentiometric surfaces are in the areas of larger, concentrated ground-water withdrawal, such as Savannah, Ga., and Fernandina Beach, Fla. However, available water, supplied by lateral or vertical flow, plays a large part in the magnitude of head decline. In Georgia, pumpage at Brunswick is about 30 percent greater than that at Savannah, but higher transmissivity and leakance make more water available at Brunswick, thus producing a much shallower cone of depression. Pumpage of nearly 130 Mgal/d (200 ft^3/s) at Jacksonville, Fla., has produced an almost imperceptible cone for the same reasons, chiefly high leakage rates (pl. 12). Lowering of the potentiometric surface along the coast, especially near Savannah, has decreased the area where wells tapping the Floridan aquifer system would have flowed in 1980. Upgradient from the Gulf Trough, where head decline has been minimal, the area where wells would have flowed has changed little, if any (pls. 12, 13).

The head-decline map, plate 13, is based on the predevelopment and present-day (1980) potentiometric surfaces of the Upper Floridan aquifer shown on plates 9 and 12, respectively. Points of data used to contour the head-decline map were derived from the differences in head values at the intersections of superposed contours from the potentiometric-surface maps (pls. 9, 12). Interpolated contours from both potentiometric-surface maps were also used to increase the density of data points and to better define the lines of equal decline. The map showing head decline indicates the change that the potentiometric surface has undergone as a result of development, chiefly that of significant declines in the coastal area.

As shown on plate 13, almost the entire study area is encompassed by a line of zero head decline. The location of the inferred line of zero head decline offshore near the estimated position of the freshwater–saltwater interface in the Upper Floridan would indicate that little movement, or in places possibly no movement, of the interface has occurred since development. Little field data are available to support this contention. Head and salinity data are available only from an abandoned Tenneco, Inc., oil-test well and three other exploratory wells in the offshore area (Johnston and others, 1982, fig. 1, p. 12). The interface within the Upper Floridan at the Tenneco, Inc., site about 55 mi offshore from Fernandina Beach, Fla., seems to be transient between the position that would be compatible with the predevelopment heads and the position that would be compatible with present-day heads. This implies that some movement of the interface probably has occurred since development (Johnston and others, 1982, p. 12). Locally, at Brunswick, Ga., Fernandina Beach, Fla., and St Marys, Ga., saltwater intrusion into the Floridan aquifer system has occurred, indicating some vertical component of movement of the interface (fig. 14).

In the northwest part of the study area, the upgradient limit of head decline (line of zero head decline) lies along the Gulf Trough. Because the trough impedes the downgradient flow of water through the aquifer, it similarly limits the upgradient expansion of head decline. Head decline in the area upgradient from the trough has been negligible because the trough limits the

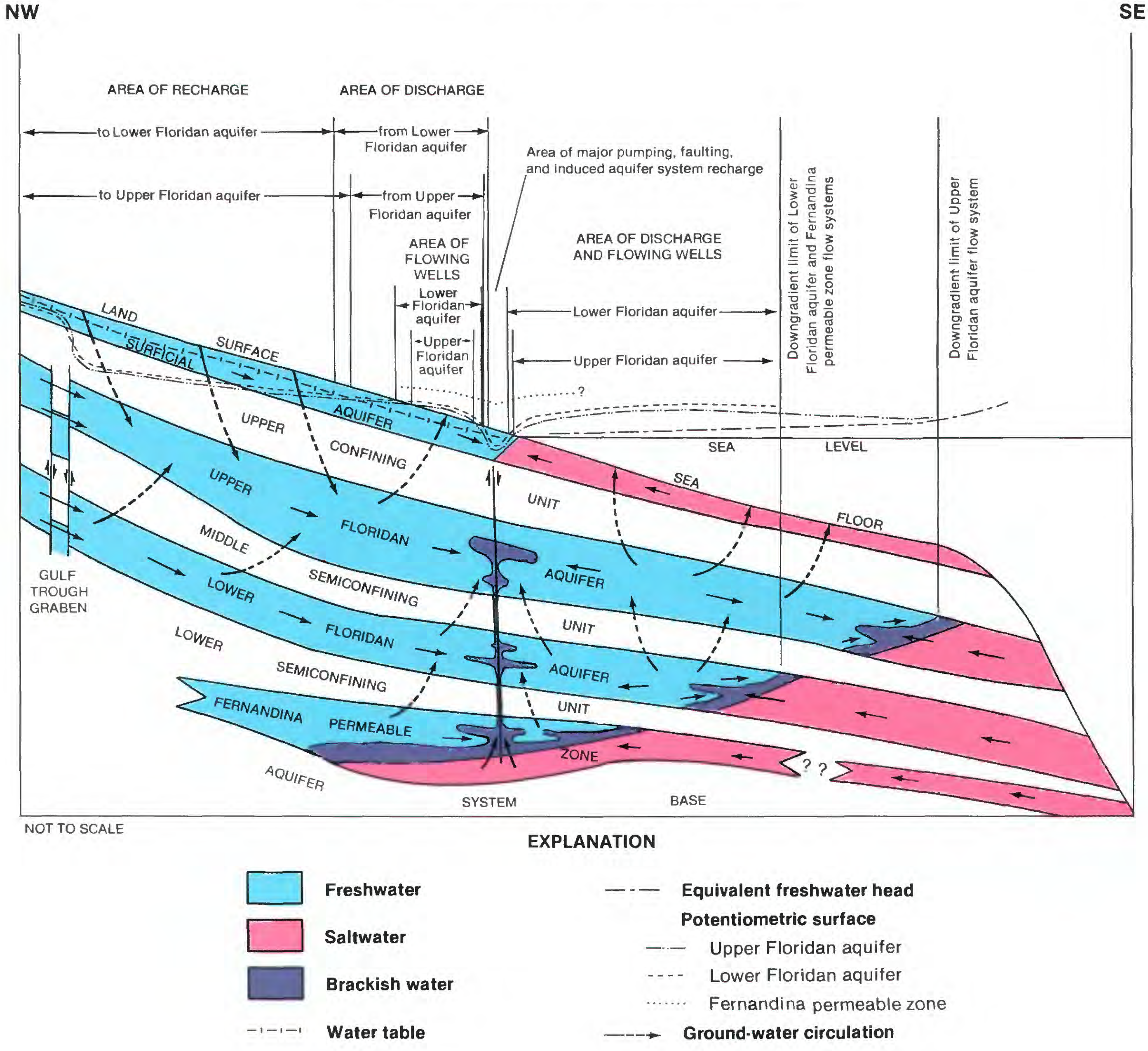


FIGURE 14.—Conceptual model of the present-day (1980) flow system for the Floridan aquifer system from the Gulf Trough in the northwest to the offshore area in the southeast.

expansion of head decline, and because of high rates of recharge and low rates of ground-water withdrawal in the area. An observation well (21T1) near Dexter (the outcrop area) in western Laurens County, Ga., indicates marked seasonal and climatic fluctuations but shows no long-term decline for the period 1964–82 (fig. 15; well location shown on pl. 13). Locally, small declines in head probably have occurred in municipal pumping centers upgradient from the trough, although the extent is unknown because of a lack of data.

Head decline in the area of the trough ranges from little or none at its upgradient side, to 15 to 30 ft at its downgradient side. Locally, head declines are probably greater within areas of the trough having lower transmissivities and moderate ground-water withdrawals. Observation wells in Vidalia, Toombs County (26R1), and Uvalda, Montgomery County (25Q1), within the graben system of the Gulf Trough, indicate head declines of about 1 ft/yr since 1974 and 1966, respectively (fig. 15; well locations shown on pl. 13).

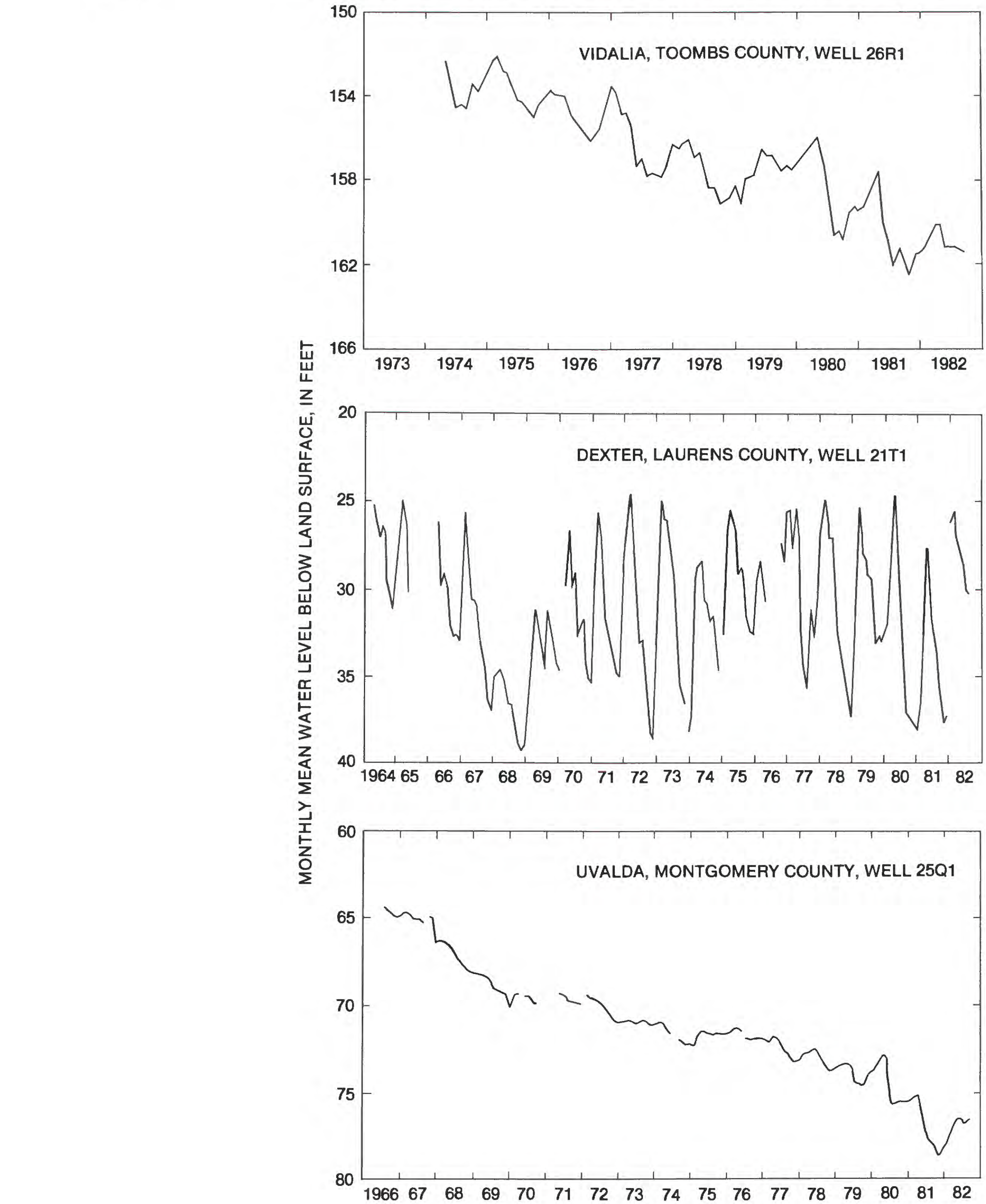


FIGURE 15.—Long-term water-level fluctuations in the Upper Floridan aquifer in Toombs, Laurens, and Montgomery Counties, Ga.

Recharge to the Upper Floridan near Valdosta, Ga., Beaufort, S.C., and Keystone Heights, Fla., limits the head decline near those areas caused by pumping throughout the study area (pl. 13). Heads in the aquifer near the areas of Valdosta, Ga., Beaufort, S.C., and Keystone Heights, Fla., showed seasonal fluctuations in response to precipitation but almost no long-term decline. The water-level trend in the Upper Floridan aquifer in the Valdosta area is closely related to precipitation and streamflow because of the direct recharge of the Upper Floridan by the Withlacoochee River. This relation, shown in figure 16, uses streamflow data from the nearby Alapaha River at Statenville, as data are not available for the Withlacoochee River in the area. Locations of the observation well and the precipitation and streamflow stations are shown on plate 13.

Head decline in the Upper Floridan along the southwestern boundary of the study area has caused significant lateral flow across the boundary that did not exist before development. Some head decline also occurred along the southern boundary of the study area where water in the Upper and Lower Floridan aquifers flowed out of the study area prior to development.

The prominent cones of head decline at Savannah, Brunswick, and Jesup, Ga., have overlapped and produced a large area of head decline that encompasses the three pumping centers. This area is defined by the 30-ft line of equal head decline shown on plate 13. This area and the nearby deep cone of head decline at St Marys, Ga., and Fernandina Beach, Fla., are separated by an area of minimal head decline in Camden County, Ga. This minimal head decline and lack of overlapping of the two closely spaced, deep cones seems to be anomalous when compared with the overlapping cones at Savannah, Jesup, and Brunswick, Ga. Comparison of the maps showing transmissivity (pl. 8) and water-level decline (pl. 13) indicates that a relation exists between transmissivity distribution and water-level decline in the area between Brunswick, Ga., and Fernandina Beach, Fla. Relatively, the transmissivity of the Upper Floridan at Brunswick is large, is substantially less along the Glynn–Camden County line, is largest in Camden County, and is lowest at Fernandina Beach. This distribution of transmissivity, primarily the alignment of low values that acts as a permeability barrier along the Glynn–Camden County line, is probably responsible for the separation of the cones of water-level decline at Brunswick and Fernandina Beach. Simulation supports this hypothesis. In addition, unusually high upward leakage from the Lower Floridan into the Upper Floridan near the south end of Brunswick, Ga., could also produce the 1980 potentiometric surface and water-level decline in the areas of Brunswick, and St Marys, Ga., and Fernandina Beach, Fla., shown on plates 12 and 13, respectively. The upward-leakage hypothesis also is supported by field evidence and by simulation.

Long-term water-level declines in three observation wells within the cone of depression at Savannah are shown in figure 17. On the basis of the estimated predevelopment potentiometric surface shown on plate 9, the water level in the vicinity of the three observation wells was probably about 30 ft above land surface prior to development. Thus, the water level has declined an estimated 110 to 170 ft at the three observation wells since development began in the 1880's. In Savannah, gradual increases in municipal and industrial pumping caused the water level to decline, with periods of accelerated pumping producing the steeper declines shown in figure 17. During the fifties and early sixties, the water level declined rapidly in response to accelerated pumping. However, since the sixties the water-level decline has leveled off because of stabilized pumping rates (fig. 17).

Typical water-level trends in wells within the cones of depression at Brunswick, Ga., and Fernandina Beach, Fla., are shown in figure 18. Prior to development, the water levels in the vicinity of the wells were about 50 to 55 ft above land surface at Brunswick, and about 42 ft above land surface at Fernandina Beach. In both areas, the water level has declined to below land surface, owing mostly to industrial pumping. At Fernandina Beach, the aquifer has apparently reached equilibrium. At Brunswick, the water level continues to decline at a slow rate in well 33H133 near the center of pumping. However, other wells in the Brunswick area farther from pumping have shown nearly no decline during the past 10 years.

LAND SUBSIDENCE

As a result of water-level decline in the Floridan aquifer system in response to ground-water withdrawal, land subsidence has occurred in the area of Savannah, Ga. (Davis, Small, and Counts, 1963; Davis, Counts, and Holdahl, 1976). First, it should be noted that the subsidence at Savannah documented through 1975 was not significant enough to be recognized as an engineering problem, and would probably have gone undetected without precise leveling. Second, this subsidence should not be confused with crustal movements of regional scale, such as that reported by Holdahl and Morrison (1974) and Brown and Oliver (1976), or with coastal submergence as reported by Wait (1968).

