Geohydrology and Evaluation of Stream-Aquifer Relations in the Apalachicola-Chattahoochee-Flint River Basin, Southeastern Alabama, Northwestern Florida, and Southwestern Georgia

United States Geological Survey Water-Supply Paper 2460

Prepared in cooperation with the U.S Army Corps of Engineers, the Alabama Department of Economic and Community Affairs, the Northwest Florida Water-Management District, and the Georgia Department of Natural Resources, Environmental Protection Division

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By LYNN J. TORAK, GARY S. DAVIS, GEORGE A. STRAIN, and JENNIFER G. HERNDON

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[Plates are in pocket]

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CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
	43.81	liter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
part per million	1,000	microgram per liter ($\mu g/L$)
foot squared per day (ft^2/d)	0.0929	meter squared per day
foot per day (ft/d)	0.3048	meter per day

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.

Acronyms

Apalachicola-Chattahoochee-Flint (ACF)

MODular Finite-Element model (MODFE)

Geohydrology and Evaluation of Stream-Aquifer Relations in the Apalachicola-Chattahoochee-Flint River Basin, Southeastern Alabama, Northwestern Florida, and Southwestern Georgia

By Lynn J. Torak, Gary S. Davis, George A. Strain, *and* Jennifer G. Herndon

Abstract

The lower Apalachicola-Chattahoochee-Flint River Basin is underlain by Coastal Plain sediments of pre-Cretaceous to Quaternary age consisting of alternating units of sand, clay, sandstone, dolomite, and limestone that gradually thicken and dip gently to the southeast. The stream-aquifer system consists of carbonate (limestone and dolomite) and clastic sediments, which define the Upper Floridan aquifer and Intermediate system, in hydraulic connection with the principal rivers of the basin and other surface-water features, natural and man made.

Separate digital models of the Upper Floridan aquifer and Intermediate system were constructed by using the U.S. Geological Survey's MODular Finite-Element model of two dimensional ground-water flow, based on conceptualizations of the stream-aquifer system, and calibrated to drought conditions of October 1986. Sensitivity analyses performed on the models indicated that aquifer hydraulic conductivity, lateral and vertical boundary flows, and pumpage have a strong influence on ground-water levels. Simulated pumpage increases in the Upper Floridan aquifer, primarily in the Dougherty Plain physiographic district of Georgia, caused significant reductions in aquifer discharge to streams that eventually flow to Lake Seminole and the Apalachicola River and Bay. Simulated pumpage increases greater than 3 times the October 1986 rates caused drying of some stream reaches and parts of the Upper Floridan aquifer in Georgia.

Water budgets prepared from simulation results indicate that ground-water discharge to streams and recharge by horizontal and vertical flow are the principal mechanisms for moving water through the flow system. The potential for changes in ground-water quality is high in areas where chemical constituents can be mobilized by these mechanisms. Less than 2 percent of ground-water discharge to streams comes from the Intermediate system; thus, it plays a minor role in the hydrodynamics of the stream-aquifer system.

INTRODUCTION

Multiple uses of limited surface- and ground-water resources within the lower Apalachicola-Chattahoochee-Flint (ACF) River Basin (fig. 1) have caused concern to water managers in Alabama, Florida, and Georgia and at federal levels, and have become the object of difficult and sometimes conflicting management decisions. The rivers and their impoundments are used as a waterway for shipping, a source for hydropower generation, a freshwater supply for agriculture and industry, and for recreational purposes. Apalachicola Bay supports an active and economically important shellfish industry that depends on a supply of nutrients to be carried to the Bay by freshwater from the Apalachicola River. The Apalachicola, Chattahoochee and Flint Rivers drain (in part) one of the most productive

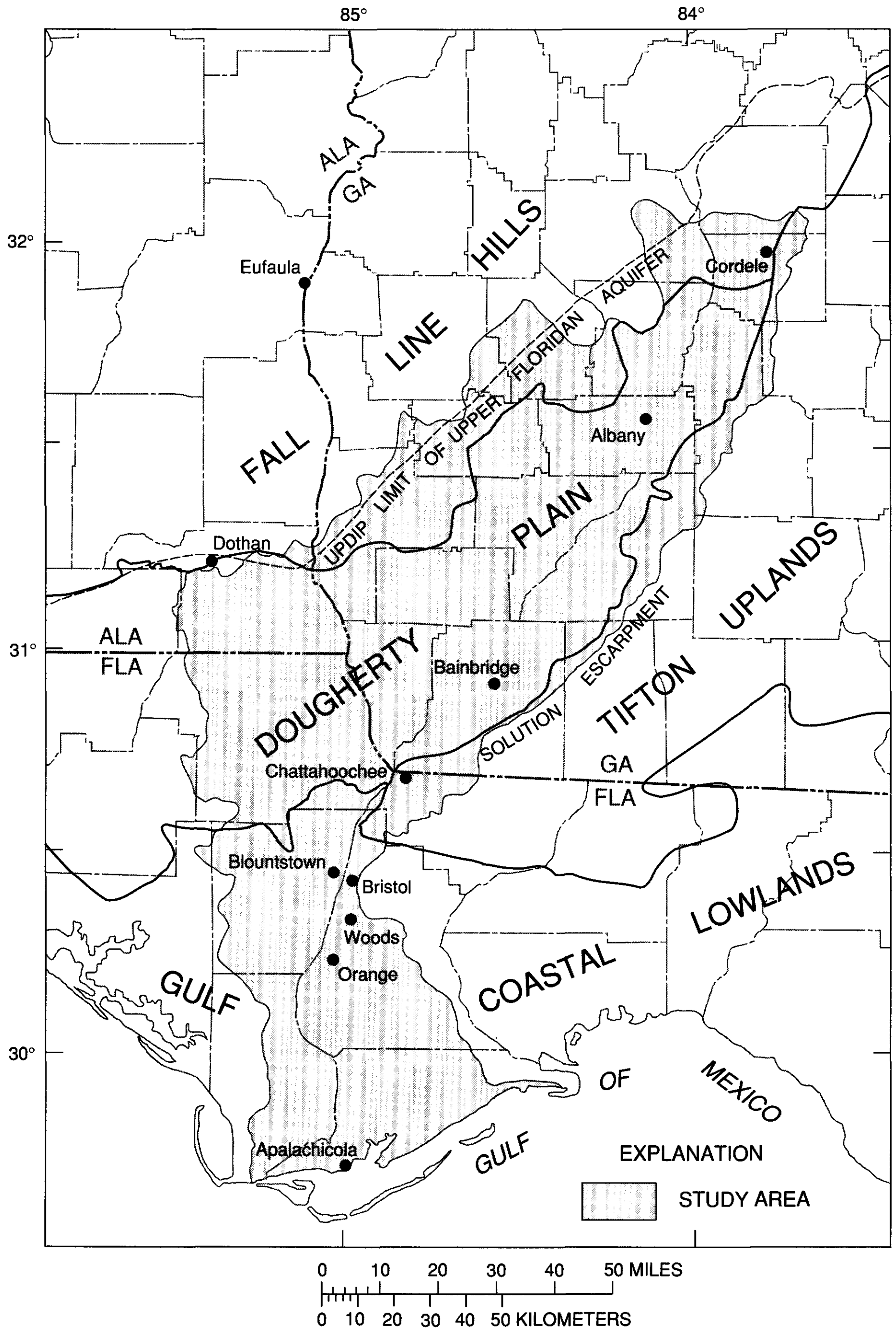


Figure 1. Location of study area, boundaries of the lower Apalachicola–Chattahoochee–Flint River Basin, and physiographic divisions of the Coastal Plain province in southeastern Alabama, northwestern Florida, and southwestern Georgia.

aquifers in the nation, the Upper Floridan aquifer; however, stream-aquifer relations are not well understood. Ground-water withdrawal from the Upper Floridan aquifer and from other aquifers connected to these rivers decrease base flow and, thus, the amount of water available for storage in Lake Seminole, which supplies freshwater and nutrients to the Apalachicola River, estuary, and Bay. Although management of water resources of the lower ACF River Basin has been the concern of water authorities for more than 160 years, drought conditions during 1980, 1981, and 1986–88 have brought attention to the many uses of surface- and ground-water supplies and to the present and anticipated conflicts in water use resulting from extremely dry climatic periods. The U.S. Army Corps of Engineers, Mobile District, Mobile, Ala., (Corps) has initiated a study with the States of Alabama, Florida, and Georgia to develop a water-management plan for the ACF River Basin. The Corps has worked in the lower ACF River Basin since 1828 on projects related to flood control, navigation, and hydropower generation. A major component of the overall study was the reinitiation, in 1984, of a study of the basin that originally was authorized for the Corps through the River and Harbor Act of 1927, in accordance with House Document No. 308, 69th Congress, and has been termed the "308" study. The Congressional document provides for studies to evaluate the feasibility of comprehensive development of water resources of specific river basins throughout the nation and to investigate long-term solutions to the basin's water-resources problems (Lawrence R. Green, Mobile District, U.S. Army Corps of Engineers, Mobile, Ala., written commun., 1984).

In October 1985, the U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers, Mobile District, Mobile, Ala., the State of Alabama Department of Economic and Community Affairs, the State of Florida Department of Environmental Regulation (now the Department of Environmental Protection), and the State of Georgia, Department of Natural Resources, Environmental Protection Division began a study under provisions of the "308" study to evaluate potential solutions to various water-resources problems that have either caused or have the potential to cause conflicts in multiple use of limited water resources of the lower ACF River Basin. Specifically, this cooperative study was established to quantitatively define and improve understanding of stream-aquifer relations in the basin and effects of ground-water pumpage on streamflow.

Purpose and Scope

The principal objectives of this report are to:

- Define the nature of stream-aquifer relations in the lower ACF River Basin by identifying the geohydrology of the ground- and surface-water-flow system, quantifying the ground-water component of streamflow, and determining effects of ground-water pumpage on streamflow
- Present a conceptual model of the stream-aquifer system that incorporates hydrologic processes which are pertinent to evaluating the relation between ground- and surface-water flow
- Evaluate this conceptual model for worst-case, drought conditions through use of a finite-element, digital-computer model of ground-water flow in aquifers that are connected hydraulically to streams
- Present a water budget for the lower ACF River Basin for worst-case, drought conditions, based on digital-model analysis, that quantifies ground- and surface-water components and important hydrologic stresses to the stream-aquifer system
- Quantify effects on individual water-budget components of possible multiple-use scenarios under extremely dry climatic conditions

Of particular interest to evaluating stream-aquifer relations is the effect on streamflow of ground-water pumpage in the Upper Floridan aquifer in the Georgia part of the ACF River Basin during worst-case, drought conditions, such as October 1986. Previous studies by Hayes and others (1983) and Torak and others (1993) indicated that base flow of streams in the lower ACF River Basin in Georgia is affected by ground-water withdrawals; however, effects of base-flow reductions on flow in the Apalachicola River were not addressed. Through simulation techniques, a range of hydrologic conditions and ground-water-withdrawal rates are used in this study to determine their effects on base flow of the Apalachicola River and of other rivers in the basin.

Simulations using drought conditions for October 1986, coupled with reasonable increases in ground-water withdrawals, provide estimates of minimum-expected-freshwater inflow to Apalachicola Bay for conditions of anticipated increased development of ground-water resources. Results of these simulations are an important part of the long-range water budget to be prepared as part of the "308" study and can aid water managers in making sound decisions on difficult, multiple-use, water-resource issues. Other results define the geohydrology of the stream-aquifer system and identify pertinent hydrologic factors that influence ground- and surface-water flow in the lower ACF River Basin.

Area of Study and Physiography

The lower ACF River Basin encompasses an area of about 6,800 square miles within the Coastal Plain physiographic province. The Coastal Plain is subdivided in Alabama, Florida, and Georgia into four districts: Fall Line Hills, Dougherty Plain, Tifton Upland, and Gulf Coastal Lowlands (fig.1). Physiographic descriptions for subdivisions of the Coastal Plain are given by Puri and Vernon (1964), Sapp and Emplaincourt (1975), Clark and Zisa (1976), and Brooks (1981), and are summarized briefly here.

The northern extent of the lower ACF River Basin is located in the Fall Line Hills district at the updip limit of the Ocala Limestone. The limestone is the principal water-bearing unit of the Upper Floridan aquifer and is drained by major surface-water features in southwestern Georgia, such as the Chattahoochee and Flint Rivers and their tributaries. The Fall Line Hills district is a highly dissected series of ridges and valleys that diminish in relief to the south and east as it grades into lowlands of the Dougherty Plain (Wagner and Allen, 1984). The eastern limit of the lower ACF River Basin coincides approximately with the boundary between the Tifton Uplands and the Dougherty Plain districts, and the Gulf Coastal Lowlands district occupies the southern part of the basin. The western-basin boundary is defined by ground-water and surface-water divides within the Dougherty Plain and Gulf Coastal Lowlands districts. The southern limit of the basin is the Gulf of Mexico. Land-surface altitudes range from more than 700 ft at the northern boundary to about 150 ft along the southern boundary (Clark and Zisa, 1976). Typically, stream valleys range from 20 to 250 ft below adjacent ridges.

The Dougherty Plain district is an inner lowland (cuesta) comprised of a series of nearly level plains (Hicks and others, 1987). Land-surface altitudes range from about 300 ft along parts of the northern border to about 150 ft along the boundary with the Tifton Uplands and to about 50 ft just south of the confluence of the Flint and Chattahoochee Rivers. Relief within most of the Dougherty Plain rarely exceeds 20 ft. In the Florida panhandle, the Dougherty Plain district includes the Marianna Lowlands (Puri and Vernon, 1964) (fig. 2).

The Dougherty Plain is characterized by karst topography having numerous shallow, circular depressions (sinkholes) ranging in size from a few tens of feet to several hundred acres. Many depressions are filled with low-permeability material and some contain water year round (Middleton, 1968). Active solutioning of Ocala Limestone in the Dougherty Plain has created underground channels that capture surface drainage; only larger streams flow in terraced valleys (Hicks and others, 1987).

A steeply sloping karst area named the Solution Escarpment by MacNeil (1947), or Pelham Escarpment (Hayes and others, 1983), faces generally west to northwest and separates the Dougherty Plain from the Tifton Upland district (fig. 1). With local relief as great as 125 ft, the crest of the Solution Escarpment forms the topographic and surface-water divide between the Flint River basin and the Ochlockonee and Withlacoochee River basins to the east. Several streams carry surface runoff westward down slopes of the escarpment and go underground in swampy areas after traveling only a short distance across the Dougherty Plain (Hicks and others, 1987).

East of the Solution Escarpment lie the narrow, rounded plateaus and well-developed drainage patterns of the Tifton Upland. The Tifton Upland district in north Florida is termed the Tallahassee Hills (fig. 2), a geomorphic subzone of the Northern Highlands (Puri and Vernon, 1964; White, 1970). This is a region of high hills composed largely of resistant clayey sands, silts, and clays (Arthur and Rupert, 1989). Land-surface altitudes range from 330 ft near the Florida-Georgia-State line to about 100 ft at the southern edge of the zone. Dendritic streams dissect the hills, typically forming V-shaped valleys. The Tallahassee Hills end abruptly at the Apalachicola River in steep bluffs that provide relief of about 150 to 200 ft above the floodplain and expose Miocene- to Holocene-age sediments.

West of the Tallahassee Hills lie the Grand Ridge and New Hope Ridge regions (fig. 2), a series of remnant hills and sand-hill ridges dissected by stream valleys (Puri and Vernon, 1964). These regions are separated by the Chipola River, the major tributary of the Apalachicola River. Land-surface altitude and relief in these regions are similar to those of the Tallahassee Hills, which, together with the Grand Ridge and New Hope Ridge probably formed a continuous, high, delta plain connecting the Northern Highlands of northern Florida with similar features to the west (Arthur and Rupert, 1989). To the north, the Grand Ridge and New Hope Ridge regions are bounded by the Holmes Valley Scarp (fig. 2), a prominent topographic feature that separates these ridges from the Marianna Lowlands in a similar manner that the Solution Escarpment separates the Tifton Uplands from the Dougherty Plain.

South of the New Hope Ridge and Tallahassee Hills are transitional physiographic features, the Fountain Slope, Green Head Slope, and Beacon Slope (fig. 2) (Puri and Vernon, 1964). Typical characteristics of these features are uniformly slop-

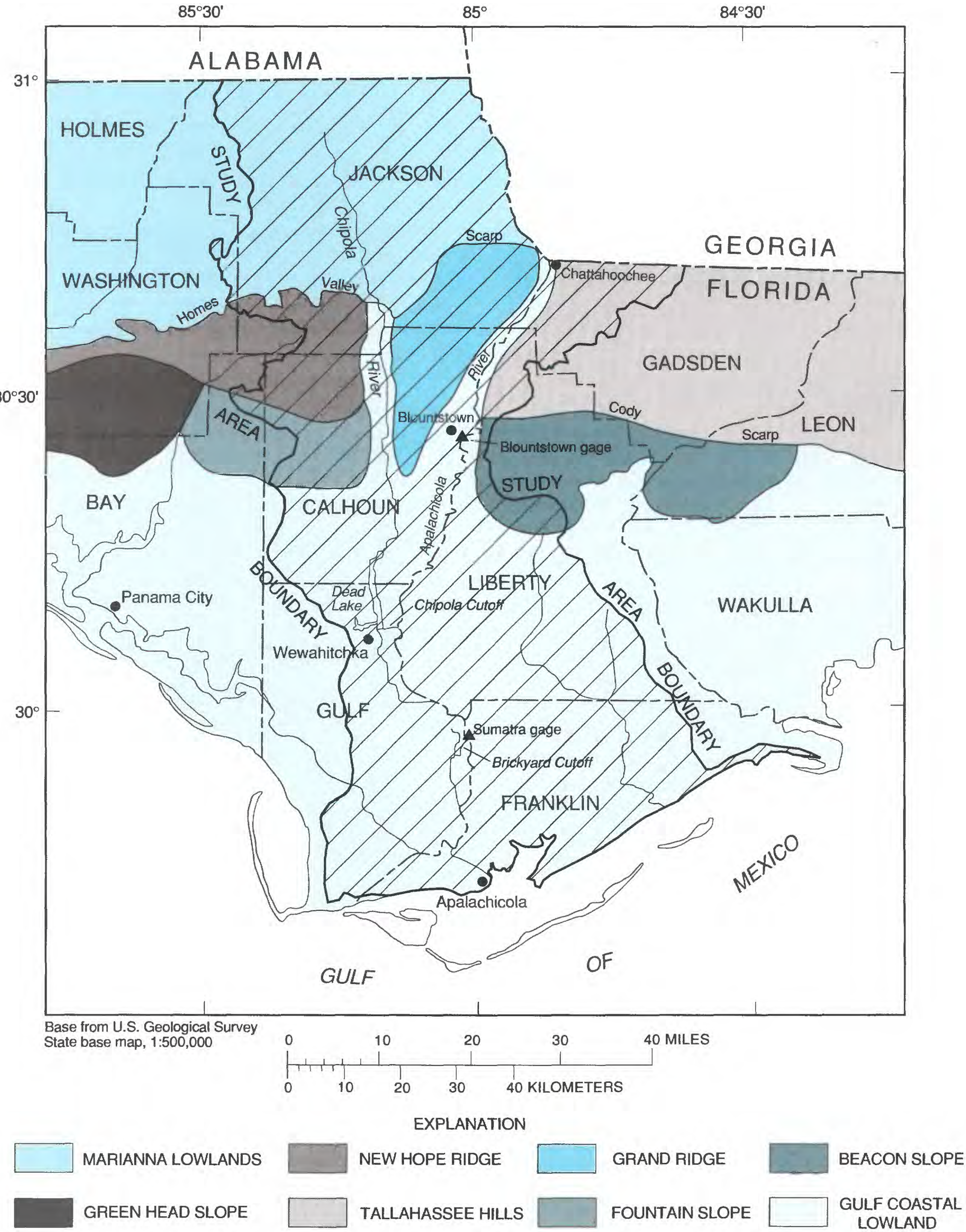


Figure 2. Physiography of the lower Apalachicola–Chattahoochee–Flint River Basin in Florida (modified from Leitman and others, 1984).

ing topography and swampy depressions and sinks where surface sediments overlie karst terrane (Arthur and Rupert, 1989). Land-surface altitudes range from about 150 ft along the northern boundaries to about 25 ft along the southern limit of the features. Along the northern boundary, the Beacon Slope is separated from the Tallahassee Hills by the Cody Scarp, which provides about 15 to 25 ft of relief between the two features. The Fountain slope and Beacon Slope provide a geomorphic link between the ridges of the north and the Gulf Coastal Lowlands to the south.

The Gulf Coastal Lowlands are characterized by a sandy, flat, seaward-sloping feature shaped mostly by wave and current activity from high-sea-level stands during the Pleistocene Epoch (Arthur and Rupert, 1989). The land surface is characterized by relic marine bars, terraces, spits, and sand-bar dunes (fig. 2) of Pleistocene age.

Methods of Investigation

Methods used to evaluate stream-aquifer relations in the lower ACF River Basin include collection, assimilation, and interpretation of geologic and hydrologic information about aquifers in contact with surface-water features; measurements of ground- and surface-water levels; streamflow measurements; base-flow estimates of streams; and numerical simulation. Much of this information, including geologists' and drillers' logs of wells, geologic sections, maps of potentiometric surfaces, tables of hydrologic information, and individual records for wells drilled in the basin, was available from a variety of published and unpublished sources from the local, state, and federal levels, and was used to develop a conceptual model of the stream-aquifer system.

Ground- and surface-water levels and streamflow were measured during extreme (worst-case) low-flow conditions, which existed in the lower ACF River Basin in late October 1986. A network of 303 wells was used to obtain ground-water levels in the Upper Floridan aquifer and in other aquifer systems that are connected hydraulically to surface water (pl. 1). Streamflow was measured at 94 locations, from which estimates of base flow were made along 37 reaches.

Numerical simulation of ground-water flow in the stream-aquifer system was performed by using the USGS's MODular Finite-Element model (MODFE) for ground-water flow in two dimensions (Cooley, 1992; Torak, 1993a,b). This model contains mathematical representations of hydrologic processes that were conceptualized as controlling ground- and surface-water flow in the lower ACF River Basin. Stream-aquifer relations were quantified in MODFE with computations of leakage rates across streambed-aquifer boundaries, and the rates were incorporated into water budgets for either selected reaches or the entire study area. Simulations represented historical, October 1986, drought conditions, and hypothetical conditions involving increases in October 1986 ground-water-withdrawal rates.

Previous Studies

Numerous studies of the geology, hydrology, and ground-water resources of the lower ACF River Basin have been made since the earliest publication dating back to the late 1890's. Most of these studies, however, give hydrologic details only in areas of greatest ground-water withdrawals. Outside of these areas, limited hydrologic information about aquifers and stream-aquifer relations is available from general-reconnaissance studies.

General descriptions of the geology and ground-water resources of the Coastal Plain have been given by McCallie (1898), Stephenson and Veatch (1915), Cooke (1943) and Herrick (1961). The geohydrology of southwestern Georgia has been described in reports by Wait (1963), Sever (1965a,b), Pollard and others (1978), Hicks and others (1981, 1987), Hayes and others (1983), and Torak and others (1993). In Alabama, reports by Scott and others (1984), Moffett and others (1985), and Moore and others (1985), provide useful background information on geology, hydrology, and water resources. Studies in Florida by Moore (1955), Kwader and Schmidt (1978), Schmidt (1978, 1979, 1984), Schmidt and Coe (1978), Schmidt and Clark (1980), and Schmidt and others (1980), describe the geology of parts of the lower ACF River Basin, and Arthur and Rupert (1989) give details about basin physiography.

