SUMMARY OF THE HYDROLOGY OF THE SOUTHEASTERN COASTAL PLAIN AQUIFER SYSTEM IN MISSISSIPPI, ALABAMA, GEORGIA, AND SOUTH CAROLINA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1410-A

Summary of the Hydrology of the Southeastern Coastal Plain Aquifer System in Mississippi, Alabama, Georgia, and South Carolina

By James A. Miller

REGIONAL AQUIFER-SYSTEM ANALYSIS—SOUTHEASTERN COASTAL PLAIN

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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

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METRIC CONVERSION FACTORS AND VERTICAL DATUM

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound units	By	To obtain metric units
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	.3048	meter per second (m/s)
foot per year (ft/yr)	.3048	meter per year (m/yr)
square foot per second (ft^2/s)	.0930	meter squared per second (m^2/s)
cubic foot per second (ft^3/s)	.02832	cubic meter per second (m^3/s)
square foot per day (ft^2/d)	.0930	meter squared per day (m^2/d)
inch (in)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
million gallons per day (Mgal/d)	.04381	cubic meter per second (m^3/s)

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

SUMMARY OF THE HYDROLOGY OF THE SOUTHEASTERN COASTAL PLAIN AQUIFER SYSTEM IN MISSISSIPPI, ALABAMA, GEORGIA, AND SOUTH CAROLINA

By JAMES A. MILLER

ABSTRACT

The Southeastern Coastal Plain aquifer system consists of a thick sequence of predominantly clastic rocks of Cretaceous to late Tertiary age that underlies an area of about 120,000 square miles in the Coastal Plain of Mississippi, Alabama, Georgia, and South Carolina. Total pumpage from the aquifer system during 1985 was estimated to be about 650 million gallons per day, with about 250 million gallons per day being pumped for public water supplies. The balance of the pumpage was primarily for irrigation and rural domestic use.

The sediments that make up the aquifer system generally dip seaward and thicken from a featheredge at the Fall Line, which marks the system's inland limit, to about 21,000 feet near the southwestern Alabama coast. The rocks were deposited in fluctuating fluvial, marginal marine, and marine environments. Accordingly, they are complexly interbedded, and their lithology and texture change greatly over a short distance in many places. For purposes of this study, these strata were grouped into seven hydrogeologic units—four regional aquifers separated by three regional confining units—on the basis of their lithology and hydraulic characteristics. On a more local scale, each of these regional units can be divided into a sequence of smaller, discrete aquifers and confining units.

The four regional aquifers, which consist mostly of sand but contain minor amounts of gravel and limestone, have been named for major rivers that cut across their outcrop areas. From shallowest to deepest, they are Chickasawhay River aquifer, Pearl River aquifer, Chattahoochee River aquifer, and Black Warrior River aquifer. Regional confining units, consisting of clay, mudstone, and chalk, carry the same name as the aquifer they overlie; for example, the Pearl River confining unit overlies the Pearl River aquifer. Some of the regional hydrogeologic units grade laterally into units that are part of other regional aquifer systems. Such gradation is particularly important in south Georgia, where the clastic beds of the Southeastern Coastal Plain regional aquifer system change facies to carbonate rocks and become part of the Floridan aquifer system.

The overall pattern of regional ground-water flow in the aquifer system is one of recharge in interstream outcrop areas, lateral movement of the ground water down the dip of the beds into confined parts of the aquifers, and discharge in downdip areas by diffuse upward leakage. In places, however, much of the lateral movement is parallel to the strike of the aquifers. Most of the precipitation that falls on the outcrop areas of the aquifers is discharged to nearby streams as overland flow, infiltrates to shallow depths and discharges to streams as base flow, evaporates, or is transpired by plants. An average rate of about 0.6 inch of precipitation per year enters the deep, confined parts of the aquifer system, and about 0.5 inch per year of this deep recharge discharges as base flow to major streams in the study area. The residual of about 0.1 inch per year, coupled with about 0.1 inch per year of downward leakage from the Floridan aquifer system, is the part of the regional ground-water flow system simulated by a regional digital computer model.

The hydraulic characteristics of the fluvial, clastic sediments that make up the Southeastern Coastal Plain aquifer system are determined primarily by the texture and degree of sorting of the sediments. These characteristics are highly variable and relate directly to the energy conditions that existed where a particular sediment was laid down. In general, coarser sediments that were deposited in higher energy environments are nearest the updip limits of the hydrogeologic units. Fine-grained sediments were deposited in the generally quieter waters in marine environments located closer to the modern coastline.

Values of transmissivity, storage coefficient, and leakance determined from aquifer tests were sparse, and the regional variations in these hydraulic properties were determined largely from digital simulation. Regional water budgets, also highly dependent on the results of modeling, were calculated for 1900 (predevelopment) and 1985 (development or pumping) conditions. Comparison of these budgets indicates that there are four sources of the simulated pumpage of about 765 cubic feet per second (about 495 million gallons per day) from the aquifer system. In order of importance, they are reduction in base flow, reduction in ground-water storage, decrease in flow to aquifers adjacent to the aquifer system in some areas, and increase in flow from aquifers adjacent to the aquifer system in other areas. The first two sources account for most of the pumpage.

The chemistry of the ground water in the Southeastern Coastal Plain aquifer system varies predictably from outcrop recharge areas to deeper, downgradient parts of the aquifers. These variations are similar for all the regional aquifers included in the aquifer system. Initial changes result from water-rock interactions, but downgradient changes are largely the result of mixing with saltwater in the deeper parts of the aquifers. Dissolved-chloride and dissolved-solids concentrations increase downgradient and directly reflect the degree of saltwater being flushed from the deeper parts of the aquifers. In contrast, dissolved-iron concentrations are highest in narrow middip bands parallel to aquifer outcrop areas and decrease downgradient as iron-bearing minerals precipitate. The water can be grouped into three dominant hydrochemical facies that result from the geochemical evolution of the ground water. From outcrop areas downgradient, the facies are calcium bicarbonate, sodium bicarbonate, and sodium chloride. Geochemical modeling was used to demonstrate the likely chemical processes that have produced the observed water chemistry. Ground-water flow rates for the Pearl River, Chattahoochee River, and Black Warrior River aquifers derived by geochemical methods are 18, 13, and 3 feet per year, respectively. These rates are compatible with rates of 14.8, 9.9, and 0.9 feet per year, respectively, independently derived from digital simulations of the flow system.

INTRODUCTION

The U.S. Geological Survey in 1978 began a nationwide program designed to study the major ground-water systems that provide a significant part of the Nation's water supply. The history, status, and progress of the program, called the Regional Aquifer-System Analysis (RASA) Program, have been discussed in detail by Sun (1986). Each RASA study is charged with defining the regional geology and hydrology of a particular aquifer system, and with establishing a data base that can be used to assess regional ground-water resources and to support detailed local studies. The general objectives of each study are to (1) define the regional hydrogeologic framework of the aquifer system, (2) describe the ground-water flow system as it existed before development and as it exists today, (3) analyze the changes that have occurred between predevelopment and present flow systems, (4) integrate the results of previous studies that address either individual aspects of the aquifer system or local geographic areas, and (5) provide some capability for evaluating the effects of future ground-water development on the system. These objectives can best be met by constructing a regional-scale digital model of the aquifer system, supplemented by more detailed subregional models, and by interpreting the distribution and evolution of observed water-quality variations. The Southeastern Coastal Plain aquifer system described in this report is one of 28 regional aquifer systems identified for study under the RASA Program.

The Southeastern Coastal Plain aquifer system consists of a thick sequence of predominantly clastic sediments of Cretaceous to late Tertiary age that underlies an area of about 120,000 mi^2 in the Coastal Plain of Mississippi, Alabama, Georgia, and South Carolina. Sand, sandstone, gravel, and minor limestone form the system's major aquifers, which are separated by confining units of clay, marl, mudstone, and chalk. The approximate areal extent of the aquifer system is shown in figure 1. The system extends eastward from the Mississippi embayment in central Mississippi to the southwestern flank of the Cape Fear Arch in northeastern South Carolina. It is the source of the water supply for many cities, including Tupelo and Columbus, Miss.; Selma and Montgomery, Ala.; and Florence, Myrtle Beach, and Charleston, S.C. In many areas it is the only source of freshwater. The amount of water pumped from the aquifer system for industrial and agricultural uses is small compared with municipal pumpage, but it has increased in recent years. Cones of depression of local to multicounty extent have developed in response to the pumping, but the aquifer system as a whole shows little hydraulic head decline from estimated predevelopment water levels.

RELATION TO OTHER REGIONAL AQUIFER-SYSTEM ANALYSIS STUDIES

The Southeastern Coastal Plain aquifer system is located among four adjacent regional aquifer systems: the Northern Atlantic Coastal Plain system to the northeast, the Mississippi embayment and Coastal lowlands aquifer systems of the Gulf Coastal Plain regional aquifer-system study to the west and southwest, and the Floridan aquifer system to the south and southeast (fig. 2). Aquifers and confining units that are part of the Southeastern Coastal Plain aquifer system grade laterally into the Northern Atlantic Coastal Plain aquifer system near the South Carolina–North Carolina State line (Meisler, 1980). In the southern parts of Alabama and Georgia, and in southeastern South Carolina, the Southeastern Coastal Plain aquifer system in part grades laterally into, and in part is overlain by, highly prolific, carbonate aquifers of the Floridan aquifer system (Miller, 1986). In southwest Alabama and central Mississippi, the Mississippi embayment and Coastal lowlands aquifer systems (Grubb, 1984) partly overlie, and partly are the lateral equivalent of, the Southeastern Coastal Plain aquifer system. Because of the physical and hydraulic interconnections of these major aquifer systems, computer simulations of adjoining parts of the aquifer systems have been compared to ensure that there are no conspicuous anomalies in hydraulic heads and that reasonable amounts of water are simulated as passing between the systems in the direction indicated by field observations.

BACKGROUND, OBJECTIVES, AND APPROACH

No previous study has considered the Southeastern Coastal Plain as a single hydrologic system. However, a regional approach is required if such problems as multicounty water-level declines or aquifer contamination by saltwater encroachment are to be properly addressed. A major advantage of such an approach is that the effect of such conditions as severe drought or widespread, intensive pumpage can be analyzed for the entire system, not just a small part of it. A regional assessment of the

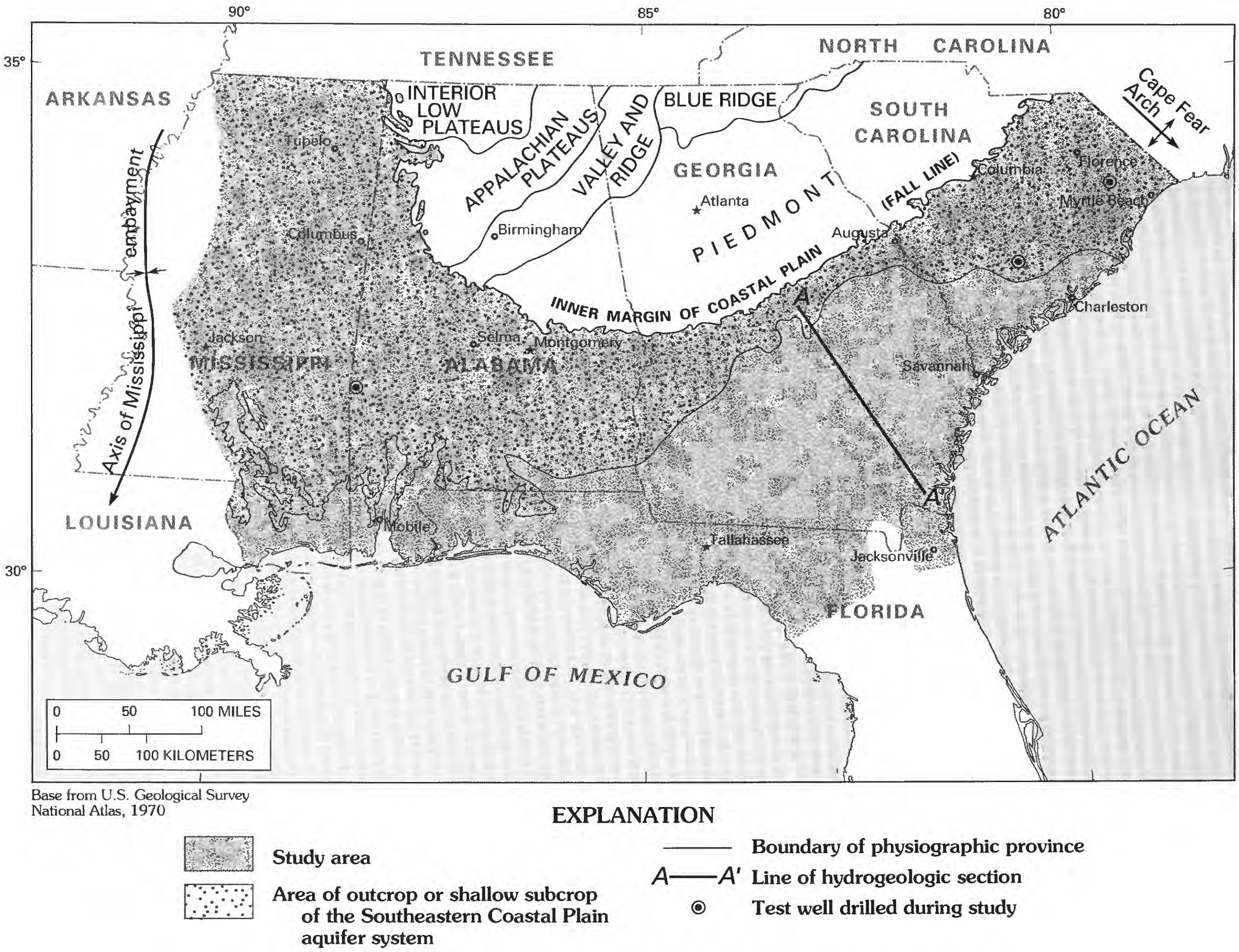


FIGURE 1.—Extent of study area, location of test wells, and line of hydrogeologic section.

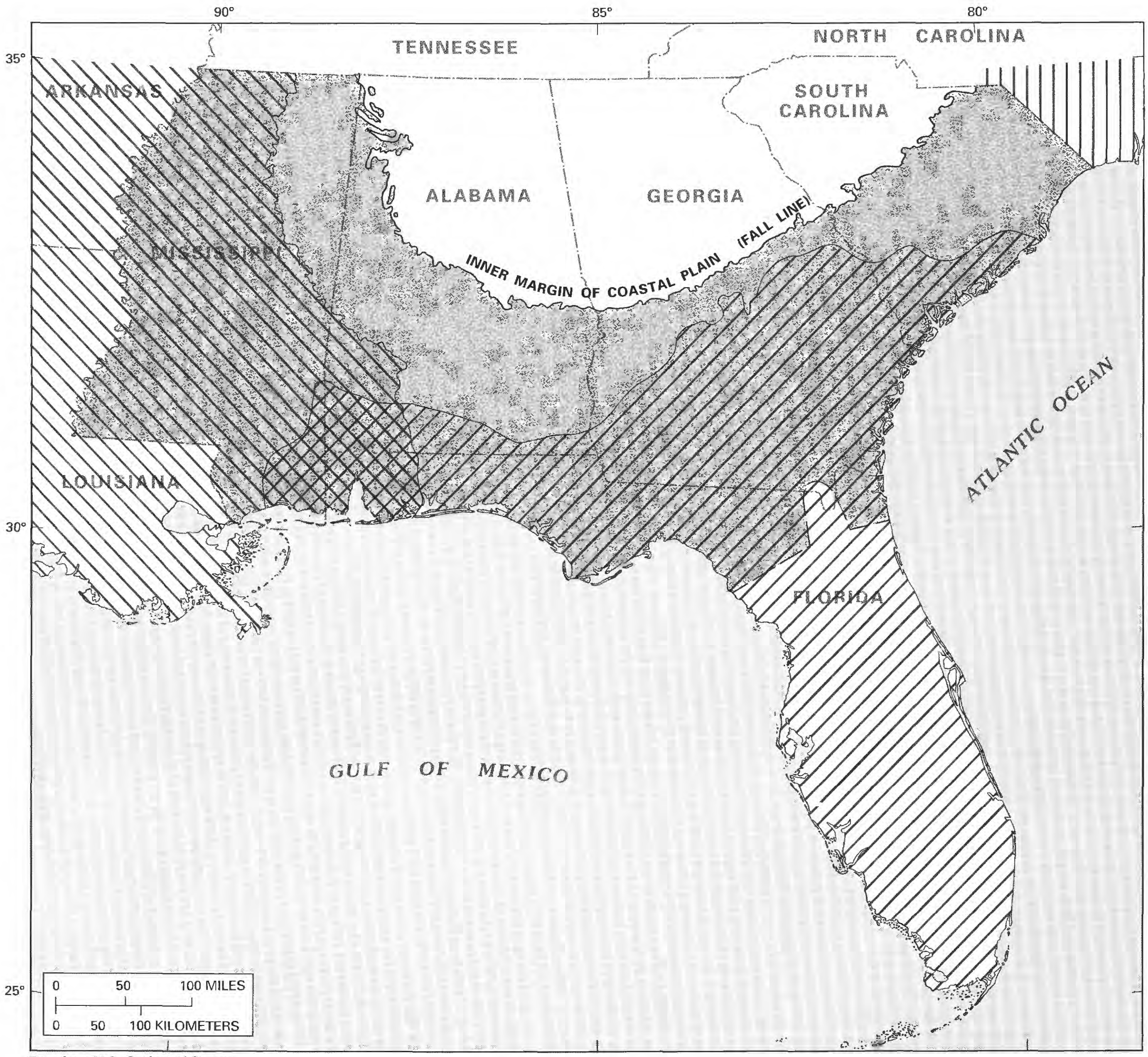
Southeastern Coastal Plain aquifer system began in 1979 and was concluded in 1987. The investigation, which is summarized in this report, involved review of previous work and compilation of existing data, collection of new data at selected places, and the use of several digital computer models to simulate all or part of the ground-water flow system. Earlier studies provided considerable information on aquifer characteristics, the geologic framework, and the ground-water flow system. Small-scale flow models had been constructed for a few areas to study individual sand aquifers or to address local water-supply problems.

The major objectives of the study were to

1. Describe the geologic and hydrogeologic framework of the aquifer system.
2. Describe the ground-water chemistry and identify the geochemical processes responsible for the different water-quality types observed.
3. Define the regional ground-water flow system.
4. Appraise the effects of increased withdrawals of ground water.

Initial project efforts involved compilation of geologic, hydraulic, and chemical data from published reports and from the files of Federal and State agencies. These data were used to prepare a series of maps and book reports describing regional and subregional aspects of the hydrology, water quality, and geology of the aquifer system. Among the more significant of these reports are those by Renken (1984), Stricker and others (1985a-c), Barker (1986), Lee (1986, 1988a, b), Mallory (1987), Aucott (1988), Renken and others (1989), and Faye and Mayer (1990).

Additional data were collected to fill major gaps in information. Two test wells were drilled in South Carolina (Reid, Aucott, and others, 1986; Reid, Renken, and others, 1986) and one was constructed in western Ala-



Base from U.S. Geological Survey
National Atlas, 1970

EXPLANATION

Aquifer systems—Where aquifer systems overlap, two or more patterns are shown

- Southeastern Coastal Plain
- Floridan
- Mississippi embayment and coastal lowlands
- Northern Atlantic Coastal Plain

FIGURE 2.—Relation of Southeastern Coastal Plain aquifer system to adjacent aquifer systems.

bama (Davis and others, 1983) to provide geologic, hydraulic, and chemical information. The locations of these wells are shown in figure 1. Water samples were collected from 105 wells at selected locations throughout the study area (Lee, 1984). The samples were analyzed for trace metals, nutrients, dissolved gases, and stable and radioactive isotopes in addition to major chemical constituents. A mass measurement of water levels over a four-State area was made in 1982 to obtain information on the areal distribution of water levels and to determine the decline in water levels in different aquifers.