Precise leveling in 1918, 1933, 1935, and 1955 indicated that subsidence of as much as 0.33 ft had occurred in the Savannah area, mostly since 1933 (Davis, Counts, and Holdahl, 1976, p. 350). By 1955, an area of

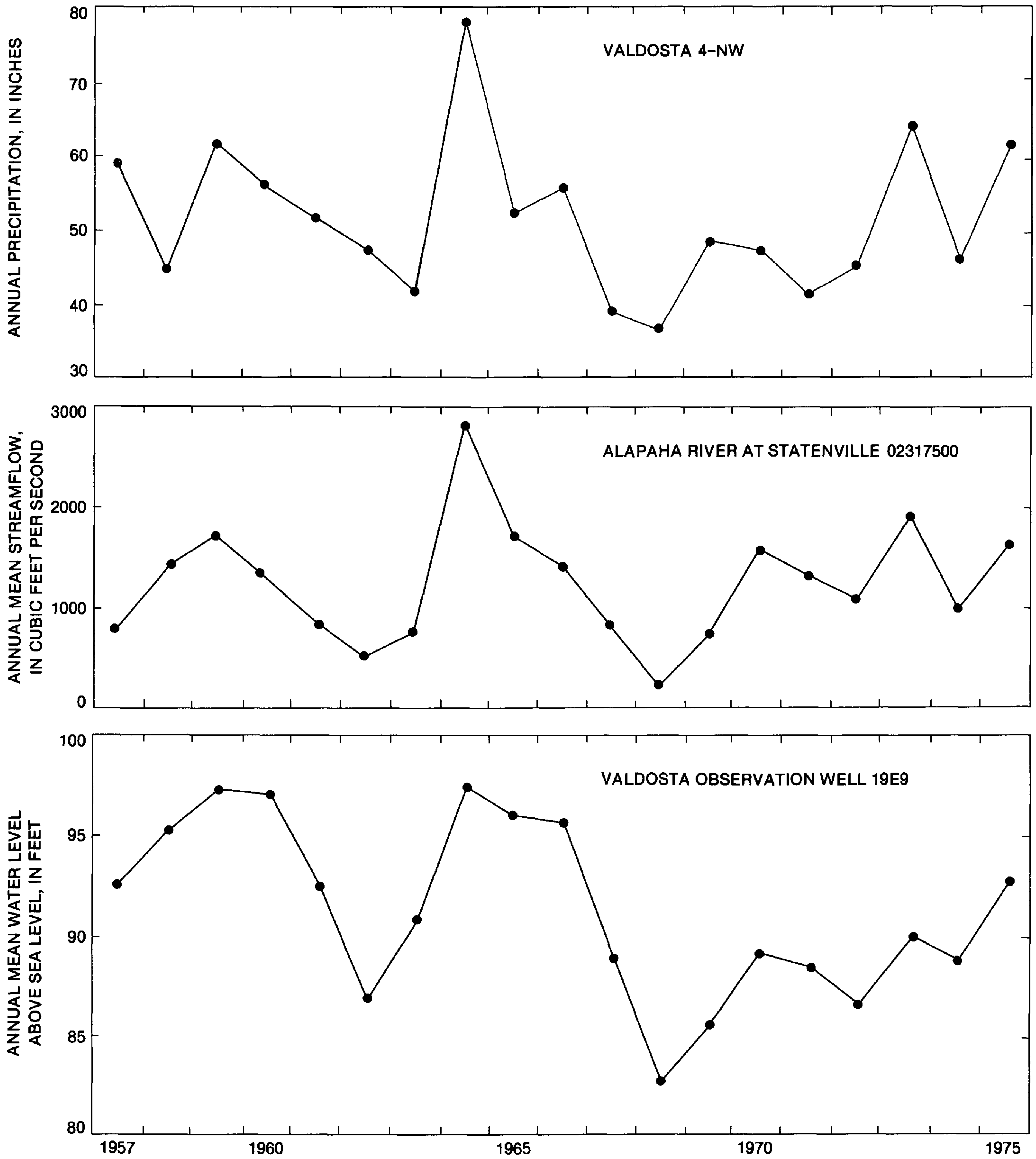


FIGURE 16.—Relation of precipitation, streamflow, and water level in the Upper Floridan aquifer, Valdosta, Ga., area, 1957–75. From Krause (1979).

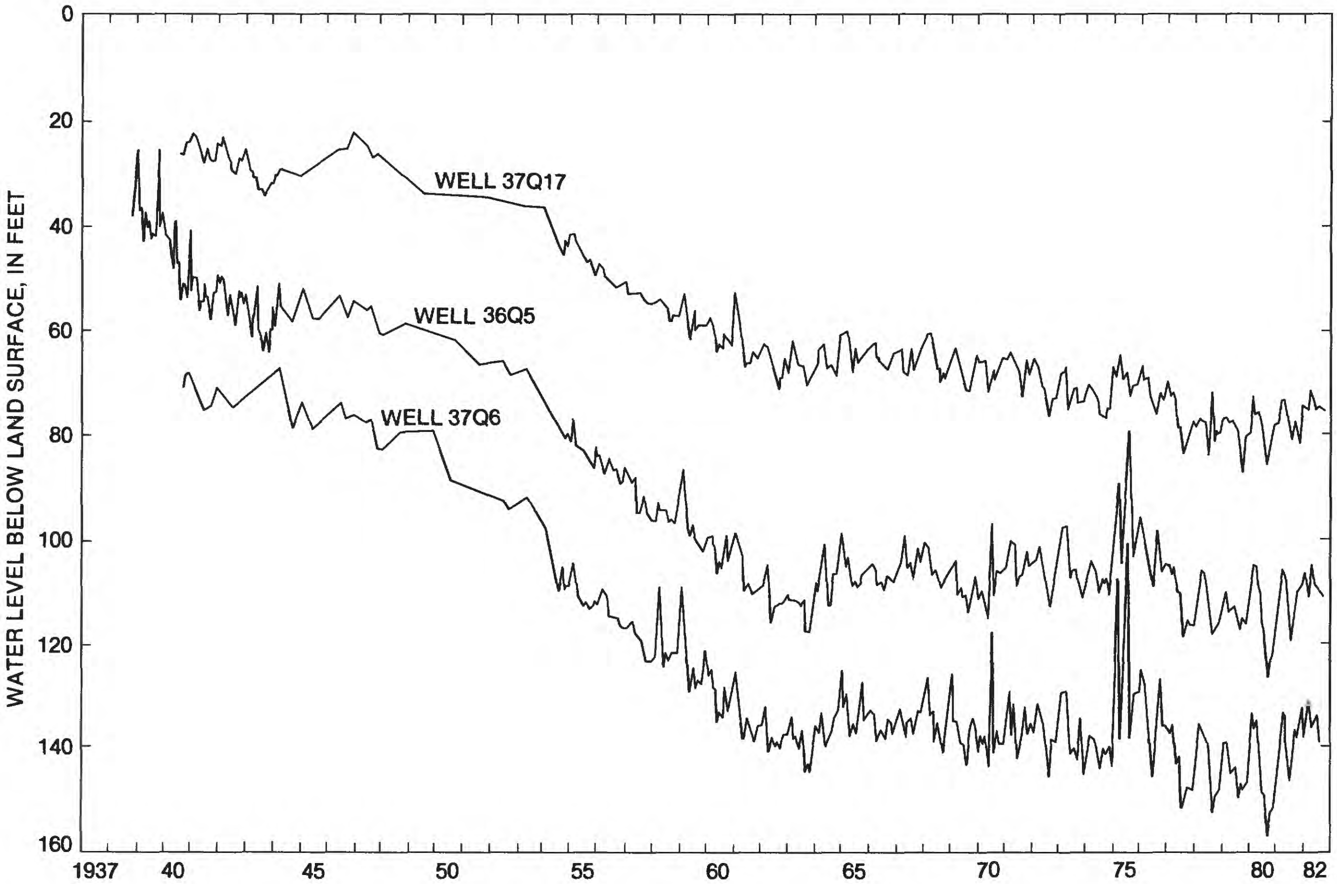


FIGURE 17.—Long-term water-level trends in the Upper Floridan aquifer, Savannah, Ga.

about 50 mi² had subsided at least 0.066 ft. The area in which subsidence exceeded 0.16 ft was limited primarily to the city of Savannah and adjacent industrial area, an area of about 15 mi². Subsequent leveling in 1975 indicated that additional subsidence of as much as 0.23 ft had occurred in Savannah since 1955. Also, the area in which subsidence exceeded 0.066 ft in the period 1955–75 is estimated to encompass at least 125 mi² (Davis, Counts, and Holdahl, 1976, p. 353).

Davis, Small, and Counts (1963) showed a close correlation between decline in water level in the Floridan aquifer system and land subsidence. Early (1933–55) data indicated a ratio of subsidence to water-level decline of about 0.0033. During the period 1955–75, subsidence continued at about the same rate despite a general lessening of water-level decline associated with stabilized pumping rates at Savannah. Accordingly, the ratio of subsidence to water-level decline increased, generally to between 0.007 and 0.016 throughout the area of maximum subsidence. Water-level and subsidence data collected through 1975 indicated that a threshold stress of about 50 ft of water-level decline had to be exceeded before subsidence began (Davis, Counts, and Holdahl, 1976, p. 353).

The increase in the ratio of subsidence to water-level decline even after the water-level decline in the Floridan had slowed supports the concept that the subsidence is related to slow drainage of water from marl, clay, silt, and fine sand of the upper confining unit to the underlying Upper Floridan aquifer (Davis, Counts, and Holdahl, 1976, p. 354). After a head gradient has been established between the Upper Floridan and the clastic materials of the upper confining unit, water from the upper confining unit continues to drain and the clastic material is slowly compacted until a new equilibrium is reached, despite the fact that the water level in the Upper Floridan has ceased to decline. Compaction of the Upper Floridan aquifer as a cause of subsidence is unlikely because of the rigid, competent skeleton of the carbonate rocks that make up the aquifer.

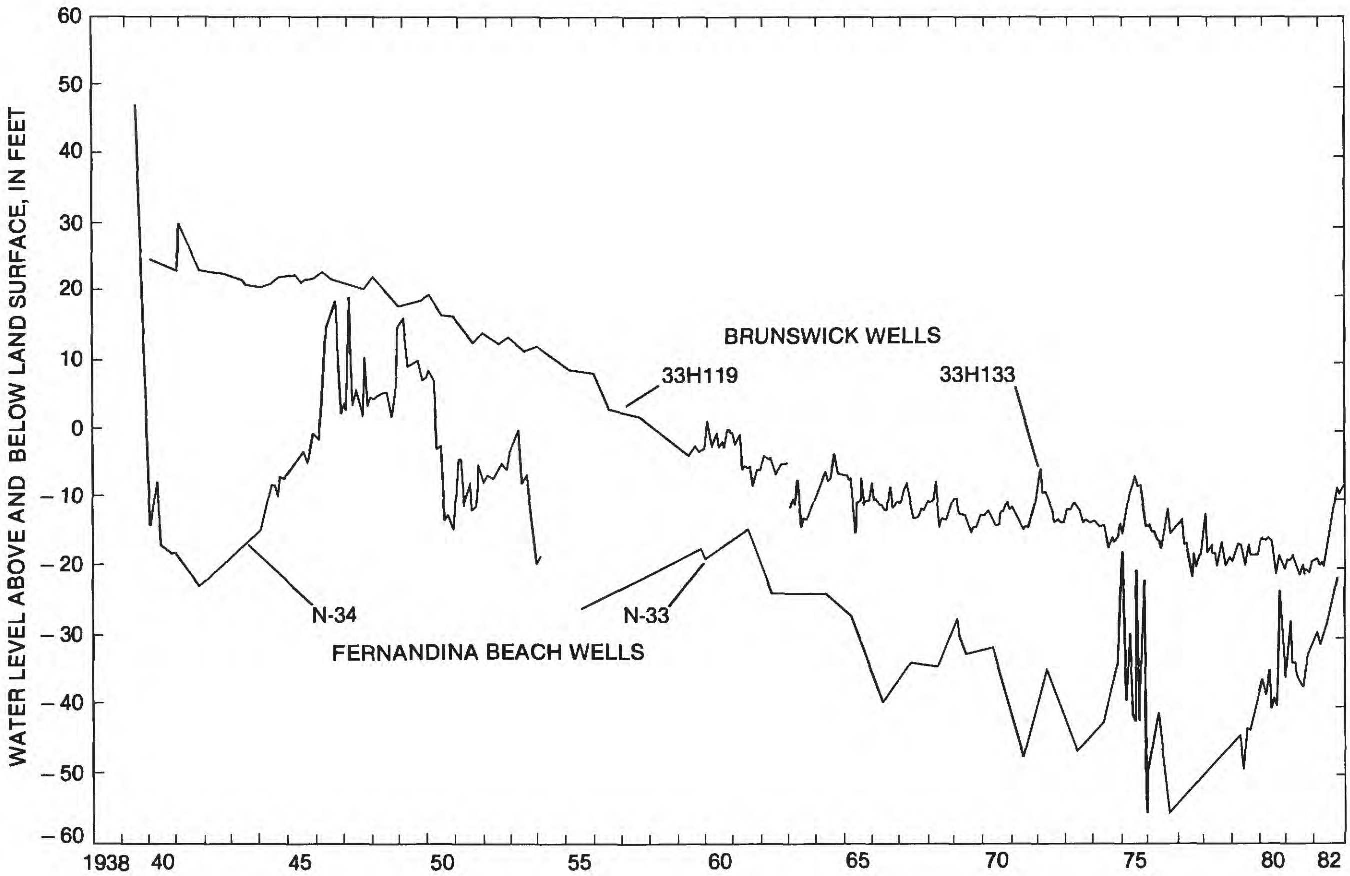


FIGURE 18.—Long-term water-level trends in the Upper Floridan aquifer, Brunswick, Ga., and Fernandina Beach, Fla.

COMPONENTS OF THE PRESENT-DAY GROUND-WATER-FLOW SYSTEM

A major change in the flow system since development is the capture by coastal pumping of downgradient flow in the Upper Floridan aquifer that had previously moved seaward. In addition, head gradients have steepened along the Gulf Trough as well as between the trough and the pumping centers, increasing the downgradient flow within the Upper Floridan toward those centers (pl. 12, fig. 14). Flow direction has also been changed, and in places reversed, especially in the area of Savannah, Ga., where the gradient is toward the pumping center in Savannah, even from offshore (pl. 12, fig. 14). This reversal of flow and the head decline near the freshwater–saltwater interface probably moved the interface slightly landward and upward (Counts and Donsky, 1963, p. 75, 76). Hayes (1979, table 14, fig. 24) and Stiles and Matthews (1983, p. 136, 137) documented increased chloride concentration in water from wells tapping the aquifer system (primarily the Upper Floridan) on Hilton Head Island, S.C. The change in chloride concentration is attributed to increased pumping, which lowered the water level and caused the landward and upward movement of the interface.

The large withdrawals of water from the Upper Floridan aquifer along the coast have also changed, and in places reversed, the vertical head gradient between the Upper Floridan and the surficial aquifer. Large areas where water from the Upper Floridan leaked upward into the surficial aquifer before development are now (1980) areas where water from the surficial aquifer leaks downward into the Upper Floridan (fig. 14; pls. 14, 15).

The changes in leakage through the upper confining unit caused by development of the aquifer system are shown on plate 15. The changes include decreased upward leakage, increased downward leakage, and a change from upward to downward leakage. In the Savannah area, for example, where the head gradient prior to development was upward and diffuse upward leakage occurred, pumping reversed the head gradient over a large area and caused downward leakage through the upper confining unit (pl. 15). As shown on plate 15, this area of reversed head gradient extends southwestward from Savannah in the area that had only a small upward head gradient under predevelopment conditions. South of this area of reversed gradient, head gradients and leakage were upward prior to development. Postdevelopment head decline in this area has decreased the upward gradient but has not reversed it, resulting in reduced upward leakage (pl. 15). The remainder of the updip area continues to be characterized by downward gradient and leakage, and the lowering of head in the Upper Floridan has increased the downward leakage from the surficial aquifer (pl. 15).

The simulated components and areal distribution of flow through the Floridan aquifer system under present-day (1980) conditions are shown in figure 19. In the area upgradient from the Gulf Trough, the recharge–discharge relation and flow through the Floridan aquifer system have undergone negligible changes as a result of development because of minimal head declines. Simulation suggests that 788 ft^3/s was recharged to the Upper Floridan in this area, an increase of about 38 ft^3/s, or 5 percent more than the predevelopment flow. Discharge to the rivers, which includes the contribution from the Lower Floridan, decreased about 43 ft^3/s, from 990 to 947 ft^3/s, or about 4 percent (figs. 12, 19). Infiltration to the Lower Floridan increased from about 90 to 95 ft^3/s, or a little more than 5 percent. Downgradient flow through the trough increased about 27 percent, from about 126 to 160 ft^3/s, but remained a small part of the total flow through the aquifer system. Pumpage from the Upper Floridan aquifer in the area upgradient from the Gulf Trough was about 29 ft^3/s (fig. 19).

Across the northern boundary of the study area, flow into the Lower Floridan remained the same, about 338 ft^3/s, and across the northwestern boundary it was about 60 ft^3/s. Updip of the Gulf Trough, the Lower Floridan discharged about 443 ft^3/s into the Upper Floridan, chiefly into the upgradient rivers, a decrease of about 3 percent from the predevelopment flow of about 456 ft^3/s. Downgradient flow through the trough increased about 16 percent, from 32 to 37 ft^3/s, but remained a small part of the total flow through the Floridan aquifer system. Pumpage from the Lower Floridan aquifer in the area upgradient from the trough was about 13 ft^3/s in 1980 (fig. 19).

Although the flow system downgradient from the Gulf Trough was sluggish prior to development, most of it became active and its flow system changed significantly with development. The ground-water withdrawal was, of course, the most significant change, but it in turn produced other major changes to the components of the flow system.