The recent study by Torak and others (1993) described the geohydrology and evaluated the water-resource potential of the Upper Floridan aquifer in the Albany area, southwestern Georgia. Two water-bearing units of the aquifer in contact with major surface-water features were identified from hydrogeologic information obtained for this study. Details about fractures and solution features, and hydraulic properties of the Upper Floridan aquifer were compiled and the results were incorporated in a finite-element model of two-dimensional ground-water flow. Model analyses indicated that ground-water pumpage intercepts less than 10 percent of the regional flow of ground water that would otherwise discharge to the Flint River, the principal drain to the aquifer in the Albany area. Other model results indicated that ground-water levels are affected minimally by pumping in the Upper Floridan aquifer and by changes in stage of the Flint River, and that ground-water resources of the aquifer tend to be controlled by large regional-flow components.

Two additional studies used simulation techniques to evaluate ground-water resources in parts of the lower ACF River Basin, but the objectives, purposes, and limitations of these studies precluded them from addressing stream-aquifer relations in the manner that is presented here. One of these studies (Maslia and Hayes, 1988) examined ground-water flow and the recharge-discharge system of the Floridan aquifer in southwestern Georgia, northwestern Florida, and southernmost Alabama. The referenced study contained general descriptions of the predevelopment-flow system and detailed descriptions of the hydrogeology and flow system of 1980 in the Dougherty Plain and near Fort Walton Beach, Fla., which is west of the present study area. The other study (Bush and Johnston, 1988) applied simulation techniques to the lower ACF River Basin as part of the USGS's Regional Aquifer Systems Analysis (RASA) program. It defined general ground-water-flow characteristics of the entire Floridan-aquifer system within the southeastern Coastal Plain of Florida, southern Georgia, South Carolina, and Alabama on a regional scale.

During 1979-81, the USGS conducted a large-scale study of the Apalachicola River, termed the Apalachicola River Quality Assessment (Elder and others, 1984). A series of reports (Elder and Cairns, 1982; Elder and others, 1984; Leitman and others, 1984; and Mattraw and Elder, 1984) describe hydrologic and ecologic investigations made for the Assessment. Water and nutrient budgets based on data collected during that study indicate the relative importance of inflows and outflows to the system, such as waterflow, total nutrient inflow and outflow, flood-plain forest, and the role of the flood plain in yielding nutrients and detritus to the river estuary (Elder and others, 1984).

As part of the study with the States of Alabama, Florida, and Georgia, the U.S. Army Corps of Engineers, Mobile District, Mobile, Ala., completed the "1984 Water Assessment" (U.S. Army Corps of Engineers, States of Alabama, Florida, and Georgia, 1984) of the entire ACF River Basin. This study was limited to available data and consisted of a main report and 6 appendices that address the following topics of concern in the basin: natural environmental setting, economic setting, water resources (surface and ground water), water use and availability, water quality, water-management setting, and problem areas and current solution efforts. As part of the study's conclusions and recommendations, the Corps identified deficiencies in the type of information required for managing water-resources in the basin. Most notable deficiencies are those of quantifying stream-aquifer relations and in determining present and future water needs for multiple uses of the basin, such as navigation, ground-water pumpage for irrigation, and freshwater supply to Apalachicola Bay.

Well- and Surface-Water-Station Numbering System

Several numbering conventions are used to identify wells which are referenced in this report. Wells located in Alabama are identified by three digits prefixed by the letters "ALA", such as ALA001. Wells located in Florida are identified by three digits prefixed by a three-letter, county code, such as JAC001 for a well in Jackson county. The other county codes and corresponding counties (in parentheses) are: CAL (Calhoun), FRA (Franklin), GAD (Gadsden), GUL (Gulf), and LIB (Liberty).

Wells in Georgia are numbered by a system based on USGS topographic maps. Each 7½-minute topographic quadrangle map in Georgia has been given a number and letter designation beginning at the southwest corner of the State. Numbers increase eastward through 39; letters advance northward through "Z," then double-letter designations "AA" through "PP" are used. The letters "I, O, II, and OO" are not used. Wells inventoried in each quadrangle are numbered sequentially beginning with "1." Thus, the forty-eighth well inventoried in the Albany West quadrangle (designated 12L) in Dougherty County is designated 12L048.

Partial- and continuous-record surface-water stations are given a station-identification number, which is assigned according to "downstream-order" (Stokes and others, 1990). No distinction is made between partial-record stations and other stations; therefore the station number for a partial-record station indicates downstream-order position in a list made up of both types of stations. The complete number for each station includes a 2-digit Part number "02" plus the downstream-order number, which can be from 6 to 12 digits. In this report, the Part number is omitted, and only the 6-digit downstream-order number is used.

Acknowledgments

The authors extend appreciation to all those who contributed valuable geohydrologic information and interpretations about the ground-water-flow system in the lower ACF River Basin. In particular, sincere appreciation is given to Jeffry R. Wagner, formerly of the Northwest Florida Water Management District, Havana, Fla., and to Frank Rupert and Walter Schmidt of the Florida Bureau of Geology, Tallahassee, Fla.

GEOHYDROLOGY

Lithologic characteristics that contribute to the fluid-flow aspects of the geologic units involved in stream aquifer relations in the study area are presented here. Detailed descriptions of the geology, lithology, and hydrology of each unit are contained in the cited references.

Geologic Setting

The study area is underlain by Coastal Plain sediments of pre-Cretaceous to Quaternary age that consist of alternating units of sand, clay, sandstone, dolomite, and limestone that dip gently, and generally thicken, to the southeast (Hicks and others, 1987). Only geologic units pertinent to the functioning of the flow system defined by aquifers and semiconfining units in contact with surface-water bodies were considered in this study. These units include late-middle-Eocene and younger sediments, and are, in ascending order, the Lisbon Formation, Clinchfield Sand, Ocala Limestone, Marianna Formation, Suwannee Limestone, Tampa Limestone, undifferentiated overburden, Intracoastal Formation, Chipola Formation, Jackson Bluff Formation, Citronelle Formation, and terrace and undifferentiated (surficial) deposits (fig. 3). The combination of these geologic units according to their hydraulic properties defines hydrologic units that are termed semiconfining units, Intermediate system, Upper Floridan aquifer, lower confining unit, and sub-Floridan confining unit (fig. 3). In Alabama, the Upper Floridan aquifer consists of the Clinchfield Sand, where present, and undifferentiated sediments of Ocala Limestone and Moodys Branch Formation, which are combined in this report and henceforth termed Ocala Limestone. Undifferentiated overburden overlies these limestones in areas where they are near the surface, such as in Georgia and Alabama, and in Jackson, Gadsden, northern Calhoun, and northern Liberty Counties, Fla.

The Lisbon Formation consists of interbedded calcareous, glauconitic sand; sandy clay; and clay that crop out north of the study area in southeastern Alabama and southwestern Georgia. Downdip the Lisbon grades into a calcareous, glauconitic clay that contains thin to thick beds of fine-grained, calcareous, glauconitic sand, and hard, sandy, glauconitic limestone (Miller, 1986). The Lisbon Formation is thick and dense throughout most of the study area and functions as a nearly impermeable base to the Upper Floridan aquifer. In Alabama, the Lisbon Formation is the principal water-bearing zone of the Lisbon aquifer, or shallow-aquifer system of Alabama, which includes the overlying Ocala Limestone and underlying sediments (Wagner and Allen, 1984). However, stratigraphic relations of the Lisbon Formation to the Ocala Limestone and geologic processes involving overlying units cause the Lisbon Formation to have a negligible influence on stream-aquifer relations in the Alabama part of the study area, as explained further in this section.

The Clinchfield Sand overlies the Lisbon Formation and crops out less than a mile beyond the updip limit of the overlying Ocala Limestone (Herrick, 1972). The Clinchfield Sand is an ancient beach deposit and generally consists of medium to coarse, fossiliferous, calcareous quartz sand. Downdip the sand grades into the Ocala Limestone (Herrick, 1972).

The Ocala Limestone overlies the Lisbon Formation and, where present, the Clinchfield Sand, and consists of two different rock types, which define two distinct flow regimes. One flow regime exists in the upper unit of the Ocala, which contains a white, soft, friable, porous coquina composed of large foraminifera, bryozoan fragments, and whole-

SERIES	GEORGIA GEOLOGIC UNIT	GEORGIA HYDROLOGIC UNIT	FLORIDA GEOLOGIC UNIT	FLORIDA HYDROLOGIC UNIT
HOLOCENE AND PLEISTOCENE	Terrace and undifferentiated deposits	Semiconfining unit	Terrace and undifferentiated deposits	Semiconfining unit
MIOCENE	Undifferentiated overburden (residuum)		Citronelle Formation	
	Miccoskee Formation		Jackson Bluff Formation	Intermediate system
	Hawthorn Formation		Alum Bluff Group: Chipola Formation, Hawthorn Formation	Underlying semiconfining unit
			Intracoastal Formation	
	Tampa Limestone	Upper Floridan aquifer	Tampa Limestone	
	Suwannee Limestone		Suwannee Limestone	
			Marianna Formation	Upper Floridan aquifer
EOCENE	Ocala Limestone; Clinchfield Sand		Ocala Limestone	
	Lisbon Formation	Lower confining unit	Lisbon Formation	Sub-Floridan confining unit

Figure 3. Correlation chart of stratigraphic and hydrologic units in the lower Apalachicola-Chattahoochee-Flint River Basin (modified from Wagner and Allen, 1984).

to-broken echinoid remains, all loosely bound by a matrix of micritic limestone. The other flow regime is in the lower unit and generally consists of fine-grained, soft to semi-indurated, micritic limestone (Miller, 1986). In the Albany, Ga., area, the lower unit generally is a recrystallized dolomitic limestone that is very hard, but fractured (David W. Hicks, USGS, Atlanta, Ga., written commun., 1994). The upper part of the Ocala Limestone is dense in most places in the Albany, Ga., area, and functions primarily to supply ground water to the lower part of the Ocala, which contains most of the lateral ground-water flow in the Upper Floridan aquifer (Torak and others, 1993). In the southeastern part of Houston County, Ala., the Ocala Limestone thickens to about 300 feet (pl. 3). The surface of the Ocala Limestone locally is irregular as a result of the dissolution of the limestone and the development of karst topography. Locally, the upper few feet of the limestone in the subsurface consists of soft, clayey residuum (Miller, 1986).

The Marianna Formation and the Suwannee Limestone crop out in south-central Jackson County, Fla. The Marianna Formation is more massive and chalky than the Ocala Limestone and pinches out downdip where it is overlain by the Suwannee Limestone (Schmidt and Coe, 1978; Schmidt,1984). The Suwannee Limestone is exposed in scattered sinkholes and road cuts near the base of the Solution Escarpment (Hicks and others, 1987). The Marianna Formation and Suwannee Limestone consist of a soft, chalky, biomicritic limestone (Wagner and Allen, 1984). Dissolution has produced numerous interconnected solution openings in the upper few feet of the Suwannee exposure. The solution openings function to supply water to the underlying Ocala Limestone. Downdip, the Tampa Limestone overlies the Suwannee Limestone.

The Tampa Limestone crops out in southern Jackson County, Fla., along the Holmes Valley Scarp (fig. 2) and in Decatur County, Ga., along the Solution Escarpment (fig. 1). The Tampa Limestone is a white to light-gray, sandy, hard to soft, locally clayey, fossiliferous limestone (Miller, 1986). West of the Apalachicola River in southern Jackson and northern Calhoun Counties, Fla., the Tampa Limestone is well dissected by surface-water features and is not as areally extensive as it is east of the river. The Tampa Limestone east of the river contains beds of carbonate muds and clays interspersed with the limestone throughout its thickness (Jeffry R. Wagner, formerly of the Northwest Florida Water Management District, Havana, Florida, written commun., 1987). Geologist's logs and core descriptions, on file at the Florida Bureau of Geology, Tallahassee, Fla., indicate the existence of a dense, greenish-olive, waxy, clay, or mixed, clay-limestone layer near the base of the Tampa Limestone east of the river in Gadsden and northern Liberty Counties, Fla. This clay layer and the overall low permeability of the Tampa Limestone confines the underlying limestones of the Upper Floridan aquifer and impedes downward movement of water, thus causing water levels in the Tampa Limestone east of the Apalachicola River to be higher than those in underlying formations (Jeffry R. Wagner, formerly of the Northwest Florida Water Management District, Havana, Florida, written commun., 1987). Downdip, the Tampa Limestone is overlain by the Intracoastal, Hawthorn, Chipola, and Jackson Bluff Formations (fig. 3).

Undifferentiated overburden and alluvial deposits consisting of alternating layers of sand, silt, and clay, overlie and semiconfine the Upper Floridan aquifer. The lower half of the overburden contains higher percentages of clay and the upper half contains more sandy deposits. Samples from 45 of 50 test wells drilled into the undifferentiated overburden contain more than 25 percent clay (Hayes and others, 1983). The lower, clayey overburden is probably residuum derived from weathering of the underlying limestone (Hayes and others, 1983; Hicks and others, 1987). It is this clayey part of the overburden that semiconfines the underlying Upper Floridan aquifer. Where present, the upper, sandy part can contain a local water table, which interacts with the Upper Floridan aquifer by vertical leakage through the lower, clayey part.

The Intracoastal Formation consists of a sandy, highly microfossiliferous, poorly consolidated, argillaceous, calcarenitic limestone (Schmidt, 1984; Schmidt and Clark, 1980) that has the ability to transmit small quantities of water. The Intracoastal Formation overlies the Tampa Limestone south of central Calhoun County, Fla., and is limited in lateral extent to coastal areas of Florida. In Liberty, Gulf, and Franklin Counties, Fla., a dark gray, dense, plastic, dolosilt between the Intracoastal Formation and the underlying limestone inhibits vertical movement of water between the Upper Floridan aquifer and the Intermediate system and semiconfines the deeper unit. The Intracoastal Formation is overlain throughout most of its areal extent in the lower ACF River Basin by the Chipola Formation; however, to a small extent in the eastern part of the study area, the Intracoastal is overlain by the Hawthorn Formation.

The Chipola Formation is a moderate-to-well-indurated sandy, fossiliferous limestone that has the ability to transmit small quantities of water. The Chipola crops out north of Bristol in Liberty County, Fla., where the Intracoastal is not present (Schmidt, 1984). In this area, the Chipola Formation overlies the Tampa Limestone. Downdip, the Chipola is sporadically thinner and is absent at some locations (Schmidt, 1984).

The Jackson Bluff Formation overlies either the Chipola or Intracoastal Formations (Wagner and Allen, 1984), Tampa Limestone, or Hawthorn Formation, depending on which unit is present. The Jackson Bluff Formation consists of three clayey, sandy, shell beds (Schmidt, 1984; Puri and Vernon, 1964) and crops out in southern Jackson and Gadsden Counties, Fla., north of the outcrop of the Chipola Formation. In southern Liberty, Gulf, and Franklin Counties, the Jackson Bluff Formation is separated from overlying sands by clay beds (Wagner and Allen, 1984). The Jackson Bluff Formation and the overlying clay beds semiconfine the deeper units and impede vertical movement of water to and from surficial deposits.

Surficial sediment of the Citronelle Formation, and terrace and undifferentiated deposits overlie the Jackson Bluff Formation throughout its areal extent. The Citronelle Formation consists of fluvial, cross-bedded sand, gravel and clay (Schmidt, 1984). Terrace deposits generally are uncemented and poorly sorted quartz sands that locally contain seams of clay (Wagner and Allen, 1984). Recent alluvium and undifferentiated deposits are prominent at and near the rivers in the study area.

Hydrologic Setting

Karst processes, hydraulic properties, and stratigraphic relations have limited the hydrologic interaction of lithologic units with surface water to those units younger than and including the Ocala Limestone. Dissolution of carbonate sediments in the Dougherty Plain has established a highly active flow system in the Upper Floridan aquifer that is characterized by high rates of direct recharge through sinkholes, swallow holes, or other circular depressions, indirect recharge by vertical leakage through the overburden, and discharge to surface water, such as the Chattahoochee River and headwater streams of the Chipola River. Stratigraphic relations and the relative contrasts in hydraulic properties between limestone units and between limestone and semiconfining units have simplified a seemingly complex ground- and surface-water flow system into one that is tractable for hydrologic analysis.

The Upper Floridan aquifer is comprised of an offlapping sequence of carbonate sediments consisting of the Ocala, Suwannee, and Tampa Limestones, Marianna Formation, and, where it exists, the Clinchfield Sand. The older sediments extend to the surface in the northern outcrop area, and successively younger sediments offlap to the south. Where they are near the surface, such as in Alabama and Georgia, and in Jackson, Gadsden, northern Calhoun, and northern Liberty Counties, Fla., the limestones are semiconfined from above by undifferentiated overburden and terrace and undifferentiated (surficial) deposits. The Upper Floridan aquifer consists primarily of the Ocala Limestone in the lower ACF River Basin. The aquifer includes the Suwannee Limestone to the east and southeast of the Dougherty Plain at the Solution Escarpment and in the Tifton Upland (fig. 1). The Tampa Limestone is included in the aquifer south of the Florida-Georgia State line, where it overlies the Suwannee Limestone and crops out in the area of the Holmes Valley Scarp (fig. 2).

Surface-water drainage, areal extent, and lithology give the Tampa Limestone different hydrologic implications for the stream-aquifer system, depending on location with respect to the Apalachicola River. West of the river, the combined effects of incomplete areal extent, sandy lithology, and a well-developed network of surface-water drainage make the Tampa Limestone hydrologically similar to the remaining, underlying limestones of the Upper Floridan aquifer. By comparison, east of the Apalachicola River, the greater areal coverage and thickness, more dense, clayey lithology, and less-developed surface-water drainage cause the Tampa Limestone to be hydrologically distinct from the deeper limestones. The Tampa Limestone east of the river contains a higher hydraulic head than the underlying parts of the Upper Floridan aquifer. This higher head, together with hydraulic characteristics that are less transmissive than the deeper units, allows the Tampa Limestone east of the Apalachicola River to function as a source of water to the remaining (underlying) units of the aquifer by downward vertical leakage. West of the river, similarities in hydraulic head and in other previouly mentioned characteristics of the limestones constituting the Upper Floridan aquifer do not permit the Tampa Limestone to function as a vertical-leakage source of water to the deeper units.

The Intermediate system represents an area of transition in the Apalachicola River basin between the Hawthorn Formation to the east and the Alum Bluff Group to the west, and consists of the Intracoastal, Chipola, Hawthorn, and Jackson Bluff Formations (fig. 3), described in detail by Schmidt (1984) and by Wagner and Allen (1984). The Intermediate system is primarily a semiconfining unit to the underlying limestones of the Upper Floridan aquifer; however, locally sandy or carbonate beds of the Intracoastal and Chipola Formations yield water to a few domestic wells.

Surficial sediment of the Citronelle Formation, and terrace and undifferentiated deposits contain a shallow water table where the deposits are medium to coarse grained. The fine-grained deposits and clay create a semiconfining unit to the underlying Intermediate system.

Hydrologic Characteristics

Variations in hydrologic characteristics and thickness the ability of geologic units comprising the stream-aquifer system to either (1) contain and transmit large amounts of ground water, such as aquifers, or (2) provide a source, or a means, of transmitting water by vertical leakage between aquifers, aquifers and other source layers, or aquifers and surface water, such as semiconfining units. Areal and vertical distributions of hydrologic characteristics control the extent to which aquifers and semiconfining units are incorporated into the stream-aquifer flow system and the relative contribution of each hydrologic unit to the water resources of the lower ACF River Basin.

Overlying Semiconfining Units

In Alabama, Georgia and Jackson County, Fla., the semiconfining unit overlying the Upper Floridan aquifer is the undifferentiated overburden. In Gadsden and northern Liberty Counties, Fla., the semiconfining unit is the clay bed at the base of the Tampa Limestone. In northern Calhoun County, Fla., the semiconfining unit consists of the Jackson Bluff Formation and the overlying surficial deposits. Within the lower ACF River Basin in Alabama, Georgia, and the northern panhandle of Florida, semiconfining units consisting of alternating layers of sand, silt, and clay overlie the Upper Floridan aquifer. South of central Calhoun County, Fla., the semiconfining unit overlies the Intermediate system, and consists of the Jackson Bluff Formation and overlying surficial deposits. In most places, the deposits contain enough sand to contain a water table, which functions as a source layer to provide recharge to, or receive discharge from, the underlying aquifer.

The dominant lithologic factor that controls hydraulic conductivity of the semiconfining unit overlying the Upper Floridan aquifer is the sand and clay content of the deposits (Hayes and others, 1983). Laboratory analyses of 16 undisturbed-core samples collected from wells in the Albany, Ga., area indicated that vertical hydraulic conductivity of sediments in the overburden range from about 0.0004 ft/d for a silty clay to about 23 ft/d for a fine to medium sand (C.A. Turner, S & ME, Inc., written commun., 1988). Regional values of vertical hydraulic conductivity were estimated to range from 0.0001 to 9 ft/d, having a median value of 0.003 ft/d (Hayes and others, 1983).

Thickness data for the undifferentiated overburden, Jackson Bluff Formation, clay at the base of the Tampa Limestone, and terrace and undifferentiated (surficial) deposits were compiled from well data on file at the USGS, District Office, Atlanta, Ga., and at the Florida Bureau of Geology, Tallahassee, Fla. Thickness of the overburden ranges from about 20 to about 150 ft; however, locally, the overburden might be absent or thickness might exceed 200 ft. Although most layers of similar lithology in the undifferentiated overburden are discontinuous and can be traced only for short distances, a layer of clay is present that might be continuous throughout the lower half of the overburden. The clay layer at the base of the Tampa Limestone in Gadsden and Liberty Counties, Fla., is about 50 ft thick. Thickness of the Jackson Bluff Formation and the surficial deposits ranges from about 20 ft near the outcrop of the Jackson Bluff Formation to about 120 ft near the coast. Clay is dominant throughout the semiconfining units and confines the underlying aquifer.

Zones of equal thickness for the predominantly clayey sediments that constitute overlying semiconfining units to the Upper Floridan aquifer and Intermediate system (pl. 2) were defined from these data and used in conjunction with vertical hydraulic conductivity to determine values of hydraulic conductance (vertical hydraulic conductivity divided by thickness). Vertical-hydraulic-conductance zones were used as input to the finite-element model (see "Conceptualization of the Flow System"); thus, to facilitate this input, zone boundaries were located approximately with element sides of the finite-element mesh.

Vertical hydraulic conductivity and thickness of the laterally continuous clay layer within overlying semiconfining units create a hydrologic barrier to vertical flow of ground water to, and from, the aquifers. The clay layer can affect ground-water flow in the aquifer system by causing perched ground water in overlying deposits following periods of heavy rainfal, decreasing the amount of ground-water recharge to the aquifer from infiltration of precipitation, and controlling the infiltration rate of surface-applied chemicals that might have the potential to contaminate ground water.

Intermediate System

The Intermediate system ranges in thickness from about 20 ft in Jackson County, Fla., where only the Jackson Bluff Formation is present, to more than 300 ft near the coast. Water-bearing units of the Intermediate system range in thickness from about 30 to 250 ft (fig. 4). The aquifer material of the Intermediate system has a low permeability, and yields to domestic wells average about 5 gallons per minute (gal/min) (Wagner and Allen, 1984). Estimated transmissivity ranges from about 400 to 4,000 ft^2/d. The water-bearing part of the Intermediate system is confined below by massive, plastic, dolosilt at the base of the Intracoastal Formation, and above by the Jackson Bluff Formation.