Computer simulation was used extensively to evaluate and help determine the regional distribution of such hydrologic properties as transmissivity and leakance, especially in downgradient parts of the flow system for which data are sparse. The effects of ground-water development were assessed primarily by use of computer simulations. Simulation was accomplished with a coarse-mesh regional model and four subregional models having smaller grid spacing (fig. 3). Reports describing the design and calibration of the models, and presenting preliminary model results, have been prepared for the regional model by Barker (1986) and for the subregional model in South Carolina by Aucott (1988).

CONTENT OF PROFESSIONAL PAPER 1410–A THROUGH 1410–H

Professional Paper 1410 consists of eight chapters, A through H, that describe different aspects of the geology, hydrology, geochemistry, and computer simulation of the Southeastern Coastal Plain aquifer system. Four of the chapters deal with regional features, and four treat subregional areas of the system in more detail. Most of the chapters emphasize the description and analysis of the ground-water flow system.

Chapter A (this report) is a summary of the hydrogeologic framework, geochemistry, hydraulic characteristics, and regional ground-water flow of the aquifer system as a whole. It also summarizes the important findings described in the four subregional chapters, which deal with local problems that can be better addressed by smaller scale studies.

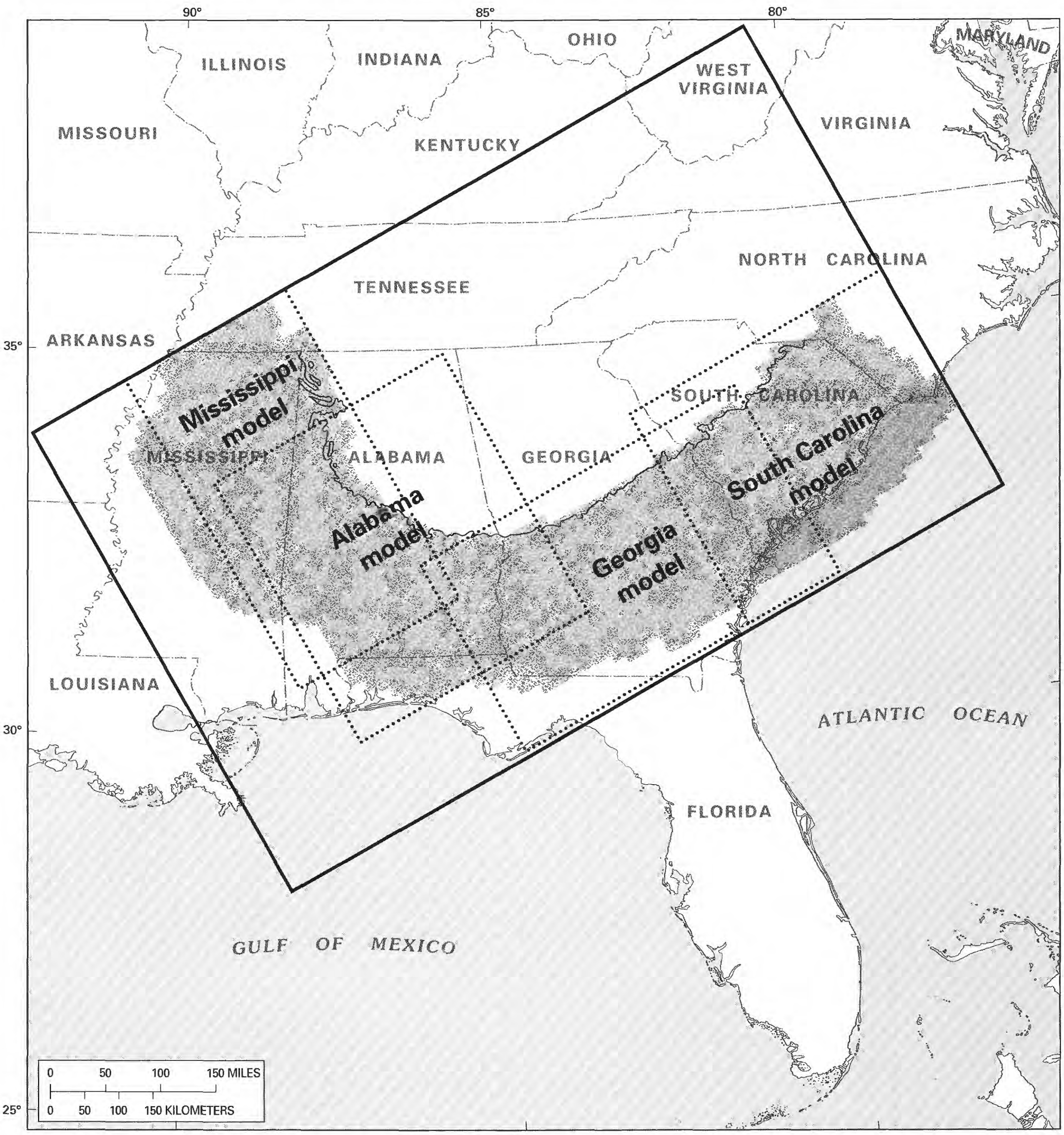
Chapter B (Renken, in press) discusses the hydrogeologic framework of the aquifer system. The rocks making up the Southeastern Coastal Plain aquifer system were divided into seven regional hydrogeologic units (aquifers and confining units) on the basis of their permeability characteristics, thus providing a framework within which hydraulic and chemical data can be grouped and analyzed. The hydrogeologic framework provides the basis for assigning layers used in the regional and subregional computer models. The hydrogeologic units differentiated do not coincide regionally with the tops or bottoms of the geologic formations. If the facies of these geologic formations change, the formations may be grouped into different hydrogeologic units. Accordingly, chapter B not only describes the major permeability breakdowns in the study area, but also addresses stratigraphy, facies distribution, and geologic structure and discusses how these factors have affected permeability distribution and, in turn, ground-water flow.

Chapter C (Barker and Pernik, in press) presents a regional appraisal of the ground-water flow system and the overall hydraulic characteristics of the regional aquifers and confining units. It also describes results of the regional ground-water flow simulation and presents comparisons of the 1985 flow system with the predevelopment system. Emphasis is placed on the regional water budget and separation of the deep and shallow components of the flow system. All analyses and results rely heavily on computer simulation. Model boundaries, model calibrations, and model sensitivity to variations in data input are documented in detail.

Chapter D (Lee, in press) describes regional ground-water chemistry within the major aquifers of the Southeastern Coastal Plain aquifer system and relates observed variations in water chemistry to changes in aquifer hydraulics and mineralogy. It presents geochemical modeling results explaining the sequence of rock-water interactions that occurs down flowpaths and produces a sequence of changes (geochemical evolution) in the ground water as it moves downgradient. Ground-water flow rates calculated from isotopic data support rates calculated independently by model simulations.

The study area was divided into four subregional areas according to the location of major ground-water divides. Investigations within each subregional area focused on local flow systems and water problems in more detail. Computer models of the flow system were constructed for each of the four areas. Chapter E (Aucott, in press) describes the hydrology of South Carolina and presents results of simulation that extended into adjacent parts of North Carolina and Georgia. Declines in water levels as a result of pumping are greater in South Carolina than elsewhere in the study area. The chapter emphasizes the differences between natural (predevelopment) and 1985 (developed) flow conditions. Because the aquifers are thickly confined near the coast in this subregional area, there is no interchange of water between the aquifers and the major streams in the lower (coastward) part of the Coastal Plain.

Chapter F (Faye and Mayer, in press) deals with the hydrology of Georgia and adjacent parts of South Carolina and Alabama. This area is characterized by many facies changes, especially in the southern half of the area where the sand aquifers of the Southeastern Coastal Plain aquifer system are overlain by, and partly grade



Base modified from U.S. Geological Survey National Atlas, 1970

EXPLANATION

- Area actively simulated
- Boundary of regional model area
- Boundary of subregional model area
- Inner margin of Coastal Plain

FIGURE 3.—Areas simulated by regional and subregional models.

laterally into, highly productive carbonate aquifers that are part of the Floridan aquifer system. The interconnection of the two aquifer systems receives special attention in this chapter. A detailed study of stream-aquifer relations is also presented.

Chapter G (Mallory, in press) addresses the hydrology of Mississippi and western Alabama. Simulation results for this subregion do not support the previously accepted concept that all the ground-water flow is down the dip of the aquifers from their outcrop to the point where they contain saline water. Rather, lateral flow, toward major streams, predominates in many areas. Although geologically simple compared with the other subregions, the area covered by chapter G is hydrologically complicated because part of the Southeastern Coastal Plain aquifer system grades into the Mississippi embayment aquifer system. Parts of the Coastal lowlands aquifer system overlie the Southeastern Coastal Plain aquifer system throughout much of this subregion, but these two systems are vertically separated by a thick and effective clay confining unit.

Chapter H (Planert and others, in press) describes the hydrology of Alabama and contiguous parts of Georgia and Mississippi. East-west and, to a lesser extent, north-south facies changes create a complex hydrogeologic framework in this area. As a result, an individual formation may function as an aquifer in one part of the subregion and as a confining unit in another part. Locally, faulting has increased the vertical hydraulic conductivity of some of the confining units; this accounts for a corresponding increase in the degree of interconnection of underlying aquifers with major streams. Simulation is used to evaluate the effects of large ground-water withdrawals near major municipalities. Interconnection between the Floridan and Southeastern Coastal Plain aquifer systems in southern and southeastern Alabama is assessed.

PREVIOUS WORK

Numerous reports have been published, chiefly by the U.S. Geological Survey and by the States of Alabama, Georgia, Mississippi, and South Carolina, that discuss various aspects of the geology, hydrology, and water chemistry of the study area. For the most part, the scope of these reports is local or subregional. Data and interpretations from many of these reports were used in preparing the chapters of this Professional Paper, and extensive lists of references are given in each chapter. Some of the more important references that deal with the study area as a whole or that provide extensive information about a particular aspect of the system are listed below.

Reports describing hydrologic conditions in parts of the Southeastern Coastal Plain aquifer system in its early stage of development include those for Georgia by McCallie (1898, 1908), Stephenson and Veatch (1915), Warren (1945), and LaMoreaux (1946); for Mississippi by Stephenson and others (1928); for Alabama by Carlston (1944); and for South Carolina by Siple (1957). More recent, statewide or multicounty reports discussing the hydrology and geohydrology of the aquifer system include those for Alabama by Barksdale and Moore (1976); for South Carolina by Siple (1967), Marine (1976), and Hayes (1979); for Georgia by Pollard and Vorhis (1980), Clarke and others (1985), and Brooks and others (1985); and for Mississippi by Boswell (1963, 1976a, b, 1977, 1978a, b) and Gandl (1982). A noteworthy report describing a digital computer model of part of the aquifer system was written by Gardner (1981), and an overview of the ground-water resources of the study area and adjacent areas was presented by Cederstrom and others (1979).

Descriptions of the regional geology and stratigraphy in the study area include those by Murray (1961) and Brown and others (1979). Contributions dealing with the surface geology include those for Mississippi by Stephenson and Monroe (1940); for Alabama by Adams and others (1926), Monroe (1941), and Copeland (1968); for Georgia by Veatch and Stephenson (1911) and Cooke (1943); and for South Carolina by Cooke (1936). Subsurface geology for South Carolina is discussed by Colquhoun and others (1983); for Georgia by Herrick (1961), Herrick and Vorhis (1963), and Applin and Applin (1964); for Alabama by Moore and Joiner (1969) and Moore (1970); and for Mississippi by Cushing and others (1964).

The most important source of information has been the great number of reports published by the States in the study area and by the U.S. Geological Survey. The data, analyses, and interpretations in these reports have provided the background and detailed information about the aquifer system, the geology, and the water chemistry throughout the four-State study area. Complete lists of the references used can be found in chapters B through H of this Professional Paper.

HYDROGEOLOGIC FRAMEWORK

REGIONAL SETTING

Sedimentary rocks in the Coastal Plain of the Southeastern United States form a wedge-shaped body of clastic and carbonate strata. These sediments generally dip and thicken seaward, and range in thickness from a featheredge at the Fall Line, which marks the updip limit of the Coastal Plain, to a maximum penetrated thickness of about 21,000 ft in southwestern Alabama. Coastal

Plain rocks dip at a low angle coastward or toward the axis of the Mississippi embayment. The gentle dip of the rocks is locally interrupted by folding or faulting (Renken, 1984). Coastal Plain strata range in age from Jurassic to Holocene and are underlain by nearly impermeable igneous, metamorphic, and sedimentary rocks of early Paleozoic to early Mesozoic age that form the Coastal Plain floor (Wait and Davis, 1986). In some parts of the study area, these low-permeability rocks are a southwestern extension of the Appalachian Mountains or a southeastern extension of Piedmont rocks. Elsewhere, they represent graben-fill sedimentary rocks and igneous intrusives of Mesozoic age that may have formed in an ancient rift system.

The poorly consolidated Coastal Plain rocks are easily eroded when exposed at the surface. Where they consist of clastic material, streams are gently to moderately incised, and low, rolling hills are developed. Where carbonate rocks are present, the topography is generally flat to slightly rolling, streams are widely spaced, and local to subregional karst topography is developed. Relief is highest (a few hundred feet) near the Fall Line and becomes progressively lower toward the coast. Extensive, slightly dissected plains are characteristic of large parts of the study area.

Coastal Plain sediments were deposited during a series of transgressions and regressions of the sea. Accordingly, the rocks represent depositional environments ranging from fluvial to shallow marine, with the exact location of each environment dependent on the relative position of landmasses, shoreline, and streams at a given point in geologic time. Local unconformities mark breaks in sedimentation that formed as the sea encroached upon or receded from parts of the study area. As in most regional studies, however, these unconformities are not synchronous surfaces that extend throughout the study area.

Changes in depositional conditions, primarily in response to changes in sea level, account for the observed complex variations in sediment lithology in the study area. Because the lithology of the sediments largely determines their hydraulic conductivity, this property likewise is highly variable. Consequently, the occurrence and direction of ground-water flow in the Southeastern Coastal Plain aquifer system are greatly controlled by the texture, composition, and character of bedding of the rocks.

The clastic rocks that are the focus of this study grade laterally southward in southern Georgia, southwestern South Carolina, and southeastern Alabama into a thick sequence of highly permeable carbonate rocks that are part of the Floridan aquifer system (Miller, 1986). Because the carbonate rocks were deposited by a generally transgressive sea, the Floridan aquifer system partly overlies the Southeastern Coastal Plain aquifer system. Thus, there is direct hydraulic connection between the two aquifer systems in many places, but the carbonate rocks are not considered an integral part of the hydrogeologic system described in this report. Deeply buried rocks of Jurassic age in Alabama and Mississippi are not considered part of the regional hydrogeologic framework. These rocks contain water everywhere having a dissolved-solids content of 10,000 milligrams per liter (mg/L) or higher, indicating that little or no freshwater is circulating through them. Rocks of Early Cretaceous age likewise are excluded from study where they contain water with similar dissolved-solids concentrations. Locally, however, Lower Cretaceous rocks in Alabama and Mississippi contain freshwater and are included as part of the Southeastern Coastal Plain aquifer system.

HYDROGEOLOGIC UNITS

The complexly interbedded, mostly clastic strata that make up the Southeastern Coastal Plain aquifer system contain numerous aquifers and confining units. Sequences of permeable sediments or local aquifers that can be shown to be hydraulically connected in varying degrees are treated in this study as a single regional aquifer. The degree of interconnection is judged primarily by the similarity in hydraulic head among the local aquifers. The difference in hydraulic head between discrete local aquifers is generally much less than the head difference between adjacent regional aquifers. Sequences of confining beds that are lithologically similar and can reasonably be assumed to be connected are grouped in a similar fashion into regional confining units. Regional confining units generally separate regional aquifers; however, where a regional confining unit pinches out, two regional aquifers may be in contact. Similarly, two regional confining units may be directly connected where the regional aquifer between them is missing.

The rocks of the Southeastern Coastal Plain aquifer system have been grouped into four regional aquifers separated by three regional confining units (Renken, 1984). Each of these seven hydrogeologic units consists for the most part of a sequence of sand or clay beds that behave together as a single hydrologic unit. It is possible to differentiate separate aquifers and confining beds within each regional hydrogeologic unit on a more local scale, and this has been done within each of the subregional areas described in chapters E through H of this Professional Paper. Subregional units have been delineated in such a fashion that they represent subdivisions of the regional hydrogeologic units. The aquifers of both regional and subregional extent consist chiefly of coarse to fine sand, but locally they include small amounts of gravel and limestone. The regional and subregional confining units are mostly clay, mudstone, or shale, except for a thick sequence of chalk in Alabama and Mississippi that forms an effective regional confining unit.

The hydrogeologic framework established for this study is intended to emphasize the contrast in permeability between regionally extensive rock units. The top and base of a regional aquifer or confining unit locally may parallel the top and base of a rock-stratigraphic unit such as a formation. Stratigraphic and hydraulic boundaries do not always coincide, however, especially when hydrogeologic units are extended over a regional area. For example, there are places where the upper part of a formation that makes up an aquifer consists of low-permeability rock. The low-permeability beds are excluded from the aquifer at such places, and the top of the aquifer, accordingly, lies within the formation rather than at its top. Regionally, the physical character of rocks that are stratigraphically equivalent varies considerably. Stratigraphically equivalent rocks may, therefore, make up part of a regional aquifer in one place and part of a confining unit elsewhere.

Many formation and aquifer names have been applied in the multistate study area to parts of the rocks that together make up the Southeastern Coastal Plain aquifer system. To avoid confusion and cumbersome terminology, the stratigraphic units that are mapped in chapter B of this Professional Paper are mostly time-rock units that include all or parts of several formations. It is likewise difficult if not impossible to apply existing formation or local-aquifer nomenclature to the regional hydrogeologic units, because the regional units encompass many small-scale rock units and permeability zones. The difficulty is due in part to the generally poor correspondence of hydrogeologic unit boundaries with stratigraphic unit boundaries, and in part to the regional extent of the hydrogeologic units. Several formations or parts of formations are included in each regional hydrogeologic unit, as shown on plate 1.

Regional aquifers were named for major rivers within the study area (Miller and Renken, 1988). The rivers chosen transect the outcrops of the aquifers that bear their names; part of each aquifer is, therefore, exposed along the nominate river. The regional aquifer names chosen are shown on plate 1. From shallowest to deepest, they are Chickasawhay River aquifer, Pearl River aquifer, Chattahoochee River aquifer, and Black Warrior River aquifer. Regional confining units carry the same name as the aquifer they overlie in order to avoid proliferation of names. Professional Paper 1410-B presents maps of the tops and thicknesses of the regional hydrogeologic units.

Except where they are covered by younger strata, the aquifers and confining units that make up the Southeastern Coastal Plain aquifer system crop out in adjacent bands from Mississippi through South Carolina (fig. 4) and extend into the subsurface either seaward or westward toward the Mississippi River. Where the regional aquifers are covered by low-permeability rocks, they contain water under confined conditions everywhere. In outcrop areas, the aquifers generally contain water under unconfined conditions, but thin beds of clay or other low-permeability rocks locally may create confined or semiconfined conditions in these areas.

All the regional hydrogeologic units do not extend everywhere throughout the study area in the subsurface, as shown in chapter B of this Professional Paper. For example, the Black Warrior River aquifer, the most extensive unit delineated, is absent in updip areas of South Carolina and eastern Georgia (fig. 5). The Chattahoochee River aquifer is absent in a large area in western Alabama and southeastern Mississippi, the Pearl River confining unit is present only in Mississippi and part of Alabama, and so on. Because they are mapped primarily on the basis of permeability, the regional aquifers have been extended beyond the point where they contain water having a dissolved-solids concentration of 10,000 mg/L, even though that concentration is thought to mark the limit of active ground-water flow. The regional ground-water flow system has not been simulated downdip from the 10,000 mg/L dissolved-solids line, however, because flow is assumed to be sluggish or stagnant there.