Of the estimated 568 Mgal/d (878 ft^3/s) withdrawn from the Upper Floridan aquifer in 1980, about 549 Mgal/d (849 ft^3/s) was withdrawn in the area downgradient from the Gulf Trough, chiefly along the coast. In the area downgradient from the Gulf Trough, flow between the surficial and Upper Floridan aquifers reversed. Flow changed from the Upper Floridan discharging a net of about 96 ft^3/s (308 $ft^3/s-212$ ft^3/s) into the surficial aquifer, to the surficial aquifer recharging a net of about 252 ft^3/s (353 $ft^3/s-101$ ft^3/s) into the Upper Floridan (figs. 12, 19). In general, downward leakage increased in the inland areas, upward leakage decreased along the heavily pumped coastal areas and offshore, and leakage changed from upward to downward in the area between and in the area of Savannah, Ga., and Hilton Head Island, S.C. (pl. 15).

At Keystone Heights, Fla., Valdosta, Ga., and Beaufort, S.C., recharge from the surficial aquifer to the Upper Floridan increased from about 85 ft^3/s to about 125 ft^3/s, or almost 50 percent. At Keystone Heights, recharge to the Upper Floridan increased from about 60 ft^3/s to 95 ft^3/s, while discharge in the area of Green Cove Springs and the St. Johns River decreased from about 50 to 30 ft^3/s. Similar quantities of recharge were estimated from field data by Phelps (1978, p. 15–17) for the recharge at Keystone Heights, and by G.W. Leve (U.S. Geological Survey, written commun., July 1981) for the discharge in the area of Green Cove Springs and the St. Johns River. Recharge at Valdosta increased from about 17 ft^3/s to about 20 ft^3/s, and at Beaufort from about 8 ft^3/s to 10 ft^3/s. The Valdosta recharge approximates that estimated from apportioning the total recharge originally estimated by Krause (1979, p. 26). The Beaufort recharge is nearly the same as that estimated by Hayes (1979, p. 50, 51).

The head decline along the southwestern boundary due to ground-water withdrawals created a gradient in the Upper Floridan across what had been a ground-water divide prior to development. This gradient produced a flow of of about 201 ft^3/s across that boundary into the study area (fig. 19). The gradient toward the southeast along the southern boundary was decreased by the ground-water withdrawals, thereby decreasing the flow out of that boundary from about 51 ft^3/s to 34 ft^3/s (figs. 12, 19). The gradient along part of the eastern boundary nearest the pumping center at Savannah, Ga., was changed from eastward to westward, resulting in a net inflow of about 6 ft^3/s into the study area compared with 2 ft^3/s predevelopment outflow.

Head decline, primarily in the Upper Floridan, also changed the vertical hydraulic gradient and in places reversed the direction of the gradient between the Upper and Lower Floridan aquifers. Most of the change was increased upward leakage in the heavily pumped coastal area. Net upward leakage from the Lower Floridan to the Upper Floridan increased from about 23 ft^3/s

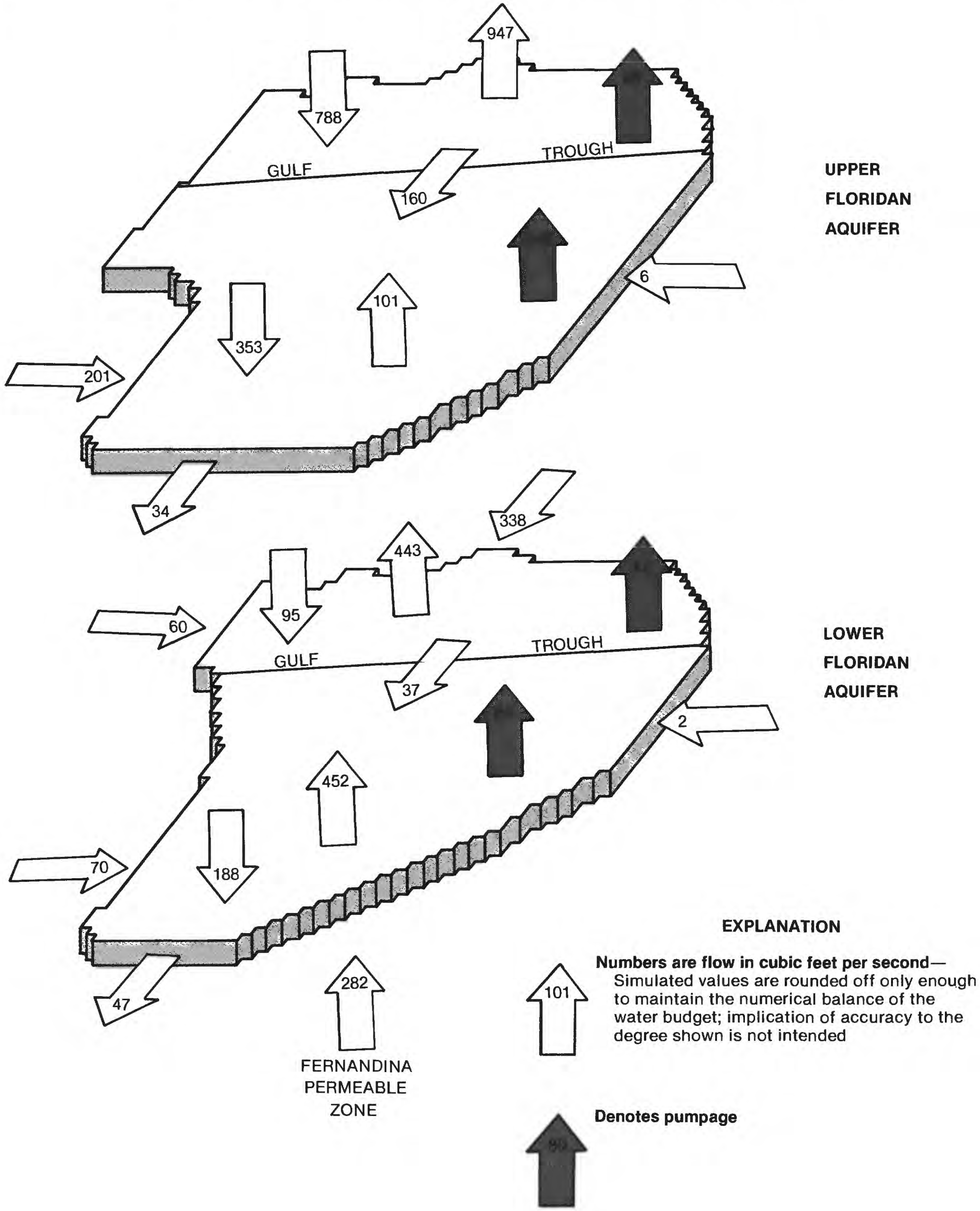


FIGURE 19.—Simulated components and areal distribution of flow through the Floridan aquifer system, present-day (1980) conditions.

($144\ ft^3/s - 121\ ft^3/s$) to about $264\ ft^3/s$ ($452\ ft^3/s - 188\ ft^3/s$) in the area downgradient from the Gulf Trough (figs. 12, 19).

The flow system of the Lower Floridan aquifer was affected mainly by ground-water withdrawal from the Upper Floridan, except in areas of high ground-water use from the Lower Floridan. Pumpage from the Lower Floridan in the area downgradient from the Gulf Trough was about $80\ ft^3/s$ in 1980. Gradient changes due to withdrawal from the Lower Floridan were similar to gradient changes in the Upper Floridan. The gradient created along the southwestern boundary resulted in a flow in the Lower Floridan of about $70\ ft^3/s$ into the study area. Flow remained about the same ($47\ ft^3/s$) out of the southern boundary, and changed from $2\ ft^3/s$ out of to $2\ ft^3/s$ into the study area along the eastern boundary (figs. 12, 19).

The relation of the Fernandina permeable zone to the rest of the flow system changed markedly owing to development in the study area. Based on simulation, leakage from the Fernandina permeable zone into the rest of the Lower Floridan increased from about $40\ ft^3/s$ to about $282\ ft^3/s$ since development (table 4; figs. 12, 19). Expectedly, most of the increased leakage was along the coast in southeastern Georgia and northeastern Florida. In these areas, the upward migration of water from the Fernandina permeable zone and consequent deterioration of water quality is well documented (Gregg and Zimmerman, 1974, for Brunswick, Ga.; Fairchild and Bentley, 1977, for Fernandina Beach, Fla.; and Leve, 1983, for the Jacksonville, Fla., area). Nearly vertical faults, which have been enlarged by solution, created conduits through which large quantities of water migrate upward (H.E. Gill and D.C. Prowell, U.S. Geological Survey, written and oral communs., May 1982; Leve, 1983).

Chiefly upward but landward movement of the freshwater–saltwater interface in the Fernandina permeable zone has probably resulted from its discharging water to the rest of the Lower Floridan aquifer and ultimately to the Upper Floridan (fig. 14). No decrease in head has been documented in the Fernandina permeable zone in the area along the coast where the zone contains brackish to saline water. Slightly inland from the coast, measured heads, albeit poorly documented, suggest that there has been an apparent decrease in head, most likely owing to the increased density of water in the zone. The equivalent freshwater head probably has remained unchanged, or has declined slightly. Head in the Fernandina permeable zone west of Jacksonville in Duval County, Fla., seems to be declining even though water from the zone remains comparatively fresh. Contribution from the Fernandina permeable zone to the overlying pumped aquifers is large there, and the distance to a possible saltwater source may be greater than it is at Fernandina Beach, Fla., or at Brunswick, Ga. In summary, the head in the Fernandina permeable zone, uncorrected for density, remains greater than that in either the rest of the Lower Floridan or the Upper Floridan aquifers.

GROUND-WATER-DEVELOPMENT POTENTIAL

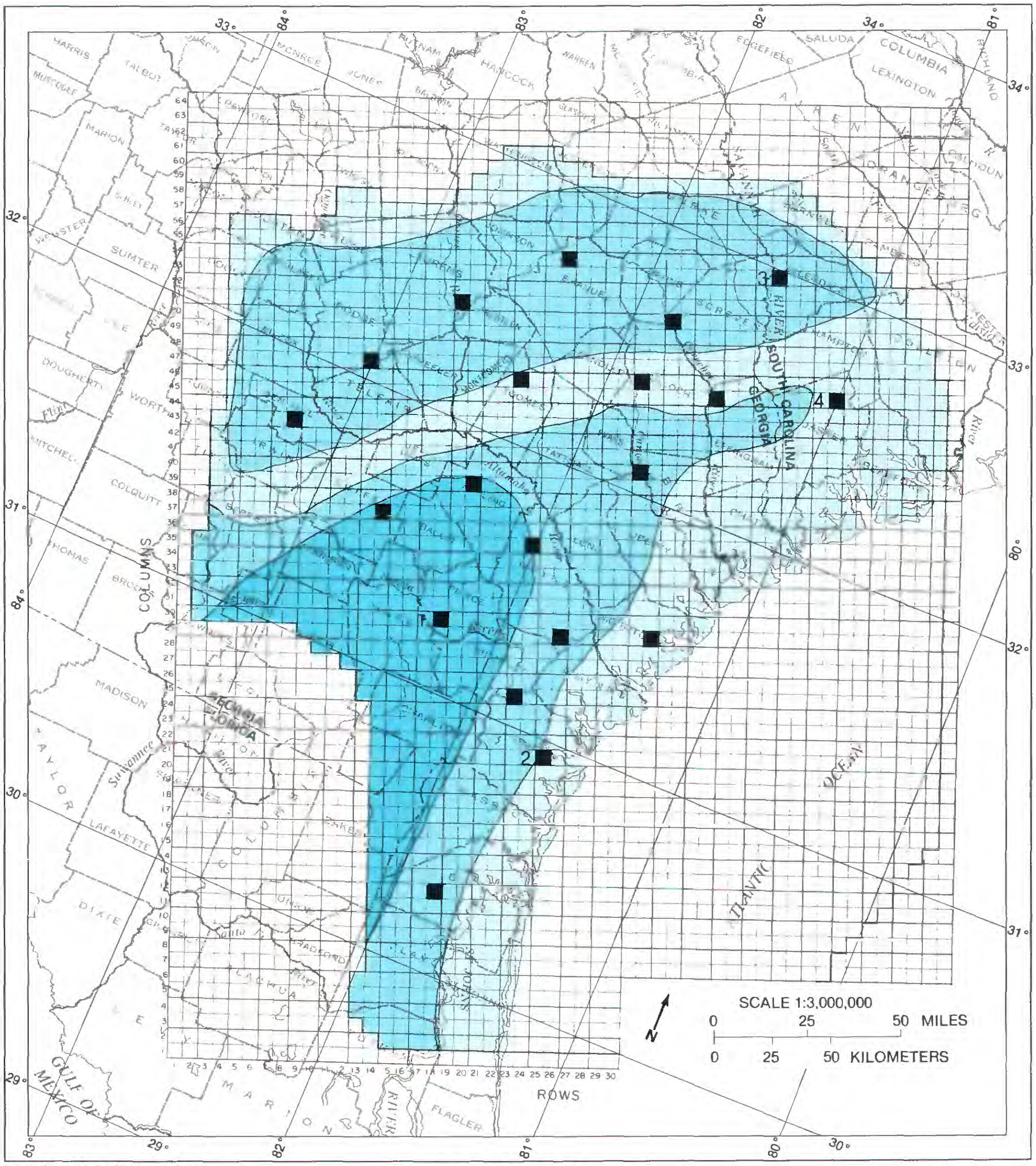
Although heavily developed, the aquifer system in parts of the study area could undergo some additional development without detrimental effects. The potential for ground-water development depends on existing hydrologic conditions as well as those expected as a consequence of the development. A ground-water-flow model was used to evaluate the ground-water-development potential of the Floridan aquifer system as it existed in 1980.

One major use of the simulation model is to predict water-level changes that might result from future pumping schemes. This allows for management plans to be evaluated before being employed. For example, the effects of pumping by a new user on the water level in the area can be estimated by simulating the new pumping stress and comparing the resulting heads with the existing heads.

The reliability of these evaluations is related to how well the model simulates the flow system under both predevelopment (1880) and present-day (1980) conditions. Although it is difficult to accurately quantify the capability of the model to predict the effects of stresses on the system, the results are expected to indicate the general magnitude of the aquifer's response to these stresses.

The purposes of the evaluation of future development potential are to determine the areas where potential development may be possible and to estimate the magnitude of those developments. This was done by selecting a network of sites where development of the Floridan aquifer system might occur. The network consisted of 20 sites, shown in figure 20, that were selected on the basis of the likelihood for development and on a random, yet areally sufficient, sampling. Aquifer-system characteristics of transmissivity, leakage, and head, as well as existing and potential future water-quality problems, were also considered in site selection. Increments of hypothetical pumping-rate increases were simulated in the Upper Floridan aquifer at selected sites, and the results were evaluated on the basis of head declines and potential water-quality problems associated with the additional pumping stress.

The development potential of the Lower Floridan was not evaluated by simulation because the accuracy of the



Base from U.S. National Atlas, 1970

EXPLANATION

- Area where potential ground-water developement ranges from 0 to about 10 million gallons per day (0 to 15 cubic feet per second) depending on locally occurring water-quality problems, threatening water-quality deterioration, or excessive reduction in ground-water level
- Area where potential ground-water developement ranges from about 10 to 26 million gallons per day (15 to 40 cubic feet per second) depending on local conditions and proximity to areas of greater and lesser developement potential
- Area where potential ground-water developement may be at least 26 million gallons per day (40 cubic feet per second)
- ■ Nodes in which the hypothetical pumping stresses were applied for determination of potential ground-water developement—Numbered node indicates that simulations are discussed in text. (1) Waycross, Ga., (2) Camden County, Ga., (3) Allendale, S.C., (4) Ridgeland, S.C.

FIGURE 20.—Estimated ground-water-development potential of the Floridan aquifer system (as of 1980).

model calibration of the Lower Floridan could not be determined and simulations used to determine development potential might have been in significant error. Also, the Lower Floridan's further development seems unlikely owing to its limited areal extent, its proximity to poor-quality water, the higher cost of well construction, and the ready availability of water from the Upper Floridan.

Each simulation began by adding pumpage of 15 ft^3/s (about 10 Mgal/d) at a single site. The results of each simulation were evaluated and a decision was made as to the acceptability of the simulated development. Acceptability was based on the head decline caused by the hypothetical pumping and on the water-quality conditions likely to result from the increased withdrawals. If the results were considered acceptable by these criteria, then a 40-ft^3/s (about 26-Mgal/d) pumpage increase was introduced at each site and the results evaluated using the same criteria. The results of the evaluations were then used to produce a map delineating areas of relative potential for ground-water development of the aquifer system (Upper Floridan) (fig. 20).

The development potential shown in figure 20 ranges from less favorable areas (where an increase in pumpage of less than 15 ft^3/s (about 10 Mgal/d) could produce adverse effects) to highly favorable areas (where an increase in pumpage of more than 40 ft^3/s (about 26 Mgal/d) may be acceptable). Maximum and minimum withdrawal rates could not be determined from simulation and are not defined in figure 20.

The simulations that were used to determine areas of potential development incorporated increases in pumpage that hypothetically are derived from the entire Upper Floridan aquifer. In addition, the model is calibrated using regional transmissivity values that apply to the entire permeable section of the Upper Floridan rather than site-specific local values. Wells that partially penetrate the aquifer probably would have greater drawdown locally; however, the head decline on a regional scale probably would be the same. The difference in localized head decline would be related to the parts of the aquifer that were penetrated by individual wells.