Underlying Semiconfining Unit

The semiconfining unit at the base of the Intermediate system south of central Calhoun County, Fla., (fig. 1) consists of a massive, clayey, dolosilt which confines the underlying Upper Floridan aquifer. Thickness of the clay bed ranges from about 5 to 30 ft, which was determined from well data on file at the Florida Bureau of Geology, Tallahassee, Fla. Zones of equal thickness for the predominantly clayey sediments (fig. 5) were defined from these data, and were used along with estimates of vertical hydraulic conductivity to determine hydraulic conductance (vertical hydraulic conductivity divided by thickness) for input to the finite-element model (see "Conceptualization of the Flow System"). Element sides of the finite-element mesh were used as zone boundaries to facilitate input to the finite-element model, in a manner similar to that described previously for the overlying semiconfining units.

Upper Floridan Aquifer

The Upper Floridan aquifer ranges in thickness from a few feet at the updip limit to more than 700 ft in Florida (pl. 3). The aquifer is confined below by low-permeability rocks of the Lisbon Formation, and generally is semiconfined above by the undifferentiated overburden to the north. The aquifer is exposed along sections of major streams such as the Apalachicola, Chattahoochee, and Flint Rivers, and Spring Creek, where erosion has removed the overburden (Maslia and Hayes, 1988).

The capacity of the Upper Floridan aquifer to store and transmit large quantities of water is attributed to the fractured nature of the Ocala Limestone (Hayes and others, 1983) and associated dissolution of limestone by ground water circulating along bedding planes and fractures (Hicks and others, 1987). Permeability of the Upper Floridan aquifer is imparted by small interconnected conduits or solution openings. A system of major solution conduits has developed in areas between the Solution Escarpment and the Flint River through which large quantities of ground water are transmitted from the Upper Floridan aquifer to springs, such as Radium Springs, which discharge water to the river. Although the cross-sectional area of solution conduits is small compared with the cross-sectional area of aquifer across which ground water flows into the river, solution conduits conduct a major part of the ground-water flow and contribute greatly to shaping the potentiometric surface of the aquifer (Hayes and others, 1983 p. 46). Consequently, the distribution of solution openings and fractures was used to define, qualitatively, zones of high and low hydraulic conductivity for the digital model of the aquifer.

Computed values of transmissivity from field tests of the Upper Floridan aquifer range from about 2,000 to 1,300,000 ft^2/d (Hayes and others, 1983; Wagner and Allen, 1984). Large variations in hydraulic conductivity occur in the aquifer owing to size and distribution of solution openings. Computed values of transmissivity, although locally accurate, might not be representative of regional transmissivity because of variability in hydraulic conductivity caused by fracture and solution features. Therefore, effective regional values of transmissivity range from about 2,000 to 300,000 ft^2/d (Hayes and others, 1983). Transmissivity is lowest near the updip limit of the Ocala Limestone, where the aquifer is relatively thin. Transmissivity generally increases to the south where the aquifer is thicker and is highest adjacent to major streams, where the Upper Floridan is thinly confined and breached by the rivers and sinkholes. At these locations, water flowing between streams and the ground-water system has accelerated the development of solution openings (Maslia and Hayes, 1988).

Lower Confining Unit

The lower confining unit consists of the Lisbon Formation. The hard, well-cemented, and clayey nature of the limestone gives this unit a distinctly lower water-yielding capability when compared with the Upper Floridan aquifer, causing it to act as a nearly impermeable base to the Upper Floridan aquifer (Hayes and others, 1983). Because of the relatively low hydraulic conductivity compared with the Upper Floridan aquifer, wells yield only a few gallons per minute from this unit, although southeast

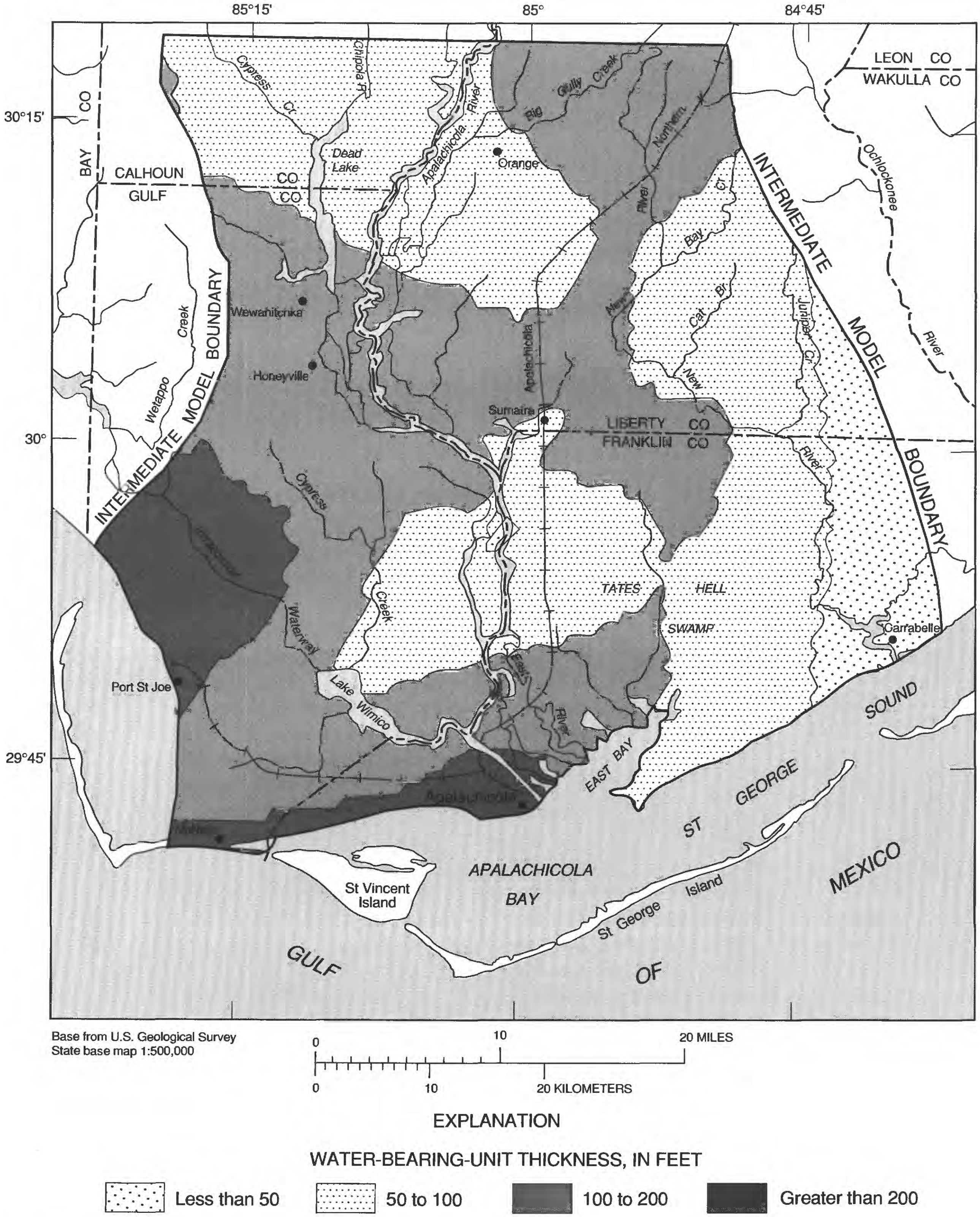
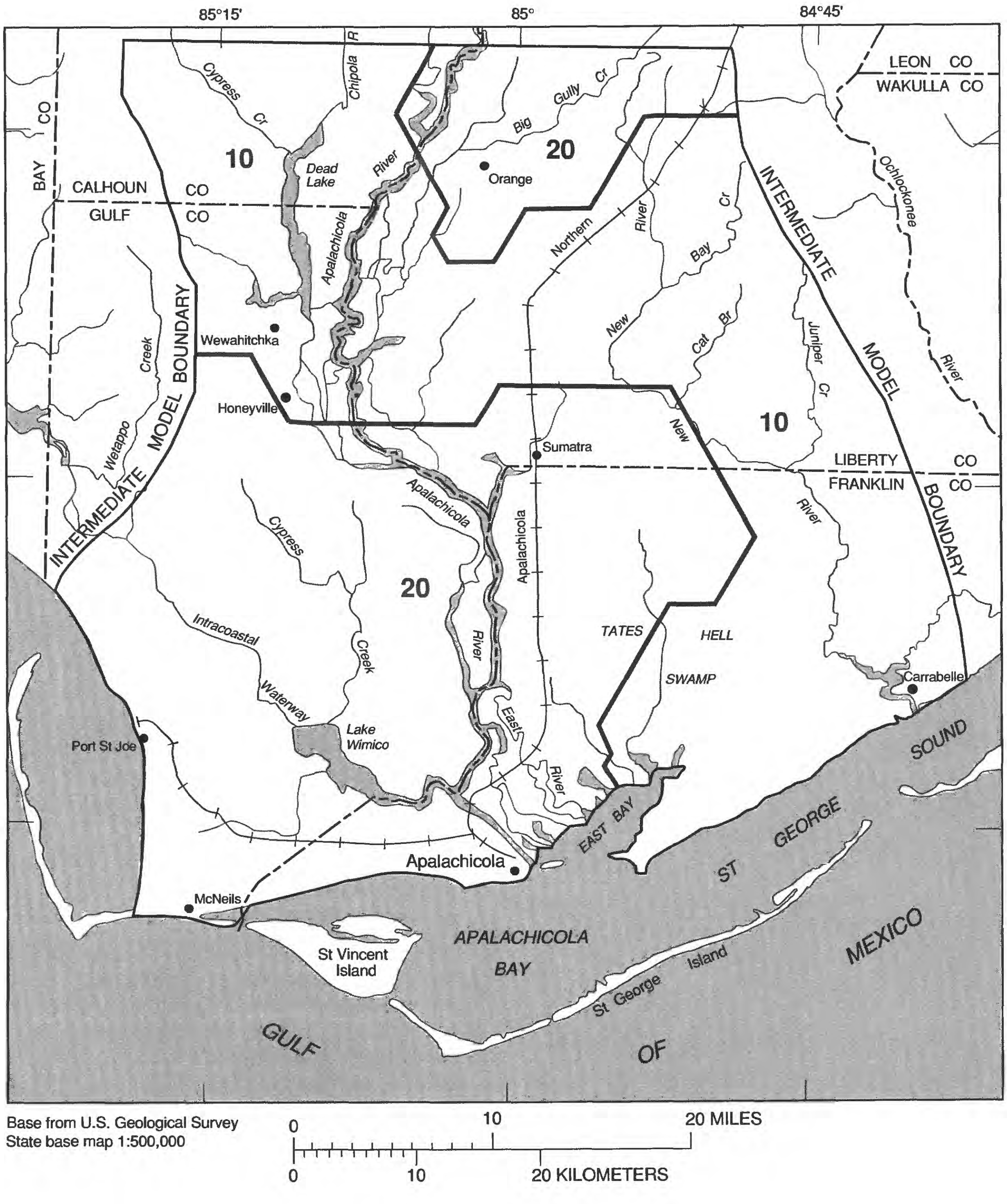


Figure 4. Thickness of water-bearing units in the Intermediate system.



EXPLANATION

——— BOUNDARY OF ZONE OF EQUAL THICKNESS OF CLAYEY SEDIMENTS UNDERLYING INTERMEDIATE SYSTEM—Element sides of finite-element mesh used as zone boundaries

20 NUMBER INDICATES CLAYEY SEDIMENT THICKNESS, IN FEET

Figure 5. Zones of thickness of predominantly clayey sediments underlying the Intermediate system.

of the Dougherty Plain, domestic supplies of water may be obtained from the Lisbon Formation (Hayes and others, 1983).

Results of a regional ground-water-flow analysis that included the Upper Floridan aquifer and Lisbon Formation indicated that the Lisbon Formation acts as a nearly impermeable base to the Upper Floridan aquifer. These results indicate that recharge by vertical leakage to the Upper Floridan aquifer across the Lisbon Formation occurs in the northernmost part of the study area at a rate of about 10 ft^3/s, and that discharge from the Upper Floridan aquifer through the Lisbon Formation occurs in the southern part at a rate of about 5 ft^3/s; no leakage was indicated in the central Dougherty Plain. In comparison, the magnitude of lateral flow through the aquifer is about 4,000 ft^3/s (Robert E. Faye and Gregory C. Mayer, U.S. Geological Survey, written commun., November, 1990).

Ground-Water Levels

Ground-water levels in water-bearing parts of the overlying semiconfining unit and Intermediate system, and in the Upper Floridan aquifer fluctuate in response to seasonal changes in recharge from infiltration of precipitation, extended periods of dry climatic conditions, discharge to pumped wells and by evapotranspiration, and interaction with surface-water features. The natural pattern of high water-level altitude (or shallow depth to water with regard to land surface) in recharge areas and low water-level altitude in discharge areas, such as near streams, can be affected by heavy pumping. Water levels range in altitude from about 340 ft in the Upper Floridan aquifer in northern parts of the study area, to slightly above sea level in the semiconfining units on the flood plain along the coast. Neither response time nor magnitude of water-level changes in the semiconfining unit, Intermediate system, or Upper Floridan aquifer is predictable; it varies areally within each hydrologic unit and can be either nearly instantaneous or very slow, and either large or barely perceptible.

Seasonal Fluctuations

The water level in the semiconfining unit overlying the Upper Floridan aquifer is highest during January or February through April, declines during summer and fall, and is at a minimum during November through December or January (fig. 6). Beginning in December and continuing through January, water levels in wells generally rise quickly in response to recharge by infiltration of precipitation. During late spring and summer, however, water-level response to precipitation is subdued, probably because most of the precipitation either replaces the soil moisture deficit in the unsaturated zone or is lost to evapotranspiration before the water can infiltrate to the saturated zone (Hayes and others, 1983). In the Albany, Ga., area, unpublished data in USGS files indicate that monthly water levels in 22 wells tapping water-bearing parts of the semiconfining unit ranged from about 1 to 22 ft below land surface for the period April 1982 through December 1984. Maximum annual-water-level fluctuations in individual wells ranged from about 10 to 16 ft. During the drought conditions of 1980 and 1981, Hayes and others (1983) reported water levels 1 to 38 ft below land surface in 21 wells located throughout the Dougherty Plain. For the measurement period of October 23 to 28, 1986, nearly all wells in the semiconfining unit in the Dougherty Plain were dry, indicating the severity of drought conditions for this period, compared with conditions in 1980 and 1981.

Seasonal water-level fluctuations in the semiconfining unit overlying the Intermediate system are affected by seasonal variations in recharge from precipitation, as described previously for the unit overlying the Upper Floridan aquifer. In addition, ground-water levels are affected by seasonal changes in river stage, depending on proximity of the semiconfining unit to the Apalachicola River. Measurements of water table and river stage for water year 1980 by Leitman and others (1984) indicated that the water level in the semiconfining unit fluctuates about 1.5 to 5.5 ft annually in response to changes in river stage; the larger seasonal fluctuations occurred along a transect across the flood plain of the river located about 3 mi north of the Blountstown gaging station; the smaller seasonal variation in water level is from another transect located near the Sumatra gaging station (fig. 2).

Ground-water levels in the Upper Floridan aquifer also fluctuate seasonally in response to precipitation, evapotranspiration, and pumping. Late winter and early spring recharge by infiltration of precipitation, coupled with low evapotranspiration and pumping rates, cause the water level in the Upper Floridan aquifer to reach a maximum during February through April (fig. 7).

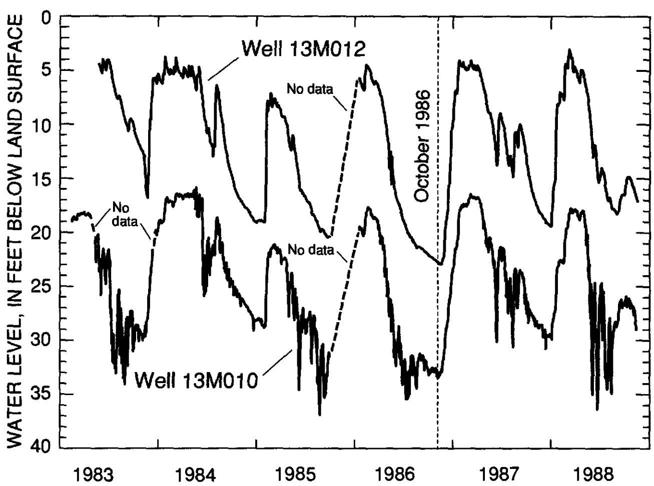


Figure 6. Water-level fluctuations in wells 13M010 and 13M012 in the semiconfining unit overlying the Upper Floridan aquifer, 1983–88. (See plate 1 for location of wells.)

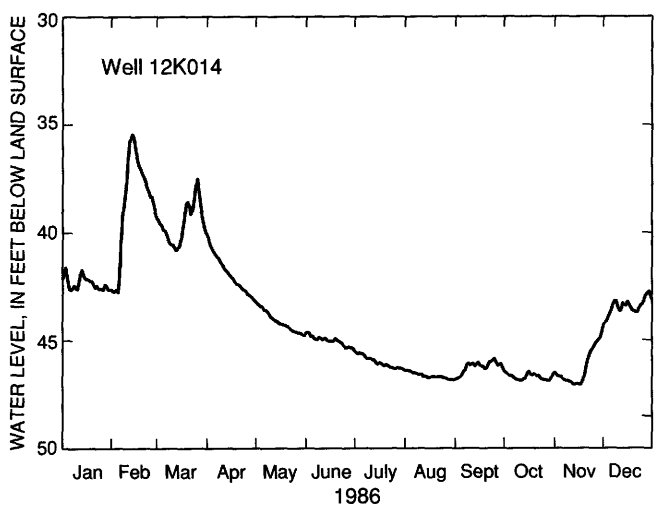


Figure 7. Water-level fluctuations in well 12K014 in the Upper Floridan aquifer, 1986. (See plate 1 for location of well.)

During the growing season, the combined effects of increased irrigation pumpage, higher evapotranspiration rates, and decreased recharge, compared with winter and spring conditions, cause ground-water levels to reach a minimum by late summer, and to be maintained there through fall. Seasonal water-level fluctuations range from about 2 ft in eastern parts of the study area in Georgia, to about 30 ft near Albany, Ga. (fig. 1). Near major agricultural and industrial pumping centers, seasonal water-level fluctuations probably exceed 30 ft and are amplified by drought conditions. However, pumpage does not result in forming distinct cones of depression (Hicks and others, 1987); rather, because of the relatively even distribution of wells and the magnitude of pumping rates, the potentiometric surface of the Upper Floridan aquifer is raised and lowered uniformly.

Very little water-level data exist to define seasonal fluctuations in wells tapping the Intermediate system. Water levels tend to decline toward the Apalachicola River (Jeffry R. Wagner, formerly of the Northwest Florida Water Management District, Havana, Fla., written communication, 1988), and the river tends to regulate ground-water levels in its proximity. Water levels in the Intermediate system also can be affected seasonally by water-level fluctuations in the overlying semiconfining unit. Because the underlying Upper Floridan aquifer is the primary source of ground water in the lower ACF River Basin, and population is low in areas of the basin where the Intermediate system is connected hydraulically to surface water, only a few wells for domestic supply tap the Intermediate system. The rural setting and small domestic-supply needs preclude large seasonal variations of pumpage and water level in the Intermediate system.

Long-Term Effects of Drought Conditions and Pumping

Ground-water levels in the Upper Floridan aquifer in the lower ACF River Basin do not indicate long-term declines from drought conditions. A typical response to drought conditions is shown by the water-level hydrograph of well 13L003 (fig. 8), in Georgia near the Dougherty-Worth County line (pl. 1). During droughts of the early and late 1960's, 1980 and 1981, and 1986, water levels in well 13L003 declined to record or near-record lows, but recovered to predrought levels with the return of normal precipitation (Hicks and others, 1987). During the drought of 1986, water levels in wells 11K015, 12L028, and 12K014 (figs. 9–11) declined to record lows, but with the return of normal precipitation during the next season, they recovered to predrought conditions.

Effects of drought conditions on water levels in wells in the Upper Floridan aquifer in Florida are not as great as in Georgia, due to the rural setting, small population, and small (about 10 ft) seasonal, ground-water fluctuation in this area. Water levels in several wells in Jackson and Gadsden Counties recovered sufficiently from the dry conditions of 1980 and 1981 to reach record-high levels in early 1983 and 1984.

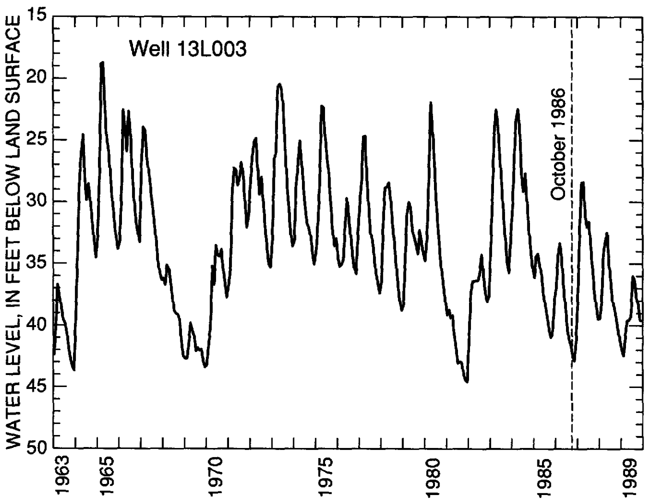


Figure 8. Water-level fluctuations in well 13L003 in the Upper Floridan aquifer, 1963–89. (See plate 1 for location of well.)

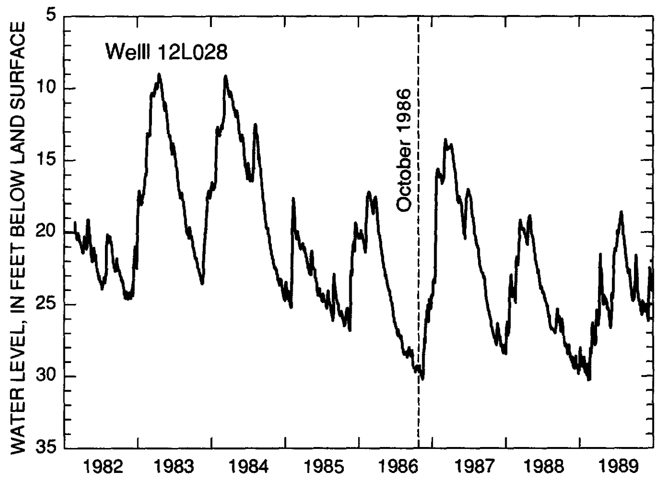


Figure 10. Water-level fluctuations in well 12L028 in the Upper Floridan aquifer, 1982–89. (See plate 1 for location of well.)

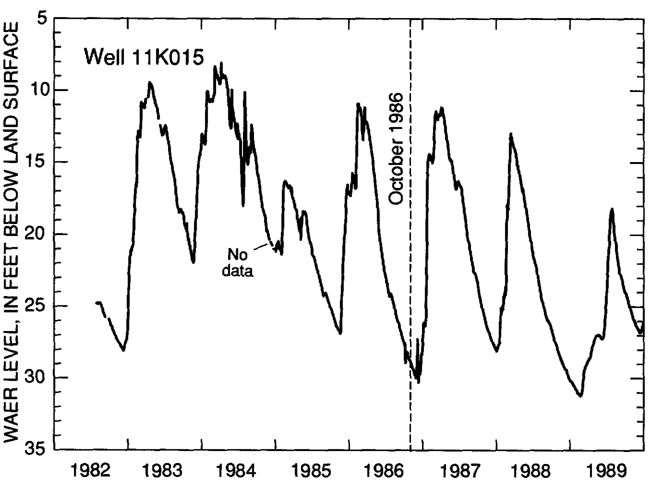


Figure 9. Water-level fluctuations in well 11K015 in the Upper Floridan aquifer, 1982–89. (See plate 1 for location of well.)