Some of the hydrogeologic units of the Southeastern Coastal Plain aquifer system grade laterally into units that are part of adjacent regional aquifer systems. In some places, this gradation is due to facies change from the predominantly clastic rocks of the Southeastern Coastal Plain aquifer system into the predominantly carbonate rocks of the Floridan aquifer system (fig. 6). In other places, thickening and thinning of aquifers and confining units, due in part to erosion and in part to facies changes within regional clastic rock units, creates a situation wherein an important aquifer in one regional aquifer system may represent only a thin, local aquifer in another aquifer system, or may pinch out altogether. The relations among hydrogeologic units of the Southeastern Coastal Plain aquifer system and those of contiguous aquifer systems are shown in table 1.

Variations in the hydraulic characteristics and water quality of the Southeastern Coastal Plain aquifer system are directly related to the geology of the strata that make up the system. The transmissivity of the regional aquifers is directly proportional to the percentage of sand they contain. The amount of sand in all the aquifers generally decreases down the dip because depositional conditions generally were more marine in that direction,

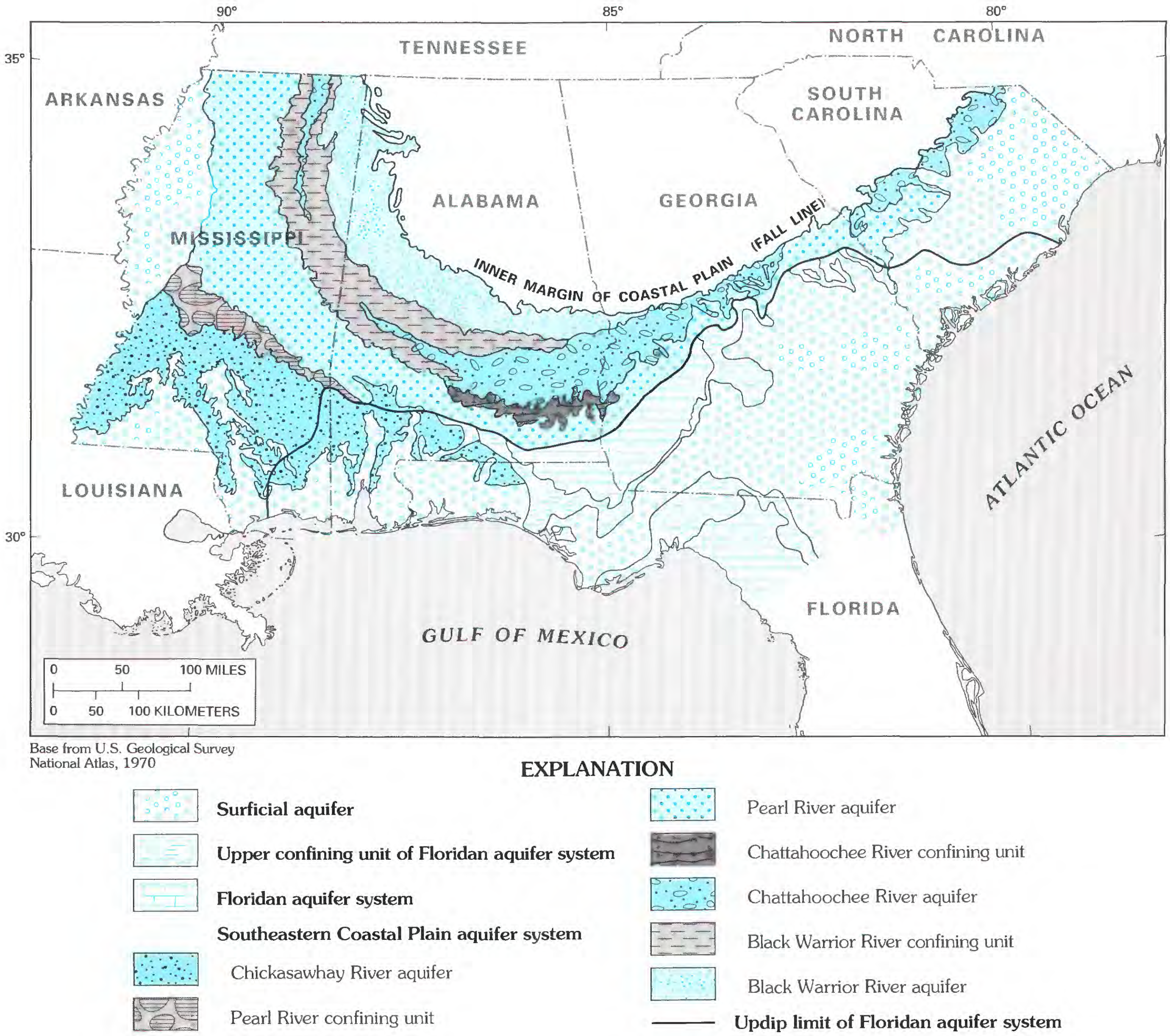


FIGURE 4.—Location and outcrop or shallow subcrop areas of major hydrogeologic units.

allowing increasing amounts of clay and other fine-grained materials to be deposited (Renken, in press, chapter B of this Professional Paper). As a result, ranges of transmissivity generally parallel the strike of the aquifers, and transmissivity values decrease seaward from aquifer outcrop areas, except where fluvial and deltaic sands of higher transmissivity have accumulated in lobes that extend coastward perpendicular to strike.

Changes in aquifer mineralogy, from feldspathic, largely fluvial sand in outcrop areas to slightly calcareous, more marine sand downdip, are directly reflected by changes in water quality that define five geochemical zones marking the chemical evolution of ground water as it moves down flowpaths from outcrop recharge areas (Lee, 1985, and chapter D of this Professional Paper). Locally, where limestone such as the Clayton Formation of eastern Alabama and western Georgia makes up part of an aquifer, dissolution of the limestone by percolating ground water has increased the aquifer's permeability. Dissolution has not affected the clastic parts of the aquifers.

The clay, mudstone, and chalk that make up the regional confining units were deposited during general transgressions of the sea. These fine-grained materials represent relatively deep water deposits. Clay lenses within the regional aquifers were mostly deposited in

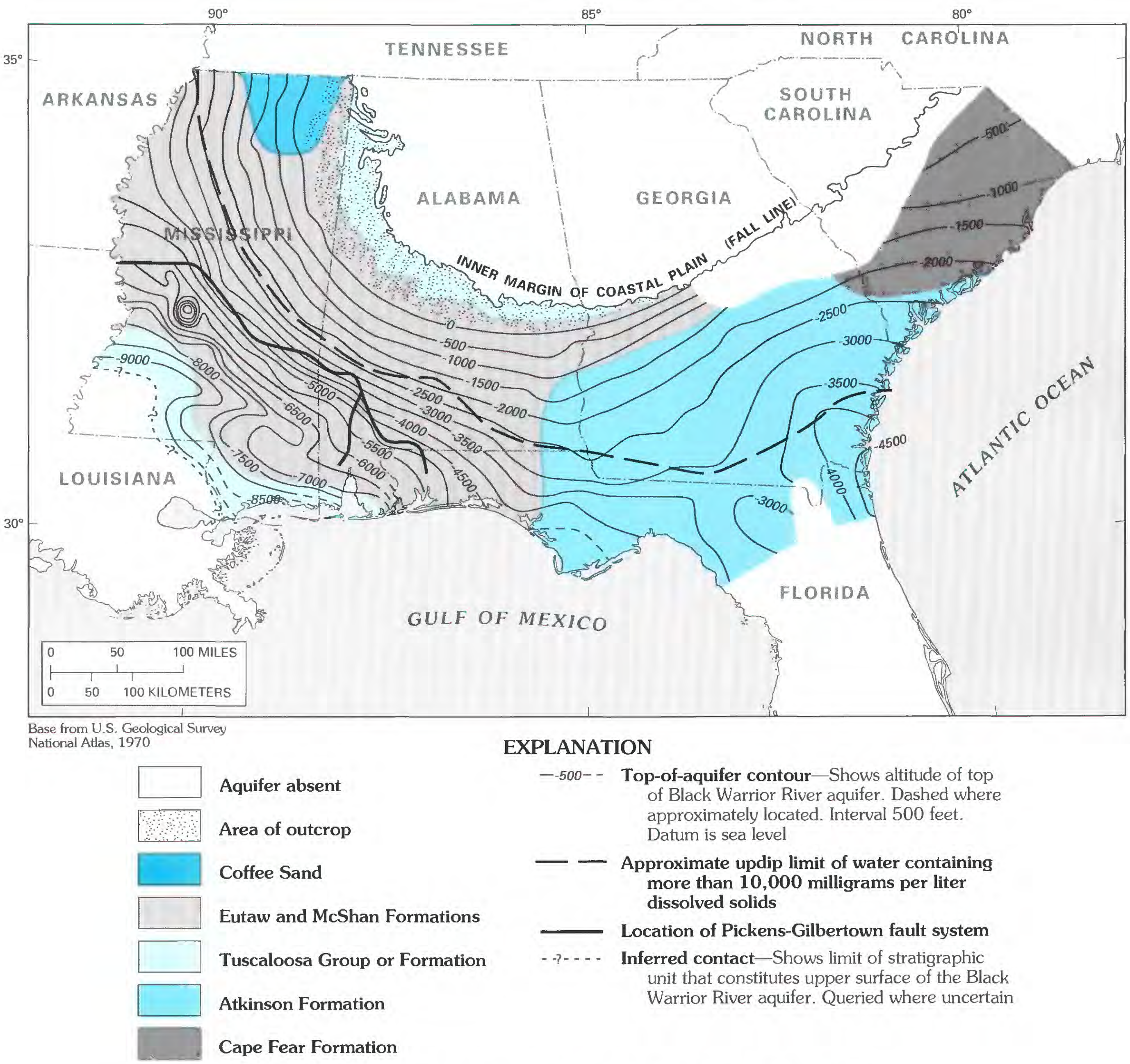


FIGURE 5.—Geology and configuration of top of the Black Warrior River aquifer.

fluvial to shallow marine environments, but such lenses, where present, substantially decrease the vertical hydraulic conductivity of the aquifers.

REGIONAL GROUND-WATER FLOW SYSTEM

Many studies have investigated local aspects of ground-water flow in the Southeastern Coastal Plain aquifer system. The work summarized in the chapters of Professional Paper 1410, however, represents the first attempt to study and describe flow within the aquifer system as a whole and to quantify regional rates of recharge and discharge.

The overall pattern of ground-water flow in the Southeastern Coastal Plain aquifer system resembles that of a classic artesian system. The ground water originates from recharge in the outcrop areas of the aquifers, moves into confined conditions down a hydraulic gradient that generally parallels the dip of the aquifers, and discharges in downdip areas predominantly by diffuse upward leakage. Directions and rates of flow depend primarily on

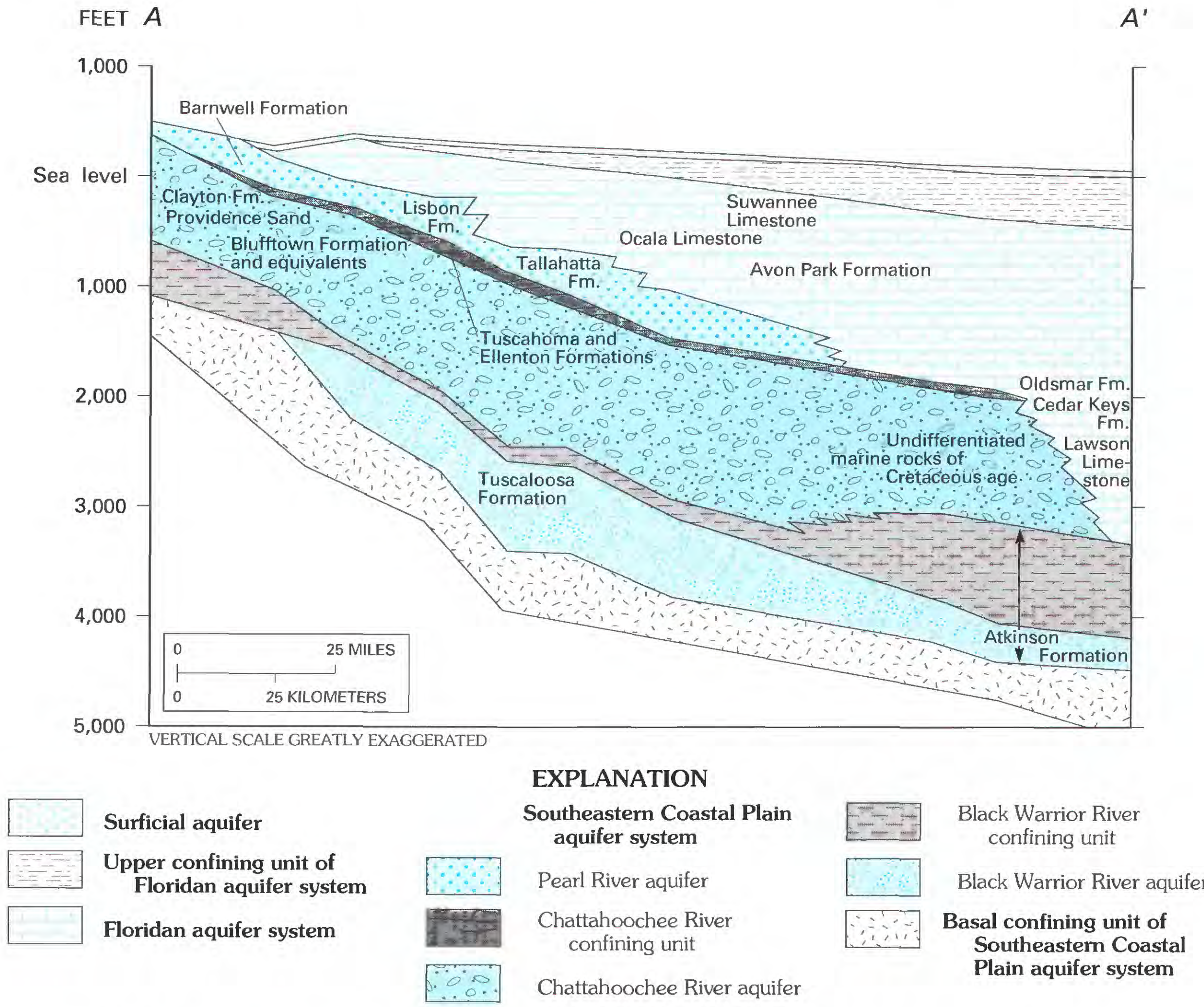


FIGURE 6.—Generalized hydrogeologic section *A–A'* in east-central Georgia (location of section shown in fig. 1).

variations in hydraulic conductivity and the distribution of recharge and discharge.

The regional ground-water flow system can best be illustrated by maps of the potentiometric surfaces of the aquifers. The configuration of the regional predevelopment potentiometric surface of the Black Warrior River aquifer is shown in figure 7. The complexity of the surface in updip areas is due in part to the greater amount of head data available where the aquifer is at or near the surface; however, the complexity is mainly the result of a highly dynamic ground-water flow system where the aquifer crops out or is not deeply buried. Figure 7 shows that in updip areas, the direction of flow in the Black Warrior River aquifer is either down the dip of the aquifer or toward major streams. Farther downdip, however, there is an important component of flow perpendicular to the dip in Mississippi, southeastern Georgia, and South Carolina. Major streams that mostly transect, but locally parallel, aquifer outcrop bands have a profound effect on the flow system because they serve as regional drains. An example of a major stream flowing parallel to outcrop is the Alabama River east and west of Montgomery, Ala. (fig. 7). This flow parallel to strike is discussed in detail in chapters E and G of this Professional Paper.

The regional predevelopment potentiometric surfaces of the Chattahoochee River aquifer (fig. 8) and the Pearl River aquifer (fig. 9), like that of the Black Warrior River aquifer, are highly complex in updip areas. In contrast to the Black Warrior River aquifer, however, the dominant direction of flow in areas where the Chattahoochee River and Pearl River aquifers are confined is down the dip of the aquifers.

Recharge to the Southeastern Coastal Plain aquifer system originates as precipitation in areas where the aquifers crop out. Recharge in interstream areas (figs. 7–9) results in potentiometric highs there. Confined parts of the aquifers receive some recharge by downward

TABLE 1.—*Relation among hydrogeologic units differentiated by the Southeastern Coastal Plain, Gulf Coast, Floridan, and Northern Atlantic Coastal Plain Regional Aquifer-System Analysis (RASA) studies*

[Sources: a, Grubb (1986) and Hosman and Weiss (1991); b, Miller (1986); c, Henry Trapp, Jr. (U.S. Geological Survey, written commun.); d, confining units between aquifers not shown; e, stratigraphic position varies]

Southeastern Coastal Plain RASA		**Gulf Coast RASA** [a]			**Floridan RASA** [b]		**Northern Atlantic Coastal Plain RASA** [c]	
		Coastal lowlands aquifer system [d]	Permeable zone A	(Holocene–upper Pleistocene deposits)		Surficial aquifer	Northern Atlantic Coastal Plain aquifer system [d]	Surficial aquifer
			Permeable zone B	(Lower Pleistocene–upper Pliocene deposits)				Upper Chesapeake aquifer
Southeastern Coastal Plain aquifer system	Chickasawhay River aquifer		Permeable zone C	(Lower Pliocene–upper Miocene deposits)		Upper confining unit [e]		Lower Chesapeake aquifer
			Permeable zone D	(Middle Miocene deposits)				
			Permeable zone E	(Lower Miocene–upper Oligocene deposits)	Floridan aquifer system	Upper Floridan aquifer [e]		Castle Hayne-Piney Point aquifer
	Pearl River confining unit	Vicksburg-Jackson confining unit						
	Pearl River aquifer	Mississippi embayment aquifer system [d]	Upper Claiborne aquifer					
			Middle Claiborne aquifer			Middle confining unit [e]		
			Lower Claiborne-upper Wilcox aquifer			Lower Floridan aquifer [e]		Beaufort-Aquia aquifer
			Middle Wilcox aquifer					
			Lower Wilcox aquifer					Brightseat-upper Potomac aquifer (upper part) [e]
	Chattahoochee River confining unit	Midway confining unit				Lower confining unit [e]		
	Chattahoochee River aquifer	McNairy-Nacatoch aquifer						Peedee-Severn aquifer
		Not studied (permeable rocks mostly contain saline water)						Black Creek-Matawan aquifer
								Magothy aquifer
	Black Warrior River confining unit							Brightseat-upper Potomac aquifer (lower part) [e]
	Black Warrior River aquifer							Middle Potomac aquifer
								Lower Potomac aquifer

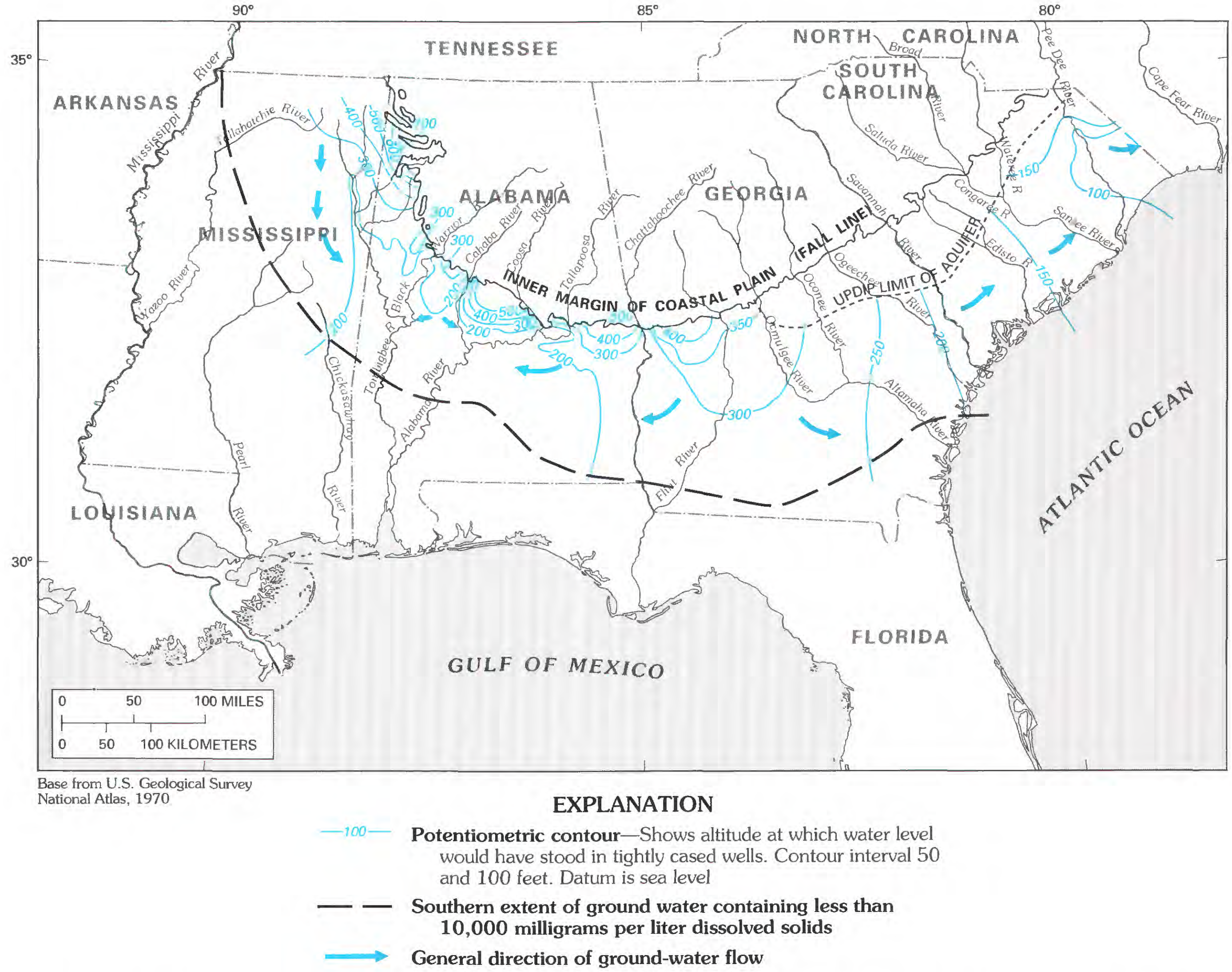


FIGURE 7.—Predevelopment potentiometric surface of the Black Warrior River aquifer (modified from Stricker and others, 1985c).

leakance where heads in an overlying aquifer are higher than those in the deeper aquifer (fig. 10). Downward leakance occurs mostly where the shallower aquifer is unconfined or thinly confined, because these are generally the only places where head relationships permit the water to move downward across the confining unit separating the two aquifers.