The amount of potential ground-water development may be less than shown in figure 20, if future development follows the practices of the past and wells do not fully penetrate or totally use the entire aquifer. In contrast, if development uses both the Upper and Lower Floridan aquifers, the development potential probably is greater than shown in figure 20, assuming water-quality problems are not created. Head declines at individual well sites also will differ from simulated declines, and the amount of potential ground-water development may differ from that shown in figure 20 if the local aquifer or confining-bed characteristics at the proposed development sites differ significantly from the regional values used in simulation. Transmissivity of the Upper Floridan and leakance of the confining units do vary significantly within short distances.

The ranges of development potential shown in figure 20 are valid only for pumping increases imposed on hydrologic conditions similar to those of 1980 at a single site in the study area, and do not depict any total or maximum quantity for the area as a whole. After any development occurs, the hydrologic regimen would change from that used to determine the development potential shown in figure 20. A new development potential would then result, and would indicate less potential in the area of the new development than that shown in figure 20. Multiple or consecutive simulations, or both, would be required to determine development potential with combinations of pumping increases.

The area of largest development potential is the region of high transmissivities in the southwestern part of the study area and is considered to have the potential to accept additional pumpage of more than 40 ft^3/s (about 26 Mgal/d) at a single site without detrimental effects. A maximum withdrawal rate could not be determined because of significant boundary effects caused by adding the large pumping increase near the boundary (discussed below as the first of four example simulations used for estimating the development potential). The location of maximum development potential is probably near the center of this area.

The areas of lowest development potential include the heavily developed coast, the Gulf Trough, and the northern outcrop area where the aquifer thins to a featheredge. In the coastal area, near major pumping centers, increased pumpage of as little as 1 to 2 ft^3/s would result in additional water-level decline and the liklihood of further encroachment of the freshwater–saltwater interface and saltwater contamination. Two areas where development potential is probably less than 1 to 2 ft^3/s are the area of Hilton Head Island, S.C., where lateral seawater intrusion is occurring, and the area of Brunswick, Ga., where saltwater moves into the Upper Floridan from the Fernandina permeable zone. Parts of the coastal areas away from major pumping centers may be capable of withstanding increases of about 15 ft^3/s without serious effects. Camden County, Ga., is one area that probably has the potential for withdrawal of about 15 ft^3/s. In the Camden County area, a small amount of water-level decline to date (1980) is a factor making the potential for development greater there than elsewhere along the coast. The Gulf Trough was determined to be an area where development potential is small, because of the low transmissivities that would result in large though localized water-level decline. The aquifer in South Carolina and in the northern outcrop also has limited potential for development because of its low transmissivity.

Results of four example simulations used for estimating development potential are discussed in the following paragraphs.

A simulation to evaluate the development potential near Waycross, Ga., was made with the hypothetical pumpage increase located between the cities of Waycross and Blackshear, Ga. (location 1, fig. 20). The large transmissivity derived from the aquifer test near Waycross and the similarly large transmissivities used in the simulation suggest that an increase of 40 ft^3/s in pumpage would not produce a large decline in head.

The simulation of that hypothetical development resulted in steady-state conditions, but the decline in head extended to the model boundary southwest of Waycross. To accommodate this decline (less than 5 ft) at the boundary, a flow into the model area was calculated by using Darcy's law and the transmissivity and head difference between the simulated head at the boundary nodes and the actual heads outside the boundary. The calculated flow across that boundary was about 18 ft^3/s, or approximately 45 percent of the total increase in the pumping rate. This comparatively large contribution to the total withdrawal is expected owing to the high transmissivities between the withdrawal site and the affected boundary. The approach of correcting the boundary condition after calibration would contribute some error to the simulation results. However, the error is probably small owing to the high transmissivities and small drawdowns in the vicinity of the boundary. Also, exact quantitative results were not sought, but instead, the determination of areas of development potential as a function of the likely drawdown.

The withdrawal had little effect on head throughout the study area; the head in the area of the center of the cone of depression was lowered only about 5 ft. Because of the minimal decline in the water level and no apparent water-quality problems, the area represented by the discharging node near Waycross was included in the area of largest potential for development (fig. 20).

A simulation was made to evaluate the development potential in the Camden County, Ga. area, between the pumping centers of Brunswick, Ga., and St Marys, Ga.–Fernandina Beach, Fla. (location 2, fig. 20). The initial assumption was that the water-quality problems present in Brunswick probably would be worsened by a nearby 15 ft^3/s increase in pumpage. However, the presence of the potentiometric high in Camden County offered a possibility that the development might induce sufficient flow from the highly transmissive areas upgradient. The simulation results support these assumptions. The water-level decline caused by the increase in pumpage of 15 ft^3/s reached a maximum of about 3 ft in the area of the cone of depression in Brunswick, and the 1-ft decline extended past Brunswick to the north and between Fernandina Beach, Fla., and St Marys, Ga., to the south. The major simulated change in vertical flow was the increase in upward leakance from the Lower Floridan to the Upper Floridan. Although the decline in water level caused by an additional 15 ft^3/s of withdrawal would be relatively minor, the water-level decline in the Upper Floridan at Brunswick would probably cause additional encroachment of brackish water from the Fernandina permeable zone into the Upper Floridan aquifer. The possible adverse effects of withdrawing an additional 15 ft^3/s at the Camden County site would have on the quality of water at Brunswick made testing the system for larger development unnecessary. Therefore, the hypothetical site in Camden County was considered to be located along the border between the development-sensitive coastal area and the upgradient areas having greater development potential (fig. 20).

A simulation to evaluate the development potential near Allendale, S.C., was used to determine water availability upgradient from the Gulf Trough. The area chosen for increased development was in Allendale County, near the Savannah River (location 3, fig. 20). Neither present nor future water-quality problems are a factor for evaluating the development potential in that area. A 15-ft^3/s increase in withdrawal was specified to determine what effects development might have on the water level. The resultant decline in the water level under the hypothetical increase in pumpage of 15 ft^3/s reached a maximum of about 15 ft in the immediate pumping area. The relatively low transmissivities in the area resulted in a steep and comparatively deep cone of depression of limited areal extent. The major simulated change in flow was induced recharge from the surficial aquifer to the Upper Floridan aquifer. Most of this change in flow was a reduction in the upward flow into the nearby Savannah River. The change in contribution from the Lower Floridan was negligible.

A simulation to evaluate the development potential near Ridgeland, S.C., was used to determine the effects of increased withdrawals in that area on the water level along the coast of South Carolina. The hypothetical withdrawal site was located in the northern part of Jasper County, S.C., about 30 mi inland and just downgradient from the Gulf Trough (location 4, fig. 20). The hypothetical pumpage increase of 15 ft^3/s caused a 25-ft decline in head in the immediate pumping area. A 1-ft decline in water level extended along most of the South Carolina coast, nearly to Savannah, Ga. These simulation results suggest that development of that magnitude in the area would cause water-quality problems along the coast as a result of the head declines. Existing water-quality problems are those of seawater infiltrating breaches in the upper confining unit into the Upper Floridan aquifer in some estuaries and sounds along the South Carolina coast. In fact, the simulation indicated that the hypothetical pumpage increase was nearly equaled by downward leakage from the surficial aquifer to the Upper Floridan aquifer, some of which occurred along the coast.

GROUND-WATER QUALITY

For a complete description of the geochemistry of the entire Floridan aquifer system, refer to chapter I of this Professional Paper series (Sprinkle, in press) and to previously published reports by Sprinkle (1982a, b, c, d). Chapter I describes the natural geochemistry, hydrochemical facies, relation between water chemistry and the flow system, and geochemical changes induced by pumping and land development. Only a brief description of the general water quality of the Floridan aquifer system in the study area follows. However, a somewhat detailed description of anomalous water-quality conditions, and of changes to the water quality brought about by development, is included herein.

NATURAL GROUND-WATER QUALITY

Water from the Floridan aquifer system in the study area is generally hard, alkaline, of the calcium-bicarbonate type, and has moderate dissolved-solids concentration. The dissolved-solids concentration generally is low in areas of recharge and increases with distance from the recharge areas and with depth.

Because of large quantities of recharge and discharge in the flow system upgradient from the Gulf Trough, water there is low in dissolved solids and is moderately hard. Water in the Upper Floridan is of the calcium bicarbonate type, although in some areas where clastic material is more abundant in the aquifer, no single cation predominates. In the area of and immediately downgradient from the Gulf Trough, sluggish circulation and the presence of evaporites in the aquifer produce water of the calcium bicarbonate and calcium magnesium sulfate types that is high in dissolved solids and is very hard. Farther downgradient from the Gulf Trough and away from areas of local recharge, circulation is also sluggish. Water in this area ranges from a mixed bicarbonate type to a calcium magnesium bicarbonate type farther downgradient, and to a calcium magnesium, bicarbonate sulfate type along the central part of the coast and probably offshore.

In the recharge areas downgradient from the Gulf Trough, water in the aquifer is chemically similar to that in the recharge areas upgradient from the trough. An exception is in the recharge area north of Valdosta, Ga. There, some of, and at times all of, the flow of the Withlacoochee River recharges the Upper Floridan aquifer with highly colored water containing large amounts of organic material (Krause, 1979, p. 39–41). The colored water is a result of the presence of dissolved humic substances that are derived from decayed vegetation in the river basin--a natural organic process. The colored water migrates downgradient from the recharge area with little natural filtering and color removal by the highly permeable limestone. Color removal ultimately occurs as a result of the microbial processes—carbon-source oxidation and sulfate reduction—and through dispersion and dilution.

Degradation of naturally occurring organic compounds by bacteria is an important process in some areas of the Floridan aquifer system. Bacteria are probably common in the Upper Floridan; aerobic, anaerobic, and sulfate-reducing bacteria were detected in water samples taken from test wells near Waycross, Ga. (Matthews and Krause, 1984; Sprinkle, in press). Sulfate-reducing bacteria have also been identified in water from deeper wells tapping the Madison Limestone at a depth of 4,000 to 6,000 ft in Montana (Olson and others, 1981). The sulfate-reducing bacteria are both heterotrophic (i.e., they need organic material to supply energy and support growth) and anaerobic (i.e., they grow in the absence of dissolved oxygen). In the Valdosta area, the source of organic material is recharge water from the Withlacoochee River. The river water is also high in dissolved oxygen. As the recharge water moves downgradient in the aquifer, it becomes depleted of dissolved oxygen by aerobic bacterial decomposition. When dissolved oxygen is absent, sulfate-reducing bacteria proliferate if present. One of the metabolic products of these bacteria is hydrogen sulfide gas. Dissolved in water, this gas produces sulfide, which occurs in high concentrations in the Valdosta area. Factors that seem to affect the local concentration of sulfide in the ground water are the rate of travel of the water through the aquifer, the amount of organic carbon available as a source of food for the sulfate-reducing bacteria, and the availability of sulfate.

The preceding discussion of color and sulfide is largely from recent work by James B. McConnell (U.S. Geological Survey, written commun., 1983). The reader is also referred to reports by Krause (1976, 1979) that address the subject.

GROUND-WATER QUALITY RESULTING FROM DEVELOPMENT

Changes in the quality of water in the Floridan aquifer system due to development range from negligible in the area upgradient from the Gulf Trough to significant in parts of the area along the coast. Slight changes in the quality of water in the Upper Floridan in the area downgradient from the Gulf Trough, exclusive of parts of the coastal area, occurred as a result of development of the aquifer system. The small changes that occurred in this area are due to (1) increased recharge to the Upper Floridan, including the locally occurring increased recharge at Beaufort, S.C., Valdosta, Ga., and Keystone Heights, Fla., (2) increased gradient, velocity, and, hence, flow through the Upper Floridan, and (3) increased leakage from the Lower Floridan to the Upper Floridan. The first and second processes have tended to decrease the dissolved-solids concentration in water from the Upper Floridan, whereas the third process has tended to increase the dissolved-solids concentration. The distribution of the various hydrochemical facies within the aquifer system probably remained unchanged, or shifted only slightly owing to changes in the flow system caused by development.

The water-level decline resulting from ground-water withdrawals along the coast locally has caused significant changes in the quality of water. The dissolved-solids concentration of the water increased and the water locally became a sodium chloride type. As a result of development, two different processes—lateral encroachment and vertical intrusion of saltwater—have produced the resulting water quality of the aquifer system.

Lateral saltwater encroachment into the Upper Floridan probably has occurred along the coast in South Carolina, extending to Tybee Island, Ga. (Counts and Donsky, 1963, p. 75; Hayes, 1979, p. 67). In this area before development, the gradient, and hence the ground-water flow, in the Upper Floridan was seaward (pl. 9). However, the freshwater head ranged from only about 5 ft at St. Helena and Hunting Islands, S.C., to about 25 ft at Tybee Island, Ga. If the Hubbert freshwater–saltwater interface relation (Hubbert, 1940, p. 872) is applicable, the predevelopment depth to saltwater was only about 200 ft at St. Helena and Hunting Islands, and about 1,000 ft at Tybee Island. The freshwater–saltwater interface is herein defined as a zone where freshwater and seawater are mixed and the chloride concentration is 10,000 mg/L. The interface is not considered to be sharp, but includes a zone of diffusion.

Since development, the large withdrawal of ground water from the Upper Floridan in the Savannah, Ga.–Hilton Head Island, S.C., area has lowered the head and reversed the gradient in the aquifer (pl. 12), resulting in the potential for migration of the freshwater–saltwater interface toward the areas of pumping. However, little change in water quality in the aquifer system has been observed in the monitoring wells in the Savannah, Ga.–Hilton Head Island, S.C., area during the past 20 years. Any change in the variability of water quality with depth in the aquifer system has remained undetected; the variability is about that expected under predevelopment conditions. In fact, only one well tapping the Upper Floridan on the extreme north end of Hilton Head Island (well 40S317, pl. 13) has water that is increasing in chloride concentration. The chloride concentration has increased from about 100 mg/L in 1978 to about 550 mg/L in 1982 (Stiles and Matthews, 1983, p. 137). The interface is moving either at a slow rate or with a long period of lag after the decline in the freshwater head (or both), either of which may explain why there has been little or no detectable change in water quality in the aquifer system elsewhere in this area.

Nevertheless, lateral saltwater encroachment is occurring on the north end of Hilton Head Island (as observed in well 40S317), and may be occurring elsewhere. Back and others (1970) measured carbon-14 activities and major constituents in ground-water samples taken from various depths and locations on the island and on Parris Island to the north. From the relative radiometric ages and chloride concentrations of the samples, they concluded that vertical recharge to the Floridan is occurring in the northern part of Hilton Head Island, and that saltwater from Port Royal Sound is entering the aquifer and moving laterally southwestward toward the pumping center near Savannah.

The slope of the interface in this area was about 80 to 100 ft/mi in 1980, based on the Hubbert freshwater–saltwater interface relation and the 1980 potentiometric surface. Therefore, seawater moving laterally downgradient has a small vertical component that moves the interface upward. The amount of upward movement could be partly impeded by the presence of low-permeability units within the aquifer system. However, almost no head difference between the Upper and Lower Floridan aquifers has been observed in the area, even though head declines have occurred in the Upper Floridan as a result of development. Therefore, the impeding of the upward movement of the interface by laterally extensive low-permeability units probably is minimal. In addition, lateral variability in the leakance of low-permeability units probably is minimal, producing little potential for upward movement of the interface. Density stratification probably is a contributing factor that tends to stabilize the vertical position of the interface in this area.

Elsewhere on Hilton Head Island, S.C., heavy ground-water withdrawal for golf-course irrigation during the summer months temporarily induces localized upconing of brackish water from the interface to the pumping wells tapping the Upper Floridan. There, and in the rest of the South Carolina coastal area, the Lower Floridan contains saltwater or brackish water.

Vertical intrusion of saltwater into the Lower and Upper Floridan aquifers has occurred in Brunswick, Ga., rendering a large part of the aquifer system in the city contaminated (Wait, 1965, p. 55–85; Wait and Gregg, 1973, p. 65–67; Gregg and Zimmerman, 1974, p. 22). In Brunswick, water from the Upper Floridan aquifer locally had a maximum chloride concentration greater than 2,000 mg/L in 1980, and in an area of more than 5 mi^2 within the city of Brunswick, the water had a chloride concentration greater than 250 mg/L—the recommended limit set for drinking water by the U.S. Environmental Protection Agency (1976) (pl. 16). In this area prior to development, the slope of the seaward gradient in the potentiometric surface of the Upper Floridan was nearly flat and the aquifer water migrated slowly past the coast (pl. 9). The predevelopment freshwater head was nearly 65 ft above sea level, theoretically placing the freshwater–saltwater interface more than 2,500 ft below sea level, and below nearly all the Lower Floridan aquifer.