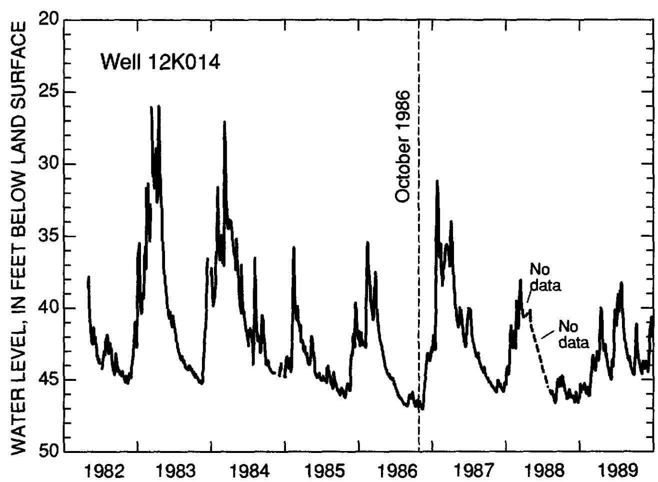


Figure 11. Water-level fluctuations in well 12K014 in the Upper Floridan aquifer, 1982–89. (See plate 1 for location of well.)

Long-term effects of pumpage on the Upper Floridan aquifer can be determined by comparing potentiometric surfaces of the aquifer prior to development (Wait, 1963) and for November 1985 (Hicks and others, 1987). Similarities in the two surfaces show that 28 years of pumpage at an average rate of about 66 Mgal/d has not produced a long-term decline in the ground-water level. Thus, the ground-water-flow system of the Upper Floridan aquifer remains in equilibrium; recharge received from normal, annual rainfall is approximately equal to combined effects of natural and man-induced discharge (Hicks and others, 1987, p. 22).

Limited water-level data indicate that water-bearing units in the Intermediate system do not exhibit long-term effects of drought conditions or pumping. Generally, predrought conditions are re-established with the return of normal precipitation in the season following dry conditions. Because ground-water pumpage is small in the Intermediate system, no long-term effects have been observed.

Water levels in the semiconfining unit above the Upper Floridan aquifer do not indicate long-term effects of drought conditions or pumpage. Although all wells tapping the water-bearing parts of this unit were dry in late October 1986, water levels respond quickly to recharge by infiltration of precipitation during December and January (fig. 6), and recover to predrought conditions following the return of normal precipitation. Water levels in the semiconfining unit overlying the Intermediate system do not exhibit long-term effects of drought or pumpage either; however, they seem to influence several hydrologic features of the flow system, namely, stage of the Apalachicola River, recharge by infiltration of precipitation, and ground-water flow from adjacent upland areas (Leitman and others, 1984).

Effects of Surface-Water Features

Effects of surface-water features on ground-water levels vary in the lower ACF River Basin. Although lithology and degree of solutioning in the central part of the basin indicate good potential for hydraulic connection between the Upper Floridan aquifer and Flint River, sudden changes in river stage for short durations do not necessarily cause a corresponding water-level change in the aquifer. From February 21 to March 4, 1987, the stage of the Flint River at Albany rose more than 12 ft in response to heavy rainfall in the northern part of the state. However, the water level in well 12K014, located less than 2 mi from the Flint River (pl. 1) increased by less than 2 ft during the same period (fig. 7).

Surface-water impoundments behind dams affect ground-water levels in the lower ACF River Basin. The largest impoundment in the study area, Lake Seminole, influences the ground-water level of the Upper Floridan aquifer and overlying semiconfining unit in the area adjacent to the lake. Lake stage is maintained at about 77 ft year round, causing water levels in the adjacent aquifer and overlying semiconfining unit to be nearly constant. Other surface-water impoundments, such as Lake Worth, located north of Albany, Ga., and Lake Blackshear, located along the northern study-area boundary (pl. 1), exert a similar influence on ground-water levels as Lake Seminole; however, levels of these lakes fluctuate more than that of Lake Seminole. In the vicinity of Lake Worth, ground-water levels in the Upper Floridan aquifer also are influenced by regional flow from the north (Torak and others, 1993).

Downstream of Lake Seminole, the stage of the Apalachicola River influences ground-water levels in the flood plain. Relations between water-level fluctuations in the flood plain and river stage were determined by Leitman and others (1984) from measurements of ground-water levels in a system of observation wells at several locations along transects across the flood plain near Blountstown and Sumatra, Fla. (pl. 1). Ground-water levels along both transects were dependent on river stage; however, water-table fluctuations were damped by movement of water through flood-plain soils (Leitman and others, 1984, p. A28).

Ground-Water Quality

Water in the Upper Floridan aquifer in the lower ACF River Basin is of good quality and generally does not contain constituent concentrations that exceed maximum contaminant levels established for drinking water by the Georgia Department of Natural Resources (1977) and the U.S. Environmental Protection Agency's (EPA) Primary or Secondary Drinking-Water Regulations (1986a,b). In the northern part of the lower ACF River Basin, water in the Upper Floridan aquifer generally is a hard, calcium bicarbonate type, less mineralized than water in deeper aquifers (Hicks and others, 1981). In the central part of the basin, water in the Upper Floridan aquifer contains slightly higher specific conductance and concentrations of dissolved solids and phosphorus than in the northern part of the basin, indicating vertical movement of ground water through overlying, phosphate-rich sediments (Mattraw and Elder, 1984). Water-quality information for water-bearing zones in the Intermediate system was not available; however, potential sources of water-quality degradation from agriculture or industry are low, and the water is assumed to be of good quality and suitable for most purposes.

Water-quality samples from the Upper Floridan aquifer and Flint River at Newton were collected as part of a previous investigation by Hicks and others (1987). The analysis by Hicks and others (1987, p. 33–36) indicated that the general quality of water in the Upper Floridan aquifer is suitable for most purposes, although trace concentrations of specific organic compounds were detected in some wells. However, as stated by Hicks and others (1987, p. 35), the samples indicated a one-time concentration of chemical constituents in the aquifer only at these specific locations, and that flushing (transport) or dilution precluded detection at a later time. In addition, water samples from wells in rural areas did not contain these constituents.

Water from a well completed in the Upper Floridan aquifer in an urban area of Albany, Ga., contained higher concentrations of trace metals and was more acidic than samples collected in rural or agricultural areas (see Hicks and others, 1987, table 2). Another well in an urban area of Albany contained a trace amount of chlordane, use of which is restricted by the EPA to subsurface injection for termite control; and two volatile organic compounds (VOC) which are used as industrial degreasers: tetrachloroethylene (5.9 μg/L) and trans-1,2-dicloroethylene (16 μg/L). Organic compounds such as aldicarb, a nematicide, its degradation products sulfoxide and sulfone, and the insecticide dieldrin were detected in some water samples from wells tapping the Upper Floridan aquifer for agricultural supply. These compounds probably entered the Upper Floridan aquifer as vertical recharge through the overlying semiconfining unit of the undifferentiated overburden, as they generally are applied to soil as agricultural pesticides. However, water samples collected from these wells 6 months later did not contain these constituents in concentrations above the detection limits (Hicks and others, 1987, p. 33).

Surface Water

Hydrologic factors affecting surface-water resources also affect the interaction of ground water by regulating flow across surface-water sediments and play an important role in evaluating stream-aquifer relations. The drainage network established by streams gives natural evidence of water-resource availability, streamflow gives a measure of resource quantity, and control structures indicate man's attempt to harness the resource for various purposes. These 3 elements of the surface-water system are discussed as they pertain to stream-aquifer relations in the lower ACF River Basin.

Drainage

The Chattahoochee River enters the central part of the study area east of Dothan, Ala., and drains about 1,800 square miles of Coastal Plain sediments (pl. 1). The river is deeply incised within its flood plain and cuts into the underlying limestone aquifer (Hayes and others, 1983). There are no large tributaries to the Chattahoochee River within the study area; only small streams and creeks, such as Sawhatchee Creek, that mostly drain the undifferentiated overburden to the limestone. The Chattahoochee River flows roughly 50 mi south-southeastward to Lake Seminole, a manmade impoundment formed at the Georgia-Florida border behind Jim Woodruff Lock and Dam at the confluence of the Chattahoochee and Flint Rivers.

The Flint River enters the extreme northern part of the study area about 7 mi north of Lake Blackshear (pl. 1) and drains about 6,000 square miles within the Coastal Plain. Major tributaries originate west of the river in the Coastal Plain and include Cooleewahee, Ichawaynochaway, Kinchafoonee, and Spring Creeks. Spring Creek rises north of Colquitt, Ga., near the Calhoun-Early County line and flow south into Lake Seminole, about 3 mi northeast of the junction of the Flint and Chattahoochee Rivers. Only minor tributaries exist east of the Flint River from the Solution Escarpment, which creates a ground-water and surface-water divide and forms the eastern basin boundary (fig. 1).

The Apalachicola River drains about 2,400 square miles of Coastal Plain sediments as it flows approximately 106 mi from Lake Seminole to Apalachicola Bay in the Gulf of Mexico (pl. 1). The major tributary to the Apalachicola River is the Chipola River, which drains half the area drained by the Apalachicola River (Mattraw and Elder, 1984). Two distributaries, Chipola Cutoff and Brickyard Cutoff (fig. 2), convey water from the Apalachicola River, but subsequently return flow to the river downstream of the diversions. Water flows from the Apalachicola River to the Chipola River near Wewahitchka, Fla., through the Chipola Cutoff, and rejoins the main stem of the Apalachicola River about 13 mi downstream (Mattraw and Elder, 1984). The Brickyard Cutoff conveys water from the Apalachicola River to the Brothers River near Sumatra, Fla. (pl. 1), and this river rejoins the Apalachicola River about 8 mi south of the cutoff. About 6 mi further downstream, the Apalachicola River joins the Jackson River and flows southeast into Apalachicola Bay.

The Apalachicola River basin was divided into 3 zones by Leitman and others (1984) on the basis of river-channel morphology, drainage characteristics, and physiography. The following drainage description is summarized from this reference. The upper-river corridor is defined as the region from Chattahoochee to Blountstown, Fla. (fig. 2). In this region, the river cuts through sediments of Miocene age. The width of the flood plain varies from 1 to 2 mi, and the channel is characterized by long, straight reaches and wide, gentle bends. The middle zone of the river from Blountstown to Wewahitchka, Fla., lies in Holocene and Pleistocene deposits and has a wider flood plain (2–3 mi) than the upper river. The river channel meanders in large loops through the Beacon Slope region (fig. 2) and has many small, tight bends to the south. The lower zone of the river from Wewahitchka to Apalachicola, Fla., lies entirely within the Gulf Coastal Lowlands physiographic district and flows over Holocene and Pleistocene deposits. The flood plain ranges in width from 2.5 to 4.5 mi, and the channel is characterized by long, straight reaches having a few small bends.

Streamflow

Streamflow in the lower ACF River Basin is highly variable in time and location and is affected by many natural and man-induced factors. Because of these factors, several reports have been prepared containing detailed descriptions of streamflow variation. Stream-stage and discharge hydrographs are given by Hayes and others (1983), and Leitman and others (1984). Flow-duration curves for streams in the Dougherty Plain were developed by Hayes and others (1983). These references, together with streamflow hydrographs at selected gaging stations and observations made during October 1986, provide the basis for descriptions of streamflow given in this report.

In general, high streamflow can be used to indicate direct runoff resulting from climatic factors, watershed physiography, and vegetation, whereas low streamflow tends to indicate base flow or the ground-water component of streamflow. Streamflow varies seasonally; low flows occur usually from September to November, and high flows from January to April each year. Flood conditions vary greatly from year to year and might not follow seasonal trends in any given year (Leitman, 1984). Streamflow is decreased by ground-water withdrawals, which are centered primarily in Georgia and remove water that normally would contribute flow to streams under natural conditions (Torak and others, 1993). Graphs of flow in the Flint River, monthly precipitation, and ground-water levels (fig. 12) show the relations of ground-water and climatic conditions with streamflow that are characteristic of the study area. A further discussion of the correlation of precipitation, streamflow, and ground-water levels is given in Hayes and others (1983). In the southern part of the basin, streamflow in the Apalachicola and Chipola Rivers is influenced more by rainfall in Georgia than by rainfall in Florida because more of the basin area resides in Georgia than in Florida (Leitman, 1984).

The upper-river corridor of the Apalachicola River (from Chattahoochee to Blountstown, Fla.) exhibits a larger range in river-stage fluctuations than the lower river (from Wewahitchka to Apalachicola, Fla.; fig. 13) for several reasons. One is that differences in basin physiography and hydraulic properties of sediments drained by the upper and lower river provide interactions of the river with ground water at different rates in the upper and lower sections. Another is the influence of natural-riverbank levees and flood-plain water on streamflow, which varies along the Apalachicola River; levees either prevent flood-plain water from entering the river or prevent river water from entering the flood plain. Streams receive ground water from the water-table in the flood plain at low stages and either lose water or do not contribute to the water-table during high stages. A detailed description of river-stage and water-table altitudes in the flood plain is given by Leitman (1984). Another reason for nonuniform river-stage fluctuations throughout the course of the Apalachicola River is the influence of tides on river stage. Tidal fluctuations in the lower river vary greatly with river stage and tidal cycles, but generally range from about 1.5 to 2.3 ft in amplitude and extend about 20 to 25 mi upstream from the mouth of the Apalachicola River (U.S Army Corps of Engineers and others, 1984).

Of particular interest to this study is the ground-water component of streamflow, or base flow. Streamflow measurements that were taken during October 23 to 28, 1986 at continuous-record gaging stations and at partial-record measurement stations (table 1), and hydrographs of stream stage and discharge at gaging stations (figs. 13–15), indicate that seasonal and low-flow conditions existed in the lower ACF River Basin during late October 1986. Some of the upper reaches of small streams were dry, further attesting to the severity of the dry climatic conditions. Although, theoretically, hydrograph-separation techniques (Linsley, Kohler, and Paulhus, 1975) can be used to distinguish individual components of total streamflow, the absence of runoff from precipitation during the exceptionally dry summer and fall of 1986 permitted stream-discharge measurements to be used as estimates of base flow.

Dams and Navigational Improvements

Three dams and associated surface-water impoundments are contained within the lower ACF River Basin. The Warwick Dam impounds Lake Blackshear and is the most upstream control structure on the Flint River (pl. 1). It is located about

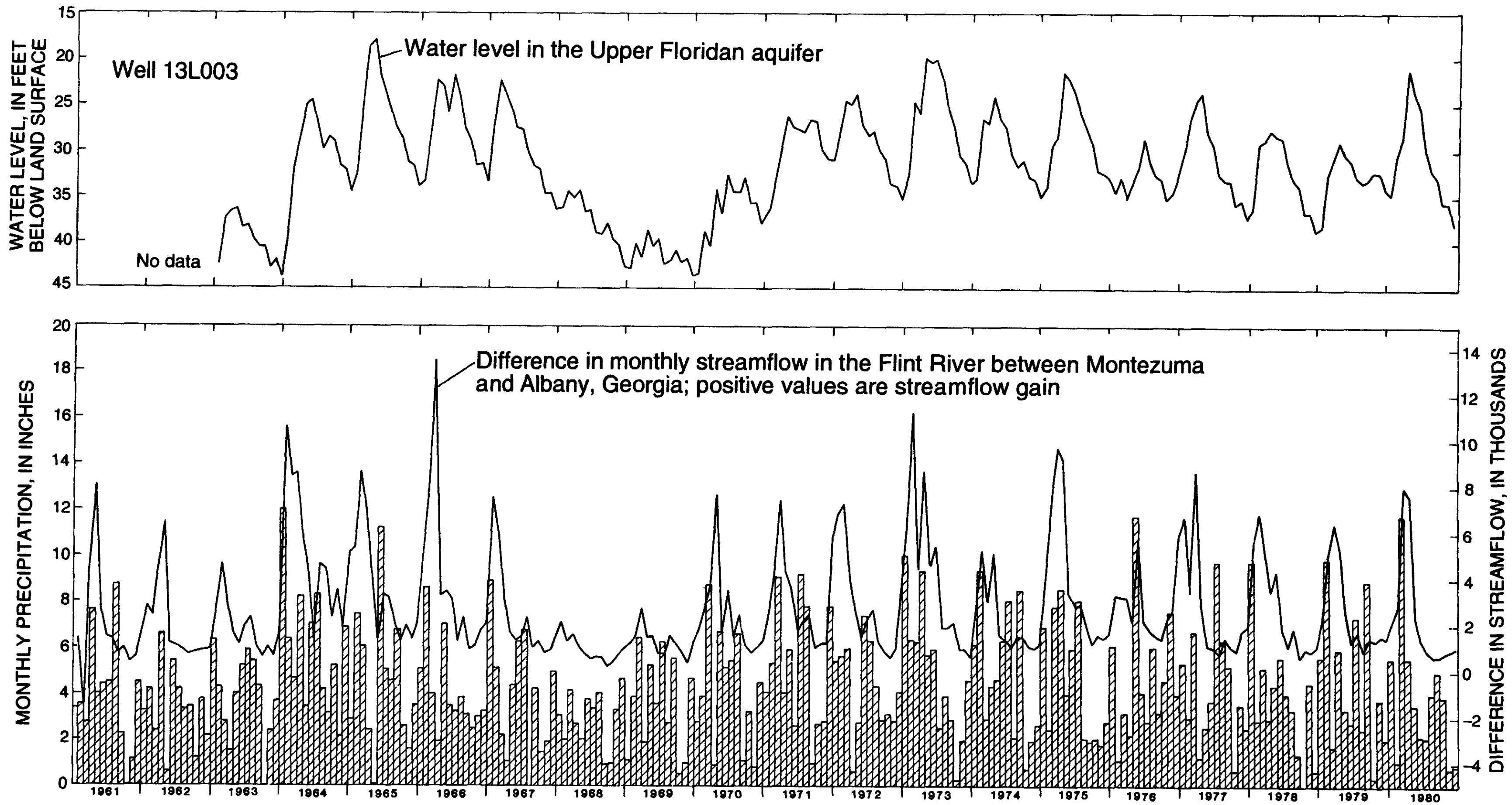


Figure 12. Difference in streamflow on the Flint River between Montezuma and Albany, Ga., precipitation, and water level in the Upper Floridan aquifer near Albany, Ga., 1961–80 (modified from Hayes and others, 1984).

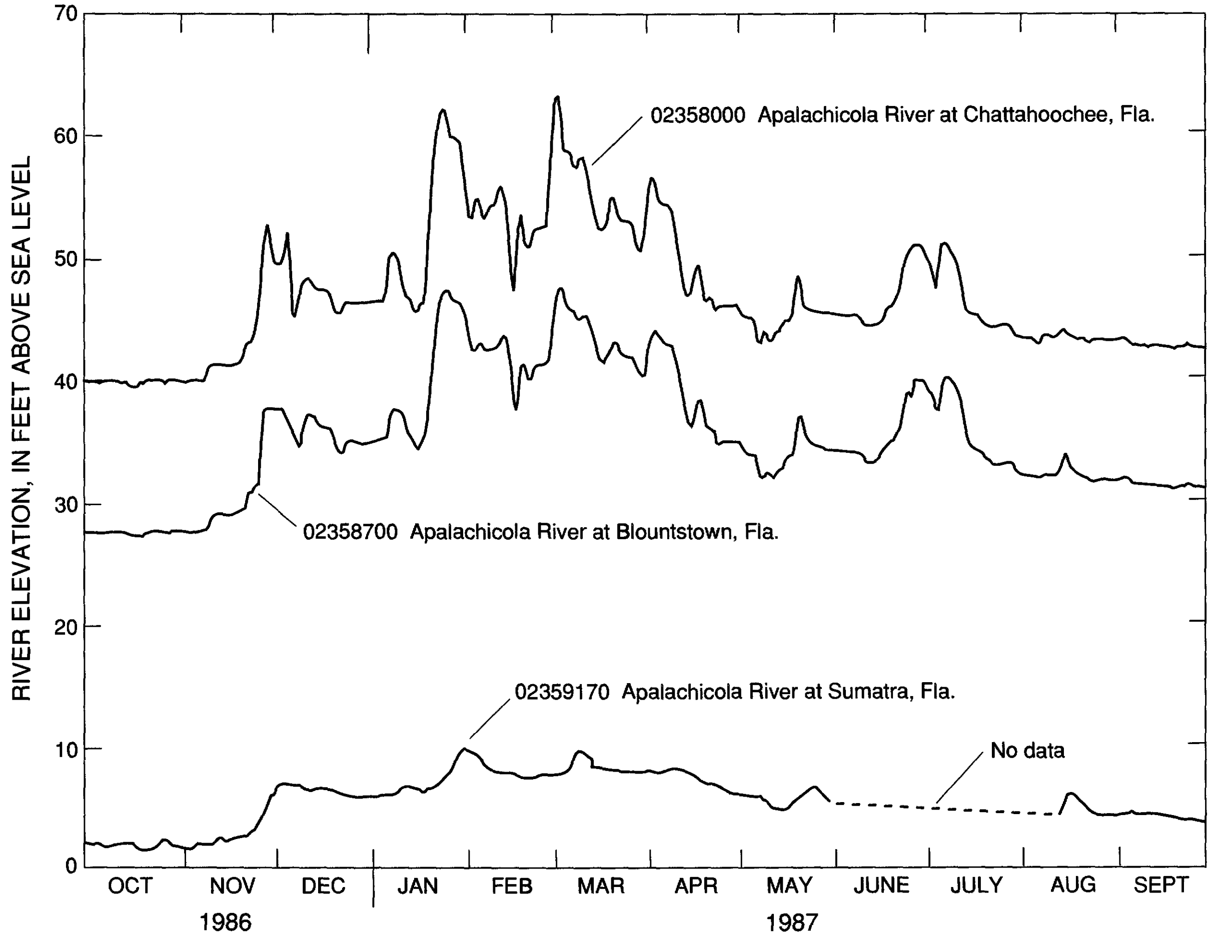


Figure 13. River stage for three gaging stations on the Apalachicola River, October 1986 to September 1987. (See plate 1 for location of gaging stations.)

33 mi upstream from Albany and is owned and operated by Crisp County, Ga., for hydropower generation. About 2 mi north of Albany is the Flint River Dam, which impounds Lake Worth (pl. 1). The Flint River Dam, owned and operated by Georgia Power for hydropower generation, actually consists of two dams, one on the Flint River and one on Muckafoonee Creek. The impoundments behind these dams are connected by an excavated channel (U.S. Army Corps of Engineers and others, 1984). Both dams are run-of-the-river structures and do not appreciably affect flows downstream.

Jim Woodruff Lock and Dam is the southernmost impoundment structure in the lower ACF River Basin. It is located about 1 mi downstream of the confluence of the Chattahoochee and Flint Rivers at the Florida-Georgia-State line and impounds Lake Seminole, a 37,600-acre reservoir which provides headwater to the Apalachicola River (pl. 1). Construction of the dam by the U.S. Army Corps of Engineers began in 1950, and filling of the reservoir to its normal-pool altitude of 77 ft occurred in stages from May 1954 to February 1957. The lake inundates about 47 mi of the Chattahoochee and Flint Rivers each, and has about 240 mi of shoreline (Leitman and others, 1984). The dam was constructed primarily to aid navigation of barge traffic on the Apalachicola, Chattahoochee, and Flint Rivers, with hydropower generation as a secondary benefit. Despite its size, Lake Seminole is essentially a run-of-the-river impoundment having less than 67,000 ac-ft of useful storage (U.S. Army Corps of Engineers and others, 1984).