A water budget for the Southeastern Coastal Plain aquifer system prior to development can be calculated by combining simulated components of the hydrologic cycle with estimates of precipitation, total runoff, and base flow derived from previous work. Such a budget is described in detail in chapter C of this Professional Paper, is briefly summarized here, and is illustrated in figure 11. Average annual precipitation ranges from 44 to 64 in over the entire study area, and averages about 51 inches in outcrop recharge areas (Cederstrom and others, 1979). Most of the precipitation is discharged to small streams in the aquifer outcrop areas as overland flow (direct runoff) or as base flow to streams, or it evaporates or is transpired by plants. Total runoff, including base flow and overland flow, generally ranges between 10 and 20 in/yr in outcrop areas, except in western Alabama and eastern Mississippi, where it ranges between 20 and 25 in/yr (Busby, 1966). Average total runoff (sum of overland flow and base flow) in the outcrop areas is about 18 in/yr. Evapotranspiration is estimated to be almost 32 in/yr.

Only a small part of the precipitation enters the deep, confined parts of the regional ground-water flow system. The average simulated rate of recharge that enters the deep, confined parts of the system from precipitation is about 0.6 in/yr; about 0.1 in/yr enters as downward leakage from the overlying Floridan aquifer system. Of

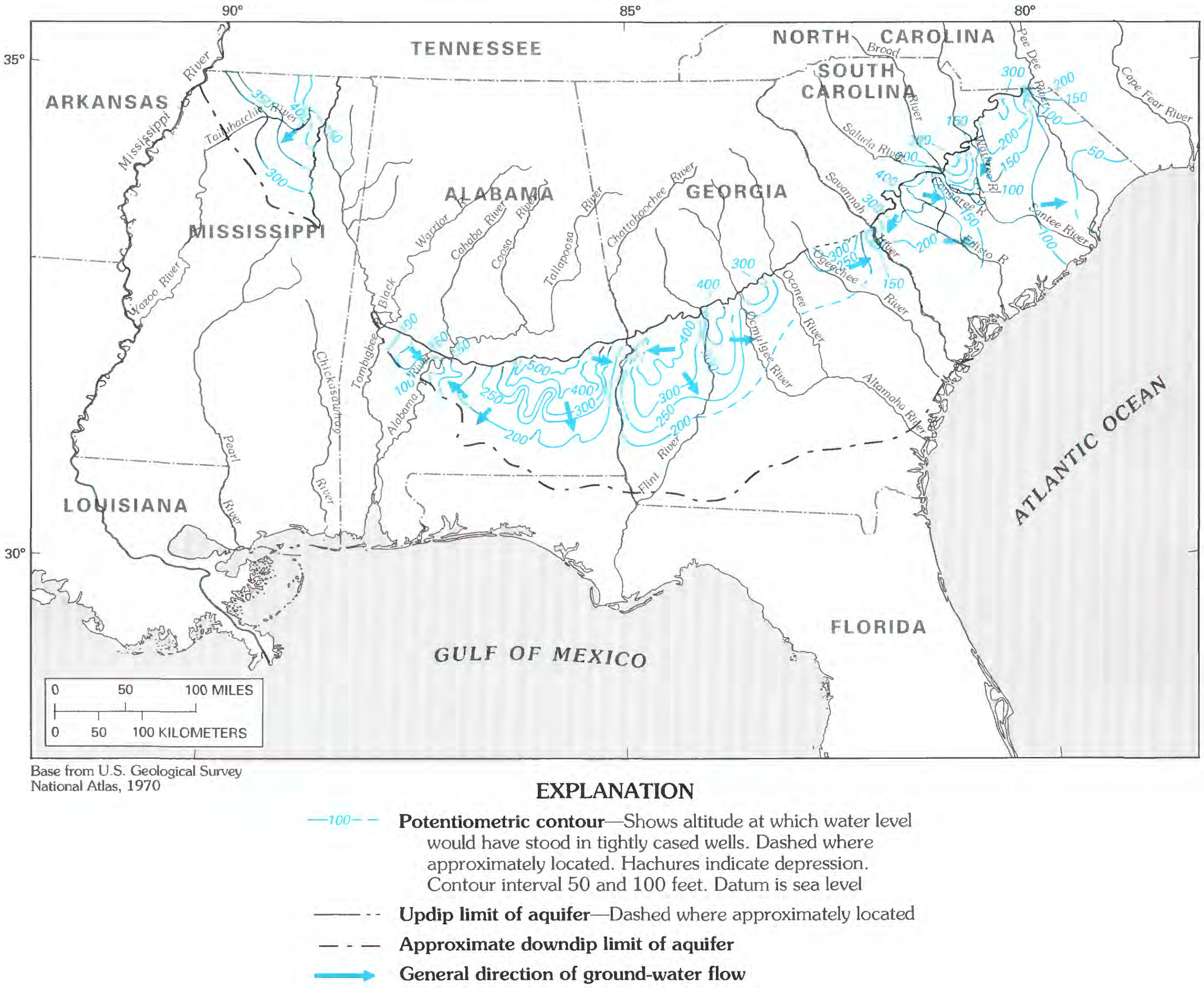


FIGURE 8.—Predevelopment potentiometric surface of the Chattahoochee River aquifer (modified from Stricker and others, 1985b).

this amount, approximately 0.5 in/yr discharges to major streams and about 0.2 in/yr discharges by diffuse upward leakage to shallower aquifers. The deep recharge and downward leakage from the Floridan aquifer system are the parts of the ground-water flow system simulated by the regional digital computer model.

The regional model used to analyze the ground-water flow system cannot simulate the system in detail, primarily because of its coarse grid, with cells of 64 mi^2. The model can simulate discharge to only the major streams shown in figures 7 through 9. Such streams have drainage basins of greater than 1,000 mi^2.

Toth (1963) proposed the existence of local, intermediate, and regional systems of ground-water flow in many areas, as shown in figure 12. Applying Toth's concept to the Southeastern Coastal Plain aquifer system, most ground water moves relatively quickly along short flowpaths such as those labeled "local" and "intermediate" in figure 12 and discharges to small- to intermediate-scale surface drains. The regional model simulates only the deep part of the flow system, labeled "regional" in figure 12, where ground water moves relatively slowly and follows long flowpaths before discharging to major streams. Because the model cannot simulate the local and intermediate parts of the flow system, only that fraction of the recharge that provides the regional component of the flow system is used in the model.

Discharge from the regional flow system under predevelopment conditions is primarily to major streams and secondarily by upward leakage across confining units into shallower aquifers. The upstream bending of poten-

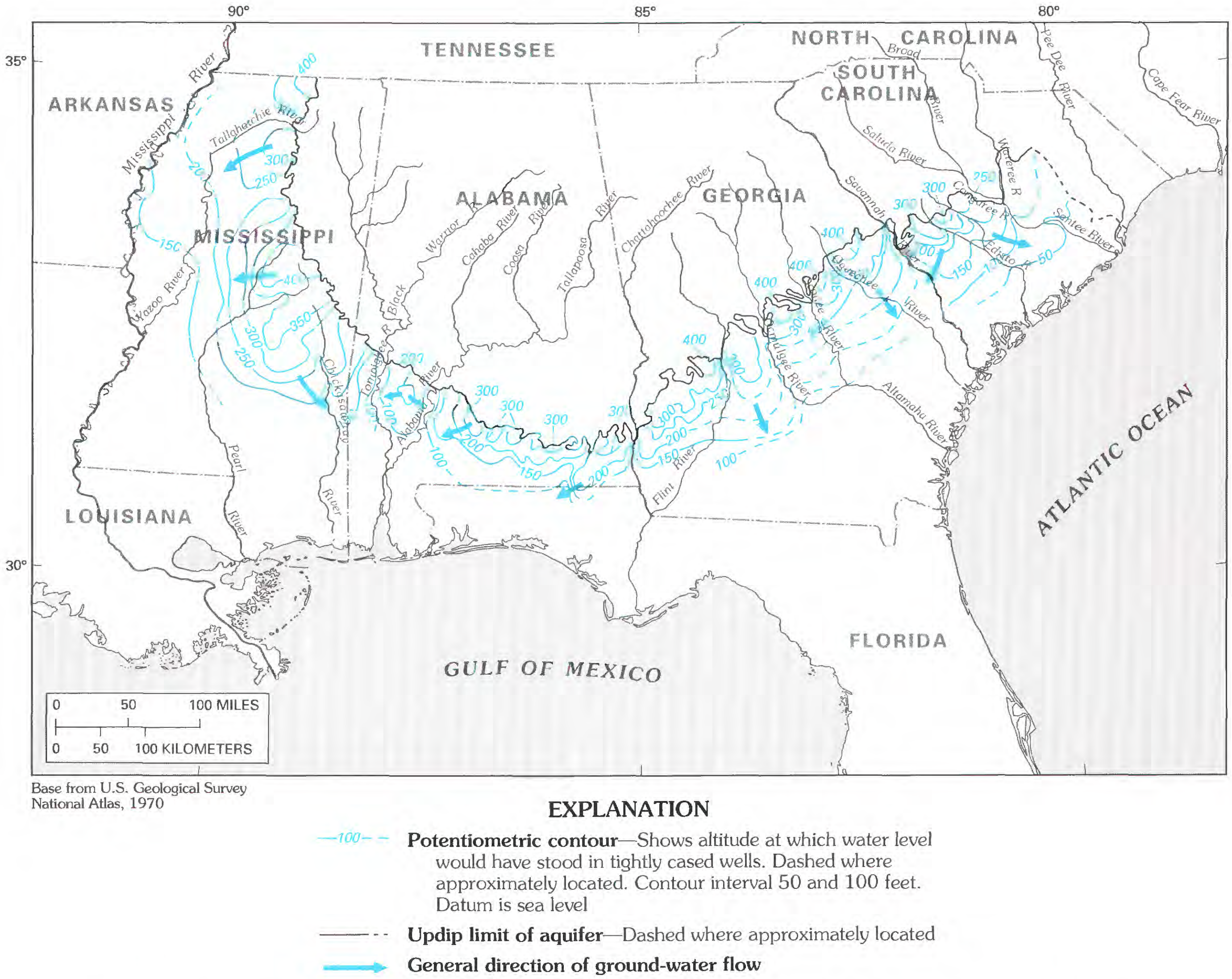


FIGURE 9.—Predevelopment potentiometric surface of the Pearl River aquifer (modified from Stricker and others, 1985a).

tiometric contours in figure 7 shows that water in the Black Warrior River aquifer is discharging to the Chattahoochee, Cahaba, and Black Warrior Rivers mostly where the aquifer is thinly confined or unconfined. In contrast, large rivers in most of Georgia and South Carolina, where the aquifer is thickly confined, have little effect on the aquifer's potentiometric surface. In such areas, water in the aquifer is discharged solely by diffuse upward leakage (fig. 10). The amount of upward leakage is small, but leakage takes place over a wide area.

Pumpage from wells in 1985 accounted for about 30 percent of the total ground-water discharge. Regionally, the aquifer system is not intensively pumped, partly because it is overlain over much of the study area by more prolific aquifers, such as the Floridan aquifer system. Ground-water development in the Southeastern Coastal Plain aquifer system is largely limited to public supplies and domestic and agricultural uses. In places, heavy pumpage has resulted in local water-level declines of as much as 100 ft below estimated predevelopment water levels. Total water use from the entire aquifer system during 1985 was estimated at about 650 Mgal/d, with about 250 Mgal/d being pumped by municipalities.

Rates and directions of ground-water flow are quite different at different places in the regional aquifer system. Where water enters the aquifers in topographically high parts of their outcrop areas, flow is mostly downward and the water moves rapidly along short flowpaths to discharge into small streams. Flow in middip areas, where the aquifers are confined, is mainly lateral and the water moves more slowly along relatively long flowpaths. Much of the lateral flow is down the dip of the aquifers; however, an important component of lateral

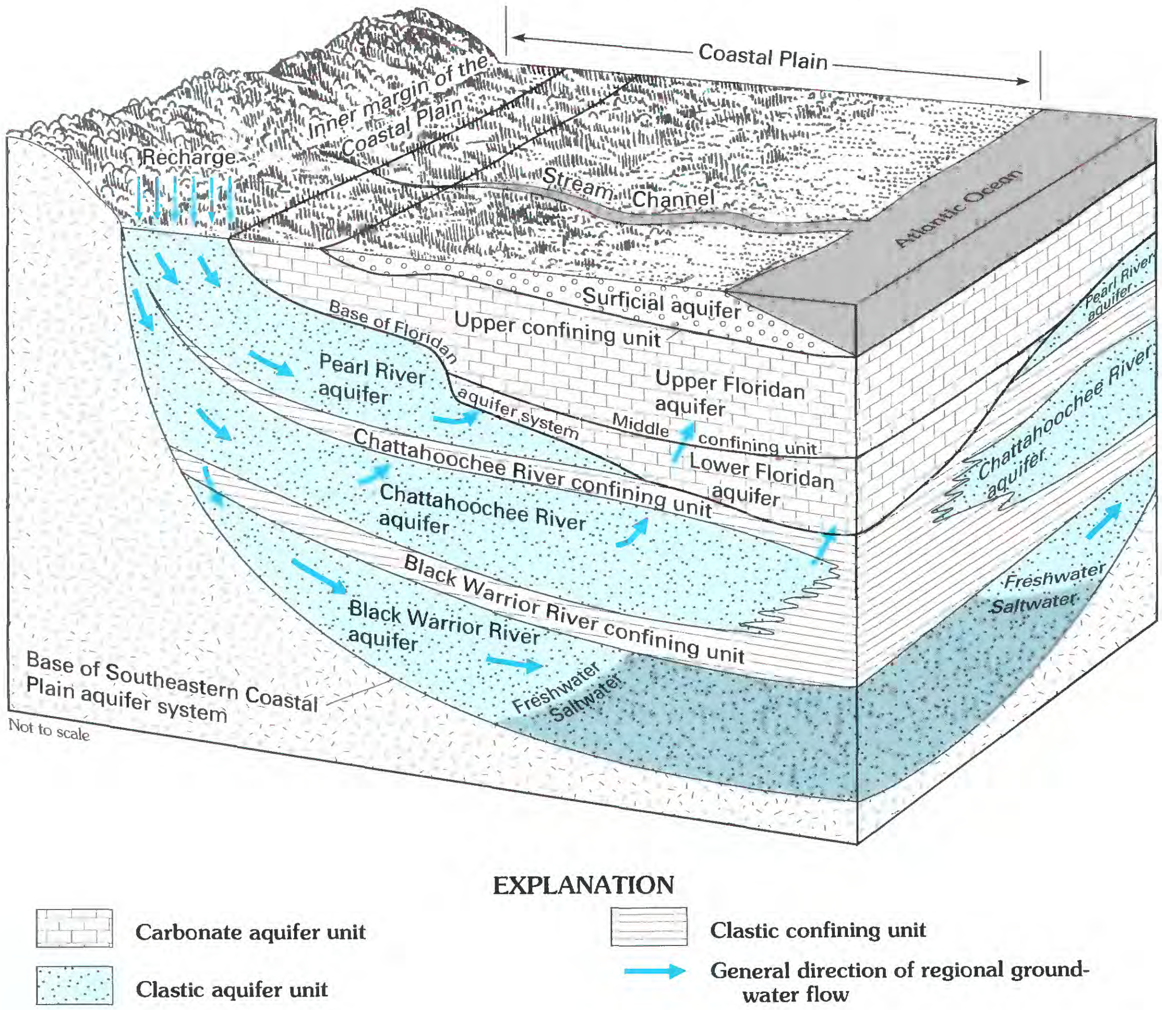
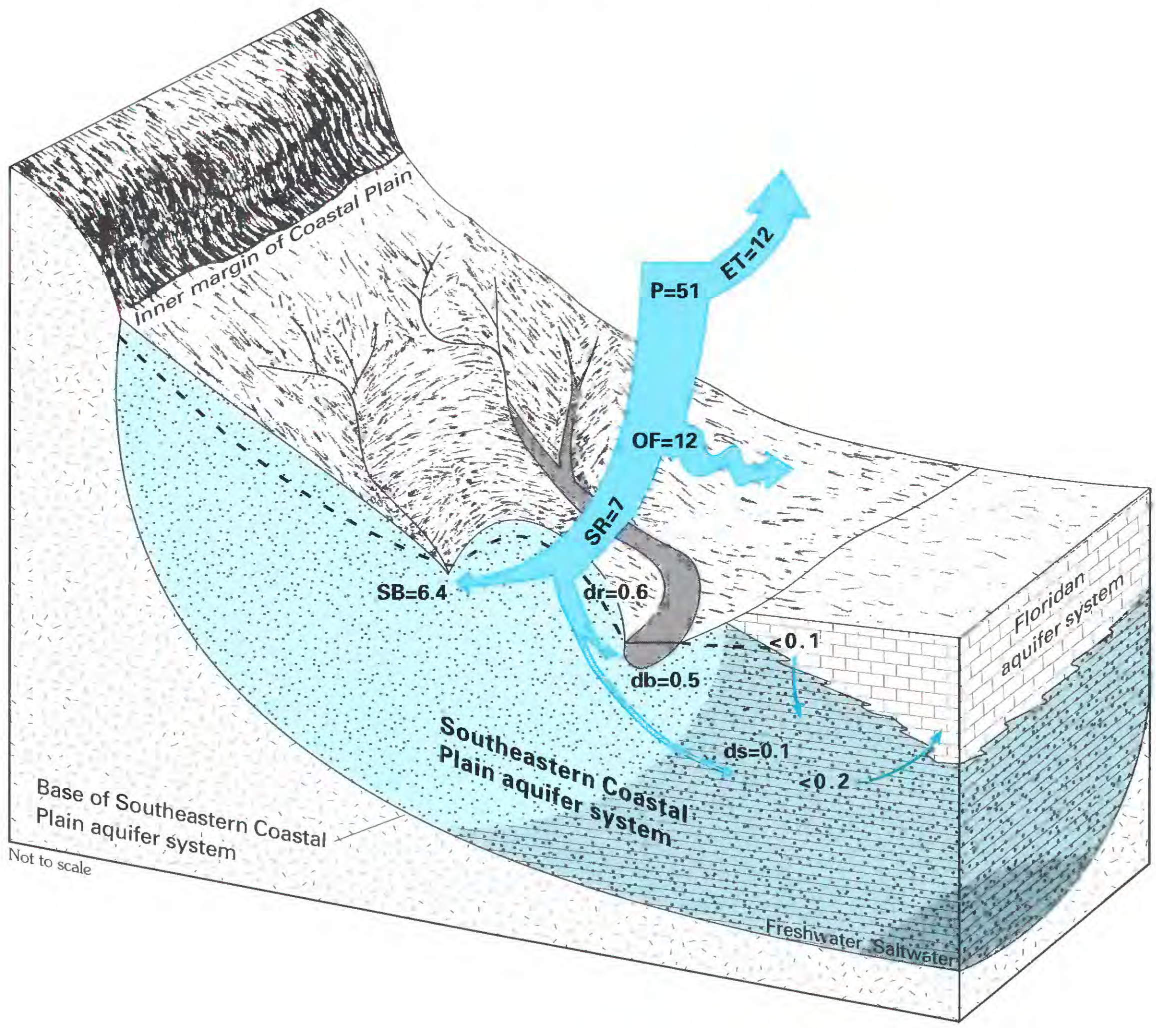


FIGURE 10.—Relation between hydrogeologic framework and simulated flow directions along a hypothetical dip section through Georgia (modified from Barker, 1986).

flow is parallel to the strike of the aquifers (see Mallory, 1987, and chapters E and G of this Professional Paper). Flow in downdip areas is mostly upward because of the combination of (1) decreasing horizontal conductivity in downdip parts of the aquifers and (2) a rapid buildup in dissolved-solids concentrations in the water, thus increasing its density. These factors combine to cause the water to move upward into shallower aquifers that are more permeable and contain fresher water.