Development of the aquifer in the Brunswick area—pumpage of about 100 Mgal/d (160 ft^3/s) in 1980—has depressed the head in the Upper Floridan to below sea level, and most of the decline has occurred in less than 50 yr (pl. 12). The head in the Lower Floridan also has declined. The Hubbert freshwater–saltwater interface relation cannot be strictly applied where the freshwater head has declined as much and as rapidly, and where the aquifer is heterogeneous and anisotropic, as at Brunswick. The rise of the freshwater–saltwater interface lags the rate of the freshwater head decline; thus the interface position cannot be related to the freshwater potentiometric surface. Stabilization of the interface probably does not occur for many years after the freshwater head ceases to decline, but the amount of time required is not known. For example, results from a test well drilled in 1976 on Colonels Island, about 3 mi west of Brunswick, indicated that the freshwater–saltwater interface was in the Fernandina permeable zone at a depth of about 2,300 ft (Gill and Mitchell, 1979, p. C–9). In this area, the freshwater head was about 20 ft above sea level, suggesting that the interface should have been about 800 ft rather than 2,300 ft below sea level.

The chloride concentration indicates a fairly sharp interface in the Colonels Island test well. Chloride concentration increased from about 5,000 to 16,000 mg/L in the interval 2,280 to 2,320 ft. The interface position in the area of the test well is probably controlled chiefly by water density stratification. Borehole televiewer and television logs show the entire interval to be cavernous, with no low-permeability beds near the interface. In this area, low-permeability confinement near the interface zone is not a factor that would restrict the adjustment of the position of the interface to new freshwater heads.

The saltwater intrusion into the Upper Floridan in the Brunswick area is localized. Saltwater has moved upward into the Upper Floridan through nearly vertical zones of preferential permeability that have breached the confining units and then laterally downgradient toward centers of pumping. The source of the saltwater is the Fernandina permeable zone. At the Colonels Island test-well site, the water in the bottom part of the Fernandina permeable zone had a chloride concentration of about 30,000 mg/L in 1982.

The conduits that permit the intrusion of saltwater from the Fernandina permeable zone into the overlying Lower and Upper Floridan aquifers most likely are nearly vertical faults. The faults, found throughout the Atlantic Coastal Plain, were active from the Late Cretaceous to as late as the Pleistocene (Prowell, 1983; Wentworth and Mergner-Keefer, 1983, p. S5) and probably would have shattered the brittle limestone and dolomite. Faults of this type have been mapped in the Brunswick area by Gregg and Zimmerman (1974, pl. 2) and in the Jacksonville, Fla., area by Leve (1966, fig. 5; 1978; 1983, fig. 3). Also, recently gathered seismic data and additional borehole geophysical data support the mapped faults of Gregg and Zimmerman (1974) and identify other faults in the area of Brunswick. Pleistocene sea-level changes and consequent freshwater–saltwater interface movement probably would have induced vertical flow along these faults, further enlarging them by solution. Finally, the freshwater-head decline that occurred as a result of pumping from the Upper Floridan induced the upward intrusion of saltwater that has contaminated the Floridan aquifer system in the area of Brunswick. The relations of the present-day freshwater–saltwater flow system, including ground-water withdrawal, freshwater-head decline, vertical intrusion of saltwater along solution-enlarged faults, and subsequent lateral migration of brackish water, is shown in figure 14. The relation between the areal extent of saltwater intrusion and the potentiometric surface of the Upper Floridan aquifer in the Brunswick area for 1980 is shown on plate 16. Although the largest quantity of pumpage and consequent head decline is at the east and west extent of the chloride plume, the locations of the point sources of saltwater intrusion, as indicated by highest concentrations of chloride, are outside the area of the two well fields (pl. 16). Simple upconing below the well fields is obviously not occurring.

Plate 16 also shows that a limited amount of dispersion of the plume has occurred. The area of contamination that was produced by the intrusion at the southern end of the plume is narrow in east-west extent. Migration of the saltwater seems to be nearly due north rather than directly toward the pumping centers. This suggests preferential flow in a northerly direction, probably along solution-enlarged faults, and minimal lateral flow and dispersion. Direct flow to the well fields occurs only in the area between the well fields. The approximate north-south alignment of the plume through the locations of the two point sources of saltwater intrusion and the lack of appreciable east-west dispersion suggest that isolated features, probably solution-enlarged faults, are responsible for the distribution of chloride contamination shown on plate 16.

The possibility of lateral seawater intrusion into the Upper Floridan aquifer in the Brunswick area has been discounted. Hanshaw and others (1965) used carbon-14 age dating of the freshwater and brackish water in the Brunswick area and concluded that the brackish water is from an underlying source rather than from the nearby ocean. They hypothesized that the source was water-bearing zones in Claibornian rocks. More recent data show the Claibornian rocks to be an intermediate host, themselves having been contaminated by saltwater from the underlying Fernandina permeable zone. Wait and Gregg (1973, p. 68, 72) used various theoretical mixtures of modern seawater and fresh ground water to determine if the brackish water might have been of a similar composition; they concluded that modern seawater was not the source of the brackish water. Also, the relation between the freshwater heads in the Floridan and the freshwater equivalent head of seawater negated the possibility of encroachment by seawater when contamination first occurred in the fifties, except in two small areas where pumping had lowered the head in the Floridan to below sea level.

Vertical intrusion of saltwater also has occurred in the Fernandina Beach, Fla.–St Marys, Ga., area, but the contamination problem is not as severe as at Brunswick. In this area, the upper part of the Fernandina permeable zone contains water having a chloride concentration of at least 9,600 mg/L. In a test well drilled at Fernandina Beach, a chloride concentration of 9,600 mg/L was the maximum determined when drilling was terminated near the freshwater–saltwater interface, about 2,100 ft below sea level (Brown, 1984). Chloride concentration increased from less than 200 to 9,600 mg/L in the interval from about 2,000 to 2,100 ft during drilling of the well, indicating that the interface zone is comparatively sharp in this area. As at Brunswick, the interface position probably is controlled chiefly by density stratification, because confinement by low-permeability units near the interface is negligible.

Also in the area of Fernandina Beach and St Marys, water in the Upper Floridan is only slightly mineralized near the center of pumping, where the chloride concentration is as high as about 190 mg/L (Brown, 1984). Chloride concentrations range from about 50 mg/L to greater than 1,000 mg/L in the Lower Floridan (Brown, 1984). The chloride concentration of water from the Lower Floridan continues to increase. The chloride contamination in the Upper Floridan in this area is undoubtedly due to the upward migration of water from the Fernandina permeable zone. Faults, or possibly fractures or improperly completed or unplugged deep wells, probably act as the conduits allowing the upward intrusion of the saltwater. Faults are the probable conduits, as they occur at Brunswick, Ga., to the north and at Jacksonville, Fla., to the south—both closer than 15 mi.

In the area of Jacksonville, Fla., Leve (1983) attributes the small but continually increasing chloride concentration in the Upper Floridan to upward movement of high-chloride water (known to be about 7,000 mg/L) from a deep (Fernandina permeable) zone in the aquifer system. The mechanisms for the intrusion are lowered freshwater head caused by pumping from the aquifer system and the presence of nearly vertical faults that act as conduits. Leve (1983) states that the areas of higher chloride concentration in the Upper Floridan are in the vicinity of known faults. Leve, using the results of theoretical studies by Plummer (1975), postulated that the mixing of saline water from the deep (Fernandina permeable) zone with freshwater in the rest of the Floridan aquifer system has caused dissolution of the carbonates along the fault planes. Although both waters are saturated with respect to calcite and dolomite, mixing the two theoretically can produce a water undersaturated with respect to the minerals, allowing the mixture to dissolve carbonate material in the area of the interface and along the faults, locally enhancing vertical permeability.

FUTURE INVESTIGATIONS

The results of this investigation provide a better understanding of the flow regimen of the Floridan aquifer system, both prior to and as a result of development. Increased knowledge and understanding of the hydrologic system acquired through additional investigations, coupled with additional data collection and a continued and improved monitoring network, probably would result in more effective management of the Floridan aquifer system.

The monitoring program is essential to obtain data on water use, including pumping rates, water levels in pumping and nonpumping wells, and water quality—areally and vertically within the aquifer system. The frequency of data collection would depend on the rate of change of the monitored data. The monitoring would thus document changes with time in the quantity and quality of water in the aquifer.

Additional data collection in the form of deep test-well drilling would fill the most obvious voids in the present knowledge of the aquifer system—head, water quality, and the position of the freshwater–saltwater interface in the lower part of the Floridan. Almost no data are available on changes in those characteristics with time or on the movement of the freshwater–saltwater interface. Drilling and testing the zones would greatly increase understanding of the aquifer system.

A significant product of this investigation is the digital model of the Floridan aquifer system. The scope and purposes of the model, as previously discussed, do not include use of the model as a management tool for site-specific resource evaluation and prediction. However, because it simulates the entire Floridan aquifer system over a large part of its area of occurrence, the model can be used as the basis for more detailed models.

Digital models that may be developed in the future will be able to use many aspects of the present model—specifically, the calibrated input data and the horizontal and vertical flows computed by the model. These values could be used directly, or more likely discretized or interpolated for more detailed models.

SUMMARY AND CONCLUSIONS

The Floridan aquifer system is the major source of water in its area of occurrence in Florida, the Coastal Plain of Georgia, and adjacent parts of South Carolina and Alabama, except where it contains saltwater. In 1980, about 625 Mgal/d (970 ft^3/s) was withdrawn from the Floridan aquifer system in the study area, chiefly for industrial uses. The study area includes the eastern half of the Coastal Plain of Georgia and adjacent parts of Florida and South Carolina. Problems have developed because of the heavy withdrawal. The problems include declining water levels, chiefly around pumping centers but areawide as well, and, locally, infiltration of mineralized water into the aquifer from underlying strata, lateral encroachment of seawater toward pumping centers from offshore, and land subsidence.

The study area lies entirely within the Coastal Plain and Continental Shelf provinces of the Atlantic Plain and ranges in topographic setting from the Coastal Lowlands to the plateaus, hills, and valleys adjacent to the Piedmont province. Precipitation ranges from about 44 to 58 in/yr, runoff from about 10 to 15 in/yr, and evapotranspiration from about 30 to 40 in/yr.

In general, the Floridan aquifer system is made up of consolidated marine and marginal marine limestone and dolomite and lesser amounts of evaporites, clay, sand, and marl. The principal formations of the carbonate facies are the Oldsmar and Avon Park Formations and the Ocala, Santee, and Suwannee Limestones, which range in age from early Eocene to Oligocene. Locally, in the area of Brunswick, Ga., rocks of Paleocene and Late Cretaceous age are also part of the aquifer system. Updip, clastic facies are hydraulically connected with the Floridan aquifer system and are thus part of the flow system. The Floridan aquifer system forms a nearly continuous, primarily carbonate sequence that is hydraulically interconnected in varying degrees. Zones of sufficiently low permeability and areal continuity exist throughout most of the area to separate the Floridan aquifer system into two regionally extensive aquifers. The Floridan aquifer system thickens from a featheredge in the outcrop area to more than 2,000 ft in coastal Georgia and to more than 2,600 ft locally in the area of Brunswick, Ga. In most of the area, the system is confined above by low-permeability beds of clastic material and below by nearly impermeable beds of clastic, evaporitic, or carbonate material.

A prominent structural feature, the Gulf Trough, is a negative, grabenlike feature trending northeast, approximately along strike, across most of the study area. The trough was probably produced by the deposition of fine clastic material into aligned grabens formed by nearly vertical faults. The aquifer system is thin and of low transmissivity in the trough, in effect partially impeding the downgradient flow of water.

The aquifer system includes the Upper and Lower Floridan aquifers and, in southeast Georgia and northeast Florida, the Fernandina permeable zone is the lower part of the Lower Floridan aquifer. Overlying the Upper Floridan is a surficial aquifer of clastic material. An upper confining unit, consisting of clay layers within the Hawthorn Formation of Miocene age, separates the surficial aquifer and the Upper Floridan. A middle semiconfining unit separates the Upper and Lower Floridan aquifers; a lower semiconfining unit overlies the Fernandina permeable zone; and the lower confining unit forms the base of the system.

The Upper Floridan aquifer consists chiefly of the Ocala Limestone and equivalents of late Eocene age and, to a lesser extent, the overlying Suwannee Limestone of Oligocene age. Secondary permeability has given the Upper Floridan extremely prolific water-bearing properties. The Upper Floridan supplies almost all the water pumped from the system in the study area except in northeast Florida, where it supplies about half the water, and in the extreme northeast part of the aquifer system in South Carolina, where it is not a significant aquifer.

The Lower Floridan aquifer consists chiefly of middle Eocene limestone and dolomite in the downdip section, and clastic materials updip from the Gulf Trough. The

Lower Floridan supplies only about 10 percent of the water from the aquifer system in the study area. It supplies about half the water to users in the Jacksonville, Fla., area.

The Fernandina permeable zone in the lower part of the Lower Floridan consists of limestone and dolomite of early Eocene and Paleocene age. Locally, in the area of Brunswick, Ga., the zone includes carbonates of Late Cretaceous age. The zone has extremely high permeability and is locally cavernous, but because of its depth—about 1,800 to 2,000 ft below land surface—and its poor water quality, it is unused for water supply.

Hydraulic characteristics of the Floridan aquifer system demonstrate its heterogeneity. Transmissivity of the Upper Floridan ranges from less than 1,000 to about 1,000,000 ft^2/d. Large solution channels and caverns in thick permeable sections produce the high transmissivities. The aquifer's updip extent and the Gulf Trough are representative of low transmissivities. Although poorly known, transmissivity of the Lower Floridan probably ranges from about 2,000 ft^2/d in the area of the Gulf Trough to nearly 400,000 ft^2/d in the area of Jacksonville, Fla. Transmissivity of the Fernandina permeable zone is not known but probably exceeds 1,000,000 ft^2/d in the area of Brunswick, Ga., where caverns are tens of feet high and of undetermined lateral extent.

Leakance characteristics of the confining units vary greatly within the study area. The upper confining unit is nearly nonleaky in the coastal Georgia area, where the bed is thickest and of very low hydraulic conductivity. In contrast, the upper confining unit provides little resistance to leakage where it is breached and the aquifer is exposed, such as at Valdosta, Ga. Leakage characteristics of the other confining units separating the aquifers within the Floridan aquifer system are poorly known. In places, confinement is effective, but along the southeast Georgia–northeast Florida coast, nearly vertical faults have breached the confining units and migration of ground water probably has further enlarged the conduits, enhancing leakage between aquifers.

Ground-water flow in the Floridan prior to development was in a state of dynamic equilibrium, generally characterized by discharge balanced by recharge, no change in storage, and an unchanging potentiometric surface. Total flow through the Floridan aquifer system in the study area was about 1,400 ft^3/s, most of which occurred in the area upgradient from the Gulf Trough. Here the flow system was fairly active, having abundant recharge through a thin (or absent) upper confining unit and discharge primarily to major rivers.

Downgradient from the Gulf Trough where the Floridan aquifer system is more thickly confined, the flow system was more sluggish, characterized by flat gradients, high aquifer transmissivities, low velocities, and, with some exceptions, low rates of recharge and discharge occurring as diffuse infiltration and leakage. Significant localized recharge took place in the areas of Keystone Heights, Fla., Beaufort, S.C., and Valdosta, Ga. Flowing wells were obtainable before development in the entire coastal area as well as along the major rivers as far inland as the outcrop area. The downgradient limit to the flow system was the freshwater–saltwater interface, as much as 55 mi offshore from the southeast Georgia coast, and near or at the coast at the north and south limits of the study area in South Carolina and Florida, respectively.

The flow system was most active in the Upper Floridan and least active in the Fernandina permeable zone—characteristic of a shallow regimen in a paleokarst environment. Less than 3 percent of the total flow in the Floridan aquifer system emanated from the Fernandina permeable zone.

The predevelopment ground-water-flow system of the Floridan aquifer system was altered as a result of withdrawals from the aquifer system. Ground-water withdrawals have, in general, lowered potentiometric surfaces, induced additional recharge and captured discharge, and increased hydraulic gradients and flow activity. Total flow through the Floridan aquifer system increased by about 50 percent, to 2,100 ft^3/s, as a result of development.

Development of the Floridan began in the 1880's in Savannah, Ga., for municipal supply and spread throughout the area, chiefly along the coast, where flowing wells furnished sufficient water to most users. By 1980, withdrawal from the Floridan aquifer system totaled approximately 625 Mgal/d (970 ft^3/s) in the study area, most of which supplied the pulp and paper industry. About 90 percent of the withdrawal was from the Upper Floridan, chiefly along the coast.

The most obvious result of the withdrawal was the lowering of the potentiometric surfaces, primarily along the heavily developed coastal area. Water-level decline encompassed nearly the entire area downgradient from the Gulf Trough but was negligible near the localized areas of recharge and in the area upgradient from the trough. Although most of the water withdrawn in this area was from the Upper Floridan, the head in the Lower Floridan declined accordingly and remained only slightly higher than that of the Upper Floridan.

Because of the lack of appreciable head decline in the area upgradient from the Gulf Trough, changes in the recharge–discharge relation and in flow through the aquifer system were negligible. Changes involved increased recharge and decreased discharge, but were less than 5 percent as a result of development.