Navigational improvements such as dredging, cutoffs, and groins (dikes partially extending into the stream channel perpendicular to banks) have been made in the principal rivers of the lower ACF River Basin by the U.S. Army Corps of Engineers. The Corps is authorized to maintain channels 100-ft wide and 3- and 9-ft deep at specific locations in

Table 1. Streamflow discharge measurements in the lower Apalachicola-Chattahoochee-Flint River Basin for October 23 to 28, 1986
[Discharge in cubic feet per second]

Station number[1]	Station name	Discharge	Station number[1]	Station name	Discharge
330400	New River near Sumatra, Fla.	12.6	354350	Chickasawhatchee Creek near Albany, Ga.	14.3
343710	Omussee Creek near Haleburg, Ala.	84.3	354410	Chickasawhatchee Creek near Leary, Ga.	0
343940	Sawhatchee Creek at Clear Springs, Ga.	9.7	354440	Kiokee Creek near Pretoria, Ga.	0
349500	Flint River at Montezuma, Ga.	877	354500	Chickasawhatchee Creek at Elmo, Ga.	2.5
349660	Sweetwater Creek near Andersonville, Ga.	11.3	355350	Ichawaynochaway Creek downstream of Newton, Ga.	231
349740	Hog Crawal Creek near Montezuma, Ga.	22.8	355600	Big Cypress Creek near Newton, Ga.	0
349800	Flint River near Drayton, Ga.	1,050	355660	Flint River at Riverview Plantation (in boat), Ga.	2,220
349900	Turkey Creek at Byromville, Ga.	4.1	355700	Flint River upstream of Bainbridge, Ga.	2,580
349910	Turkey Creek near Drayton, Ga.	17.7	355785	Big Slough near Camilla, Ga.	0
349960	Little Pennahatchee Creek near Lilly, Ga.	0.8	355830	Big Slough at State Road 65 south of Camilla, Ga.	0
349980	Pennahatchee Creek at Drayton, Ga.	2.7	355880	Big Slough near Pelham, Ga.	0
350080	Lime Creek near Cobb, Ga.	11.5	355950	Big Slough at State Road 97 near Bainbridge, Ga.	0
350220	Gum Creek at Coney, Ga.	10.9	356100	Spring Creek near Arlington, Ga.	0
350300	Cedar Creek at State Road 300 near Cordele, Ga.	1.3	356220	Spring Creek at Damascus, Ga.	1.5
350360	Swift Creek near Warwick, Ga.	9.2	356290	Dry Creek near Blakey, Ga	5.1
350405	Flint River downstream of Warwick Dam, Ga.	819	356460	Dry Creek near Hentown, Ga	3.6
350509	Jones Creek at State Road 300 near Oakfield, Ga.	2.3	356600	Long Branch near Colquitt, Ga.	0
350512	Flint River near Leesburg, Ga.	770	356640	Spring Creek near Colquitt, Ga.	16.9
350524	Abrams Creek near Oakfield, Ga.	9.1	356860	Big Drain Creek near Boykin, Ga	0
350527	Mill Creek near State Road 300, Ga.	11.9	356970	Aycocks Creek downstream of Colquitt, Ga.	0
350543	Piney Woods Creek upstream of Albany, Ga.	0	357000	Spring Creek near Iron City, Ga.	12.7
350600	Kinchafoonee Creek at Preston, Ga.	52.6	357025	Dry Creek near Iron City, Ga.	0
350860	Kinchafoonee Creek near Smithville, Ga.	163	357050	Spring Creek at Brinson, Ga.	59.9
350900	Kinchafoonee Creek near Dawson, Ga.	151	357310	Fishpond Drain near Donaldsonville, Ga.	0
351000	Kinchafoonee Creek near Leesburg, Ga.	156	358000	Apalachicola River at Chattahoochee, Fla.	[2]5,978
351500	Muckalee Creek near Americus, Ga.	40.8	358500	North Mosquito Creek at Chattahoochee, Fla.	30.9
351700	Muckalee Creek near Smithville at State Road 118, Ga.	83.3	358519	Mosquito Creek at Chattahoochee, Fla.	51.9
351780	Muckaloochee Creek near Americus, Ga.	13.7	358600	Flat Creek near Chattahoochee, Fla.	17.3
351800	Muckalee Creek at Smithville, Ga.	28.1	358661	Ocheesee Creek near Altha, Fla.	2.6
351890	Muckalee Creek at State Road 195 near Leesburg, Ga.	100	358673	Sweetwater Creek near Block Bluff, Fla.	25.7
351900	Muckalee Creek near Leesburg, Ga.	96	358683	Graves Creek at Selman, Fla.	8.7
351930	Muckalee Creek downstream of Leesburg, Ga.	115	358696	Stafford Creek near Selman, Fla.	2.0
352500	Flint River at Albany, Ga.	981	358700	Apalachicola River near Blountstown, Fla.	[2]6,105
352760	Dry Creek near Putney, Ga.	0	358737	Big Gully Creek near Orange, Fla.	7.3
352790	Flint River near Putney, Ga.	1,530	358754	Apalachicola River near Wewahitchka, Fla.	[2]6,332
352920	Raccoon Creek near Baconton, Ga.	0	358760	Marshall Creek near Campbellton, Fla.	32.7
352970	Cooleewahee Creek near Albany, Ga.	0	358770	Big Creek near Madrid, Ala.	24.8
352980	Cooleewahee Creek at Newton, Ga.	0.5	358772	Cowarts Creek near Malone, Fla.	18.7
353000	Flint River at Newton, Ga.	2,060	358789	Chipola River at Marianna, Fla.	172
353100	Ichawaynochaway Creek near Dawson, Ga.	64.2	358900	Dry Creek near Oakdale, Fla.	88.6
353200	Little Ichawaynochaway Creek near Shellman, Ga.	28.1	358998	Holliman Branch near Altha, Fla.	0.9
353265	Ichawaynochaway Creek near Morgan, Ga.	120	359000	Chipola River near Altha, Fla.	515
353350	Carter Creek near Carnegie, Ga.	20.6	359012	Tenmile Creek near Clarksville, Fla.	76.8
353400	Patchitla Creek near Edison, Ga.	79.2	359035	Fourmile Creek at Clarksville, Fla.	71.6
353460	Ichawaynochaway Creek near Leary, Ga.	203	359059	Juniper Creek at Frink, Fla.	105
353500	Ichawaynochoway Creek at Milford, Ga	203	359101	Chipola River downstream of Dead Lake, Fla.	855
354300	Chickasawhatchee Creek near Dawson, Ga.	10.1	359170	Apalachicola River near Sumatra, Fla.	[2]7,326

[1]Downstream-order number only; two-digit part number, 02, omitted.
[2]Mean streamflow for October 1986 at continuous-record station.

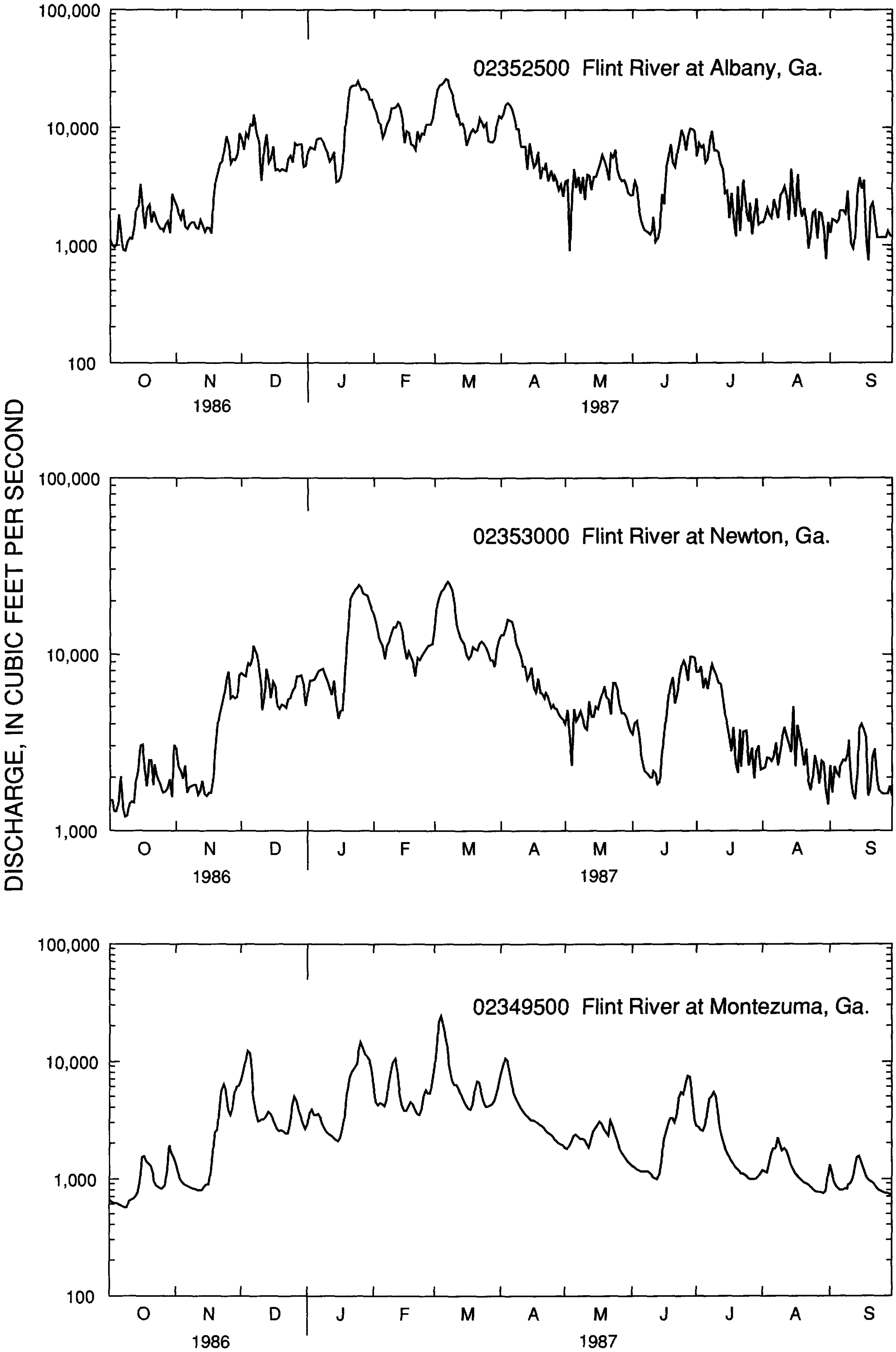


Figure 14. Streamflow for three gaging stations on the Flint River, October 1986 to September 1987. (See plate 1 for location of gaging stations.)

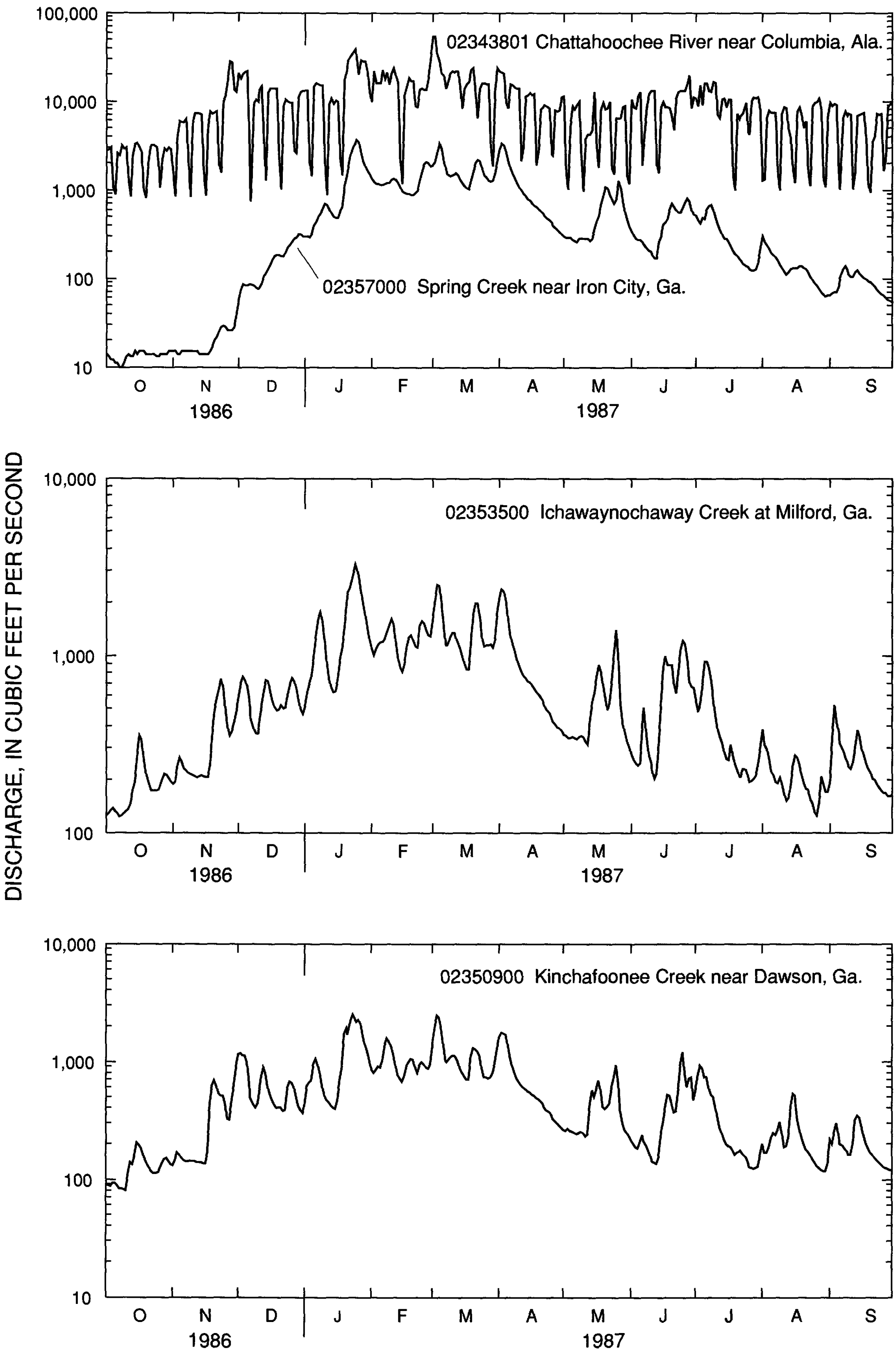


Figure 15. Streamflow for gaging stations on the Chattahoochee River and on Ichawaynochaway, Kinchafoonee, and Spring Creeks, October 1986 to September 1987. (See plate 1 for location of gaging stations.)

these rivers. Upstream of the Flint River Dam to Montezuma, Ga., (north of Lake Blackshear and the study-area boundary; plate 1) the channel of the Flint River is maintained suitable for navigation of light-draft vessels. On the Flint River from Albany to Bainbridge, Ga., the channel is maintained at a 3-foot depth, and from Bainbridge, Ga., to Jim Woodruff Lock and Dam, and in the Apalachicola River, a 9-foot-deep channel is maintained. A 9-foot-deep channel also is maintained on the Chattahoochee River from Columbus, Ga., to the dam. Dredging for the 9-foot depth began in 1956 in preparation for completion of Jim Woodruff Dam (Leitman and others, 1984). Seven cutoffs were made at meanders (bends) in the Apalachicola River since 1956 to straighten the channel for barge navigation. One cutoff, the Chipola Cutoff, is located about 10 mi upstream of the confluence of the Chipola and Apalachicola Rivers (fig. 2). Groins, made of wooden pilings or stone, were installed mostly in the upper part of the Apalachicola River to create channel scour and improve navigation. Twenty-nine sets of groins were installed in the Apalachicola River; each set contains 4 groins, but as few as 2 or as many as 8 were installed in some locations (Leitman and others, 1984).

EVALUATION OF STREAM-AQUIFER RELATIONS IN THE LOWER APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN

Stream-aquifer relations in the lower ACF River Basin are defined as the interaction of hydrologic factors associated with surface- and ground-water-flow systems in the study area. Quantification of this interaction constitutes evaluation of stream-aquifer relations in the basin and is the focus of the remainder of this report.

Surface- and ground-water-flow systems are connected hydraulically by a streambed or lakebed; hence, evaluation of stream-aquifer relations involves quantifying leakage across streambeds or lakebeds. This leakage depends on two factors; hydraulic properties and relative water levels of both systems. Changes to these factors by either natural or manmade processes in the basin affect stream-aquifer relations.

Stream-aquifer relations in the lower ACF River Basin are evaluated in this study by quantifying effects on the surface- and ground-water-flow system of worst-case drought conditions and increased ground-water development. Effects of these hydrologic stresses on the flow system maximize stream-aquifer interaction, as streamflow is mostly base flow during extremely dry climatic conditions such as droughts. Aquifer water-level decline (drawdown) and reduction in aquifer contribution to streamflow resulting from increased ground-water development were simulated to quantitatively define stream-aquifer relations in the basin. The simulation results can be used to define possible effects of increased development on other uses for water resources of the basin, such as maintaining streamflow for navigation and to ensure an adequate supply of freshwater, nutrients, and detritus to Apalachicola Bay.

Computer simulation of the surface- and ground-water-flow system was used to evaluate stream-aquifer relations in the lower ACF River Basin. The simulations tested various flow-system concepts developed from interpreting hydrologic data and results of previous studies. Complexities associated with the evaluation, such as irregularly shaped aquifer- and flow-system geometry, variability of hydraulic properties, and analysis of the effects of different hydrologic conditions of pumpage and streamflow established the need for using simulation to represent the stream-aquifer system. Computer models of two-dimensional, ground-water flow in the Upper Floridan aquifer and Intermediate system, the principal water-bearing units in contact with surface-water features in the basin, were simulated in two models; the Upper Floridan model and Intermediate model, respectively. The models were calibrated to the steady-state, low-flow conditions of October 1986, which represented an historic, worst-case, drought condition that was documented by field measurements of ground- and surface-water conditions. Simulations of calibration conditions and conditions of increased ground-water pumpage were used to develop water budgets that quantitatively describe stream-aquifer interaction and flow-system response to current and possible, future, increased ground-water development.

Conceptualization of the Flow System

Conceptualization of the surface- and ground-water-flow system in the lower ACF River Basin was based on interpretation of available hydrologic data, described in preceding sections. This conceptualization was a prelude to forming a working hypothesis, or conceptual model, of the stream-aquifer system, which was tested by using simulation.

Water levels in wells completed in the Upper Floridan aquifer, Intermediate system, and semiconfining units were either at or near seasonal or record lows in October 1986, and had been maintained there for a period of time necessary for the surface- and ground-water-flow system to equilibrate, or achieve steady-state. The extremely dry climatic conditions in the lower ACF River Basin during most of the year virtually eliminated significant recharge to the stream-aquifer system by infiltration of precipitation; vertical leakage from clayey sediments in the semiconfining units provided one of the few sources of water to the aquifer for October 1986. Other aquifer recharge included lateral flow across surface-water divides and vertical leakage from surface water. Aquifer recharge was balanced identically by discharge to surface water and pumped wells, and by discharge across lateral and vertical flow boundaries. These hydrologic mechanisms produced stable ground-water-level conditions that defined a steady-state condition for the flow system.

For ease of conceptualizing the flow system, the study area was divided into 3 parts (fig. 16) according to the hydrologic units that contacted surface-water features and that contributed to stream-aquifer relations. In each part of the study area, descriptions of these units provided the basis for conceptualization and subsequent development of digital models to evaluate stream-aquifer relations.

In the northern part of the study area, the Upper Floridan aquifer consists entirely of the Ocala Limestone, and is semiconfined above by alluvium containing undifferentiated overburden and terrace deposits (fig. 17). The northern boundary is defined as the saturated, updip limit (outcrop) of the aquifer. Surface-water features (streams, reservoirs, and lakes) are in hydraulic connection with the Upper Floridan aquifer and alluvium; however, only the aquifer contributes significantly to streamflow as most of the water-bearing zones in the alluvium were dry during October 1986. The Lisbon Formation, underlying the Upper Floridan aquifer, functions as an impermeable base, and is termed the lower confining unit in Georgia and sub-Floridan confining unit in Florida (fig. 3).

Clayey sediments in the lower half of the undifferentiated overburden serve as a limited source of water to the Upper Floridan aquifer by vertical downward leakage (fig. 17). The low hydraulic conductivity of the clayey sediments inhibits lateral flow to streams and vertical leakage to the aquifer. Variations in thickness and content of sand and clay in the overburden (Hayes and others, 1983) create areas of locally large and small leakage rates across this upper vertical boundary of the aquifer with the semiconfining unit. Head in the clayey lower half of the overburden was nearly constant for October 1986 conditions.

The Upper Floridan aquifer is well drained in the northern part of the lower ACF River Basin by the Chattahoochee and Flint Rivers and by numerous tributary streams. There is direct hydraulic connection of the aquifer with surface water where rivers and streams cut into and expose aquifer material (fig. 17). Hydraulic connection is less direct in other areas where the overlying semiconfining unit in the undifferentiated alluvium separates the aquifer from surface water. Although local water-bearing zones in the overlying semiconfining unit would supply small amounts of water to streams under normal climatic conditions, streamflow contribution from semiconfining units during drought conditions, such as in October 1986, was either nonexistent or negligible; nearly all streams that bottom in this unit were observed to be dry at that time. These features, and other surface-water features typical of karst areas, have minor effects on shaping the potentiometric surface of the Upper Floridan aquifer.

Regional and local inflows and outflows affect ground-water flow in the northern part of the study area, primarily in the Upper Floridan aquifer. Regional ground-water inflow to the aquifer occurs across the eastern study-area boundary in upland areas of the Solution Escarpment. A small amount of regional inflow occurs across the western boundary and discharges to the drainage network of the Chattahoochee River. Regional ground-water outflow from the northern part of the study area includes flow across the southern boundary of the northern part into the central part, and discharge to major rivers, such as the Chattahoochee and Flint Rivers. Local ground-water inflows and outflows to the northern part occur as aquifer recharge to, or discharge from, other surface-water features, vertical leakage to and from the overlying semiconfining unit, and well discharge.