SIMULATION OF THE REGIONAL FLOW SYSTEM

Computer models were used to simulate ground-water flow within the aquifers of the Southeastern Coastal Plain aquifer system. The models were most useful in simulating the large-scale effects of the hydrologic cycle on the ground-water flow system and in quantifying flow rates. They were also helpful, however, in assessing the regional hydraulic properties of aquifers and confining units and in estimating predevelopment potentiometric surfaces. Additionally, the models served as a mechanism for checking the logic and concepts of the regional hydrogeologic framework. As previously mentioned, data compiled for the construction of four subregional models were incorporated in a regional model that simulates flow conditions over the entire study area (fig. 3). The subregional models allow greater resolution than the regional model because of their finer scale (grid cells 4 mi on a side versus 8 mi on a side for the regional model). The hydraulic properties of an aquifer are assumed to be constant over the area of a grid cell. The value of a particular aquifer property, such as transmissivity, is averaged for the cell area. The regional model calculates a water budget for the entire aquifer system and simulates flow across the common boundaries of contiguous subregional models. All the simulations use a modular three-dimensional finite-difference ground-water flow



EXPLANATION

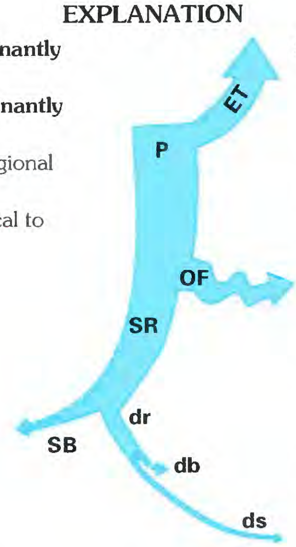
Aquifer in outcrop area, under predominantly unconfined conditions

Aquifer in subcrop area, under predominantly confined conditions

Major stream—Interacts primarily with regional flow system

Small stream—Interacts primarily with local to intermediate flow system

- - - **Hydraulic head**



Schematic depiction of average annual water budget—Based on published data and results of steady-state simulation. Numbers are flow rates, in inches per year

Nonsimulated:

P=**Precipitation**

ET=**Evapotranspiration**

OF=**Overland flow**

SR=**Shallow (total) recharge**—The percolation of precipitation below land surface that is lost neither to overland flow nor evapotranspiration

SB=**Shallow base flow (to small streams)**

Simulated:

dr=**Component of shallow (total) recharge that percolates to deep and confined part of the aquifer system**

db=**Deep base flow (to major streams)**

ds=**Deep seepage**—Component of total recharge that does not discharge to streams but discharges as diffuse upward leakage

FIGURE 11.—Generalized diagram relating simulated and nonsimulated components of the hydrologic cycle and annual predevelopment water budget for the Southeastern Coastal Plain aquifer system (modified from Barker, 1986).

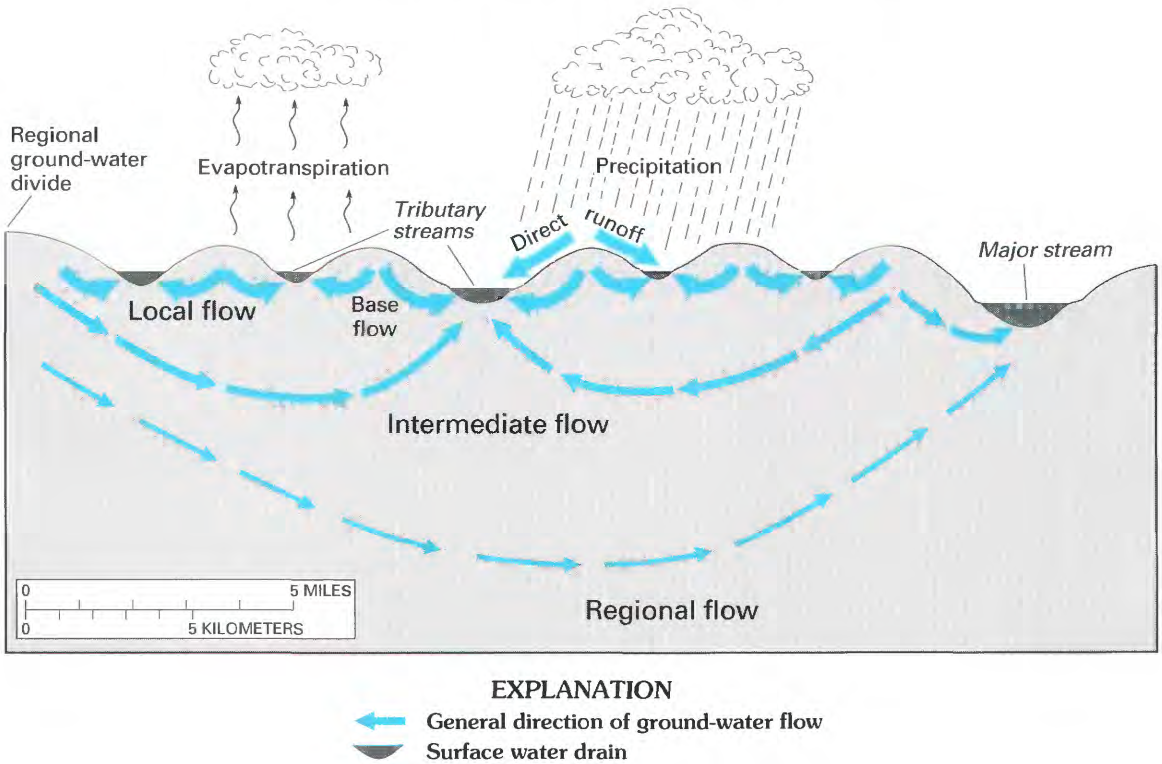


FIGURE 12.—Relation between stream size and components of the ground-water flow system discharging into the surface drainage system (modified from Toth, 1963).

model developed by McDonald and Harbaugh (1984). The subregional models generally conform to the regional model, but they may depart from it in order to more accurately simulate local features or conditions. The design of the regional model, the assumptions used in its construction, and the preliminary modeling results are discussed in a report by Barker (1986). A report by Aucott (1988) on the South Carolina subregional model describes its design and preliminary results. The regional model is described in chapter C, and detailed discussions of the final results of the four subregional models are presented in chapters E through H of this Professional Paper.

Figure 13 shows schematically how the different hydrogeologic units of the Southeastern Coastal Plain aquifer system were translated into model units. In the regional model, the Pearl River, Chattahoochee River, and Black Warrior River aquifers were simulated actively by separate layers. These actively simulated aquifer layers are overlain by an aquifer layer that was treated as a source-sink bed and represents either (1) the Chickasawhay River aquifer where the aquifer is a water-table aquifer (unconfined), (2) the Upper Floridan aquifer (Miller, 1986), or (3) rocks hydraulically connected to the Upper Floridan aquifer in South Carolina that were called the "surficial aquifer" by Renken (1984). Bush and Johnston (1988) simulated the Floridan aquifer system; their simulated heads for the Upper Floridan aquifer were assumed to be constant and were used for the source-sink layer in the Southeastern Coastal Plain model. Locally, in Mississippi and western Alabama, aquifers equivalent to the Pearl River aquifer have been simulated as part of the Mississippi embayment aquifer system by the Gulf Coastal Plain RASA study. Accordingly, these aquifers were also treated as a source-sink layer, and either heads or flux simulated by the Gulf Coastal Plain RASA were used in the Southeastern Coastal Plain model. In southeastern Georgia, the Pearl River aquifer grades by facies change into carbonate rocks that are part of the Lower Floridan aquifer. Where the Pearl River and Lower Floridan aquifers are hydraulically connected to form a single unit having predominantly lateral ground-water flow, they were treated as a single model layer in order to most accurately simulate the interconnection between the Floridan and Southeastern Coastal Plain aquifer systems.

The boundary conditions chosen for the regional model reflect field conditions and are consistent with conditions in contiguous aquifer systems. No-flow boundaries were used to represent three types of conditions in the Southeastern Coastal Plain aquifer system. The first type is the contact that marks the updip limit of a given aquifer where it pinches out. The second is the downdip location where freshwater movement becomes insignificant

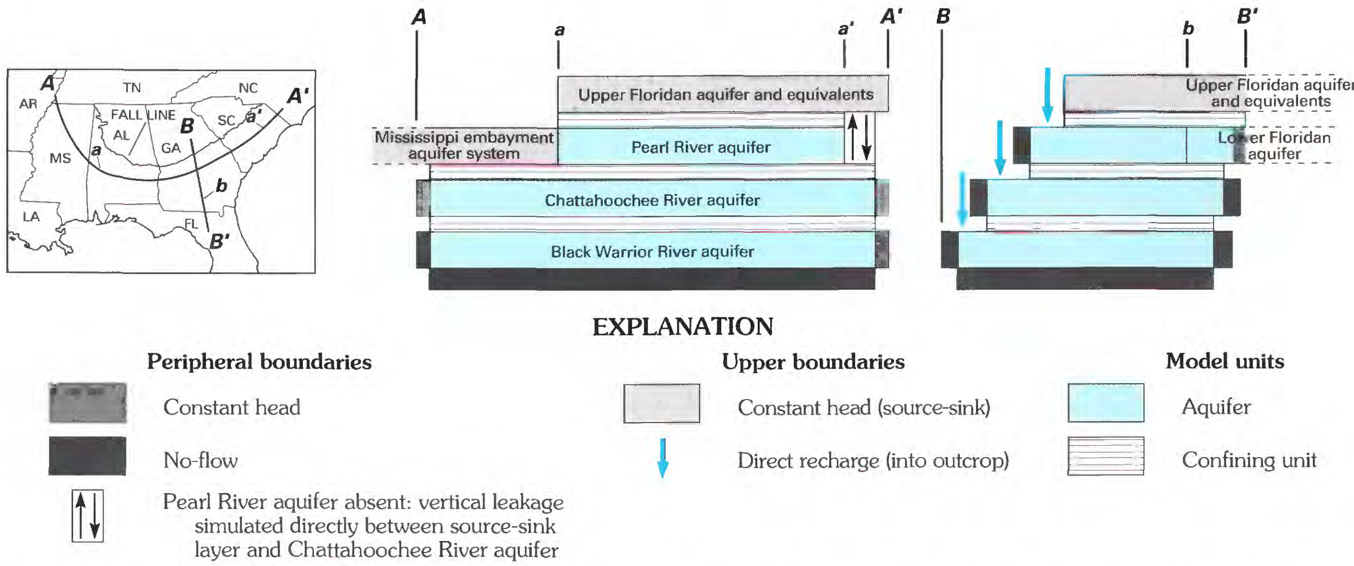


FIGURE 13.—Schematic sections *A–A′* and *B–B′* showing simulated aquifers, confining units, and boundary conditions in the regional flow model (from Barker, 1986).

either because the permeability of an aquifer decreases by facies change or because the freshwater-saltwater interface is encountered. The interface is defined in this study as the zone where ground water contains dissolved-solids concentrations of 10,000 mg/L. Third, no-flow boundaries were used in the vicinity of the Mississippi-Tennessee State line in the lowermost active model layer. This was done in order to artificially truncate these layers along lines nearly perpendicular to equipotential lines where these aquifers become part of an abutting aquifer system. Constant-head boundaries were used at the edges of other active model layers in the vicinity of these State line boundaries because differences in the potentiometric surfaces preclude the use of no-flow boundaries for these layers. Constant-head boundaries were also used for the source-sink layer that overlies the active layers in many places. Heads simulated by models of the Floridan and Mississippi embayment aquifer systems were incorporated in the source-sink layer, thus coupling the simulation results of the adjacent regional models.

The Southeastern Coastal Plain aquifer system in each of the four subregions (fig. 3) was studied in greater detail than was possible for the regional assessment of the system. As part of this more detailed scrutiny, the regional aquifers and confining units were subdivided into smaller, discrete hydrogeologic units in the subregions. The subdivisions of the regional hydrogeologic units in each of the four subregions and the correlation of the local aquifers and confining units from State to State are shown in figure 14.

All the regional aquifers and confining units are subdivided in at least one of the subregional areas. For example, the Black Warrior River aquifer is subdivided into two aquifers separated by a confining unit in all States except South Carolina. In Georgia, the Chattahoochee River aquifer is divided into three local aquifers and two confining units. Several other subdivisions were made and are discussed in chapters E through H of this Professional Paper.

Although the regional hydrogeologic units have been subdivided at a subregional scale, their overall hydrologic character is similar throughout the study area. The strata included in the Black Warrior River aquifer, for example, are everywhere more permeable than the rocks of the overlying and underlying regional confining units. There is a confining unit that extends from Mississippi through Georgia within the Black Warrior River aquifer (fig. 14), but most of the rocks included in the regional aquifer and its subregional divisions constitute aquifers. The tops and bases of practically all the regional aquifers correspond to the tops and bases of some combination of subregional aquifers. The tops and bases of regional confining units likewise correspond to those of combinations of subregional confining units.

HYDRAULIC CHARACTERISTICS OF AQUIFERS

The clastic sediments that compose the aquifers and confining units of the Southeastern Coastal Plain aquifer system are complexly interbedded, and the thickness and lithology of the sediments are extremely variable. Accordingly, the hydraulic properties of the aquifers and

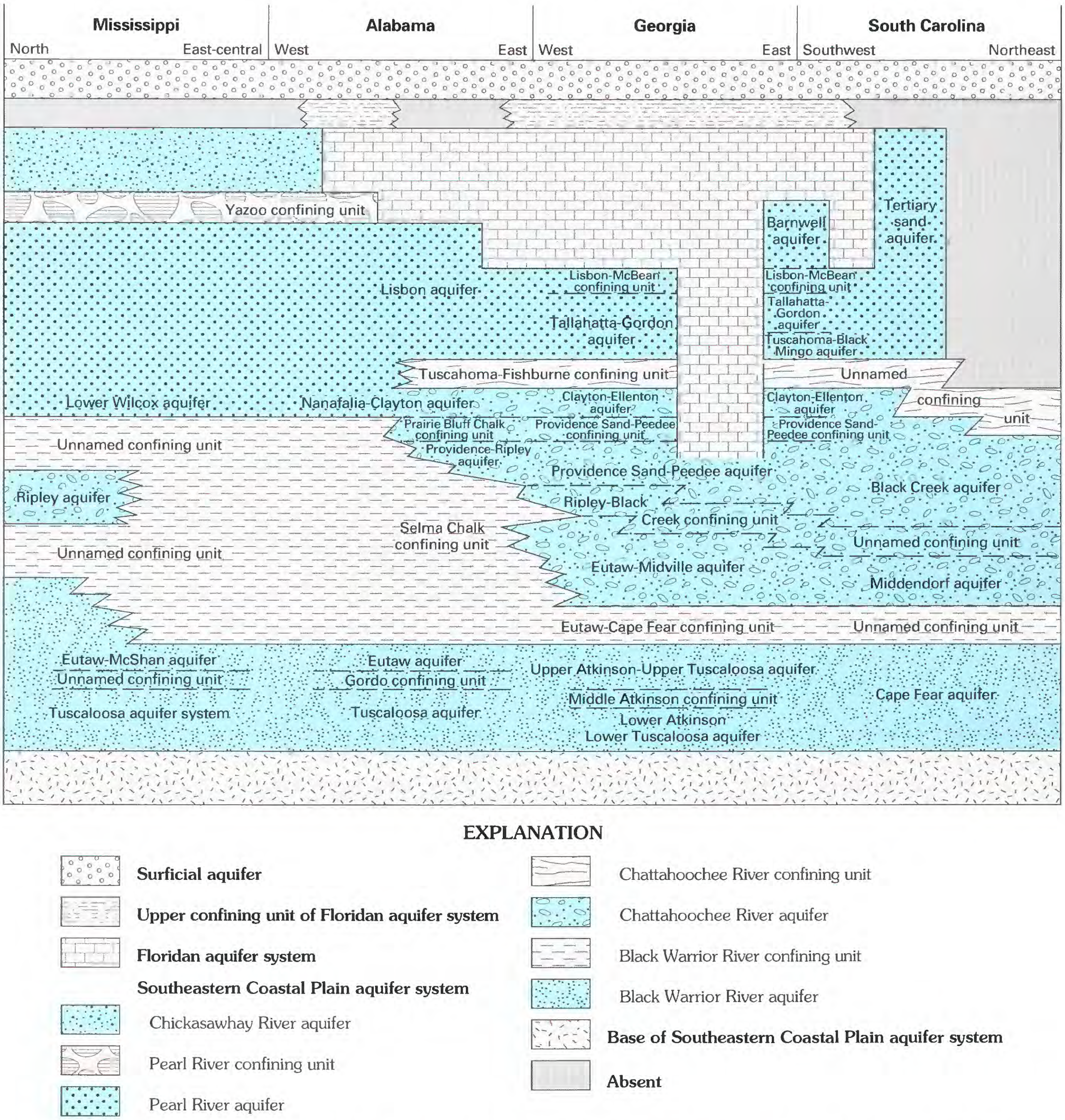


FIGURE 14.—Relation among regional and subregional hydrogeologic units in the Southeastern Coastal Plain aquifer system.

confining units also vary, because these properties are determined largely by sediment grain size and sorting, and by bed thickness and extent. The permeability, transmissivity, and storage coefficient of the aquifers, and the leakance of the confining units separating the aquifers, are all greatly affected by variations in geology.

PERMEABILITY

The permeability of the clastic sediments that make up the aquifers of the Southeastern Coastal Plain aquifer system is determined primarily by the texture and degree of sorting of the sediment, which, in turn, are largely determined by the energy conditions present in a particular depositional environment. For example, coarse sand or gravel are likely to be laid down where strong currents winnow away finer material. Such coarse materials make up excellent aquifers, particularly if they are well sorted. Silt and clay, in contrast, are more likely to be deposited in quiet waters; these materials make up effective confining units, particularly where they are thick and continuous. Because clastic sediments are relatively chemically inert, they are not greatly affected by diagenesis, and their original hydraulic characteristics are preserved more or less intact, especially in places like the study area where they are not deeply buried.