The flow system in the area downgradient from the Gulf Trough became active as a result of heavy withdrawal. In general, downward leakage from the surficial aquifer increased in the inland areas, upward leakage decreased along the coast, and upward leakage changed to downward leakage in the area between.

Upward leakage from the Lower Floridan also increased as a result of lowering of heads in the Upper Floridan. Flow into the area also was induced in the southwest part of the study area by the withdrawal and subsequent head decline in the coastal area.

The relation of the Fernandina permeable zone to the rest of the flow system changed as a result of development of the Floridan aquifer system (primarily of the Upper Floridan aquifer). Estimated leakage from the permeable zone into the overlying aquifers through solution-enlarged faults increased from about 40 ft^3/s to about 280 ft^3/s.

Although heavily developed, the aquifer system in parts of the study area could undergo some additional development without detrimental effects. In general, development potential ranges from 40 ft^3/s (about 26 Mgal/d) or more in the inland area downgradient from the Gulf Trough and centered in the area of Waycross, Ga., to nearly zero along the coast, where heavy development has already caused problems, especially problems of saltwater encroachment and intrusion.

Water from the Floridan aquifer system generally is hard, alkaline, of the calcium-bicarbonate type, and has moderate dissolved-solids concentration. Dissolved-solids concentration generally is low in areas of recharge, increasing with distance from the recharge area and with depth.

Where development of the Floridan aquifer system has significantly changed the flow system, it has also changed the quality of its water, although data are insufficient to document this, except locally. Increased recharge from the surficial aquifer and increased flow through the system would have tended to decrease the dissolved-solids concentration, whereas increased leakage from the Lower Floridan and the Fernandina permeable zone would have tended to increase the dissolved-solids concentration.

The most significant changes in water quality brought about by development occurred in the coastal area. Dissolved-solids concentration increased, and in parts of the area the hydrochemical facies changed to a sodium chloride type. The latter occurred as a result of both lateral and vertical saltwater encroachment and intrusion.

Lateral saltwater encroachment into the Floridan aquifer system has occurred on the north end of Hilton Head Island, S.C., as a result of ground-water withdrawals and subsequent head decline in the Savannah area and on Hilton Head Island. Vertical saltwater intrusion into the Floridan aquifer system has occurred in the area of Brunswick, Ga. At Brunswick, heavy pumping lowered heads, allowing saltwater in the Fernandina permeable zone to migrate upward through vertical openings, probably solution-enlarged faults and other conduits, into the Upper Floridan. Some vertical intrusion is also documented for northeast Florida, but the problem is not as severe as at Brunswick, Ga.

SELECTED REFERENCES

Applin, P.L., and Applin, E.R., 1944, Regional subsurface stratigraphy and structure of Florida and southern Georgia: American Association of Petroleum Geologists Bulletin, v. 28, no. 12, p. 1673–1763.

Back, William, Hanshaw, B.B., and Rubin, Meyer, 1970, Carbon-14 ages related to occurrence of salt water: Journal of the Hydraulics Division, ASCE, v. 96, no. HY11, Proceedings Paper 7702, p. 2325–2336.

Bentley, C.B., 1977, Aquifer test analyses for the Floridan aquifer in Flagler, Putnam, and St. Johns Counties, Florida: U.S. Geological Survey Water-Resources Investigations 77–36, 50 p.

Bermes, B.J., Leve, G.W., and Tarver, G.R., 1963, Geology and ground-water resources of Flagler, Putnam, and St. Johns Counties, Florida: Florida Geological Survey Report of Investigations No. 32, 97 p.

Brown, D.P., 1980, Geologic and hydrologic data from a test-monitor well at Fernandina Beach, Florida: U.S. Geological Survey Open-File Report 80–347, 36 p.

———1984, Impact of development on availability and quality of ground water in eastern Nassau County, Florida, and southeastern Camden County, Georgia: U.S. Geological Survey Water-Resources Investigations Report 83–4190, 113 p.

Brown, D.P., Johnson, R.S., and Baker, J.S., 1984, Hydrogeologic data from a test well at Kathryn Abbey Hanna Park, City of Jacksonville, Florida: U.S. Geological Survey Open-File Report 84–143, 41 p.

Brown, L.D., and Oliver, J.E., 1976, Vertical crustal movements from leveling data and their relation to geologic structure in the United States: Reviews of Geophysics and Space Physics, v. 14, no. 1, p. 13–35.

Buie, B.F., 1978, The Huber Formation of eastern central Georgia, *in* Short contributions to the geology of Georgia: Georgia Geologic Survey Bulletin 93, p. 1–7.

Bush, P.W., 1982, Predevelopment flow in the Tertiary limestone aquifer, Southeastern United States: A regional analysis from digital modeling: U.S. Geological Survey Water-Resources Investigations Report 82–905.

Bush, P.W., and Johnston, R.H., in press, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–C.

Callahan, J.T., 1964, The yield of sedimentary aquifers of the Coastal Plain, Southeast River Basins: U.S. Geological Survey Water-Supply Paper 1669–W, 56 p.

Carter, R.F., and Stiles, H.R., 1983, Average annual rainfall and runoff in Georgia, 1941–70: Georgia Geologic Survey Hydrologic Atlas 9, 1 sheet.

Causey, L.V., 1975, Depth to water table, recharge areas, drainage basins, and relief of Duval County, Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 52–75, 4 sheets.

Cederstrom, D.C., Boswell, E.H., and Tarver, G.R., 1979, Summary appraisals of the Nation's ground-water resources—South

Atlantic–Gulf Region: U.S. Geological Survey Professional Paper 813–O, 35 p.

Chen, C.S., 1965, The regional lithostratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin 45, 105 p.

Clark, W.E., Musgrove, R.H., Menke, C.G., and Cagle, J.W., Jr., 1964, Water resources of Alachua, Bradford, Clay, and Union Counties, Florida: Florida Geological Survey Report of Investigations No. 35, 170 p.

Cooke, C.W., 1936, Geology of the Coastal Plain of South Carolina: U.S. Geological Survey Bulletin 867, 196 p.

———1939, Scenery of Florida interpreted by a geologist: Florida Geological Survey Bulletin 17, 118 p.

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

———1945, Geology of Florida: Florida Geological Survey Bulletin 29, 339 p.

Counts, H.B., and Donsky, Ellis, 1963, Salt-water encroachment, geology, and ground-water resources of Savannah area, Georgia and South Carolina: U.S. Geological Survey Water-Supply Paper 1611, 100 p.

Counts, H.B., and Krause, R.E., 1976, Digital model analysis of the principal artesian aquifer, Savannah, Georgia, area: U.S. Geological Survey Water-Resources Investigations 76–133, 4 sheets.

Davis, G.H., Counts, H.B., and Holdahl, S.R., 1976, Further examination of subsidence at Savannah, Georgia, 1955–1975: International Association of Hydrological Sciences Proceedings of the Anaheim Symposium, December 1976, Publication No. 121, p. 347–354.

Davis, G.H., Small, J.B., and Counts, H.B., 1963, Land subsidence related to decline of artesian pressure in the Ocala Limestone at Savannah, Georgia: Geological Society of America Engineering Geology Case Histories, no. 4, p. 1–8.

Dohrenwend, R.E., 1977, Evapotranspiration patterns in Florida: Florida Scientist, v. 40, no. 2, p. 184–192.

Duncan, D.A., 1972, High resolution seismic study, *in* Port Royal Sound Environmental Study: South Carolina Water Resources Commission, p. 85–106.

Dyar, T.R., Tasker, G.D., and Wait, R.L., 1972, Hydrology of the Riceboro area, coastal Georgia: Georgia Water Quality Control Board, Final Report, 74 p.

Ewing, J.I., Ewing, Maurice, and Leyden, Robert, 1966, Seismic-profiler survey of Blake Plateau: American Association of Petroleum Geologists Bulletin, v. 50, no. 9, p. 1948–1971.

Fairchild, R.W., and Bentley, C.B., 1977, Saline-water intrusion in the Floridan aquifer in the Fernandina Beach area, Nassau County, Florida: U.S. Geological Survey Water-Resources Investigations 77–32, 27 p.

Faulkner, G.L., 1973, Geohydrology of the Cross-Florida Barge Canal area, with special reference to the Ocala vicinity: U.S. Geological Survey Water Resources Investigations 1–73, 117 p.

Faye, R.E., and Prowell, D.C., 1982, Effects of Late Cretaceous and Cenozoic faulting on the geology and hydrology of the Coastal Plain near the Savannah River, Georgia and South Carolina: U.S. Geological Survey Open-File Report 82–156, 30 p.

Fenneman, N.M., 1938, Physiography of Eastern United States: New York, McGraw-Hill, 714 p.

Furlow, J.W., 1969, Stratigraphy and economic geology of the eastern Chatham County phosphate deposit: Georgia Geological Survey Bulletin 82, 40 p.

Gelbaum, Carol, 1978, The geologcy and ground water of the Gulf Trough, *in* Short contributions to the geology of Georgia: Georgia Geologic Survey Bulletin 93, p. 38–49.

Gill, H.E., and Mitchell, G.D., 1979, Results of Colonels Island deep hydrologic test well, *in* Investigations of alternative sources of ground water in the coastal area of Georgia: Georgia Geologic Survey Open-File Report 80–3, p. C1–C13.

Gregg, D.O., and Zimmerman, E.A., 1974, Geologic and hydrologic control of chloride contamination in aquifers at Brunswick, Glynn County, Georgia: U.S. Geological Survey Water-Supply Paper 2029–D, 44 p.

Hanshaw, B.B., Back, William, Rubin, Meyer, and Wait, R.L., 1965, Relation of carbon-14 concentrations to saline water contamination of coastal aquifers: Water Resources Research, v. 1, no. 1, p. 109–114.

Hayes, L.R., 1979, The ground-water resources of Beaufort, Colleton, Hampton, and Jasper Counties, South Carolina: South Carolina Water Resources Commission Report No. 9, 91 p.

Healy, H.G., 1962, Piezometric surface and areas of artesian flow of the Floridan aquifer in Florida, July 6–17, 1961: Florida Board of Conservation, Division of Geology, Map Series No. 4, 1 sheet.

Herrick, S.M., and Vorhis, R.C., 1963, Subsurface geology of the Georgia Coastal Plain: Georgia Geological Survey Information Circular 25, 80 p.

Holdahl, S.R., and Morrison, N.L., 1974, Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data: Tectonophysics, v. 23, p. 373–390.

Holdridge, L.R., 1967, Life zone ecology: San Jose, Costa Rica, Tropical Science Center, p. 184–192.

Hubbert, M.K., 1940, The theory of ground-water motion: The Journal of Geology, v. 48, no. 8, pt. 1, p. 785–944.

Hughes, G.H., 1978, Runoff from hydrologic units in Florida: Florida Department of Natural Resources, Bureau of Geology Map Series 81, 1 sheet.

Husted, J.E., 1972, Shaler's line and Suwannee Strait, Florida and Georgia: American Association of Petroleum Geologists, Geological Notes, p. 1557–1560.

Johnston, R.H., 1978, Planning report for the Southeastern limestone regional aquifer system analysis: U.S. Geological Survey Open-File Report 78–516, 26 p.

Johnston, R.H., and Bush, P.W., in press, Summary of the hydrology of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–A.

Johnston, R.H., Bush, P.W., Krause, R.E., Miller, J.A., and Sprinkle, C.L., 1982, Summary of hydrologic testing in Tertiary limestone aquifer, Tenneco offshore exploration well—Atlantic OCS, Lease-block 427 (Jacksonville NH 17–5): U.S. Geological Survey Water-Supply Paper 2180, 15 p.

Johnston, R.H., Healy, H.G., and Hayes, L.R., 1981, Potentiometric surface of the Tertiary limestone aquifer system, Southeastern United States, May 1980: U.S. Geological Survey Open-File Report 81–486, 1 sheet.

Johnston, R.H., Krause, R.E., Meyer, F.W., Ryder, P.D., Tibbals, C.H., and Hunn, J.D., 1980, Estimated potentiometric surface for the Tertiary limestone aquifer system, Southeastern United States, prior to development: U.S. Geological Survey Open-File Report 80–406, 1 sheet.

Kohler, M.A., Nordenson, T.J., and Baker, D.R., 1959, Evaporation maps for the United States: U.S. Weather Bureau Technical Paper 37, 13 p.

Kohout, F.A., Hathaway, J.C., Folger, D.W., Bothner, M.H., Walker, E.H., Delaney, D.F., Frimpter, M.H., Weed, E.G.A., and Rhodehamel, E.C., 1977, Fresh ground water stored in aquifers under the Continental Shelf: Implications from a deep test, Nantucket Island, Massachusetts: American Water Resources Association Bulletin, v. 13, no. 2, p. 373–386.

Krause, R.E., 1972, Effects of ground-water pumping in parts of Liberty and McIntosh Counties, Georgia, 1966–70: Georgia Geological Survey Information Circular 45, 15 p.

———1976, Occurrence and distribution of color and hydrogen sulfide in water from the principal artesian aquifer in the Valdosta area, Georgia: U.S. Geological Survey Water-Resources Investigations Open-File Report 76–378, 11 p.

———1979, Geohydrology of Brooks, Lowndes, and western Echols Counties, Georgia: U.S. Geological Survey Water-Resources Investigations Report 78–117, 48 p.

———1982, Digital model evaluation of the predevelopment flow system of the Tertiary limestone aquifer, southeast Georgia, northeast Florida, and southern South Carolina: U.S. Geological Survey Water-Resources Investigations Open-File Report 82–173, 27 p.

Krause, R.E., and Counts, H.B., 1975, Digital model analysis of the principal artesian aquifer, Glynn County, Georgia: U.S. Geological Survey Water-Resources Investigations 1–75, 4 sheets.

Krause, R.E., and Gregg, D.O., 1972, Water from the principal artesian aquifer in coastal Georgia: Georgia Geological Survey Hydrologic Atlas 1, 1 sheet.

Krause, R.E., and Hayes, L.R., 1981, Potentiometric surface of the principal artesian aquifer in Georgia, May 1980: Georgia Geologic Survey Hydrologic Atlas 6, 1 sheet.

LaForge, Lawrence, Cooke, C.W., Keith, Arthur, and Campbell, M.R., 1925, Physical geography of Georgia: Georgia Geological Survey Bulletin 42, 189 p.

Leve, G.W., 1966, Ground water in Duval and Nassau Counties, Florida: Florida Geological Survey Report of Investigations No. 43, 91 p.

———1978, Altitude and configuration of the top of the Floridan aquifer, Duval County, Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 77–114, 1 sheet.

———1983, Relation of concealed faults to water quality and the formation of solution features in the Floridan aquifer, northeastern Florida: Journal of Hydrology, v. 61, p. 251–264.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Matthews, S.E., Hester, W.G., and O'Byrne, M.P., 1981, Ground-water data for Georgia, 1980: U.S. Geological Survey Open-File Report 81–1068, 94 p.

Matthews, S.E., and Krause, R.E., 1984, Hydrogeologic data from the U.S. Geological Survey test wells near Waycross, Ware County, Georgia: U.S. Geological Survey Water-Resources Investigations Report 83–4204, 29 p.

McCallie, S.W., 1898, A preliminary report on the artesian-well system of Georgia: Georgia Geological Survey Bulletin 7, 214 p.

McCollum, M.J., and Counts, H.B., 1964, Relation of salt-water encroachment to the major aquifer zones, Savannah area, Georgia and South Carolina: U.S. Geological Survey Water-Supply Paper 1613–D, 26 p.

Meyer, F.W., 1974, Evaluation of hydraulic characteristics of a deep artesian aquifer from natural water-level fluctuations, Miami, Florida: Florida Bureau of Geology Report of Investigation 75, 32 p.

Miller, J.A., 1982a, Thickness of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Open-File Report 81–1124, 1 sheet.

———1982b, Geology and configuration of the base of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Open-File Report 81–1176, 1 sheet.

———1982c, Configuration of the base of the upper permeable zone of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Water-Resources Investigation Open-File Report 81–1177, 1 sheet.

———1982d, Geology and configuration of the top of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Open-File Report 81–1178, 1 sheet.

———1982e, Thickness of the upper permeable zone of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81–1179, 1 sheet.

———1985, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–B, 91 p.

Miller, J.A., Hughes, G.H., Hull, R.W., Vecchioli, John, and Seaber, P.R., 1978, Impact of potential phosphate mining on the hydrology of Osceola National Forest, Florida: U.S. Geological Survey Water-Resources Investigations 78–6, 159 p.

Olson, G.J., Dockins, W.S., McFeters, G.A., and Iverson, W.P., 1981, Sulfate-reducing and methanogenic bacteria from deep aquifers in Montana: Geomicrobiology Journal, v. 2, no. 4, p. 327–339.

Parker, G.G., Ferguson, G.E., Love, S.K., and others, 1955, Water resources of southeastern Florida, with special references to the geology and ground water of the Miami area: U.S. Geological Survey Water-Supply Paper 1255, 965 p.