In the central part of the lower ACF River Basin, variations in lithology and hydraulic properties of the Upper Floridan aquifer and in the pattern of

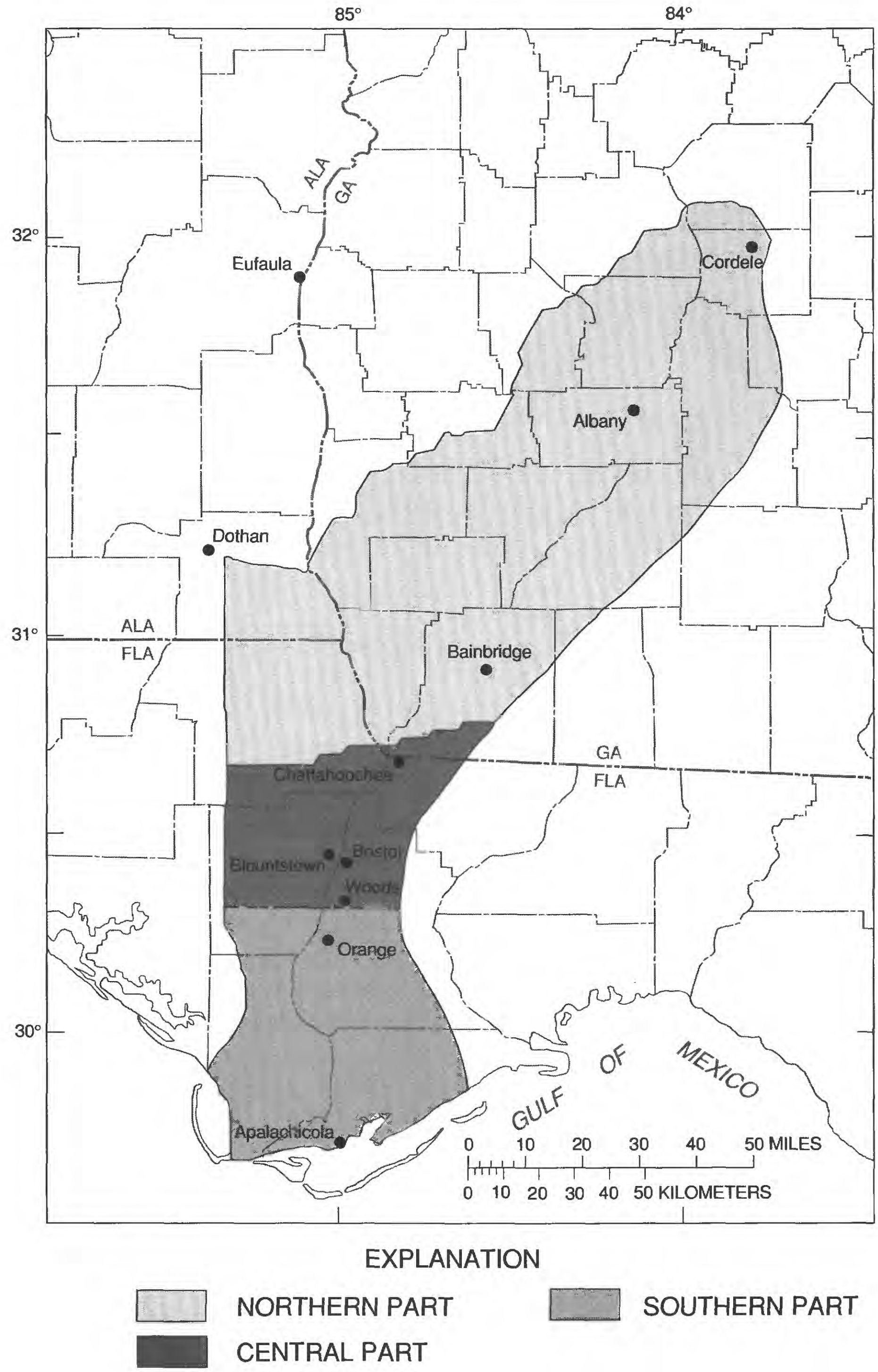


Figure 16. Division of study area into northern, central, and southern parts for conceptualization of flow system.

surface-water drainage create two distinct flow regimes for the stream-aquifer system, depending on location with reference to the Apalachicola River (fig. 18). The Upper Floridan aquifer consists of the following geologic units; in descending order, the Tampa and Suwannee Limestones, Marianna Formation, and Ocala Limestone (fig. 3). Surface-water features are in hydraulic connection primarily with the Upper Floridan aquifer. Small amounts of ground water contribute to surface water from zones in the overlying semiconfining unit and in the Intermediate system, but were considered negligible for

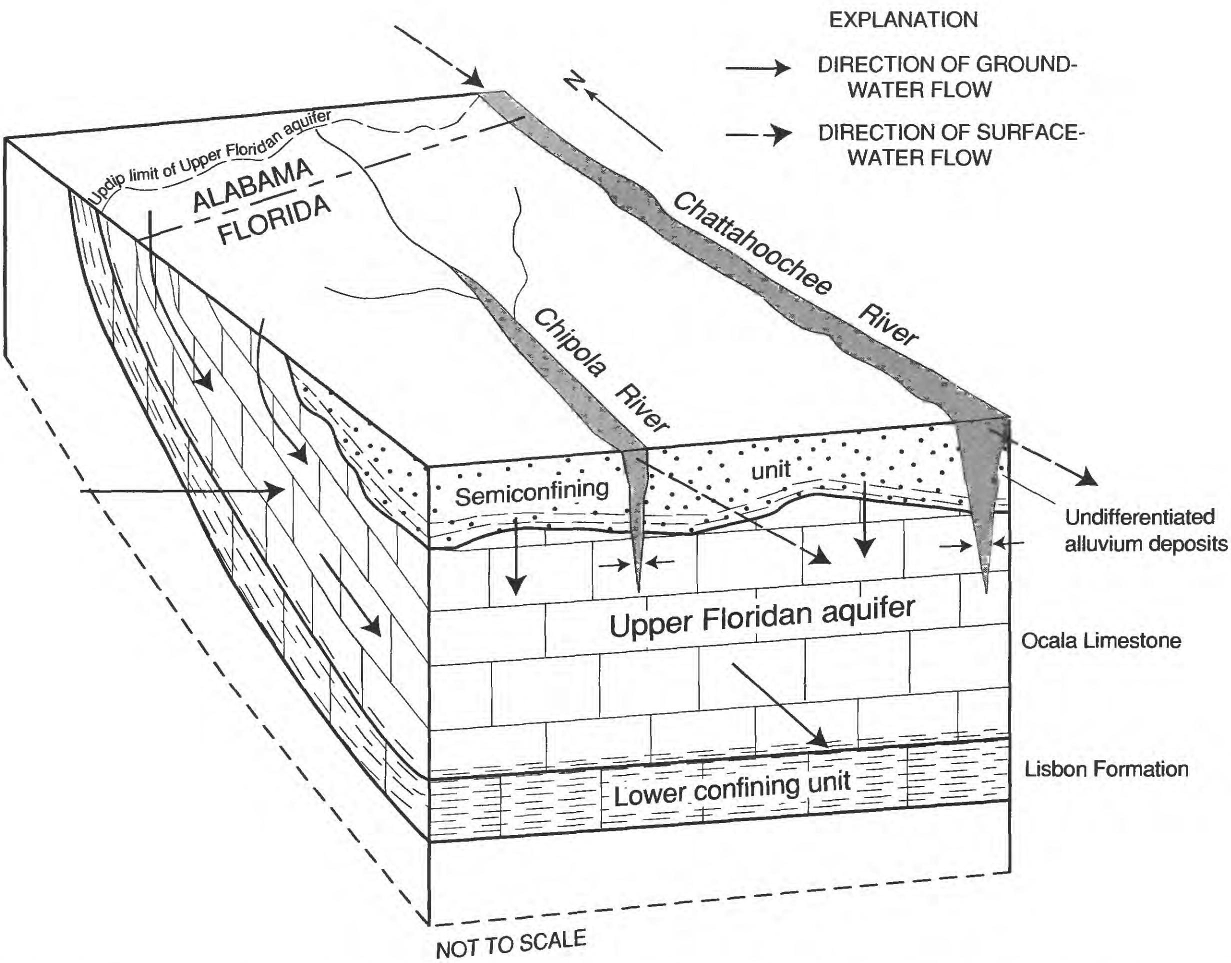


Figure 17. Idealized block diagram of the northern part of the lower Apalachicola–Chattahoochee–Flint River Basin and conceptualization of ground-water flow (modified from Wagner, 1984).

the drought conditions of October 1986 and for this conceptualization.

The distinction in flow regimes in the Upper Floridan aquifer east and west of the Apalachicola River focuses on whether to consider the Tampa Limestone as part of the aquifer in contact with surface water or as part of the overlying semiconfining unit. The Tampa Limestone is not in hydraulic connection with surface water east of the Apalachicola River, because the river has incised below the base of this unit, exposing limestone in bluffs along the eastern boundary of the flood plain. Also, east of the Apalachicola River, there is a lack of well developed surface-water drainage in the Tampa Limestone. Here, the fine-grained and clayey lithology of the Tampa Limestone has the potential to support higher ground-water levels than deeper limestones of the Upper Floridan aquifer. This is evidenced by potentiometric surfaces prepared for a previous investigation, which show water levels in Tampa Limestone east of the river that are 70 to 90 ft higher than water levels in deeper units (Jeffry R. Wagner, formerly with the Northwest Florida Water Management District, Havana, Fla., written commun., 1988). Therefore, the combination of poor surface-water drainage and low water-transmitting ability enables the Tampa Limestone east of the Apalachicola River to function as a semiconfining unit, supplying water to the deeper units of the Upper Floridan aquifer and being disconnected, hydraulically, from surface water.

West of the Apalachicola River, the Tampa Limestone and deeper units are cut by a well developed drainage network of the Chipola and Apalachicola Rivers. The sandy lithology of the Tampa Limestone west of the Apalachicola River, in comparison to the more clayey lithology to the east, enables it to be drained easily by surface water, creating nearly uniform ground-water levels in all units of the Upper Floridan aquifer. Therefore, west of

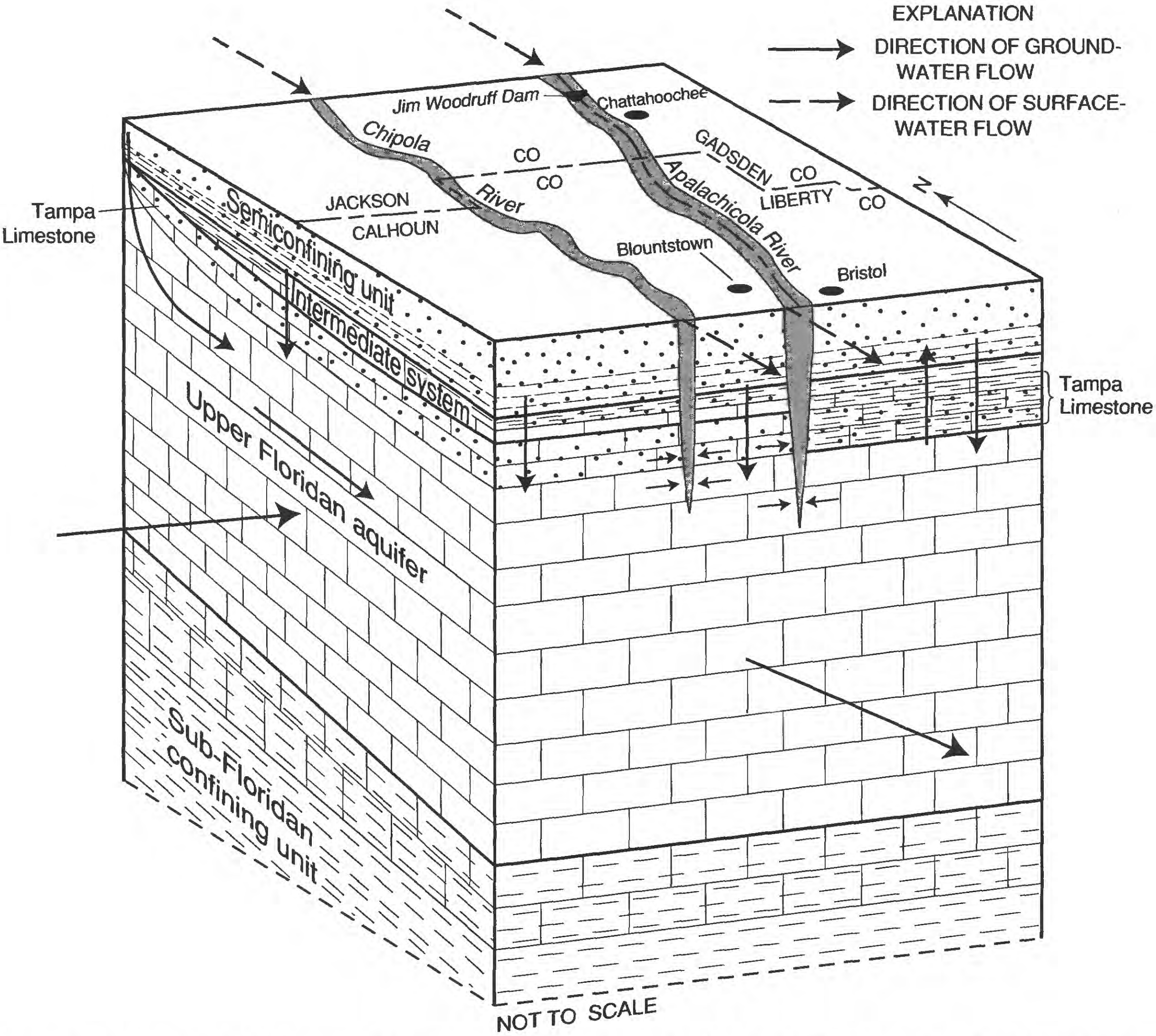


Figure 18. Idealized block diagram of the central part of the lower Apalachicola–Chattahoochee–Flint River Basin and conceptualization of ground-water flow (modified from Wagner, 1984).

the Apalachicola River, all limestone units of the Upper Floridan aquifer are in hydraulic connection with surface-water features, and the aquifer is semiconfined above by clayey sediments in the overlying semiconfining unit and Intermediate system. On both sides of the river, the Upper Floridan aquifer is confined effectively from below by the sub-Floridan confining unit.

Regional ground-water flow in the Upper Floridan aquifer in the central part of the lower ACF River Basin follows the same general directions as that described for the northern part. Ground-water levels in wells indicate that the Upper Floridan aquifer receives inflow across the eastern and western basin boundaries and from the northern part. Ground water discharges from the Upper Floridan aquifer to the Chipola and Apalachicola Rivers, and flows regionally across the southern boundary of this part of the study area, where the aquifer is stratigraphically too deep to be connected hydraulically with surface water.

In the northern and central parts of the lower ACF River Basin, ground water discharges to springs that emanate from the Upper Floridan aquifer. Springflow occurs from the aquifer at points that are located either directly along stream bottoms (in-channel springs) or at a distance from surface-water features (off-channel springs). Off-channel springs are located principally in Gadsden, Jackson, and Liberty Counties, Fla. (pl. 1), and cause local changes to regional ground-water movement. In-channel springs contribute to the streamflow gain along a reach and might be indistinguishable from other in-channel ground-water discharge.

In the southern part of the lower ACF River Basin, water-bearing zones in the Intermediate system and overlying semiconfining unit discharge ground water to surface-water features. The underlying Upper Floridan aquifer is too deep stratigraphically to be in hydraulic connection with surface water (fig. 19). It plays an indirect role in stream-aquifer relations, supplying water by vertical leakage to the overlying units. The hydraulic connection between the Intermediate system and surface water also is indirect, as ground-water discharge to surface water occurs through alluvium deposits having low hydraulic conductivity. Water-bearing zones in the overlying semiconfining unit are neither laterally continuous nor areally extensive. Although they contribute some water to surface water, their effect on stream-aquifer interaction is considered negligible for the conceptualization in this part of the basin.

Recharge to and discharge from the Intermediate system in the southern part of the lower ACF River Basin occur as vertical leakage across aquifer boundaries with the overlying and underlying semiconfining units (fig. 19). To the north, vertical leakage from source layers in the overlying semiconfining unit provides recharge to the Intermediate system. To the south, recharge is from below, as the underlying Upper Floridan aquifer contains slightly higher water levels than the Intermediate system, thus providing the hydraulic potential for leakage (Jeffry R. Wagner, formerly of the Northwest Florida Water Management District, Havana, Fla., written commun., 1988). Locally, these general patterns of vertical leakage are reversed in areas where ground water in the Intermediate system discharges through the overlying semiconfining unit to surface-water features. In the southwestern part of the study area, downward vertical leakage from source layers in the overlying semiconfining unit causes ground water to flow through the Intermediate system to the Upper Floridan aquifer. Water levels in semiconfining units to the Intermediate system were nearly constant during October 1986, creating steady rates of vertical leakage into and out of the Intermediate system.

Disadvantages and Limitations of a Steady-State Analysis

Because steady-state ground-water flow is neither time dependent nor time variant, temporal hydrologic processes of releasing water from or taking up water into storage within aquifers, semiconfining units, and stream and lake sediments are not represented in the steady-state analysis used in this study. These processes cause a time delay for flow-system equilibration to changes in stress, and for analyzing the ultimate flow-system response, until changes in water stored in the hydrologic units are no longer significant. The inability of a steady-state analysis to account for storage effects and transient hydrologic responses of the flow system to changes in stress can be a disadvantage if time-variant-flow conditions are important to the evaluation of water resources and stream-aquifer relations in the basin.

Although the time-varying response of hydrologic units to stress changes eventually dissipate, they might represent an important source (or sink) of water to the flow system before dissipating completely and leaving only steady-state and steady-leakage conditions. Thus, a limitation of a steady-state analysis is that temporal-storage processes in hydrologic units are neither evaluated nor represented. Consequently, estimates for the hydraulic storage properties that directly affect real-time, transient responses of aquifers, semiconfining units, streambeds, and lakebeds cannot be derived from a steady-state analysis of the stream-aquifer system.

Advantages of a Steady-State Analysis

Near steady-state conditions of low flow and low-water level in October 1986 provide an opportunity to observe worst-case conditions (or, obtain conservative estimates) of long-term effects of ground-water development on the stream-aquifer system. Increased ground-water pumpage imposes additional stress on a flow system that already exhibits low-flow and low-water-level conditions; hence, the aquifers become stressed beyond conditions that actually might occur in the basin during normal periods of seasonal precipitation. By simulating additional stress until new steady-state conditions are established in the flow system, conservative estimates of the potential for increased ground-water development and the effects of this development on other uses for water resources in the basin are obtained.

Stream-aquifer relations in the lower ACF River Basin are most easily evaluated under worst-case conditions attained at steady-state during conditions of low flow and low-water level. Transient effects in hydrologic units, discussed in the previous section, create a time delay in achieving worst-case conditions, especially when additional ground-water

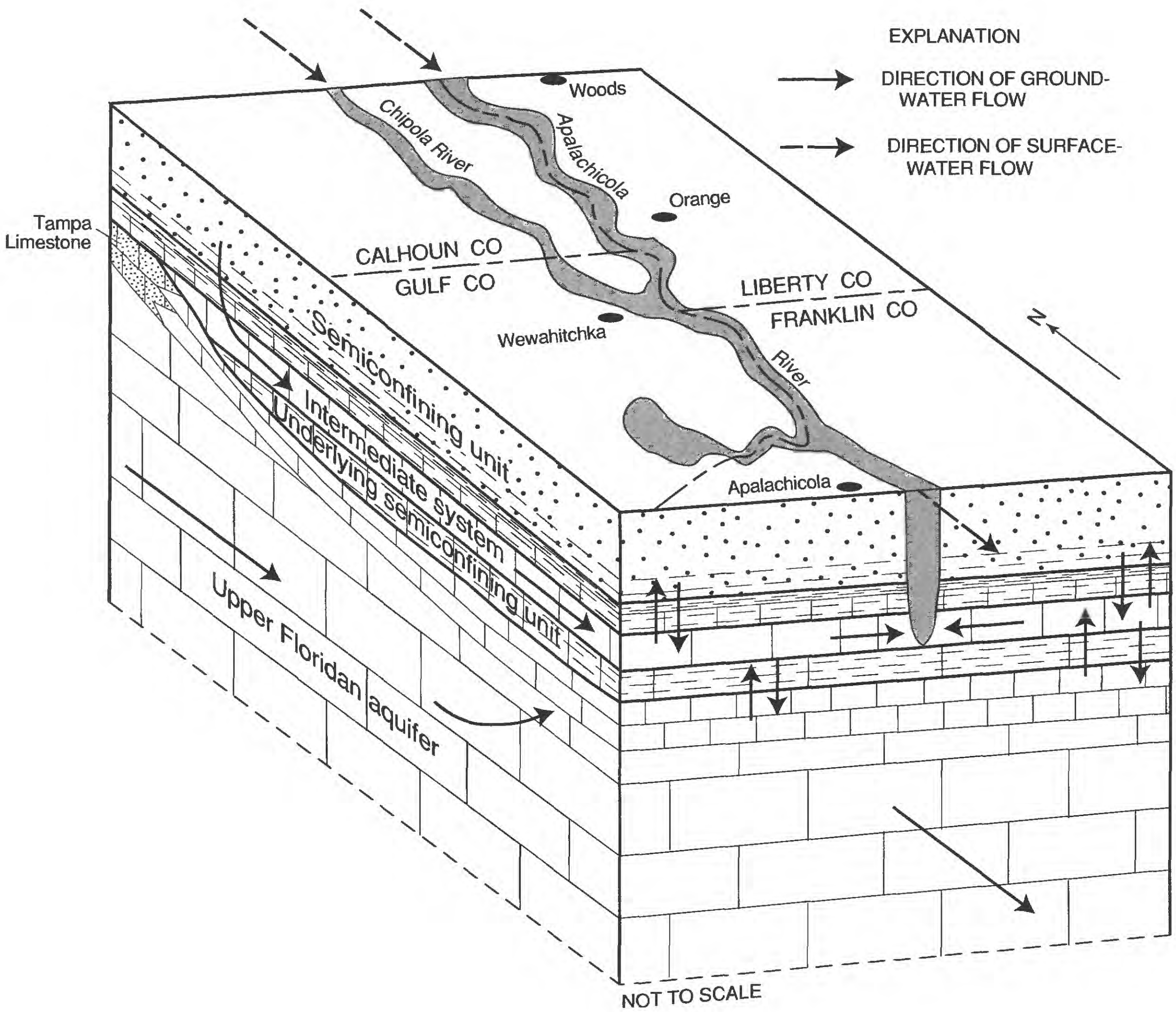


Figure 19. Idealized block diagram of the southern part of the lower Apalachicola–Chattahoochee–Flint River Basin and conceptualization of ground-water flow (modified from J.R. Wagner, formerly with Northwest Florida Water Management District, Havana, Florida, written communication, 1987).

pumpage is applied to the flow system. Droughts, such as in 1986, or extended periods of unusually low precipitation, such as occurred in two other periods during the last decade, exacerbate an already low-flow and low-water-level condition and create ideal hydrologic conditions for evaluating stream-aquifer relations, namely, the ground-water component of streamflow. These conditions, coupled with a rapid-response time of the aquifer to adjust to stress, renders the time variance of transient effects within hydrologic units in the basin irrelevant to the evaluation.

By analyzing steady-state conditions, temporal, short-term responses of semiconfining units to contribute water to the aquifers by transient leakage are eliminated. In addition to creating smaller declines in aquifer water level than would occur under steady-state conditions, transient leakage also delays establishment of a flow-through (steady) component of leakage, which delays the migration of water through semiconfining units. In some instances, the ultimate fate of chemical constitutents, or contaminants, that are introduced to the stream-aquifer system, either intentionally or unintentionally, at the land surface, is required to be known. By analyzing steady-state conditions, transient leakage is neglected, and steady leakage from (or flow through) semiconfining units can occur at the same instant that additional stress is applied to the system, thus indicating general flow paths through these units. Long-term, worse-case estimates are obtained for rates at which contaminants can enter the aquifers due to increased pumpage or introduction through land-surface application or surface-water sources.

Mathematical Model

The mathematical model used to simulate ground-water flow with stream-aquifer relations in the lower ACF River Basin consists of partial-differential equations and the appropriate boundary conditions that are assumed to describe the physics of fluid flow in porous media. Variants of the governing equation and boundary conditions given in Cooley (1992) are presented as they apply to flow in the Upper Floridan aquifer and Intermediate system.

Governing Equation

Ground-water flow in the Upper Floridan aquifer and in water-bearing units of the Intermediate system, within boundaries of any discontinuities in transmissivity or within external boundaries, is assumed to be governed by the following two-dimensional, steady-state flow equation

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}+T_{xy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}+T_{yy}\frac{\partial h}{\partial y}\right)+R(H-h)+P=0, \quad (1)$$

where

(x,y) = Cartesian coordinate directions [length];

$h(x,y)$ = aquifer hydraulic head [length];

$H(x,y)$ = hydraulic head in the source layer [length];

$\begin{bmatrix} T_{xx}(x,y) & T_{xy}(x,y) \\ T_{yx}(x,y) & T_{yy}(x,y) \end{bmatrix}$ = symmetric transmissivity tensor written in matrix form [length^2/time];

$R(x,y)$ = vertical hydraulic conductance (vertical hydraulic conductivity divided by thickness) of a confining bed, [time^{-1}]; and

$P(x,y)=\sum_{j=1}^{p}\delta(x-a_j)\,\delta(y-b_j)$ = Dirac-delta designation for p point sources or sinks, each having strength Q_j [length/time] and located at (a_j,b_j). Q_j is positive for injection.