The texture of the sediments in the regional aquifers of the Southeastern Coastal Plain aquifer system is highly variable because the rocks were laid down in complexly varying depositional environments. All the regional aquifers, however, are generally more permeable in updip areas because the sediments constituting them are largely of fluvial origin there. These rocks grade seaward into deltaic deposits that contain more clay beds but are thicker in aggregate than the fluvial deposits. Farther coastward, the deltaic beds grade into marginal marine rocks that are sandy if they represent shoreline deposits or clayey if they were deposited in marshes or lagoons. Still farther downdip, the percentage of fine-grained material such as silt and clay increases in all the regional aquifers, reflecting deposition in quieter, marine waters. Permeability in the regional aquifers, therefore, is higher in updip areas and decreases in the direction of the present-day coastline and toward the axis of the Mississippi embayment.

The thickness of the regional confining units increases, and their permeability decreases, toward the present-day coast as a result of more marine depositional environments downdip. Accordingly, analysis of aquifer-test data from multiple-well tests primarily used the Theis (1935) procedure for nonleaky aquifers, except where confining units are thin and (or) discontinuous. In such places, the Hantush-Jacob (Hantush and Jacob, 1955) method for analysis of leaky confined aquifers was used.

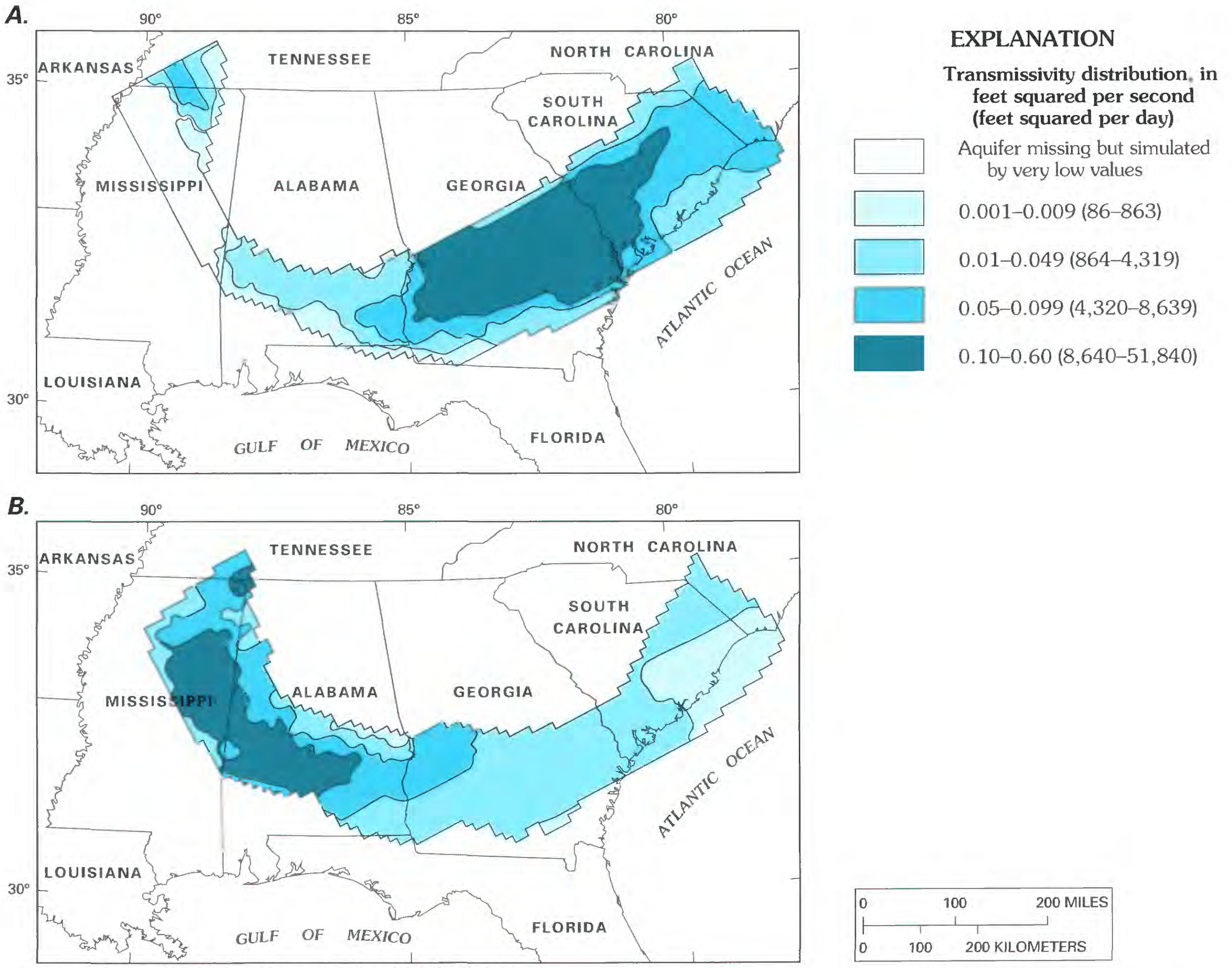
TRANSMISSIVITY

Transmissivity values for the regional aquifers of the Southeastern Coastal Plain aquifer system were derived from several sources, including aquifer-test results, specific-capacity estimates, and aquifer-diffusivity calculations. Prior to this study, no regional maps of transmissivity distribution existed, and no attempt had been made to group the numerous small-scale aquifers into regional aquifers. Accordingly, most published and unpublished transmissivity values were derived from aquifer tests where only part of a regional aquifer was penetrated. About 225 transmissivity values were available from aquifer-test data; most of these were from the Chattahoochee River aquifer in Georgia and South Carolina. Nearly 300 transmissivity estimates were made from specific-capacity data, the majority of them for the Chattahoochee River aquifer in Alabama and Georgia. Thirteen additional transmissivity estimates were made by Stricker (1983) from calculations of hydraulic diffusivity in small stream basins in the study area. Finally, in downdip areas for which hydraulic data of any type are sparse, estimates of transmissivity were made on the basis of the geology of the regional aquifers.

The distribution of calibrated transmissivity values used in simulating the Chattahoochee River and Black Warrior River aquifers is shown in figure 15. Both aquifers show a general coastward decrease in transmissivity because of increasing amounts of clay and silt in a downdip direction. This is not the case everywhere, however. The highest transmissivities in the Chattahoochee River aquifer are in central and eastern Georgia and southwestern South Carolina (fig. 15*A*) because the aquifer is thickest there. The high transmissivities in the Black Warrior River aquifer in eastern Mississippi and western Alabama (fig. 15*B*) are due in part to aquifer thickness and in part to the coarse-grained nature of the sediments making up the aquifer there.

Calibrated transmissivities used in modeling the Chattahoochee River aquifer range from about 0.001 to about 0.6 ft^2/s, or 86 to 52,000 ft^2/d. Transmissivity variations are best defined for this aquifer because more aquifer-test data are available for it. Most transmissivity values exceed 0.01 ft^2/s (864 ft^2/d), and the average for the entire aquifer is about 0.1 ft^2/s (8,640 ft^2/d). Variations primarily reflect differences in the grain size and sorting of aquifer sediments, but values are also strongly influenced by the thickness of the aquifer.

The distribution of calibrated transmissivity values used in simulating the Black Warrior River aquifer is shown in figure 15*B*. This aquifer, which is the most widespread aquifer in the Southeastern Coastal Plain aquifer system, has a range in transmissivity from about 0.001 to about 0.2 ft^2/s (86 to 17,280 ft^2/d), similar to that of the overlying Chattahoochee River aquifer. The average transmissivity of the Black Warrior River aquifer is about 0.06 ft^2/s (5,184 ft^2/d), somewhat less than the average of the Chattahoochee River aquifer. The westward increase in transmissivity in the Black Warrior River aquifer (fig. 15*B*) results from a combination of coarsening of aquifer materials and thickening of the aquifer toward the axis of the Mississippi embayment. The Black Warrior River aquifer is thin and consists of less permeable rocks from central Georgia eastward.



Base modified from U.S. Geological Survey digital data, 1:2,000,000. 1972

FIGURE 15.—Distribution of calibrated transmissivity values for simulations of (*A*) the Chattahoochee River aquifer and (*B*) the Black Warrior River aquifer (modified from Pernik, 1987).

STORAGE COEFFICIENT

Data on storage coefficient and specific yield in the study area are scarce. Fewer than 100 storage coefficient or specific yield calculations have been made from aquifer tests throughout the aquifer system. Accordingly, average values of storage properties were applied throughout each model layer during transient simulation and were adjusted during calibration so as to match observed hydrograph trends. The average initial values of storage coefficient used where the aquifers are confined were 1×10^{-4} for the layer simulating the Black Warrior River aquifer, 5×10^{-4} for the Chattahoochee River aquifer, and 5×10^{-3} for the Pearl River aquifer. Updip, outcropping parts of the Black Warrior River and Chattahoochee River aquifers have storage coefficients ranging from about 0.001 to about 0.1, and averaging about 0.01 (Barker and Pernik, in press, chapter C of this Professional Paper). These values are transitional between those usually considered to represent confined and unconfined conditions and suggest that these aquifers contain clay beds that create semiconfined conditions at and near their outcrop. In these semiconfined areas, some of the water from aquifer storage probably comes from dewatering and some from elastic compression of the aquifer system, thus accounting for the intermediate storage coefficient values. Updip parts of the Pearl River aquifer, in contrast, have average specific yield values of between 0.15 and 0.2, more typical of unconfined conditions. Regardless of the absolute values, all the aquifers show the expected coastward decrease in storage coefficient as the aquifer changes from unconfined to confined conditions.

LEAKANCE

Leakance of the confining units separating the regional aquifers in the Southeastern Coastal Plain aquifer system is highly variable and depends on the thickness of the confining units and the character of the material that makes them up. The aquifer system's confining units consist mostly of clay, but locally they are made up of silt or chalk of similar hydraulic properties. Although the thicknesses of the confining units have been mapped (Renken, in press, chapter B of this Professional Paper), almost no quantitative data exist for the vertical hydraulic conductivity of these units. Accordingly, initial leakance used for simulation was estimated from a hydraulic conductivity of 1×10^{-10} ft/s, derived from published values of clay conductivities divided by known confining unit thickness. Trial-and-error calibration of the computer model resulted in the maps of leakance distribution shown in figure 16.

Leakance of all the regional confining units generally is higher updip and decreases downdip. This is because the confining units, like the regional aquifers, are thinner and consist of coarser grained sediments updip. As the thickness of clay beds increases coastward, so does the amount of clay in the confining units. Accordingly, downdip leakance values in places are as small as about 5×10^{-16} per second, indicating a confining unit that is nearly impermeable. The overall leakance of the Pearl River confining unit (fig. 16*A*) is largest, and that of the Black Warrior River confining unit (fig. 16*C*) is smallest. In updip parts of the confining units, where leakance values are as large as 5×10^{-9} per second, water can be freely interchanged between regional aquifers. Much of the recharge to the Black Warrior River aquifer in eastern Georgia and western South Carolina occurs as downward leakage through the Black Warrior River confining unit.

EFFECTS OF DEVELOPMENT

Widespread water-level declines have occurred in the Southeastern Coastal Plain aquifer system in response to pumpage, which began about 1900 and by 1985 was about 495 Mgal/d. The aquifer system has adjusted to pumpage by a combination of increased inflow, decreased outflow, and a reduction in the amount of water in storage. The regional extent and magnitude of these changes are summarized here and discussed in detail in chapter C of this Professional Paper; more local effects are reported in chapters E through H. Simulation of the flow system using the regional and subregional models has aided understanding of the system's response to development.

Pumpage data were incorporated in the calibrated steady-state models, which were then recalibrated under transient conditions to approximate hydrograph trends and 1985 potentiometric surfaces. Figure 17 shows the simulated change in the hydraulic head of the Chattahoochee River aquifer from predevelopment (1900) conditions to 1985. As mentioned previously, the model cannot simulate local conditions exactly because of its relatively coarse grid. The simulated decline in water level shown in figure 17 is therefore not as large as the actual change in the areas of greatest decline. However, the most important areas of change, such as in eastern South Carolina, are closely matched by the model.

The Chattahoochee River aquifer is the most heavily pumped aquifer in the Southeastern Coastal Plain aquifer system, yielding more than half the total water withdrawn from the system. Figure 18 shows the amount of simulated pumpage from each of the aquifers of the system, as well as the magnitude of other components of the water budget for each aquifer, under 1981–85 conditions. During 1981–85, average pumpage was about 95 ft^3/s, or about 60 Mgal/d, from the Pearl River aquifer; about 495 ft^3/s, or 320 Mgal/d, from the Chattahoochee River aquifer; and about 175 ft^3/s, or 115 Mgal/d, from the Black Warrior River aquifer.

The effect of pumpage on the total ground-water flow system is summarized in figure 19, which compares simulated predevelopment (about 1900) and 1981–85 water budgets for the Southeastern Coastal Plain aquifer system. Simulation suggests that prior to development (fig. 19*A*), about 1,720 ft^3/s of the outcrop recharge of about 1,990 ft^3/s was discharged as base flow to major streams. Lateral inflow from the Mississippi embayment aquifer system in Mississippi and the McNairy-Nacatoch aquifer in Tennessee contributed a total of about 10 ft^3/s, equally divided between the two aquifers. About 5 ft^3/s discharged by lateral outflow from the combined Chattahoochee River and Black Warrior River aquifers to the Northern Atlantic Coastal Plain aquifer system. Lateral discharge of about 30 ft^3/s passed from the Pearl River aquifer into its carbonate equivalent, the lower part of the Floridan aquifer system, primarily in downdip areas of Georgia. Where the upper part of the Floridan aquifer system overlies the Southeastern Coastal Plain aquifer system, about 160 ft^3/s leaked downward from the Floridan. Farther downdip, the hydraulic gradient between the two aquifer systems is reversed, and about 385 ft^3/s leaked upward into the Floridan. The surficial aquifer in South Carolina received about 20 ft^3/s of water by upward leakage from the underlying Chattahoochee River aquifer. In updip areas where the Mississippi embayment aquifer system overlies the Southeastern Coastal Plain aquifer system, the latter system receives about 5 ft^3/s as downward leakage, which is offset by about 5 ft^3/s of upward leakage farther down the dip. A thick and effective confining unit separates these two

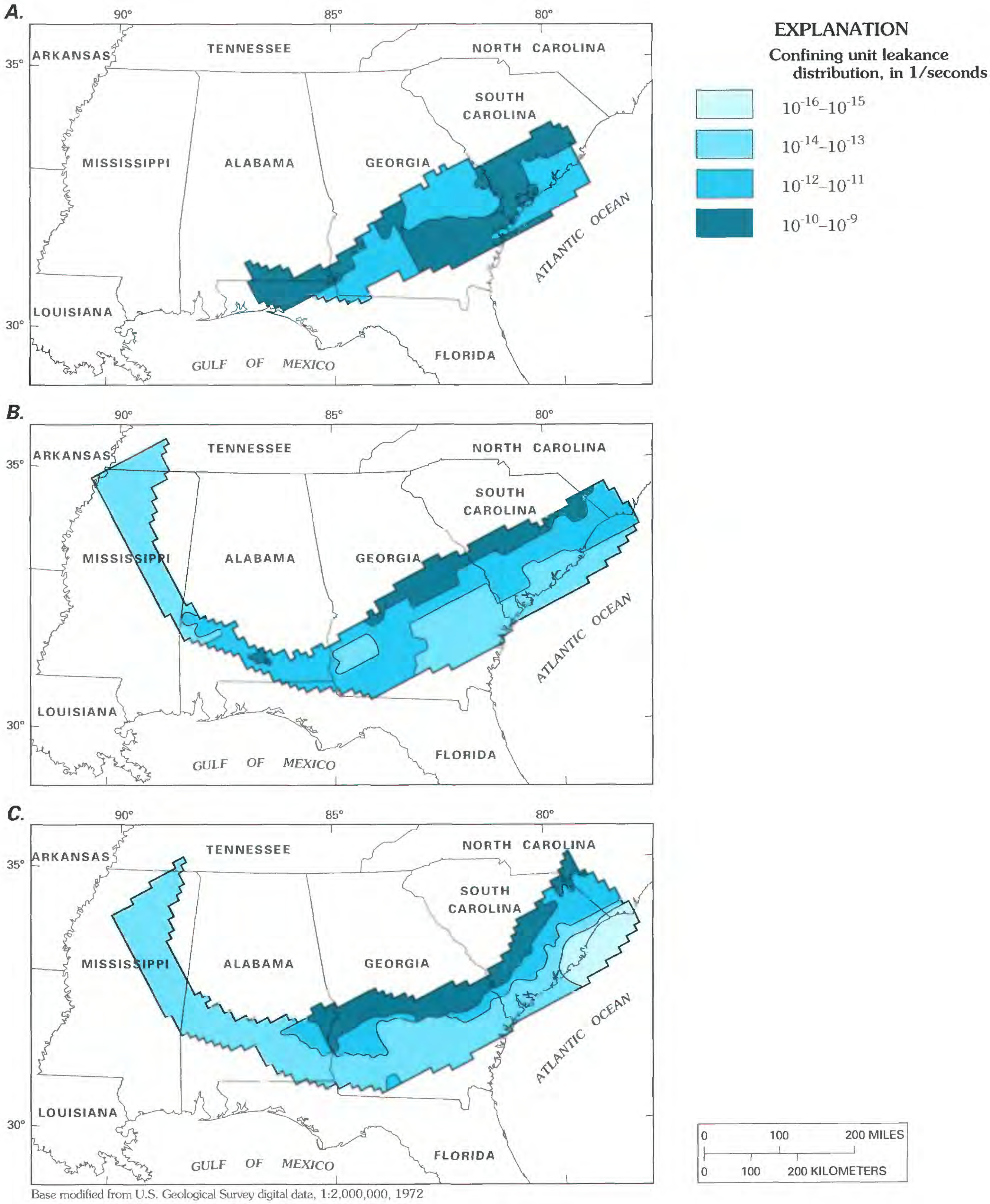


FIGURE 16.—Distribution of calibrated leakance values for simulations of (*A*) the Pearl River confining unit, (*B*) the Chattahoochee River confining unit, and (*C*) the Black Warrior River confining unit (after Pernik, 1987).