Paull, C.K., and Dillon, W.P., 1979, The subsurface geology of the Florida-Hatteras Shelf, Slope, and Inner Blake Plateau: U.S. Geological Survey Open-File Report 78–448, 94 p.

Phelps, G.G., 1978, Methods of estimating recharge to the Floridan aquifer in northeast Florida: U.S. Geological Survey Water-Resources Investigations 77–109, 19 p.

Pierce, R.R., Barber, N.L., and Stiles, H.R., 1982, Water use in Georgia by county for 1980: Georgia Geologic Survey Information Circular 59, 180 p.

Plummer, L.N., 1975, Mixing of seawater with calcium carbonate ground water: Geological Society of America, Memoir 142, p. 219–235.

Poland, J.F., Lofgren, B.E., and Riley, F.S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal: U.S. Geological Survey Water-Supply Paper 2025, 9 p.

Prowell, D.C., 1983, Index of faults of Cretaceous and Cenozoic age in the Eastern United States: U.S. Geological Survey Miscellaneous Field Investigations Map MF–1269, 2 sheets.

Randolph, R.B., and Krause, R.E., 1984, Analysis of the effects of proposed pumping from the principal artesian aquifer, Savannah, Georgia, area: U.S. Geological Survey Water-Resources Investigations Report 84–4064, 26 p.

Ryder, P.D., 1982, Digital model of predevelopment flow in the Tertiary limestone aquifer system in west-central Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 81–54, 61 p.

Siple, G.E., 1975, Ground-water resources of Orangeburg County, South Carolina: South Carolina State Development Board Bulletin 36, 59 p.

Snell, L.J., and Anderson, Warren, 1970, Water resources of northeast Florida: Florida Geological Survey Report of Investigations No. 54, 77 p.

Spigner, B.C., and Ransom, Camille, 1979, Report on ground-water conditions in the Low Country area, South Carolina: South Carolina Water Resources Commission Report No. 132, 144 p.

Sprinkle, C.L., 1982a, Sulfate concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81–1101, 1 sheet.

———1982b, Total hardness of water from the upper permeable zone of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81–1102, 1 sheet.

———1982c, Chloride concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81–1103, 1 sheet.

———1982d, Dissolved-solids concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 82–94, 1 sheet.

———in press, Geochemistry of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–I.

Stephenson, L.W., and Veatch, J.O., 1915, Underground waters of the Coastal Plain of Georgia, *and a discussion of* The quality of the waters, by R.B. Dole: U.S. Geological Survey Water-Supply Paper 341, 539 p.

Stiles, H.R., and Matthews, S.E., 1983, Ground-water data for Georgia, 1982: U.S. Geological Survey Open-File Report 83–678, 147 p.

Stone, H.L., 1968, Iterative solution of implicit approximations of multidimensional partial differential equations: Society for Industrial and Applied Mathematics, Journal for Numerical Analysis, v. 5, no. 3, p. 530–558.

Stricker, V.A., 1983, Base flow of streams in the outcrop area of southeastern sand aquifer: South Carolina, Georgia, Alabama, and Mississippi: U.S. Geological Survey Water-Resources Investigations 83–4106, 17 p.

Stringfield, V.T., 1936, Artesian water in the Florida peninsula: U.S. Geological Survey Water-Supply Paper 773–C, p. 115–195.

———1966, Artesian water in Tertiary limestone in the Southeastern United States: U.S. Geological Survey Professional Paper 517, 226 p.

Thomson, M.T., and Carter, R.F., 1955, Surface-water resources of Georgia during the drought of 1954: Georgia Geological Survey Information Circular 17, 79 p.

———1963, Effect of a severe drought (1954) on streamflow in Georgia: Georgia Geological Survey Bulletin 73, 97 p.

Tibbals, C.H., 1981, Computer simulation of the steady-state flow system of the Tertiary limestone (Floridan) aquifer system in east-central Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 81–681, 31 p.

Toulmin, L.D., 1955, Cenozoic geology of southeastern Alabama, Florida, and Georgia: American Association of Petroleum Geologists Bulletin, v. 39, no. 2, p. 207–235.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75–438, 99 p.

Trescott, P.C., and Larson, S.P., 1976, Supplement to Open-File Report 75–438, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 76–591, 21 p.

U.S. Environmental Protection Agency, 1976, National interim primary drinking water standards: Washington, D.C., U.S. Government Printing Office, 159 p.

U.S. Geological Survey, 1978a, Water-resources data for Florida; Northeast Florida, 1978: U.S. Geological Survey Water-Data Report FL–78–1.

———1978b, Water-resources data for Florida; Northwest Florida, 1978: U.S. Geological Survey Water-Data Report FL–78–4.

———1978c, Water-resources data for Georgia, 1978: U.S. Geological Survey Water-Data Report GA–78–1.

———1978d, Water-resources data for South Carolina, 1978: U.S. Geological Survey Water-Data Report SC–78–1.

Wait, R.L., 1965, Geology and occurrence of fresh and brackish water in Glynn County, Georgia: U.S. Geological Survey Water-Supply Paper 1613–E, 94 p.

———1968, Submergence along the Atlantic coast of Georgia: U.S. Geological Survey Professional Paper 600–D, p. D38–D41.

Wait, R.L., and Gregg, D.O., 1973, Hydrology and chloride contamination of the principal artesian aquifer in Glynn County, Georgia: Georgia Department of Natural Resources Hydrologic Report 1, 93 p.

Warren, M.A., 1944, Artesian water in southeastern Georgia, with special reference to the coastal area: Georgia Geological Survey Bulletin 49, 140 p.

Wentworth, C.M., and Mergner-Keefer, Marcia, 1983, Regenerate faults of small Cenozoic offset—Probable earthquake sources in the Southeastern United States, *in* Gohn, G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886—Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313, p. S1–S20.

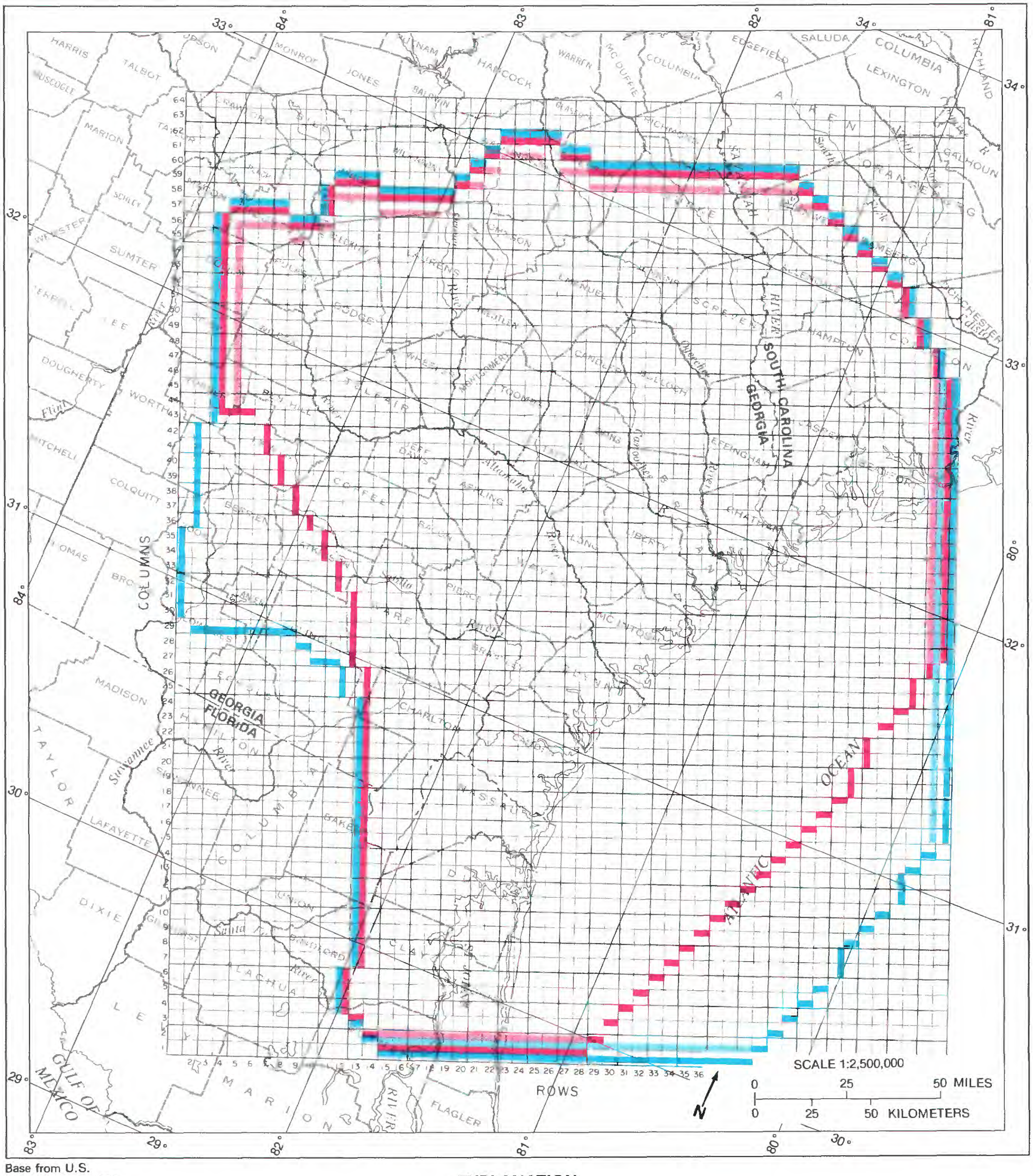
Wienstein, H.C., Stone, H.L., and Kwan, T.V., 1969, Iterative procedure for solution of systems of parabolic and elliptic equations in three dimensions: Industrial Engineering Chemistry Fundamentals, v. 8, no. 2, p. 281–287.

SUPPLEMENT I—COMPUTER SIMULATION OF THE FLORIDAN AQUIFER SYSTEM

The analysis of the ground-water-flow system in the study area was accomplished by using a quasi-three-dimensional finite-difference computer model. The code for the model was developed by Trescott (1975) and Trescott and Larson (1976). The digital model solves a set of simultaneous finite-difference equations that describe flow in the aquifer system by using a strongly implicit procedure (SIP), originally described by Stone (1968) for problems in two dimensions and extended to three dimensions by Wienstein and others (1969).

The quasi-three-dimensional model used herein is actually a two-dimensional horizontal-flow model coupled with one-dimensional vertical-flow components used to represent steady leakage vertically through confining units. This type of quasi-three-dimensional model operates on the premise that horizontal flow and storage in the confining units are negligible relative to that within the aquifer, and that head changes across these confining units are simultaneous. Therefore, the only flow related to the confining units is vertical leakage from one aquifer to another. In contrast, only horizontal flow in the plane of each aquifer is considered; the vertical flow components within them are negligible and are also ignored.

The modeled area was subdivided using a finite-difference grid having equally spaced nodal dimensions. The grid consists of 52 rows and 64 columns, constituting 3,328 nodes, each of which measures 4 mi on a side. The positioning of the grid on the study area is shown in figure 21. Orientation of the grid coincides with the position of the coarse-mesh grid used in the regional model of the entire aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama (Bush and Johnston, in press). This coincident orientation facilitates the transfer of data between the regional model and the subregional model described herein.



EXPLANATION

Boundary designation

UPPER FLORIDAN AQUIFER	No-flow	Constant head
LOWER FLORIDAN AQUIFER	No-flow	Constant head

FIGURE 21.—Finite-difference grid and boundary conditions for the simulation of the Floridan aquifer system, prior to development.

Within the rectangular area of the grid (fig. 21) is the area of the Floridan aquifer system that was simulated and is considered the "active" part of the model area. The model boundaries are also shown in figure 21 and will be discussed in a later section.

The flow system was divided into four layers for the purpose of simulation. These layers include two "active" layers, in which flow was simulated, and two inactive layers above and below, in which flow was not simulated. The active layers are the Upper and Lower Floridan aquifers. The inactive layers are the surficial aquifer overlying the Upper Floridan and the Fernandina permeable zone of the Lower Floridan, where present. The inactive layers are sources or sinks for vertical leakage to or from the active layers, and the water levels in these inactive layers do not change with time.

The model simulated both the predevelopment and the present-day (1980) flow systems under steady-state conditions.

The present-day (1980) flow system was considered to be under steady-state conditions rather than transient conditions for the entire study area, with the possible exception of the coastal area from Hilton Head Island, S.C., to Brunswick, Ga. In the coastal area, average yearly water-level declines were estimated to range from nearly zero to about 1 ft (Matthews and others, 1981). If these declines are not associated with any undocumented increases in pumpage, then they are an indication of aquifer storage depletion. However, this is a high ground-water-use area, and undocumented increases in pumpage are possible. Even if these water-level declines are a result of aquifer depletion, the amount of water released from storage is small (approximately 1.3 ft^3/s) compared with total withdrawal, and probably can be neglected, as indicated by the following calculation. Using an average storage coefficient of 3×10^{-4}, determined from aquifer tests and reported by Counts and Donsky (1963, p. 42) and Dyar and others (1972, p. 12), and the 5,000 mi^2 area of 1 ft/yr water-level decline, the rate of water released from aquifer storage can be calculated by the following equation:

$$Q=0.884\ h\ S\ A,$$

where

Q = rate of water released from aquifer storage (ft^3/s),
h = average areal head decline (ft/yr),
S = storage coefficient (dimensionless), and
A = area where head decline occurs (mi^2).

The calculated rate of water released from aquifer storage is about 1.3 ft^3/s, which is less than 1 percent of the total pumpage (more than 300 ft^3/s) in the area where the 1 ft/yr water-level decline occurs. This small amount of water contributed from aquifer storage to the withdrawal creates negligible error if neglected in model simulation. Therefore, the decision to simulate the present-day (1980) flow system as steady state is reasonable.

BOUNDARY CONDITIONS

Boundary conditions are used to define the lateral and vertical extent of the simulated flow system and its variations with time. One of the boundary conditions used in this study is the no-flow boundary, which is used to represent the lateral extent of the aquifer, where transmissivity becomes negligible, the freshwater–saltwater interface, where lateral freshwater flow is assumed to cease, and ground-water divides, where the boundary is perpendicular to potentiometric contours.

Another type of boundary condition used is the constant-head boundary, which represents a head that does not change with time. This boundary condition allows flow to enter or leave the active part of the system.

The third type of boundary condition is the constant-flux boundary, which represents a specified flux across the boundary that does not change with time. To account for a change in the flow system caused by development, boundary fluxes are added along boundaries where flow, which did not cross the boundary in the unstressed system, subsequently crosses what had been a no-flow boundary. This type of boundary assumes that approximately the same quantity of water is always flowing into the active aquifer at the boundary for a given flow condition, and therefore may be considered constant with time.

Model boundaries are generally chosen to coincide with hydrologic boundaries unaffected by pumping. However, the boundaries between subregional study areas (fig. 1) could not coincide with unchanging hydrologic boundaries. Because this model is a part of a regional model covering the entire Floridan aquifer system, boundary conditions can be simulated by the regional model as internal fluxes that are not boundary-influenced and can be supplied to this subregional model.

A constant-head boundary was used to simulate the water table in the surficial aquifer, which represents the top boundary of the flow system. The head in the Fernandina permeable zone, where present, also was designated a constant-head boundary (pl. 3). In areas where the Fernandina permeable zone is not present, the bottom of the system was considered impermeable and was designated a no-flow boundary. The predevelopment flow model used a no-flow boundary condition for most of the lateral boundaries in the Upper Floridan. A constant-head boundary was used along part of the

Atlantic Ocean off South Carolina and along the entire southern boundary in northeast Florida and the Atlantic Ocean offshore. These conditions were used in order to allow flow into and out of the model where flow existed across the boundary. The Lower Floridan also was laterally bounded by using constant-head and no-flow conditions. The eastern and southern boundaries, like the Upper Floridan, were constant head. In addition, most of the northern and northwestern boundaries were constant-head to allow lateral flow into the model area through the Lower Tertiary clastic material, which is hydraulically connected downgradient to the Lower Floridan.

The simulation of the present-day (1980) flow system, like the predevelopment flow system, used constant-head boundary conditions for the surficial aquifer and the Fernandina permeable zone. A no-flow boundary was used for the base in areas where the Fernandina permeable zone does not exist. The lateral boundaries of the Upper and Lower Floridan are similar to those for the simulation of predevelopment conditions, except along the southwestern boundary (fig. 22). This boundary was placed along what had been a flow line under predevelopment conditions and was thus treated as a no-flow boundary for simulation of predevelopment conditions. However, when the aquifer system was stressed by pumping, head decline occurred at the no-flow boundary, thus making the no-flow condition at the boundary invalid. This no-flow boundary was replaced by a constant-flux boundary assigned to both Upper and Lower Floridan aquifers. The quantity of flux across those boundaries at each node was calculated by using Darcy's law. Because the width and length of a node are equal and cancel out, the simplified form of Darcy's law can be expressed by the following equation:

$$Q=\Delta h\ T,$$

where

Q = flux across the boundary for each node (ft^3/s),
Δh = head difference across the boundary (ft), and
T = transmissivity of the node inside and adjacent to the boundary (ft^2/s).