Boundary and Initial Conditions

Equation 1 is subject to the following boundary and initial conditions:

- At a discontinuity in transmissivity (an internal boundary) the normal component of ground-water flow and the hydraulic head are unchanged as the discontinuity is crossed (Bear, 1979, p. 100–102). Thus, at a discontinuity in transmissivity between aquifer zones a and b,

$$q_n\big|_a=q_n\big|_b\,, \quad (2)$$

and

$$h\big|_a=h\big|_b\,, \quad (3)$$

where $\big|_i$, $i=a$ or b, indicates evaluation of q_n and h at the boundary of the discontinuity within respective zones, q_n is the normal component of ground-water flow across the discontinuity and is expressed as a unit-discharge rate [length^2/time], that is, volumetric flow rate per unit length of boundary [(length^3/time)/length].

- The normal component of flow at a discontinuity, q_n, is given by the sum of a specified component, q_B, and a head-dependent component, $\alpha(H_B-h)$ (Bear, 1979, p. 117–120), or

$$q_n=q_B+\alpha(H_B-h), \quad (4)$$

where

$\alpha(x,y)$ = parameter equal to "infinity" for a specified-head (Dirichlet) condition and to zero for a specified-flow (Neumann) condition; a general (Cauchy) boundary condition is specified by a finite and positive value for α [length/time] (Cooley, 1983);

$q_B(x,y)$ = specified component of flow normal to a boundary [length^2/time]; and

$H_B(x,y)$ = specified (controlling) head at a boundary [length].

- The initial hydraulic head is known everywhere in the aquifer for the steady-state period, or

$$h=h_o\,, \quad (5)$$

where $h_o(x,y)$ is the initial head [length] (required for water-table conditions as transmissivity is a function of hydraulic head).

Artesian (linear) and water-table (nonlinear) conditions exist in the Upper Floridan aquifer and water-bearing units of the Intermediate system, and both are represented by equation 1. Ground-water flow under artesian conditions is linear (having linear boundary conditions), because terms in equation 1 that multiply either aquifer hydraulic head, $h(x,y)$, or derivatives of head are not functionally dependent on head. Water-table or semiconfined conditions cause nonlinear ground-water flow, as some terms in equation 1 are functionally dependent on aquifer hydraulic head. Transmissivity is a function of saturated aquifer thickness, which in turn is a function of hydraulic head, and steady-vertical leakage, expressed as $R(H-h)$ in equation 1 for the linear case, is a function of the difference between head in the overlying semiconfining unit and either the altitude of the top of the aquifer or aquifer head, whichever is lower. The changing form of the leakage expression causes the nonlinear condition.

Likewise, boundary conditions in the study area are expressed by using linear and nonlinear forms of equation 4. A unit discharge across and normal to the outer boundary of the aquifer is represented by equation 4, and is positive for inflow. The sum of specified and head-dependent components on the right side of this equation is termed a Cauchy-type boundary, for convenience, because each component represents a special case of the Cauchy-boundary condition (Norrie and deVries, 1973; and Cooley, 1983). Details of the nonlinear nature of these boundary conditions are given in the following sections for specific applications.

Numerical Model

The numerical model used to simulate ground-water flow in the Upper Floridan aquifer and water-bearing units of the Intermediate system is the MODular Finite-Element model (MODFE) of the U.S. Geological Survey (Cooley, 1992; and Torak, 1993a,b). The model approximates the governing equation and boundary and initial conditions (eqs. 1-5) by using the extended Galerkin finite-element method with triangular elements and linear coordinate (basis) functions in space (Cooley, 1983, and Zienkiewicz, 1977, chapter 3). Approximate solutions to the governing equation are obtained at intersections of element sides, which are called nodes.

Simulation Approach

The lower ACF River Basin was divided into two areas for simulation of stream-aquifer relations on the basis of the hydrologic units in contact with surface water and conceptualization of the flow system. One area encompasses the northern and central parts of the study area (figs. 17 and 18), where the ground-water component of stream-aquifer relations is provided by the Upper Floridan aquifer. The other area is the southern part, where the Intermediate system interacts with surface water. For convenience, simulation of the northern and central parts of the study area is termed the Upper Floridan model, and simulation of the southern part is termed the Intermediate model.

In the Upper Floridan model, two-dimensional, horizontal, ground-water flow in the Upper Floridan aquifer was simulated by computing hydraulic head for this unit, which was represented in MODFE as a model layer. The overlying semiconfining unit, containing terrace and undifferentiated (surficial) deposits and undifferentiated overburden (fig. 3), was simulated in MODFE by using a steady vertical leakage function, which provided recharge to, and discharge from, the Upper Floridan aquifer. Source-layer head for this leakage was assigned as the top of the lower-half thickness of clayey sediments in the semiconfining unit and was held constant for all simulations. Field observations (described previously) indicated that the clayey sediments were saturated during October 1986; thus, dewatering of these sediments was negligible during the drought. The vertical boundary of the simulated aquifer with the lower confining unit (Lisbon Formation, fig. 3) was simulated as a no-flow boundary due to the Lisbon Formation creating an effective impermeable base to the stream-aquifer system. These details of the simulation approach for the Upper Floridan model are summarized as follows

Upper Floridan Model

Hydrologic unit (fig. 3)	Simulation approach
Semiconfining unit	Steady vertical leakage
Upper Floridan aquifer	Simulated model layer
Lower confining unit	No-flow boundary

Other hydrologic characteristics of the stream-aquifer system in the Upper Floridan model, namely, regional ground-water flow, flow across streambeds, and springflow, were simulated in MODFE by using mathematical boundary conditions to ground-water-flow equation 1 that account for recharge to, or discharge from, the simulated Upper Floridan aquifer. In addition, the outcrop area of the Upper Floridan aquifer was represented with specified-head boundaries. Regional inflows and ouflows were represented with computations that simulated lateral flow across boundaries of the Upper Floridan aquifer with aquifer material located beyond the model area. Flow across streambeds was simulated in MODFE as either aquifer discharge to, or recharge from, streams by using computations that involve the hydraulic properties and general geometry of the streambed, and relative head differences between stream stage and the Upper Floridan aquifer. Simulation of in-channel springflow was combined with flow across streambeds, as hydrologically, and mathematically, both are identical features that cause aquifer discharge to streams. Off-channel springflow was simulated in a manner identical to well discharge, because both of these features are point discharges from the aquifer. Thus, a point-discharge function in MODFE was used to represent these hydrologic features for simulation.

In the Intermediate model, the Intermediate system was represented in MODFE as the model layer for which hydraulic head was computed; thus, simulating two-dimensional, horizontal, ground-water flow. In this part of the basin, the Upper Floridan aquifer and sub-Floridan confining unit (fig. 3) are stratigraphically too deep to be considered part of the stream-aquifer system; consequently, neither of these two hydrologic units were represented in MODFE by using a model layer. Steady vertical leakage through overlying and underlying semiconfining units and through lakebeds was simulated in MODFE to provide recharge to, and discharge from, the simulated aquifer of the Intermediate system. The hydraulic potential for vertical leakage was provided by appropriate values of source-layer head that represent the overlying semiconfining unit (fig. 3), underlying Upper Floridan aquifer, and lake levels. Head in semiconfining units and lake levels were nearly constant in the southern part during October 1986; therefore, source layer head was held constant in the Intermediate model. The following table summarizes these details of the simulation approach for the Intermediate model.

Intermediate Model

Hydrologic unit (fig. 3)	Simulation approach
Overlying semiconfining unit	Steady vertical leakage
Intermediate system	Simulated model layer
Underlying semiconfining unit	Steady vertical leakage
Upper Floridan aquifer	Source layer for steady vertical leakage
Sub-Floridan confining unit	Not simulated

In the Intermediate systenı, well discharge was negligible, and springflow was nonexistent; therefore, they were not simulated in the Intermediate model. Stream-aquifer interaction was simulated in the Intermediate model as vertical flow across streambed sediments in the identical manner as that used in the Upper Floridan model.

Finite-Element Mesh

A finite-element mesh, a network of triangular elements, was constructed for both model areas in the lower ACF River Basin to represent variations in hydraulic properties, boundary geometry, surface-water features, and hydraulic head (pl. 4). The mesh for the Upper Floridan model consists of 12,295 elements and 12,113 nodes; for the Intermediate model, 4,024 elements and 3,963 nodes were used. Physical boundaries of the lower ACF River Basin were used as limits for the finite-element mesh in each area. Hydrologic boundaries of both models were defined from general patterns of ground-water movement and stream-aquifer relations, described previously, and are depicted in figures 17–19.

The meshes contain mostly equilateral triangles of two sizes, 2,083 and 4,167 ft on a side. Smaller elements permitted details in computed hydraulic head and aquifer-property variability to be represented more accurately than for larger elements. Hence, smaller triangles were used along curved stream reaches and in the adjacent aquifer. In addition, some element sizes were adjusted by moving nodes so that specific flow-system geometries were represented, such as tight meanders of stream reaches or irregular shapes in the external-model boundary. Thus, with selected-node movement, the size of element sides ranged from about 1,100 ft to about 4,750 ft.

Selection of the sizes and shapes of elements used in this study was the result of preliminary simulations which tested the ability of various element sizes and shapes to accurately represent changes in aquifer properties, boundary geometry, and hydraulic head. The finite-element mesh was designed to approximate more complex features in the potentiometric surface than actually existed for October 1986, such as distinct cones of depression caused by pumping, or large changes in hydraulic gradient over relatively short distances.

Boundary Conditions

Hydrologic boundaries to the model areas consisting of regional flow, vertical leakage across semiconfining units, and leakage across streambeds and lakebeds were represented in MODFE by using line and areally distributed, head-dependent, Cauchy-type boundaries (Cooley, 1992; and Torak, 1993a,b) and steady-vertical-leakage functions. Line features, such as regional flow and flow across streambeds, were represented with linear and nonlinear forms of an equation similar to equation 4. Regional flow was represented with a linear form of this boundary condition, and flow across streambeds was represented by using linear and nonlinear forms. The nonlinear form was used to represent small streams that were partially dry during October 1986, as it was assumed that the streams could only discharge water from the aquifers, thus creating nonlinear discharge-only conditions in the aquifer. The nonlinear form also was used to represent large streams if the potential existed for them to go dry for cases where simulated pumpage increases from the October 1986 rates caused ground-water levels to drop below the bottom of the streambed.

Vertical leakage to and from overlying semiconfining units and across areally extensive lakebeds such as Dead Lake and Lake Seminole (pl. 1), was simulated with a nonlinear, areally distributed, head-dependent, Cauchy-type boundary. The nonlinear form of this function was used to limit recharge to the Upper Floridan aquifer and Intermediate system for cases where aquifer water levels drop below the top of the aquifer, creating water-table (phreatic) conditions. This occurs during simulation of increased pumpage from the October 1986 rates. Vertical leakage from the underlying Upper Floridan aquifer in the Intermediate model was represented by the linear, steady-vertical leakage function, given by the $R(H-h)$ term in equation 1.

Specified-head boundaries were used to represent the water level in the outcrop area of the Upper Floridan aquifer. Additionaly, an alternate form of the specified-head condition is contained in head-dependent parts of linear and nonlinear Cauchy-type boundaries, which were used to represent lateral-flow boundaries and rivers.

Regional Ground-Water Flow

Regional inflow and outflow across external model boundaries was simulated with the head-dependent part of a Cauchy-type boundary, given by equation 4, and with specified-head boundaries. The general form of this boundary condition is expressed as the right side of equation 4 with q_B set to zero. For regional flow, the controlling head, H_B, of equation 4 is located in the aquifer but external to the model area, situated transverse to and at a distance L from the boundary (or element) side so that it is unaffected by water-level changes in the model area. Each node defining an element side on a Cauchy-type boundary has an external (or controlling) head, H_B, associated with it. Thus, for an element side defined by nodes k and l, the flow rate across the boundary is expressed as

$$Q_B=(\tfrac{1}{2})\alpha L_{kl}(H_{Bi}-h_i), \qquad (6)$$

and

$$\alpha=\frac{Kb}{L}, \qquad (7)$$

for which K and b are, respectively, the average (estimated) hydraulic conductivity and thickness, of the aquifer between the model boundary and H_B, that is, within the distance, L, from the boundary, and L_{kl} is the length of the element side. A distance of 3 mi was used for L to separate the external head, H_B, from the model boundary and to compute α. Values of H_{Bi} for each node i ($=k$ or l) on the boundary side were interpolated from water-level measurements made in October 1986 for the Upper Floridan aquifer and from other measurements obtained for the Intermediate system (Jeffry R. Wagner, formerly of the Northwest Florida Water Management District, written commun., 1988).

Element sides that simulated regional flow by using the head-dependent part of a Cauchy-type boundary were grouped into zones (pl. 4) according to α values that were calculated from equation 7. Of the 72 zones representing the linear form of this boundary condition, 12 represented regional flow in the Upper Floridan and Intermediate models (table 2), the other zones represented flow across streambeds (discussed in the following section). Use of zones to identify these boundary conditions aided in data input to MODFE, model calibration, and sensitivity analysis.

Specified-head boundaries were used to represent ground-water level and regional-flow conditions in outcrop areas of the Upper Floridan aquifer because water levels in those areas fluctuate only a few feet during the year. Specified-head boundaries were represented in MODFE with nodes that were assigned a constant value of head (pl. 4) for the simulation. Effects on regional flow and on simulation results of using specified-head values other

Table 2. Head-dependent (Cauchy-type) boundaries of Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin, by zone
[Boundary-coefficient values, in feet per day, obtained from calibrated models]

Zone(s) (plate 4)	Boundary coefficient, α	Description
Upper Floridan model		
1, 2	0.13	Flint River.
3	.06	Flint River.
4	5.0	Lake Worth.
5	100	Flint River at Flint River Dam.
6	1,000–2,000	Flint River at Albany, Ga.
7–17	100–500	Flint River downstream of Albany, Ga., to Lake Seminole.
18, 19	10–12	Muckalee Creek[1].
20–24	2.0–6.0	Muckalee Creek[1].
25	8.0	Muckaloochee Creek[1].
26–31	0.5–6.0	Kinchafoonee Creek[1].
32	18	Ichawaynochaway Creek[1].
33	4.5	Ichawaynochaway Creek[1].
34, 35	10	Ichawaynochaway Creek[1].
36	18	Patchitla Creek[1].
37	2.0	Chattahoochee River.
38, 39	60–100	Chattahoochee River.
40	150	Chattahoochee River.
41–45	12–20	Chipola River.
46	6.0	Chipola River.
47–50	6.0–12	Apalachicola River.
51	30	Southwestern model boundary; regional flow.
52	30	Southern model boundary; regional flow.
53	55	Southern model boundary, regional flow.
54	55	Southeastern model boundary; regional flow.
55	120	Eastern model boundary, southern part; regional flow.
56	100	Northeastern model boundary; regional flow.
57	45	Northeastern model boundary; regional flow.
58	0–35	Northeastern model boundary; regional flow.
Intermediate model		
59–61	6.0–12	Apalachicola River.
62	2.0	Chipola River, upstream of Dead Lake.
63	2.0–3.0	Chipola River and cutoff, downstream of Dead Lake.
64	2.5	Brothers River.
65	5.0	St. Marks River.
66	5.0	East River.
67	2.5	Jackson River.
68	5.0	Cypress Creek.
69	0.64–3.0	Northern model boundary; regional flow.
70	2.0	Northwestern model boundary; regional flow.
71	1.0	Southwestern model boundary; regional flow.
72	1.0–2.0	Southern model boundary; regional flow.

[1]Tributary to Flint River.

than those obtained from calibration were tested in a sensitivity analysis, discussed in a later section.

Regional outflow along the southern boundary of the Upper Floridan model was not represented with a corresponding component of lateral inflow along the northern boundary of the Intermediate model (pl. 4), although the models are adjacent to each other. The hydrologic units represented in each model by simulated layers are not aligned vertically across adjacent lateral boundaries; the Intermediate model contains the Intermediate system as the simulated model layer, and the Upper Floridan model contains the Upper Floridan aquifer as a model layer. Stratigraphically, the Upper Floridan aquifer underlies the Intermediate system in the area simulated by the Intermediate model (shown in fig. 19 as the southern part of the study area); thus, the Upper Floridan aquifer is a vertical-leakage boundary to the Intermediate system. However, the limited thickness and areal extent of the Intermediate system in the area of the Upper Floridan model (figs. 17, 18) causes it to be represented either as part of the simulated layer with the Upper Floridan aquifer or to be consolidated with the overlying semiconfining unit and vertical-leakage boundary. The vertical and stratigraphic separation of these units causes a discontinuity in lateral-flow between the models.

Flow Across Streambeds

Flow across streambeds was simulated with the head-dependent part of a Cauchy-type boundary, which is similar to the representation of regional flow discussed previously. However, for flow across streambeds, the α term in equations 4 and 6 is defined as

$$\alpha = \frac{K_r W_r}{b_r}, \qquad (8)$$

where K_r is vertical hydraulic conductivity of the streambed, W_r is streambed width, and b_r is streambed thickness. Values for α were specified either by reach (element side) or by zone, where a zone is a collection of reaches that contain the same hydraulic properties (pl. 4; table 2). Controlling head, H_{Bi}, in equation 6 is the stream stage (or lake level), associated with node i ($=k$ or l) defining the element side on the boundary. Values of H_B for all nodes on a reach were obtained by interpolating between measurements of surface-water levels. Nodes are aligned along the stream reach or other surface-water feature and width, W_r, is the average width of the surface-water feature, measured transverse to the element side.

Initial values of the boundary coefficient, α, were based on estimates of a similar parameter used in a previous digital-modeling study by Hayes and others (1983), which was performed in the Dougherty Plain. These values were adjusted during calibration to account for differences in simulation techniques used to represent surface-water features in both models; finite-differences used by Hayes and others (1983), and the finite-element model, MODFE, used in this study. Because three physical properties of surface-water features—vertical hydraulic conductivity, width, and sediment thickness—are combined in one term, α, variations in any of these properties change the value of α. Values of the boundary coefficient that were used in the calibrated models are listed in table 2 by zone.

A nonlinear form of the head-dependent (Cauchy-type) boundary condition was used to simulate small streams that would go dry if the water level in the aquifer was below the altitude of the bottom of the streambed. The boundary condition is nonlinear because the mathematical expression of streambed leakage is dependent on the relative positions of the aquifer head, h, and the altitude of the bottom of the streambed, z_r. Thus, for node i ($=k$ or l) on an element side that represents the surface-water feature as a nonlinear head-dependent (Cauchy-type) boundary, leakage expressions are given as

$$Q_{ri} = \begin{cases} C_{ri}(h_{ri} - h_i), & h_i > z_{ri} \\ C_{ri}(h_{ri} - z_{ri}), & h_i \le z_{ri} \end{cases} \qquad (9)$$

where

Q_{ri} = nodal volumetric flow rate [length^3/time];
C_{ri} = nodal coefficient, given as $(1/2)\alpha L_{kl}$ [length^2/time];
h_{ri} = nodal stream stage [length], and;
z_{ri} = nodal altitude of streambed bottom [length], and;

α and L_{kl} have been defined previously for equations 8 and 6, respectively.

Creeks and streams in upland areas of the lower ACF River Basin (Upper Floridan model only) were represented with nonlinear head-dependent (Cauchy-type) boundaries (table 3; pl. 4), as some of these streams were observed to be dry or nearly so during October 1986. Also, other streams were represented with the nonlinear boundary if the potential existed for them to go dry during simulation of increased pumpage from October 1986 rates. In addition to dry reaches, the nonlinear condition in equation 9 allowed streams to represent discharge-only boundaries that drain the aquifer if ground-water levels were higher than stream stages, and to dry up if ground-water levels were below the bottom of the streambed (thus eliminating the source of streamflow). This mathematical representation is consistent with the concept that small streams in the northern part of the lower ACF River Basin function only to drain the Upper Floridan aquifer and would dry up if ground-water levels drop below the streambed.

The dry condition was effected in MODFE upon data input by setting the altitude of the streambed bottom, z_{ri}, equal to the surface-water level, h_{ri}, for node $i=k$ or l. Thus, the volumetric flow rate,

Table 3. Nonlinear head-dependent (Cauchy-type) boundaries of Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin, by zone
[Boundary-coefficient values, in feet per day, obtained from calibrated Upper Floridan model]

Zone(s) (plate 4)	Boundary coefficient, α	Description
1	0.5	Limestone Creek[1].
2, 3	1.0–2.0	Gum Creek[1].
4	2.0–3.0	do.[1]
5–8	0.6–1.0	Cedar Creek[1].
9	1.0	Swift Creek[1].
10	2.0	do.[1]
11	1.0	Swift Creek, North Branch[1].
12–14	0.75	Jones Creek[1].
15–16	1.0	Abrams Creek[1].
17–19	3.5	Mill Creek[1].
20–25	1.8–2.0	Cooleewahee and Chickasawhatchee Creeks[1].
26–28	1.5–1.8	Chickasawhatchee Creek[1].
29–31	0.5	Spring Creek.
32, 33	2.0	do.
34	8.0	do.
35	27	do.
36	32	do.
37, 38	0.2	Dry Creek.
39	1.0	do.
40	2.5	do.
41–43	1.3–2.0	Sawhatchee Creek.
44, 45	5.0	Cowarts Creek.
46, 47	5.0	Marshall Creek.
48–50	16	Dry Creek (Fla.).
51–54	5.0	Tenmile and Fourmile Creeks.
55, 56	6.0	Juniper Creek.

[1]Tributary to Flint River.

Q_{ri}, is zero for the case where aquifer head, h_i, is situated below z_{ri} (or h_{ri}), and the reach is considered to be dry for the simulation.

Values of the boundary coefficient, α, and surface-water levels, h_r, for the nonlinear boundaries, were obtained in the same manner as that described previously for the linear boundaries. The α values used in the calibrated Upper Floridan model are listed in table 3. The nonlinear boundary was used for small streams that were located only in the Upper Floridan model as streams in the Intermediate model were not expected to go dry during simulation. An analysis was performed of the sensitivity of computed water levels in the Upper Floridan model to changes in the surface-water level, h_r, for nonlinear head-dependent (Cauchy-type) boundaries and is discussed in a later section.

Vertical Leakage

Vertical leakage to and from overlying and underlying semiconfining units was simulated with linear and nonlinear forms of a steady-vertical-leakage function, expressed generally by the term $R(H-h)$ in equation 1. The general form represents linear vertical leakage and was used only in the Intermediate model to represent the underlying semiconfining units to water-bearing zones of the Intermediate system. A nonlinear form of the vertical-leakage function (Cooley, 1992; and Torak, 1993a,b) was used to represent vertical flow to and from overlying semiconfining units in both models. The nonlinear form limits recharge by vertical leakage for water-level declines that cause water-table conditions and hydraulic separation of the aquifer from the overlying semiconfining unit.

The volumetric-flow rate, Q_{ai}, across the vertical boundary of the aquifer with the overlying semiconfining unit is expressed for node i as

$$Q_{ai}=\begin{cases}C_{ai}(H_i-h_i),\ h_i>z_{ti}\\ C_{ai}(H_i-z_{ti}),\ h_i\le z_{ti}\end{cases},\qquad (10)$$

where

Q_{ai} = nodal volumetric flow rate for steady vertical leakage [length³/time];

C_{ai} = nodal vertical-leakage coefficient [length²/time], given as

$$(⅓)\sum_{e_i} R^e\Delta^e$$

h_i = nodal hydraulic head [length];

H_i = nodal head in semiconfining unit overlying simulated aquifer [length];

z_{ti} = nodal altitude of aquifer top or base of overlying semiconfining unit [length];

and R^e and Δ^e are vertical hydraulic conductance and area, respectively, of element e. Aquifer recharge is limited to a maximum rate by equation 10 when aquifer head drops below the base of the overlying semiconfining unit or top of the aquifer. Discharge from the aquifer to the overlying semiconfining unit is not limited by the nonlinear function.