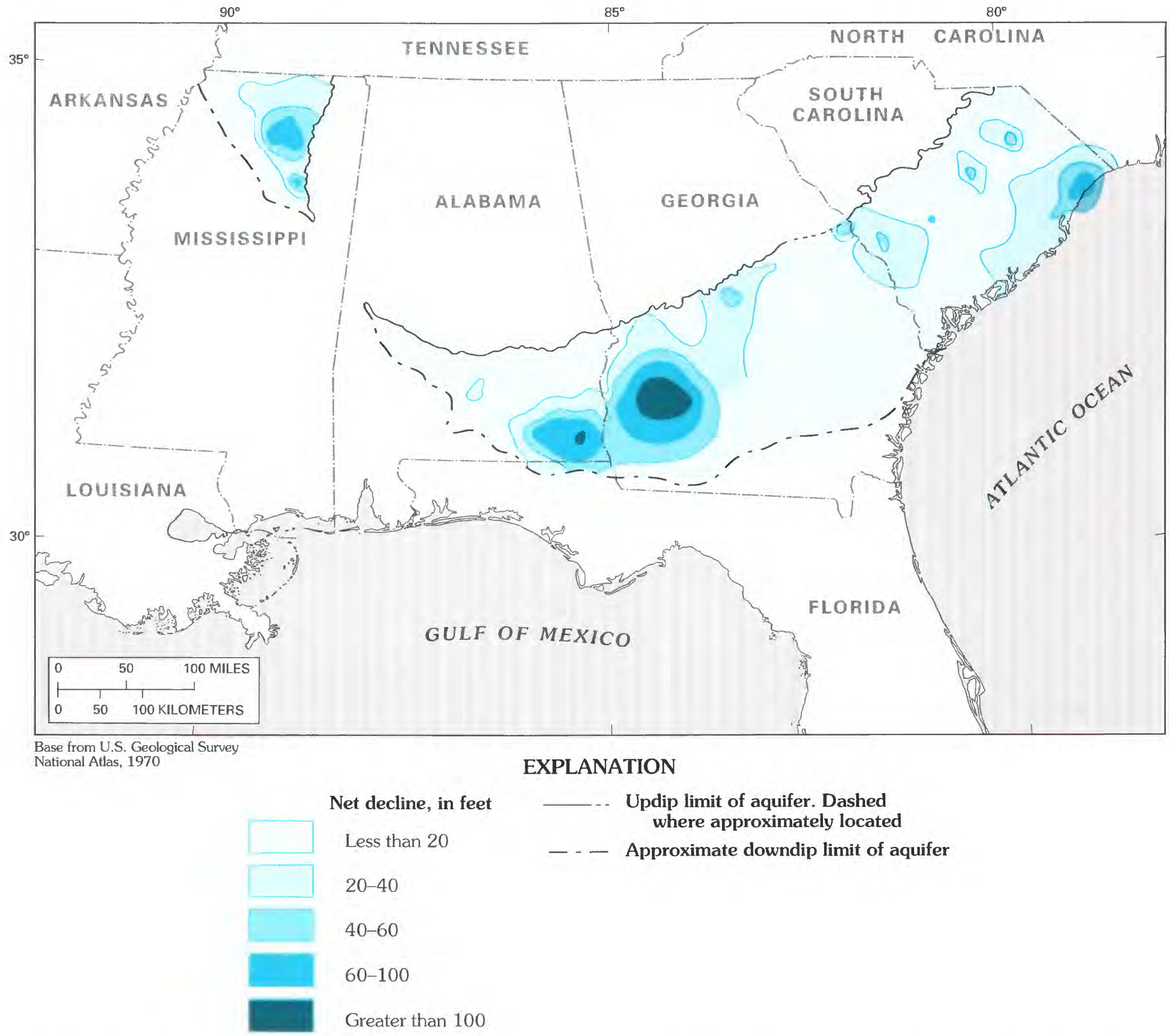


FIGURE 17.—Simulated change in hydraulic head in the Chattahoochee River aquifer from 1900 to 1985 (modified from Barker and Pernik, in press).

aquifer systems, accounting for the small amount of flux between them.

Figure 19*B* shows appreciable changes in some budget components when simulated pumpage of about 765 ft^3/s (495 Mgal/d) is applied to the aquifer system. Outcrop recharge was simulated as 1,990 ft^3/s, the same as the predevelopment recharge rate. The recharge rate was kept constant because most of the pumping centers are located in middip areas of the aquifer system, not in outcrop areas. Except in a few places, water levels in outcrop areas have not been affected by pumpage, as shown by field observations and suggested by simulation (fig. 17). In the few places where water levels in the outcrop areas have changed, the recharge rate undoubtedly has increased. However, with the large cell size (64 mi^2) of the regional flow model, it is impossible to simulate these changes in very small areas. Further discussion of these budget components and the rationale for specifying constant recharge rates for predevelopment and pumping simulations are presented in chapter C of this Professional Paper (Barker and Pernik, in press).

The small amounts of lateral and vertical flux between the Mississippi embayment and Southeastern Coastal

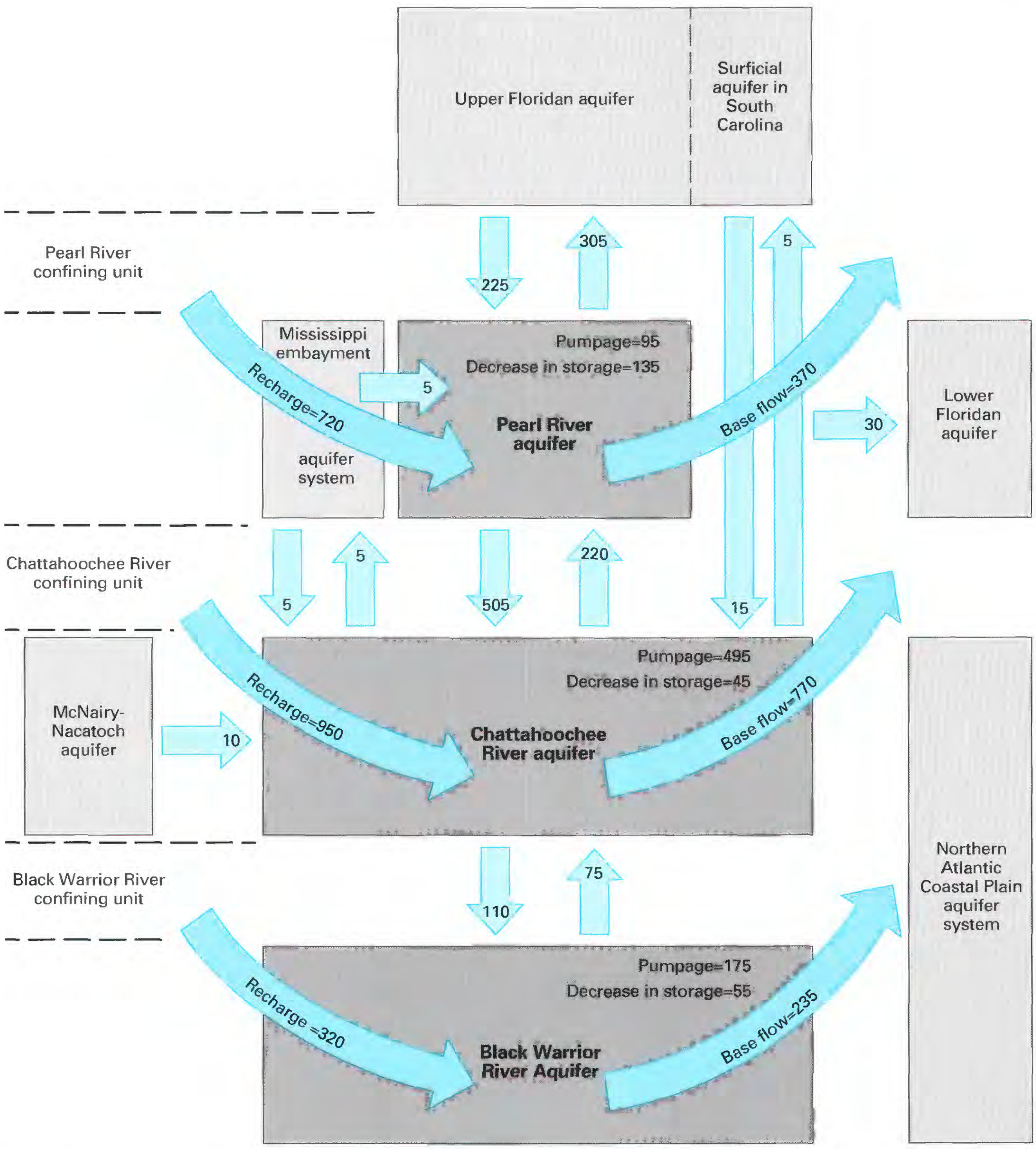


FIGURE 18.—Simulated water budgets for individual aquifers in the Southeastern Coastal Plain aquifer system, 1981–85 conditions. In cubic feet per second; values rounded to nearest 5 cubic feet per second (modified from Barker and Pernik, in press).

Plain aquifer systems and the lateral flow from the Pearl River aquifer into the Lower Floridan aquifer are also simulated as remaining constant. Lateral outflow into the Northern Atlantic Coastal Plain aquifer system decreases to practically nothing, and lateral inflow from the McNairy-Nacatoch aquifer is doubled, becoming about 10 ft^3/s. Simulated upward leakage to the Floridan aquifer system decreases by about 80 ft^3/s (from about 385 to 305 ft^3/s). Downward leakage from the Floridan increases about 65 ft^3/s (from about 160 to 225 ft^3/s).

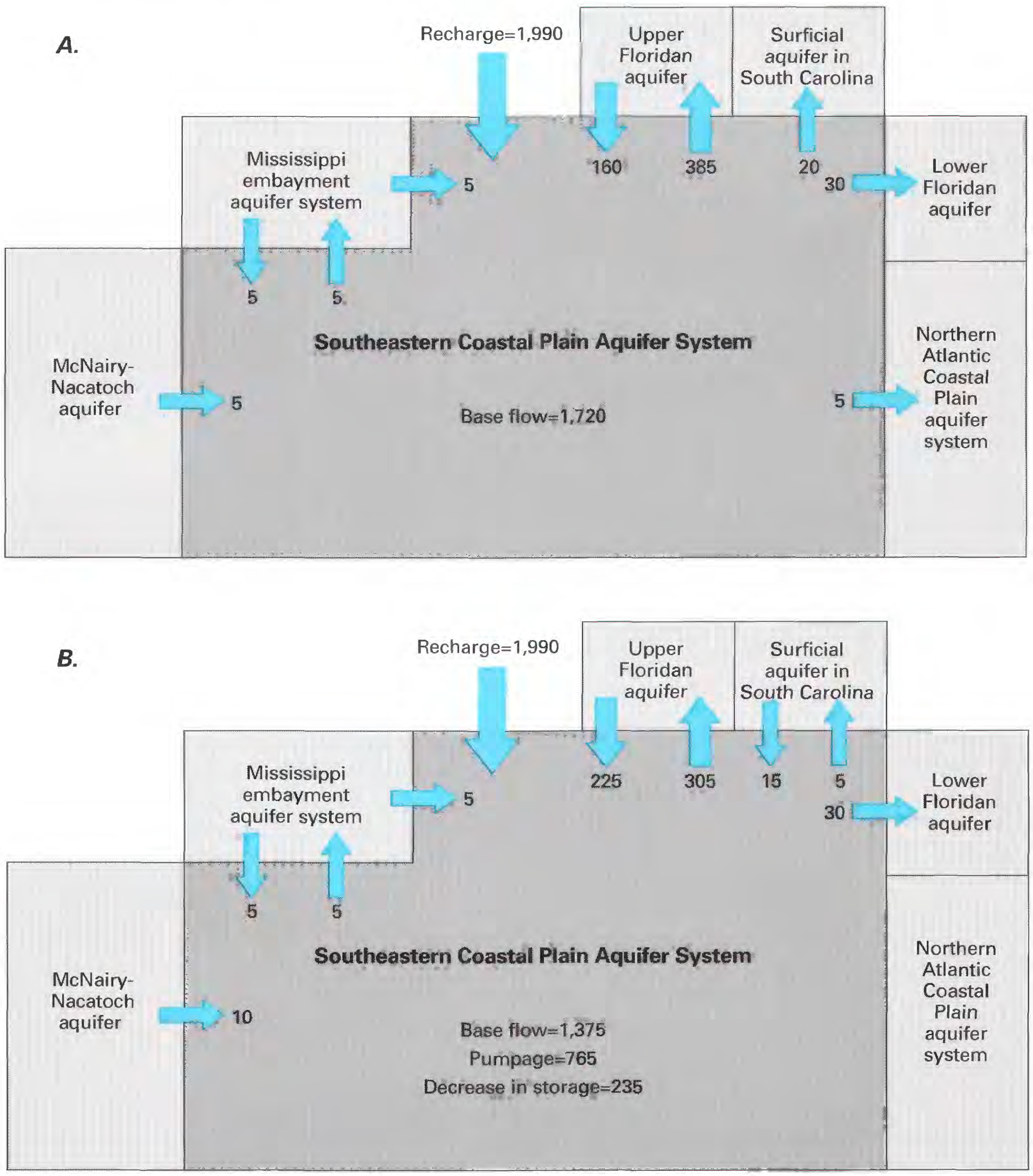


FIGURE 19.—Simulated water budgets for the Southeastern Coastal Plain aquifer system: *A*, Predevelopment (about 1900); *B*, 1981–85 conditions. In cubic feet per second; values rounded to nearest 5 cubic feet per second.

Upward leakage to the surficial aquifer in South Carolina is reduced about 15 ft^3/s (from 20 to 5 ft^3/s). About 15 ft^3/s leaks downward from this surficial aquifer into the Chattahoochee River aquifer. The greatest changes produced by the simulated pumpage are a decrease of about 345 ft^3/s in base flow (from about 1,720 to 1,375 ft^3/s) and the removal of about 235 ft^3/s from aquifer storage.

Comparison of figures 19*A* and 19*B* shows that there are four sources from which the simulated pumpage of about 765 ft^3/s (495 Mgal/d) is derived. Simulated reduction in base flow accounts for about 345 ft^3/s. Decreases in boundary outflow account for about 100 ft^3/s, and increases in boundary inflow contribute about 85 ft^3/s. The majority of the simulated change in boundary flux is between the Floridan and Southeastern Coastal Plain aquifer systems. The balance of about 235 ft^3/s is simulated as water derived from storage. The decrease in storage is documented by a long-term continuing head decline in the deeper aquifers. During the 1981–85 period of the water budget shown in figure 18, an average water-level decline of 2 to 3 ft/yr was observed in wells located in five pumping centers in both the Chattahoochee River and Black Warrior River aquifers. (See hydrographs presented in Professional Paper 1410–C (Barker and Pernik, in press)).

GROUND-WATER CHEMISTRY

Water in all the regional aquifers of the Southeastern Coastal Plain aquifer system generally shows the same changes in chemical quality as it moves down the hydraulic gradient from outcrop recharge areas to deeper, downgradient parts of the aquifers. Initial changes in water quality are gradual and result from water-rock interactions. More abrupt changes that occur downgradient are the consequence of mixing of freshwater with saline water. These changes, which are summarized here, are discussed in detail in chapter D of this Professional Paper. Chapter D also includes maps showing areal variations in ground-water quality, discusses the results of geochemical modeling, and provides estimates of flow rates based on isotope data.

Three water-bearing zones have been chemically delineated in the Black Warrior River (Lee, 1986) and Pearl River (Lee, 1988a) aquifers. Although they are chemically distinct, these water-bearing zones cannot be separated hydraulically except very locally. Chemical data for the Chattahoochee River aquifer show little or no vertical differences, and, accordingly, it is treated as a single zone (Lee, 1988b).

CHEMICAL CHARACTER OF THE GROUND WATER

Dissolved solids, dissolved chloride, and dissolved iron are three of the principal constituents of ground water whose concentrations vary spatially in the Southeastern Coastal Plain aquifer system. Variations in these constituents, when observed in conjunction with hydrochemical facies, which also vary spatially, provide evidence of the geochemical processes occurring in the aquifers. Concentrations of dissolved solids generally are less than 50 mg/L in outcrop recharge areas, and increase down the hydraulic gradient to as much as 500 mg/L as the result of mineral-water interactions (Lee, 1985). Waters having dissolved-solids concentrations of less than 500 mg/L are mostly sodium bicarbonate-dominated but may locally be calcium bicarbonate-dominated, especially in recharge areas where dissolved-solids concentrations are very low. Concentrations of dissolved solids greater than 500 mg/L usually occur in the deep parts of the aquifer system and result largely from mixing of freshwater and saline water. Sodium and chloride are the dominant ions in these mixed waters, whose dissolved-solids concentrations may exceed 100,000 mg/L in places. Much of the mixed sodium chloride water is seawater that has not been flushed from the aquifers. However, piercement salt domes in southern Mississippi are the source of locally high concentrations of dissolved solids in some ground waters (Spiers and Gandl, 1980). Brown and others (1979) reported dissolved-solids concentrations of greater than 100,000 mg/L in brines from deeply buried sand aquifers in south Georgia. The dissolved-solids distribution in the middle water-bearing zone of the Black Warrior River aquifer (fig. 20) is representative of the trend in concentrations of dissolved solids in all the regional aquifers.

Concentrations of dissolved chloride generally parallel the trends in dissolved-solids concentrations. In general, dissolved-chloride concentrations directly reflect the extent and degree of freshwater flushing in the aquifers. The freshwater may displace either relict seawater or brines. Concentrations of dissolved chloride gradually increase downgradient to the point where freshwater is mixed with saltwater and concentrations increase sharply. The distribution of dissolved chloride in the middle water-bearing zone of the Black Warrior River regional aquifer (fig. 21) is typical of the general trend in chloride concentrations in all the aquifers studied. In southern Mississippi, locally high concentrations of dissolved chloride reflect the influence of piercement salt domes. Sparse chemical data downgradient from the freshwater-saltwater mixing zone show that the very deep parts of the regional aquifers contain sodium chloride brines.

Dissolved-iron concentrations generally are less than 100 micrograms per liter (μg/L) in recharge areas, but they increase rapidly downgradient as chemically reducing environments develop within the aquifers. Where such conditions exist, dissolved-iron concentrations commonly increase to 1,000 μg/L and may exceed 10,000 μg/L. The high concentrations tend to occur in narrow bands approximately parallel to the trend of aquifer outcrop areas (fig. 22) as iron dissolves from the aquifer minerals. As chemical conditions change, iron precipitates downgradient and the concentrations decrease to less than 100 μg/L. Most of the iron precipitates as siderite (Lee, 1985). Still farther downgradient, concentrations of dissolved iron again increase as the salinity of the ground water increases, because iron solubility increases with increasing dissolved chloride.

Water can be classified into hydrochemical facies on the basis of the dominant major cations and anions it contains. The classification of ground water used in this study is patterned after, but differs slightly from, that of Back (1961). To illustrate the classification, a calcium

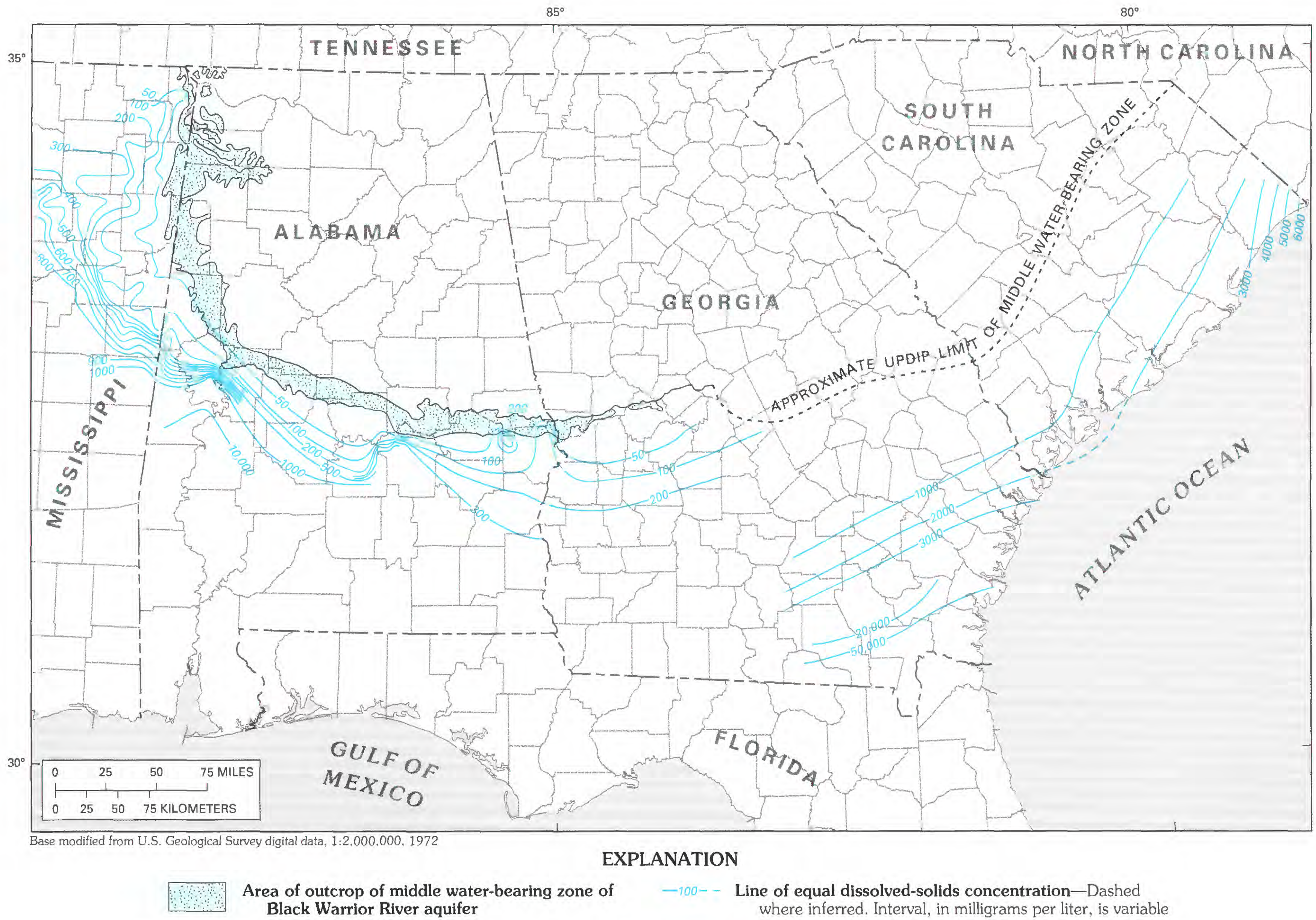


FIGURE 20.—Dissolved-solids concentrations in water from the middle water-bearing zone of the Black Warrior River aquifer (after Lee, 1986).