DATA REQUIREMENTS

Data input involved superposing the grid matrix and the maps of the hydrogeologic data. The data were interpolated at the center of each active node and values were assigned for each aquifer and confining unit. However, within each node the aquifer and confining unit are considered isotropic; therefore, an average value that represents the aquifer or confining-unit characteristic is assigned to each node.

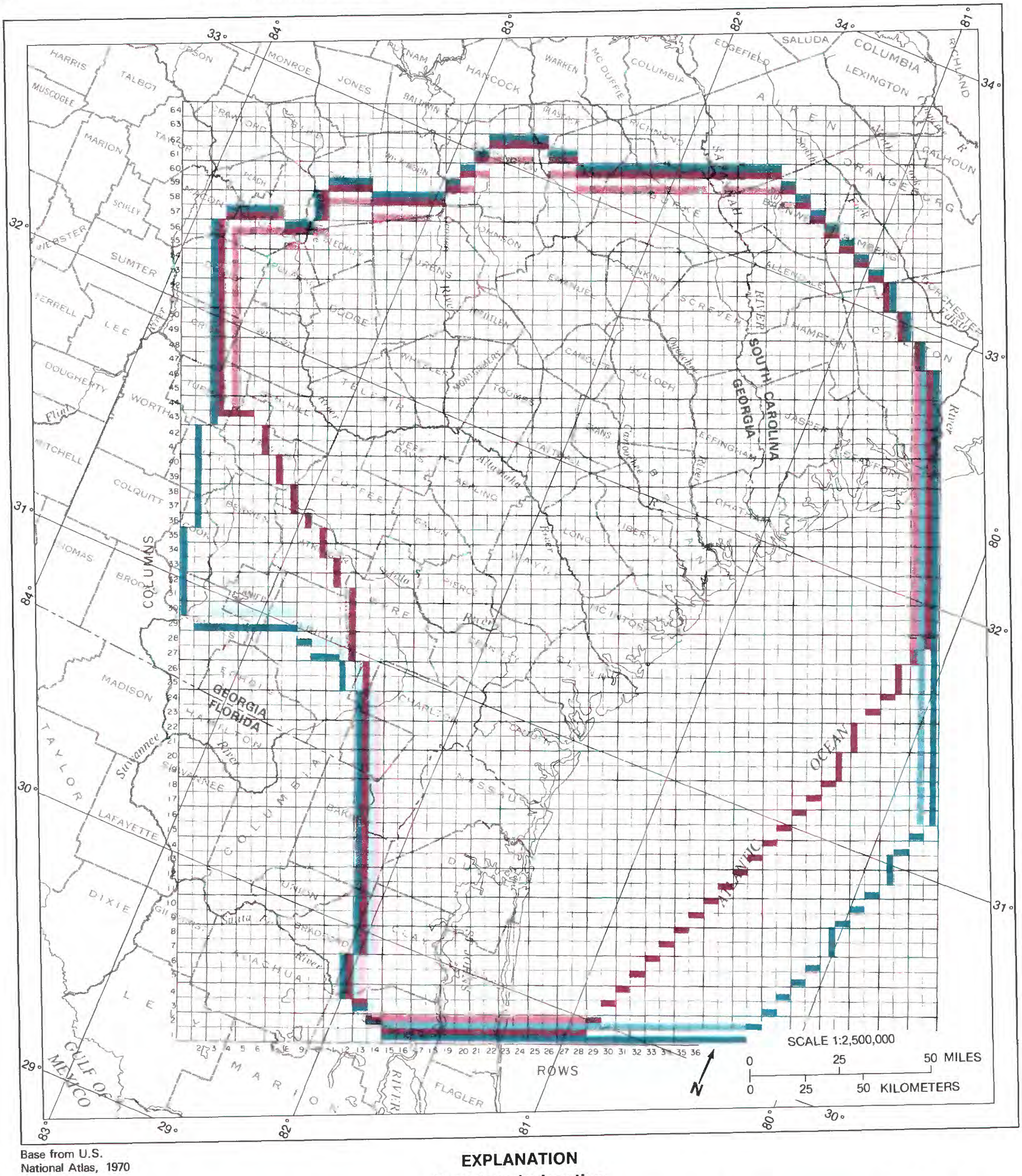
The estimated predevelopment potentiometric surface of the Upper Floridan aquifer provided the basis for the steady-state head matrix for both the Upper and Lower Floridan aquifers. For the Upper Floridan, the head values for each node were interpolated directly from the aquifer's potentiometric contours (pl. 9). The Upper Floridan head matrix and the estimated head differences between the Upper and Lower Floridan provided head data for the Lower Floridan.

The potentiometric surface used in the simulation of the present-day flow system was that of May 1980 (pl. 12). These data are considered more reliable than those of the predevelopment surface owing to an increased number of data points, better vertical datum, and a better overall understanding of the flow system. The 1980 potentiometric surface was discretized in the same manner as the predevelopment potentiometric surface. The assumptions about the previously discussed relation between the Upper and Lower Floridan aquifers under stressed conditions were applied.

Although the water level in the surficial aquifer fluctuates seasonally owing to climatic influences, it is considered constant because the fluctuations are small. The water level in the surficial aquifer was simulated as a constant-head boundary that acts as a source or sink, depending on the direction of the gradient between the surficial aquifer and the underlying Upper Floridan aquifer. Therefore, the leakage between the Upper Floridan and the surficial aquifer can be simulated without having to simulate the response of the water table itself.

The altitude of the water level in the surficial aquifer was estimated from the altitude of land surface and of bodies of water taken from topographic contour maps. In topographically high areas and where thick deposits of permeable material exist, such as along the Pleistocene shoreline ridges paralleling the modern-day coast, the water level is estimated to be about 15 to 20 ft below land surface. In the area along the coast, the water level is estimated to be 5 to 10 ft below land surface, and in salt-marsh and estuarine areas, the water level is at sea level. Water-level altitudes elsewhere were interpolated. Estimates of water-level altitudes made in coastal areas compared well with those measured in Duval County, Fla., and reported by Causey (1975), and in Alachua, Bradford, Clay, and Union Counties, Fla., reported by Clark and others (1964, fig. 74).

The head in the Fernandina permeable zone was estimated to be slightly higher than the predevelopment head in the rest of the Lower Floridan aquifer, although few data points are available to support this assumption. The Fernandina permeable zone was simulated as



EXPLANATION

Boundary designation

UPPER FLORIDAN AQUIFER	No-flow	Constant head	Constant flux
LOWER FLORIDAN AQUIFER	No-flow	Constant head	Constant flux

FIGURE 22.—Finite-difference grid and boundary conditions for the simulation of the Floridan aquifer system, present-day (1980) conditions.

a constant-head layer because of insignificant changes in its water level since predevelopment. The extent of freshwater in the Fernandina permeable zone is defined from only a few data points and from some knowledge of upward movement of water from the Fernandina permeable zone to the overlying part of the Lower Floridan in areas around Jacksonville, Fla., where the Fernandina permeable zone contains freshwater, and at Brunswick, Ga., where the permeable zone contains saline water. If the head in the Fernandina permeable zone locally has decreased by a significant amount, then its designation as a constant-head boundary would be invalid, and locally, the simulated leakance of the lower semiconfining unit would be lower than that expected in the field. However, the resultant simulated leakage rates are reasonable, indicating little, if any, error and an acceptable set of values for head in the Fernandina permeable zone and leakance of the lower semiconfining unit.

Values for the initial transmissivity distribution of the Upper Floridan aquifer were interpolated from ranges of transmissivity derived from field data of transmissivity, hydraulic conductivity, aquifer thickness, and specific capacity. The discretized values of transmissivity ranged from about 1,000 to 800,000 ft^2/d. Because of a lack of data for the Lower Floridan, the distribution of transmissivity values of this layer was estimated on the basis of the hydrogeology of the Lower Floridan. Discretized values in the Lower Floridan varied from less than 2,000 ft^2/d along the Gulf Trough to about 400,000 ft^2/d in the Jacksonville, Fla., area.

Transmissivity values used in the model generally represent the average conditions within the nodes. However, highly localized hydrologic features may exist in the area represented by that node, such as solution channels, clastic infilling, and faults. These hydrologic features having extremely high or low hydraulic conductivities are simulated by the model only if they affect the flow system at the scale that the model addresses. For example, the presence of one or two large-diameter solution channels responsible for transmitting most of the water across the width of a node may have an effective transmissivity of more than 1,000,000 ft^2/d. However, the carbonate medium within which the channels occur may have a transmissivity of 10,000 ft^2/d or less. An average transmissivity for a 4- by 4-mi node would be only slightly greater than 10,000 ft^2/d because the solution channels' width is only a fraction of a percent of the width of the node. The effective transmissivity, and that specified for the model, however, would have to be weighted to a value more like that of the solution channels in order for the model to properly simulate flow. Analogous to this, but of a contrasting relation, might be the presence of a low-permeability, clastic-infilled fault zone lying perpendicular to the direction of ground-water flow. The fault zone might occupy only a small part of the area, and be of low permeability lying in a carbonate medium of much larger transmissivity and area. An effective, and model-specified, transmissivity would have to be much smaller than an average and weighted to a value more like that of the fault zone. Both of these conditions are known to exist in the Floridan aquifer system and are accounted for in the simulation.

Model input values of leakance, or leakage coefficient, defined as the ratio of the vertical hydraulic conductivity of the confining unit to the confining unit's thickness, were derived from few field data of hydraulic conductivity and reasonably well known thicknesses. In addition to the assumption that horizontal flow in the confining units can be neglected, water released from storage in the confining units is also negligible and can be neglected.

The assumption that water released from storage in the confining units is negligible may not be entirely valid for the upper confining unit in the Savannah, Ga., area and would thus produce some error in the leakance and leakage of the unit. In addition to the leakage to the Upper Floridan from the surficial aquifer, water may also be released from storage in the upper confining unit. Comparatively, the upper confining unit's vertical hydraulic conductivity is low and its hydraulic diffusivity is small. Also, the head decline in the Upper Floridan aquifer has been large, producing a consequently large cone of depression and a large head difference between the Upper Floridan and the overlying saturated sediments of the upper confining unit and surficial aquifer.

A slow drainage of water from the fine-grained clastic sediments of the upper confining unit in response to head decline in the Upper Floridan aquifer is suggested by Davis, Counts, and Holdahl (1976, p. 354) as the cause of the land subsidence in the Savannah area. There, as ground-water withdrawal from the Upper Floridan establishes a new vertical head gradient, the fine-grained sediments of the upper confining unit slowly drain and compact until a new equilibrium has been reached. The drainage and compaction, and hence subsidence, continue to occur for an indeterminate amount of time after the head in the Upper Floridan ceases to decline (Davis, Counts, and Holdahl, 1976, p. 354).

The leakage from the surficial aquifer and the upper confining unit, each supplying an indeterminate percentage of the total leakage quantity to the Upper Floridan aquifer, does not invalidate the simulation of the Floridan aquifer system. Under steady-state conditions, the flow system of the Upper Floridan is unaffected by the undetermined percentage contributions from the two sources, as it receives the resultant, total quantity of leakage from one source or the other, or both. If water is released from storage in the upper confining unit and it leaks to the Upper Floridan aquifer, the estimated leakance of the upper confining unit and the simulated leakage through the unit would be in error. The actual leakance of the unit would be lower, and leakage quantities smaller.

Like the transmissivity matrix, leakance values used in the simulation generally represent the average condition in each node. Local, anomalous hydrologic features that may be present in the area, such as streams sinking into and springs discharging from the Upper Floridan and solution-enlarged joints and faults through the confining units, are represented by using weighted, high leakance values.

Although it is generally simpler to use a single value for large blocks of input data, the heterogeneity of the aquifer necessitates some node-by-node differences. Anomalies that affect only local flows cannot be simulated as part of the regional flow system, but the anomalies that affect the regional flow system must be included.

CALIBRATION

The purpose of the calibration is to improve the simulation of the flow system based on the initial input data: hydrologic characteristics, boundary conditions, and stresses. The ability to accurately simulate the system with reasonable values and little adjustment to the field data supports the accuracy of the conceptual model. The inability to achieve calibration would show that the system contains characteristics not presently understood and offers information on where the anomalies might lie.

The procedure of calibration is to improve the match between observed and simulated potentiometric surfaces by adjusting input data within estimated ranges of field data. Because the model calibration was based on matching the observed potentiometric surface of the Upper Floridan aquifer, inaccuracies in that surface affect the validity of the calibration. The predevelopment potentiometric surface is probably accurate to about ± 20 ft in the offshore areas and in the area upgradient from the Gulf Trough, and to about ± 10 to 15 ft elsewhere (Johnston and others, 1980). The May 1980 potentiometric surface is more accurate than the predevelopment surface (probably ± 10 ft except offshore), and, therefore, the simulation is considered more reliable when calibrated against that surface. Criteria for model calibration were based on the above-stated ranges of accuracies in the potentiometric surfaces. Calibration was considered to be achieved when the differences between the simulated and observed heads were less than the ranges of accuracy.

The calibration procedure progressed by adjusting the model values of transmissivities and leakance. The adjustments were based on the results of previous simulations as well as on any new data that became available. Adjustment of the model values is somewhat subjective and the results of successful adjustments do not necessarily give a unique solution; therefore, understanding the limitations and acceptable ranges of the aquifer-system characteristics is of utmost importance. Calibration centered on adjusting the transmissivity of the Upper Floridan and the leakance through the confining units. The simulated heads were greatly influenced by adjustments to both of these values. The resulting matrix of transmissivity values was in close agreement with the original field data. The calibration of the predevelopment flow system was accomplished before the Fernandina permeable zone was added, but the inclusion of that zone affected the original calibration and simulation only slightly. A discussion of the calibration of the predevelopment model is given by Krause (1982).

Calibration of the present-day (1980) flow system involved small and anticipated changes in the conceptual model. The southwestern no-flow boundaries of the Upper and Lower Floridan aquifers (ground-water divides under predevelopment conditions) were changed to constant-flux boundaries. The major change to the simulation of the present-day flow system involved the relation between the Fernandina permeable zone and the rest of the Floridan aquifer system. Minor changes in transmissivity and leakance were also required. The area upgradient from the Gulf Trough required no changes from the predevelopment analysis. The final calibration of the model was reached through an iterative refinement of both the predevelopment and the present-day simulations until both were within an acceptable range of accuracy. For comparison, the observed and simulated potentiometric surfaces for predevelopment and present-day conditions are shown on plates 17 and 18, respectively.

The "error" in the calibrated model was measured by the difference between the observed and interpolated heads and the heads simulated by the model for each node. The average of the absolute values of the head errors in all nodes for a given simulation was then calculated. The following table summarizes these average errors as well as maximum positive (simulated head, high) and maximum negative (simulated head, low) errors for the Upper Floridan aquifer in both the predevelopment and present-day simulations.

	Average absolute error per node (feet)	Maximum error in the simulated head (feet)	
		Low	High
Predevelopment (1880)	2.3	11.1	13.2
Present-day (1980)	3.6	11.3	14.1

Although not quantitatively determined, larger errors in simulated head occurred in the offshore area, where heads were least known. Less effort went into the calibration of the offshore area. Because the average absolute error per node includes the poorly calibrated offshore area, the error for the land area only is lower than that shown in the table. In addition, simulated heads in the nodes representing withdrawals are generally higher than those observed because the model simulates the average head over the area of the node. Also, the model was calibrated by using transmissivity that applies to the entire vertical, permeable section of the Upper Floridan aquifer, whereas the pumpage simulated in the model is from wells that generally do not fully penetrate the aquifer. For these partially penetrating, discharging wells, the simulated drawdown is somewhat less than that measured. The difference is related to the percentage of permeable section that the discharging wells have used. In spite of these errors in the offshore area and locally within pumping nodes, the calibration is adequate for the purpose of this study.

Although the Upper Floridan is the only aquifer considered to be fully calibrated, the simulations of the Lower Floridan seem to be as adequate as those of the Upper Floridan. The simulated heads match the observed heads for the Lower Floridan nearly as well as the simulated heads match the observed heads for the Upper Floridan. However, the poor areal coverage of observed heads in the Lower Floridan makes its calibration less certain. It is believed, however, that the entire Floridan aquifer system is calibrated to an acceptable degree, because the Upper Floridan, which is closely associated with and controlled by the functioning of all components of the system, is calibrated. Also, the Upper Floridan is the part of the system of greatest importance for water-supply.

A sensitivity analysis of the simulation of the predevelopment flow system was made to determine the sensitivity of simulation to changes in input parameters and was described by Krause (1982). The analysis was used to determine if the differences between simulated and actual heads could be accounted for by a likely range of error in the input data. The analysis thus provided a measure of the reasonableness of calibration. Briefly, the simulation results are most sensitive to transmissivity of the Upper Floridan aquifer and the leakance of the upper confining unit and middle semiconfining unit.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1989 O - 233-556 QL 3

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879- 1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962- 1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971- 1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849