FIGURE 21.—Dissolved-chloride concentrations in water from the middle water-bearing zone of the Black Warrior River aquifer (after Lee, 1986).

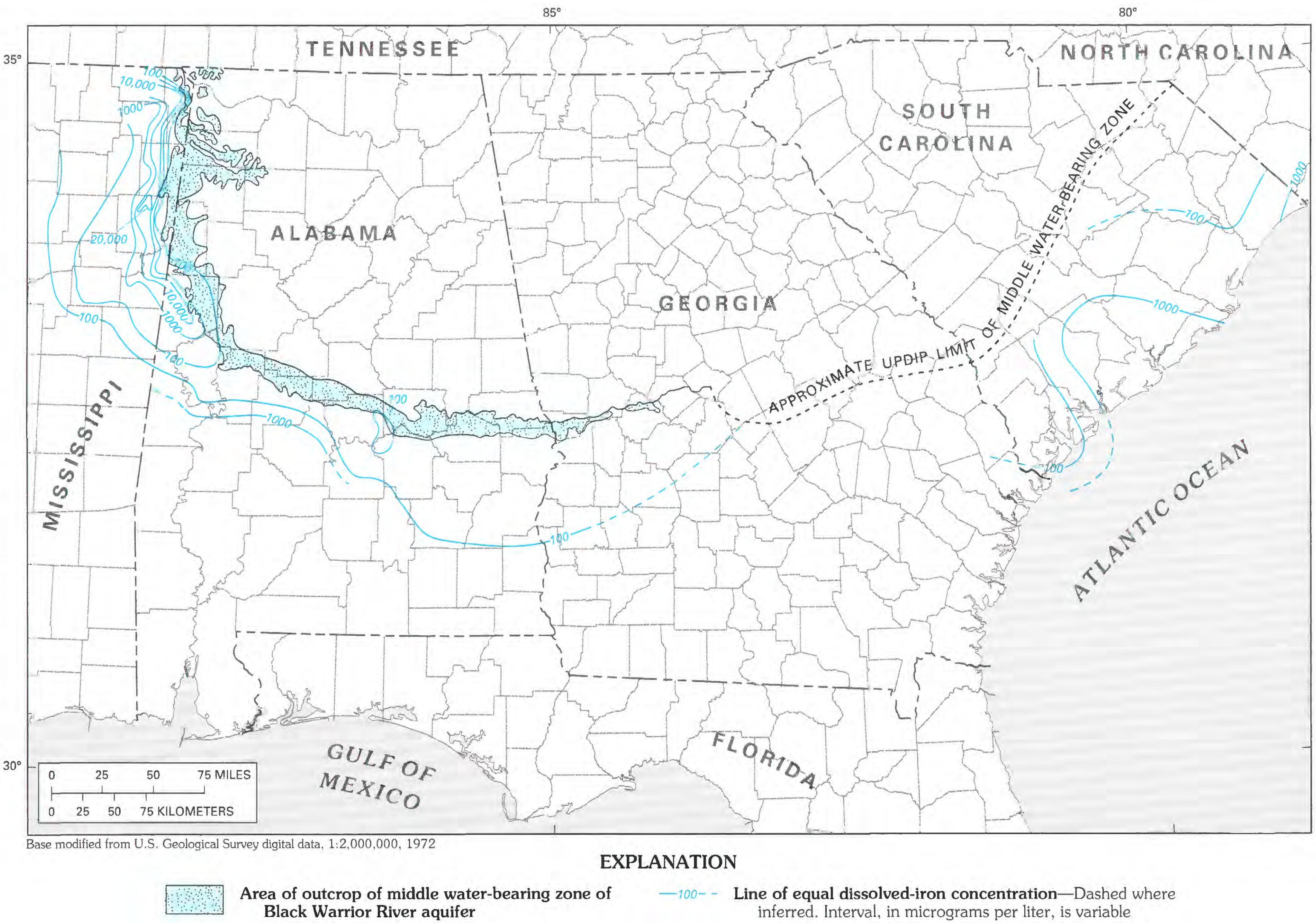


FIGURE 22.—Dissolved-iron concentrations in water from the middle water-bearing zone of the Black Warrior River aquifer (after Lee, 1986).

bicarbonate-dominated water is one in which the calcium ion is greater than 50 percent of the total milliequivalents of cations, and the bicarbonate (plus carbonate) ion is greater than 50 percent of the total milliequivalents of anions. In a sodium chloride-dominated water, sodium and chloride account for more than 50 percent of the total milliequivalents of cations and anions, respectively. Where no ion exceeds 50 percent, as, for example, in outcrop areas where dissolved-solids concentrations are very low, the water is termed "no dominant facies."

Aquifers in the Southeastern Coastal Plain aquifer system generally show three dominant hydrochemical facies. Calcium bicarbonate is the major facies in and near recharge areas. Sodium bicarbonate is the prevalent facies downgradient, primarily resulting from mineral-water interactions. Sodium chloride is the predominant facies farther downgradient, where freshwater and saltwater mixing occurs. The distribution of hydrochemical facies in the middle water-bearing zone of the Black Warrior River aquifer (fig. 23) is representative of the water-quality patterns in all the regional aquifers studied.

GEOCHEMICAL EVOLUTION OF THE GROUND WATER

Changes in the quality of the ground water as the water moves downgradient from recharge areas are similar in all the regional aquifers of the Southeastern Coastal Plain aquifer system. The specific changes that occur down a flowpath in western Alabama and eastern Mississippi have been studied in detail by Lee (1985) and are representative of regional geochemical processes taking place in the sand aquifers that make up the aquifer system. Mineralogic analyses were done on cuttings and cores taken from wells along, or adjacent to, the flowpath. The mineralogic data, in conjunction with chemical data for ground water from wells along the flowpath, were entered in the geochemical models WATEQ2 (Truesdell and Jones, 1974) and PHREEQE (Parkhurst and others, 1980). The results of these geochemical models, coupled with mass-balance calculations, were used to develop a plausible series of mineral-water and water-mixing reactions judged to have produced the observed downgradient changes in ground-water chemistry.

Five geochemical zones have been recognized that characterize the geochemical evolution of the ground water as it moves downgradient from recharge areas to places where the aquifers are deeply buried. Four of these zones (A–D) are shown in figure 24, and the chemical reactions that are responsible for the observed water quality in the four zones are summarized in table 2. Water in outcrop areas and at shallow depth (zone A, fig. 24) is low in dissolved solids and iron, has a pH of 4.5 to 6.0, and contains dissolved oxygen in concentrations of 2 to 10 mg/L. This water is usually calcium bicarbonate-dominated, and its chemical character results primarily from mineral-water interactions. Just downgradient from outcrop areas (zone B, fig. 24), the water is sodium bicarbonate-dominated and has dissolved-solids concentrations of 100 to 200 mg/L, a pH of about 6.0 to 7.0, negligible dissolved oxygen, and iron concentrations ranging from 500 to 20,000 μg/L. Ferric iron reduction is greatest in this zone, accounting for the extremely high dissolved-iron concentrations. Farther downgradient, in zones C and D (fig. 24), the water is sodium bicarbonate-dominated, with a pH of about 7.0 to 9.0, dissolved-solids concentrations of 300 to 500 mg/L, and dissolved-iron concentrations of less than 300 μg/L. The decrease in iron concentration in zones C and D is due primarily to siderite precipitation. Chloride concentration increases with depth in zones C and D. Still farther downgradient, in zone E (not shown in fig. 24 and table 2), the water is sodium chloride-dominated, with a pH of about 8.0 to 9.0, dissolved-solids concentrations of 1,000 to greater than 100,000 mg/L, and concentrations of dissolved iron up to 5,000 μg/L. The chemical character of the water in zone E results chiefly from the mixing of fresh and saline water.

TABLE 2.—*Zonation of chemical reactions of water along a flowpath from Alabama to Mississippi*

[Location of flowpath shown in fig. 24. After Wait and others (1986)]

Recharge water:	Rainfall-input chemistry, atmospheric carbon dioxide + soil carbon dioxide + dissolved oxygen
Zone A:	Calcite dissolution Sodium feldspar hydrolysis to kaolinite Oxidation of carbonaceous matter by dissolved oxygen
Zone B:	Calcite dissolution Sodium feldspar hydrolysis to kaolinite Ferric iron redution to siderite to saturation of siderite Oxidation of carbonaceous matter Silica precipitation
Zone C:	Calcite dissolution Solium feldspar hydrolysis to kaolinite Siderite precipitation Ferric iron reduction Oxidation of carbonaceous matter Silica precipitation
Zone D:	Smectite precipitation Calcite dissolution Na-Ca cation exchange Gypsum dissolution Sulfate reduction FeS_2 precipitation Ferric iron reduction Oxidation of carbonaceous matter Silica dissolution

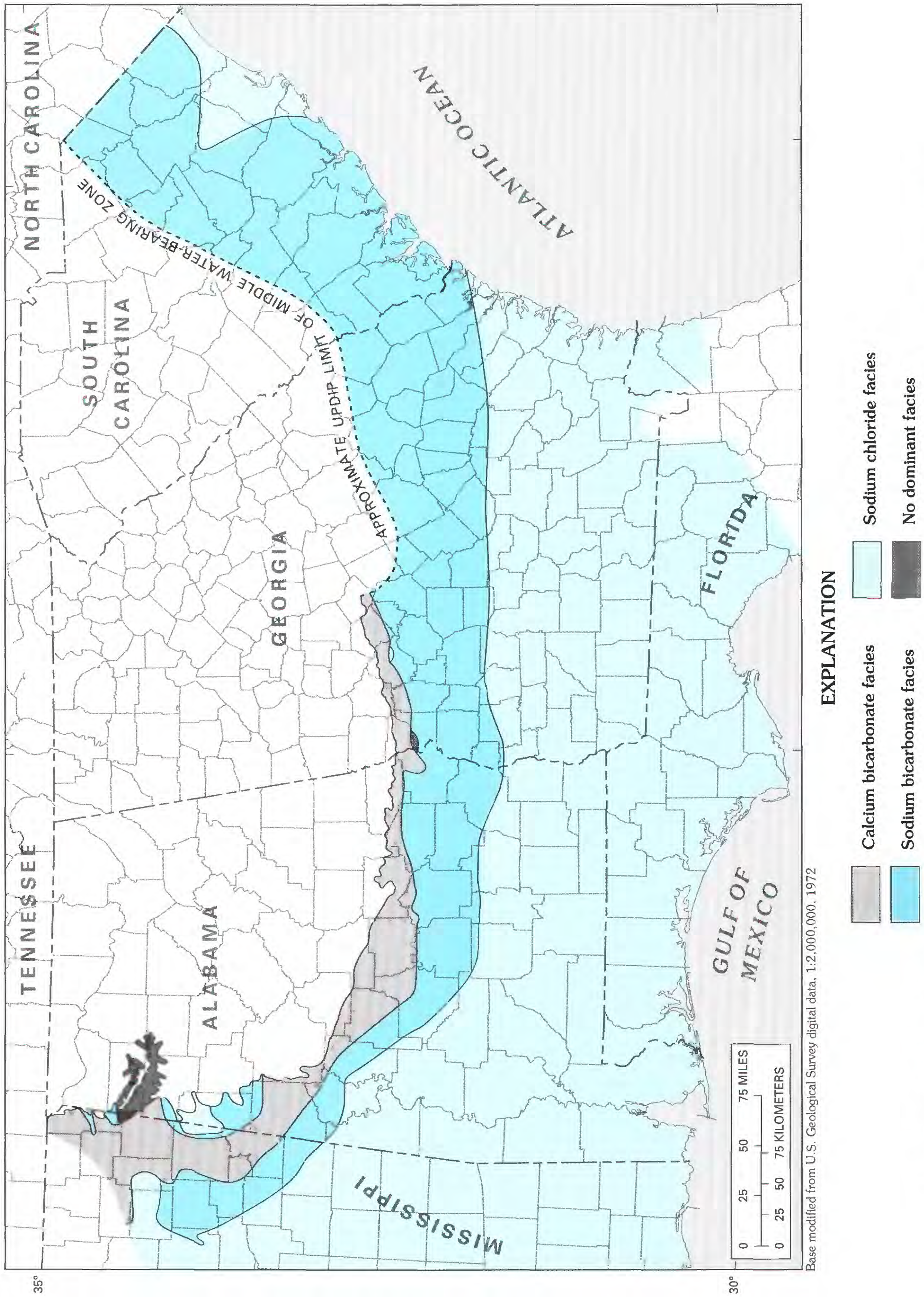


FIGURE 23.—Distribution of hydrochemical facies in water from the middle water-bearing zone of the Black Warrior River aquifer (after Lee, 1986).

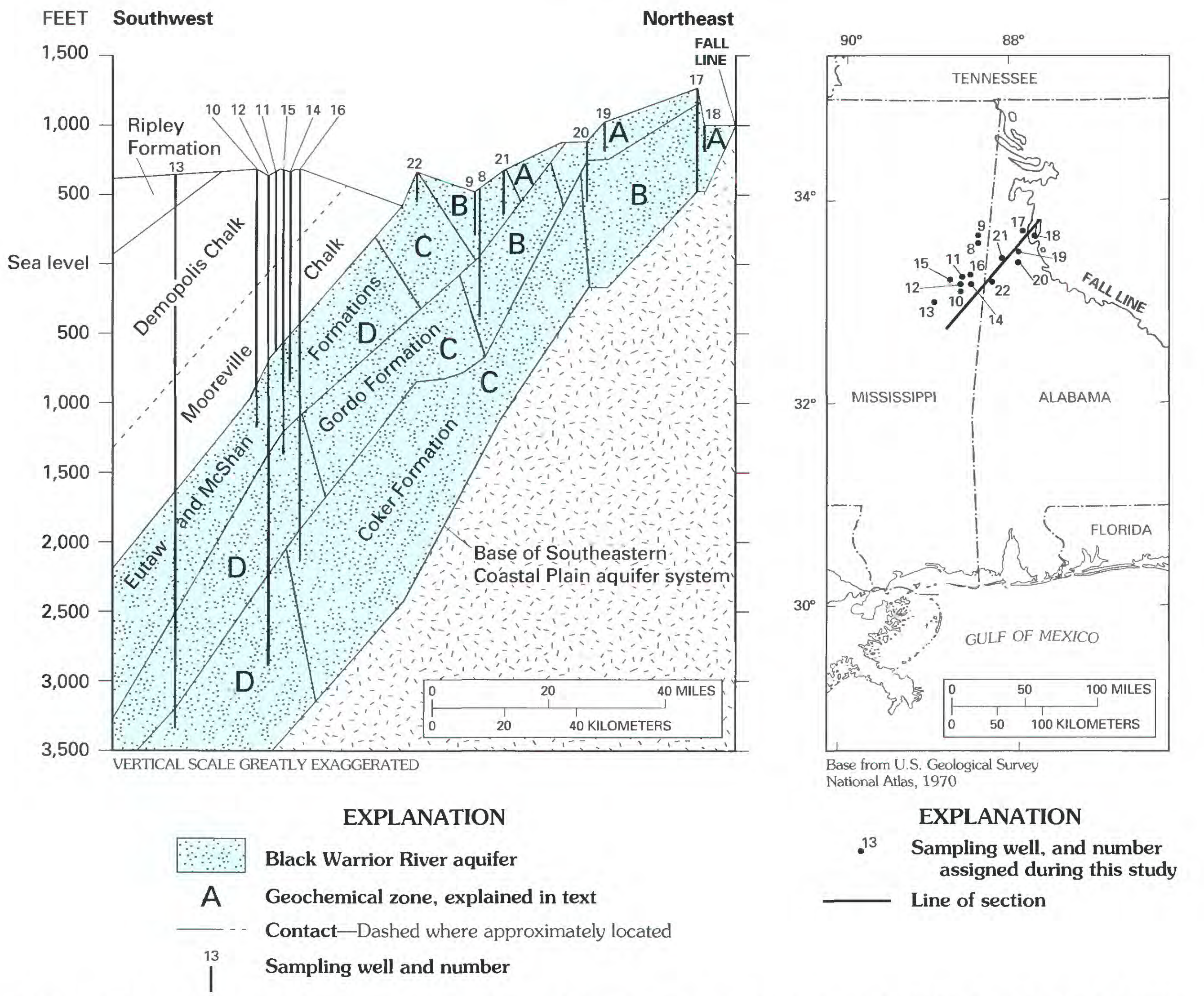


FIGURE 24.—Generalized geologic section along a flowpath from Alabama to Mississippi showing approximate location of geochemical zones A–D (after Wait and others, 1986).

GEOCHEMICAL PROCESSES BASED ON MODELING

Geochemical modeling has demonstrated the likely chemical processes that produced the observed water chemistry in the regional aquifers of the Southeastern Coastal Plain aquifer system. Sodium feldspar hydrolysis is the dominant process upgradient in sandy, low-calcite aquifers such as the Black Warrior River and Chattahoochee River aquifers. This process produces relatively low (less than 100 mg/L) concentrations of dissolved solids. Downgradient in these two aquifers, more calcite is dissolved, approaching saturation. Calcium-for-sodium cation exchange, enhanced by CO_2 emanating from the decay of lignite, increases calcite dissolution and produces the sodium bicarbonate facies characteristic of ground water in middip parts of the Black Warrior River and Chattahoochee River aquifers. High iron concentrations in chemically reducing environments just downgradient from recharge areas are controlled by the solubility of siderite, followed by pyrite farther downgradient. Precipitation of these minerals causes iron concentrations in the ground water to decrease. Subsequently, dissolved-iron concentrations increase farther downgradient in response to increased concentrations of dissolved chloride near the freshwater-saltwater interface.

Ground water in the Pearl River aquifer is largely calcium bicarbonate-dominated, owing to the relatively high content of calcite in the aquifer. Local areas where sodium bicarbonate water dominates may reflect upward leakage from deeper aquifers. Sodium-for-magnesium cation exchange takes place where the Pearl River aquifer is dolomitic in southern Georgia, resulting from incongruent dissolution of dolomite accompanied by calcite precipitation (Sprinkle, 1989).

GEOCHEMICALLY DERIVED GROUND-WATER FLOW RATES

The occurrence of measurable amounts of carbon-14 in ground water of the Southeastern Coastal Plain aquifer system permits estimation of both the age and the flow velocity of the ground water. Radiocarbon-age estimates were made by correcting for dilutions of the carbon-14 reservoir by geochemical mass transfer of inorganic carbon during the chemical evolution of the ground water. In some cases, the ground water contains insufficient carbon-14 for flow-rate determination, indicating that these waters are older than 40,000 years before present.

Approximate flow velocities in confined areas differ among the regional aquifers. Flow rates estimated from carbon-14 data are lowest, about 3 ft/yr, in the Black Warrior River aquifer, compared with flow rates calculated from ground-water model results of about 0.9 ft/yr. For the Chattahoochee River aquifer, higher flow rates of approximately 13 ft/yr were derived from carbon-14 data, compared with 9.9 ft/yr estimated from ground-water flow simulation. The greatest calculated flow rates were for the Pearl River aquifer—about 18 ft/yr estimated from carbon-14 data compared with about 14.8 ft/yr derived from simulation.

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