Initial values of vertical hydraulic conductance, R^e, input to the Upper Floridan and Intermediate models were computed from a value for vertical hydraulic conductivity of 0.0001 ft/d, given by Hayes and others (1983), and from values of clay thickness in the semiconfining units. This value for vertical hydraulic conductivity is representative of clay and clay-sized sediment that exist in the lower half of the overlying semiconfining unit to the Upper Floridan aquifer. As discussed by Hayes and others (1983), more clay and less sand in the lower half of the undifferentiated overburden (termed residuum in their report) than in the upper half makes the lower half of the sediments less transmissive than the upper half. Thus, it was reasonable to assume that only the thickness of sediments in the lower half of the undifferentiated overburden, specifically, the clay thickness, functions as a semiconfining unit in the Upper Floridan model. This approach to evaluating vertical leakage coefficients was used successfully in the northern part of the lower ACF River Basin near Albany, Ga., in a previous study that simulated stream-aquifer relations and effects of ground-water pumpage on streamflow (Torak and others, 1993).

Thicknesses of clay and clayey sediments that overlie and underlie water-bearing zones in the Intermediate system were used to represent, respectively, overlying and underlying semiconfining units in the Intermediate model. The value of 0.0001 ft/d for vertical hydraulic conductivity of the overlying semiconfining unit in the Upper Floridan model was used initially to compute values of vertical hydraulic conductance for both semiconfining units in the Intermediate model.

Zones of clay thickness in the semiconfining units represented in the Upper Floridan and Intermediate models were established from data collected during a study by Hicks and others (1987) in the Albany, Ga., area and from other data on file at either the U.S. Geological Survey, District Office, Atlanta, Ga., or Florida Bureau of Geology, Tallahassee, Fla. These data consist of drillers' logs and lithologic descriptions of well-bore sediments, and were compiled into zones of equal thickness in the study area. Element sides of the finite-element mesh were used as zone boundaries. For overlying semiconfining units (pl. 5), zones were assigned a zero value of vertical hydraulic conductance in areas where the unit either was absent, had a total thickness less than 10 ft, or had a clay thickness of zero. In these areas, it was assumed that sediments overlying the Upper Floridan aquifer and water-bearing units of the Intermediate system could neither supply enough water nor act as a semiconfining unit to the simulated aquifers. Zones of vertical hydraulic conductance for the underlying semiconfining unit to the Intermediate system are shown on plate 6, and zone values used in the calibrated models are listed in table 4.

Values for source-layer head, *H*, of equation 1, for vertical leakage were input to the Upper Floridan and Intermediate models by node. Source-layer head in the Upper Floridan model represented the altitude of the ground-water level above the clay or clayey sediments in the lower half of the overlying semiconfining unit. Drought conditions during 1986 caused ground-water levels to approach either seasonal or record lows by October; thus, it was assumed that only the clay in the lower-half thickness of the semiconfining unit overlying the Upper Floridan aquifer was saturated. In the Intermediate model, the water table of the overlying semiconfining unit to the Intermediate system functioned as the source-layer head, *H*. Nodal values for the water table were assumed to be approximately 5 ft below land surface for input to the Intermediate model. Observations made during October 1986 of dry conditions in previously swampy areas attested to the assumption of a shallow water table overlying the Intermediate system. To account for the effects of these estimates of source-layer head on model results, a sensitivity analysis was performed and is described in a later section.

Springflow

Ground-water discharge to springs, or springflow, was simulated in the Upper Floridan model by using two mathematical representations; a point-discharge function, *P*, in equation 1, and a head-dependent (Cauchy-type) boundary, described previously for flow across streambeds. The point-discharge function represents springflow in the identical manner as point withdrawal from wells. The head-dependent (Cauchy-type) boundary incorporates springflow into ground-water discharge to a stream reach, because the occurrence of springflow in stream channels is indistinguishable, both hydrologically and mathematically, from other discharge from the to streams. Use of either mathematical representation for springflow was based on whether or not the spring discharged directly into a stream channel (in-channel spring), or whether the discharge occurred at some distance away from a stream (off-channel spring). Springflow is simulated only in the Upper Floridan model, as springs do not emanate from the Intermediate system.

Springs in Gadsden, Jackson, and Liberty Counties, Fla., were represented as off-channel springs; therefore, they were simulated with point-discharge functions. Locations and discharge rates of springs in the Upper Floridan aquifer were obtained from reports by Ferguson and others (1947), Rosenau and others (1977), and Bush and Johnston (1988). Off-channel springs required assigning a constant volumetric flow rate to a node in the finite-element mesh nearest to the spring location (table 5). Nodal-discharge rates were adjusted from published values to obtain estimates for October 1986 springflow, as springflow was not measured for this study. The rates used in the calibrated Upper Floridan model are listed in table 5 and total 332.6 Mgal/d. Off-channel springflow was held constant at the estimates for October 1986 for all simulations because data were not available to estimate springflow for the hypothetical conditions of simulated pumpage increases. Therefore, off-channel springflow was assumed to be unaffected by changes in stream stage and aquifer head that might occur during the simulated pumpage scenarios.

Springs in Alabama and Georgia were represented as in-channel springflow; for example, Radium Springs in Dougherty County, Ga., which discharges directly to the Flint River. In-channel springflow can vary with changes in aquifer head and stream stage; therefore, pumpage-induced changes to these components can change discharge rates of in-channel springflow. The head-dependent (Cauchy-type) boundary that represents in-channel springs in MODFE combines computations for

Table 4. Zone values of vertical hydraulic conductance for semiconfining units in calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin
[Vertical hydraulic conductance in feet per day per foot]

Upper Floridan model						Intermediate model			
Overlying semiconfining unit (zones on plate 5)						Overlying semiconfining unit (zones on plate 5)		Underlying semiconfining unit (zones on plate 6)	
Zone	Vertical hydraulic conductance	Zone	Vertical hydraulic conductance	Zone	Vertical hydraulic conductance	Zone	Vertical hydraulic conductance	Zone	Vertical hydraulic conductance
1	0	14	5.2×10^{-6}	27	1.1×10^{-4}	39	0	1	1.5×10^{-4}
2	8.4×10^{-10}	15	8.4×10^{-6}	28	2.0×10^{-4}	40	8.4×10^{-6}	2	1.5×10^{-4}
3	6.7×10^{-9}	16	9.5×10^{-6}	29	2.1×10^{-4}	41	1.1×10^{-5}	3	7.5×10^{-4}
4	9.0×10^{-9}	17	1.3×10^{-5}	30	2.5×10^{-4}	42	1.4×10^{-5}	4	7.5×10^{-4}
5	5.5×10^{-8}	18	2.0×10^{-5}	31	3.0×10^{-4}	43	2.1×10^{-5}	5	7.5×10^{-4}
6	3.4×10^{-7}	19	2.1×10^{-5}	32	3.8×10^{-4}			6	3.0×10^{-4}
7	4.2×10^{-7}	20	3.0×10^{-5}	33	4.0×10^{-4}			7	7.5×10^{-4}
8	5.0×10^{-7}	21	5.0×10^{-4}	34	5.0×10^{-4}			8	3.0×10^{-4}
9	6.7×10^{-7}	22	4.7×10^{-5}	35	6.1×10^{-4}			9	7.5×10^{-4}
10	1.7×10^{-6}	23	5.0×10^{-5}	36	8.4×10^{-4}				
11	2.1×10^{-6}	24	6.7×10^{-5}	37	9.8×10^{-4}				
12	2.5×10^{-6}	25	9.4×10^{-5}	38	8.0×10^{-3}				
13	4.2×10^{-6}	26	1.0×10^{-6}						

springflow and other ground-water discharge to the stream reach into one volumetric flow rate at the boundary node. As a result, individual rates for in-channel springflow and other discharge are not available from simulation results, an apparent mathematical limitation. However, the limitation is also hydrologic in that flow from most in-channel springs can neither be measured accurately nor separated from nonspringflow-related discharge from the aquifer that occurs through the streambed. Another consequence of representing in-channel springflow and other discharge to a stream reach with the same head-dependent (Cauchy-type) boundary is that in-channel springflow could not be calibrated, notwithstanding that springflow measurements were unavailable. Thus, calibrated flow rates to in-channel springs are not listed in table 5 in the same manner as for off-channel springs. Rates of ground-water discharge to streams and in-channel springs are listed in water-budget tables as a single component (see tables 11, 13, 16). Because springs are discharge-only features, the water-budget component listed in these tables as recharge from streams does not include springflow.

Hydraulic-Property Zones

Variations in areally distributed hydraulic properties that affect ground-water flow and stream-aquifer relations in the lower ACF River Basin were represented in MODFE by using hydraulic-property zones (pl. 6). Each zone consists of a group of elements that are assigned identical values for aquifer hydraulic conductivity and vertical hydraulic conductance of semiconfining units that are represented using linear vertical leakage, as described previously. Variations in hydraulic conductivity of the Upper Floridan aquifer were determined from transmissivity and thickness data compiled in the Dougherty Plain by Hayes and others (1983) and Torak and others (1993), and from data on file at the U.S. Geological Survey, District Office, Atlanta, Ga. Sufficient spatial coverage of data describing the frequency and distribution of fractures and solution openings in the Albany, Ga., area (see Torak and others, 1993, fig. 8) permitted detailed zones of hydraulic conductivity to be constructed there. Variations in thickness and hydraulic conductivity of water-bearing units of the Intermediate system were determined from data contained in reports by

Table 5. Calibrated spring discharge from Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin
[Discharge in million gallons per day]

Name	Node	Discharge
Chattahoochee Spring	2593	0.02
Glen Julia Springs	3110	.37
Indian Springs	2443	.45
White Spring	1634	1.22
Black Spring	1075	47.31
Double Spring	1075	24.24
Blue Spring	1751	92.75
Blue Hole Spring	1972	41.15
Bosel Spring	2046	52.37
Gadsden Spring	1074	11.63
Hays Spring	2497	14.96
Mill Pond Spring	1076	21.46
Sand Bag Spring	757	7.48
Springboard Spring	1145	11.25
Daniel Spring	2901	5.98
Total		**332.64**

Schmidt (1978, 1979, 1984) and Schmidt and others (1978, 1980), and from aquifer-test results provided by Jeffry R. Wagner, formerly of the Northwest Florida Water Management District (written commun., 1988). From these data, 52 zones for hydraulic properties in the Upper Floridan model were established, and 9 zones were established for the Intermediate model. Values of hydraulic conductivity used in the calibrated models are listed in table 6 by hydraulic-property zone.

Distribution of Well Pumpage

The distribution of ground-water withdrawal from municipal, industrial, and irrigation wells in the northern and central parts of the lower ACF River Basin for October 1986 was determined by compiling pumpage records that were on file at the USGS District Office, Atlanta, Ga., and that were obtained from various State offices within whose jurisdiction specific parts of the study area reside. In Georgia, locations and pumping rates for irrigation wells in the Dougherty Plain were obtained from data collected for the State Irrigation Well Survey of 1980, Georgia Irrigation Reporting System (GIRS), and from miscellaneous files and communication with water managers, such as county-extension agents of the U.S. Department of Agriculture, which updated the 1980 data to 1986 conditions. In Alabama and Florida, the distribution of pumpage was determined from estimates of withdrawals and from water-use information, such as location and type of use (public supply, irrigation, or domestic) that was reported incidentally with water-level and geohydrologic data. Average pumping rates were assigned to each water-use type at the well locations for the pumpage estimates.

Compilation of GIRS data indicated that irrigation pumpage from wells during October 1986 was about one-fifth of that reported during the peak of the growing season. Therefore, maximum-reported pumping rates at all irrigation wells in the study area were decreased to one-fifth of their values for input to the Upper Floridan model. Growing-season pumping rates for irrigation totaled about 2.2 billion gallons per day; hence, October 1986 pumpage used in the Upper Floridan model was about 432.5 Mgal/d. Municipal and industrial pumpage for October 1986 totaled about 42.5 Mgal/d. The distribution of pumped wells in the northern and central parts of the lower ACF River Basin is shown in plate 7.

Pumping rates of wells in the Upper Floridan aquifer were represented as point withdrawals at nodes in the finite-element mesh that were nearest to actual well locations. This procedure distributed pumping rates from the well locations shown on plate 7 to 1,380 nodes (pl. 8). Element sizes in the mesh permitted pumpage to be represented at nodal locations that were generally within 2,000 ft of the wells. This manner of approximately positioning wells with nodes of the finite-element mesh is supported by the absence of distinct drawdown cones from the potentiometric surface of the Upper Floridan aquifer in the Albany, Ga., area (Hicks and others, 1987). This surface indicates an overall decrease of ground-water levels in the lower ACF River Basin due to pumpage. Well pumpage represented in this manner was applied successfully in a previous study that simulated stream-aquifer relations and the effects of ground-water development in the Upper Floridan aquifer near Albany, Ga. (Torak and others, 1993), which is located in the present study area. Therefore, locating pumpage approximately by using the nearest nodes in the finite-element mesh to wells was assumed to have little effect on accurately simulating the potentiometric surface of the Upper Floridan aquifer for October 1986. The relative insensitivity of computed water levels to well pumping rates further attests to the validity of this approximation method and is discussed in the section "Sensitivity Analysis."

Ground-water pumpage in the Intermediate system was considered negligible due to the insignificant number of low-yield domestic-supply wells that tap this unit (Jeffry R. Wagner, formerly of the Northwest Florida Water Management District, Havana, Fla., written commun., 1988). Thus, pumping was not simulated in the Intermediate model; neither was it considered a factor in shaping the potentiometric surface of the Intermediate system or in evaluating stream-aquifer relations for this unit.

Calibration

Acceptance of model results for evaluating stream-aquifer relations in the lower ACF River Basin depends on the accuracy of the models to simulate ground-water levels and associated stream-aquifer processes for the historical period of October 1986, for which hydrologic data exist. The process of adjusting model inputs of hydraulic properties, within plausible limits, to produce a computed solution that satisfies error criteria established with regard to observations of the hydrologic system during the historical period is termed calibration. Therefore, the objective of model calibration in the lower ACF River Basin was to produce simulations that, within acceptable error bounds, represent actual conditions of ground-water flow and stream-aquifer interaction in the Upper Floridan aquifer and Intermediate system for October 1986, as indicated by observations of pertinent hydrologic phenomena.

Procedure

The calibration procedure involved trial-and-error adjustments to hydraulic properties that affected computed values of ground-water levels and volumetric flow rates across streambeds, termed stream-aquifer fluxes. Comparisons were made of computed ground-water levels with measured values at discrete points (wells), and of computed (model-derived) stream-aquifer fluxes with fluxes that were calculated on the basis of streamflow measurements for selected reaches. Adjustments to the following hydraulic properties were made within plausible limits to achieve calibration:

- Hydraulic conductivity of Upper Floridan aquifer
- Vertical hydraulic conductance of overlying semi-semiconfining units
- Head in overlying semiconfining units
- Head in Upper Floridan aquifer in outcrop areas
- Hydraulic conductivity of Intermediate system
- Vertical hydraulic conductance of the underlying semiconfining unit in the Intermediate model (between the Upper Floridan aquifer and Intermediate system)
- Head in the underlying semiconfining unit in the Intermediate model
- Leakage coefficients for Cauchy-type boundaries that represent boundary conditions and surface-water features
- Controlling head to boundary conditions and surface-water features

Well pumping rates were not adjusted during calibration; however, effects of changing pumping rates on computed water levels were addressed in a sensitivity analysis and are discussed in a later section.

An acceptance criterion of 7 ft was established for comparing computed ground-water levels with measured values. This criterion was established after evaluating the combination of innaccuracies related to reporting land-surface altitude at wells, which can be up to 5 ft, and the expected accuracy of simulated ground-water levels derived from models that were constructed using a generalized hydrologic characterization of the flow system. Generalizations for the hydrologic characterization of the flow system were made in specific areas of the basin using little or no data because more complete data were not available. Computed values of ground-water levels and the distribution of water-level residuals were analyzed after each simulation. Changes to hydraulic properties by zone were made in an attempt to meet the acceptance criterion for ground-water levels and to obtain a random distribution of water-level residuals, in both magnitude and sign. This would indicate an unbiased calibration procedure.

After satisfying the acceptance criterion for ground-water levels, acceptability of the model to simulate stream-aquifer relations was determined by comparing computed (model-derived) stream-aquifer fluxes with values calculated from streamflow measurements, and by evaluating two error terms that relate computed flux to magnitude of streamflow. Individual acceptance criteria were established for each of the 37 reaches used in the comparison (pl. 9). Each criterion reflected the level of uncertainty contained in the flux value that was calculated from streamflow measurements—as the measurements contained different amounts of error—and the uncer-

Table 6. Calibrated hydraulic conductivity values by zone from Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin
[Zone numbers on plate 6; hydraulic conductivity in feet per day]

Upper Floridan model						Intermediate model		
Zone number	Number of elements	Hydraulic conductivity	Zone number	Number of elements	Hydraulic conductivity	Zone number	Number of elements	Hydraulic conductivity
1	149	1,350	27	873	130	1	73	20
2	53	2,100	28	15	2,000	2	1,165	25
3	53	1,800	29	8	9,000	3	163	10
4	13	1,200	30	10	10,500	4	144	20
5	2	1,200	31	196	200	5	866	40
6	8	600	32	683	900	6	416	60
7	4	720	33	397	1,344	7	1,165	20
8	715	1,100	34	1,857	1,300	8	15	60
9	12	5,500	35	47	500	9	17	20
10	11	9,500	36	623	1,700			
11	3	130	37	92	1,200			
12	81	750	38	15	1,500			
13	135	130	39	40	130			
14	606	1,600	40	92	1,500			
15	16	15,000	41	452	400			
16	20	4,000	42	545	600			
17	43	18,500	43	453	480			
18	88	250	44	679	1,300			
19	36	900	45	65	1,000			
20	167	8,000	46	201	280			
21	58	8,500	47	379	200			
22	65	350	48	252	500			
23	45	2,200	49	375	1,800			
24	818	2,700	50	554	1,600			
25	13	20,000	51	130	1,200			
26	36	1,150	52	12	0			

tainty in actual ground-water levels. As a result, each model-derived stream-aquifer flux was expected to lie within a "target" range of values that was established for a corresponding reach; the width of the range reflected the uncertainty of the "known" fluxes due to errors in streamflow measurements.

Target ranges of stream-aquifer flux were calculated for each of the 37 stream reaches to account for possible errors contained in the flow measurements used in their computation. The inaccuracy of streamflow records is reported routinely as 5, 10, or 15 percent, or "poor," depending on the degree to which measurements meet the criteria mentioned for the station (Stokes, and others, 1990). Although stream-discharge measurements were accurate to within 5 or 10 percent of actual values, use of upstream and downstream measurements to compute stream-aquifer flux could cause errors in computed flux in the 0-to-20-percent range, as measurement errors will either compound or cancel one another during flux calculations. In like manner, sensitivity analyses of stream stage and simulated ground-water levels that were performed in a previous model study in the Albany, Ga., area (Torak and others, 1993), indicate that model-derived stream-aquifer fluxes could contain about 5-percent error due to measurement errors in stages and ground-water-levels, which are used to achieve model calibration. Although the model-derived stream-aquifer fluxes seem to have less error than the measurement-based fluxes, the model-derived fluxes cannot be expected to have greater accuracy than is allowed by the level of uncertainty caused by errors of precision in streamflow measurements. Therefore, to account for the greater variability in measurement-based stream-aquifer fluxes than in model-derived (computed) values, the model-derived fluxes were accepted for calibration if they resided within the target range of flux that was established for the corresponding reach. Thus, acceptable tolerance levels for the model-derived stream-aquifer fluxes are defined by target ranges for the measurement-based fluxes.

The concept of a target range for stream-aquifer flux is based on the occurrence of measurement errors in upstream and downstream flows of a reach, and the possibility that errors in computed stream-aquifer flux can be quantified with regard to the magnitude of average streamflow in a reach. Although larger flows might contain a greater error-induced variation in stream-aquifer flux than smaller flows, the percent error in the larger flow measurements actually might be smaller. Therefore, for reaches having an average flow of less than 250 ft³/s, the target range was computed by applying an error factor, *EF*, of 0.1 (10-percent error) to measurements at the upstream and downstream ends of the reach, Q_u and Q_d, respectively. For streams having an average flow greater than 250 ft³/s, an error factor of 0.05 (5-percent error) was applied to measurements Q_u and Q_d. A lower limit of the target range, *Fluxmin*, was computed by adjusting upstream and downstream flow measurements with the error factor to give the smallest streamflow gain (stream-aquifer flux) over the reach when upstream flow is subtracted from downstream flow. This is demonstrated in the expression for *Fluxmin*:

$$Fluxmin = (Q_d - EF \times Q_d) - (Q_u + EF \times Q_u). \quad (11)$$

Similarly, an upper limit of the target range, *Fluxmax*, is calculated by using *EF* to adjust upstream and downstream flow measurements to give the largest stream-aquifer flux over the reach. The calculation of *Fluxmax* is given as

$$Fluxmax = (Q_d + EF \times Q_d) - (Q_u - EF \times Q_u). \quad (12)$$

The following example demonstrates the use of equations 11 and 12 to compute a target range for stream-aquifer flux along a reach. Suppose that upstream and downstream stations of a reach contain measured flows of 300 ft³/s and 500 ft³/s, respectively. Errors in these measurements of about 5 percent require the error factor, $EF=0.05$, to be used to compute values of *Fluxmin* and *Fluxmax* as

$$Fluxmin = (500\ ft^3/s - 0.05 \times 500\ ft^3/s) - (300\ ft^3/s + 0.05 \times 300\ ft^3/s) = 160\ ft^3/s,$$

and

$$Fluxmax = (500\ ft^3/s + 0.05 \times 500\ ft^3/s) - (300\ ft^3/s - 0.05 \times 300\ ft^3/s) = 240\ ft^3/s.$$

Target-range limits of stream-aquifer flux, given by *Fluxmin* and *Fluxmax* (eqs. 11, 12), represent possible variations in stream-aquifer flux that can occur undetected over a reach due to measurement error. In this example, the target range allows a 20-percent variation in flux about a mean of 200 ft³/s. A flux value derived from model results is accepted if it falls within the target range. However, as described previously, model-derived (computed) fluxes might contain less error than measurement-based (average) values to which they are compared.

The ability of model-derived stream-aquifer fluxes to exhibit less variation than fluxes computed from streamflow measurements gives simulated ground-water levels the flexibility to attain values that might extend beyond the acceptability criterion of 7 ft while, at the same time, yielding model-derived fluxes in the target range. The sensitivity of model-derived stream-aquifer fluxes to changes in simulated ground-water levels near reaches that are used in flux calculations determines the need for simulated ground-water levels to satisfy the acceptability criterion (7 ft) so that the model-derived fluxes would reside in the target range. Conversely, the degree of accuracy required for simulated ground-water levels to produce stream-aquifer fluxes in the target range is determined by the sensitivity of the measurement-based (average) stream-aquifer fluxes to changes in stage and nearby ground-water levels. That is, actual ground-water levels near a reach might vary by more than 7 ft and still yield fluxes that are within the target range. For this case, the stream-aquifer system might exhibit less sensitivity to changes in actual stage and ground-water level than is allowed by the calibration criteria. Therefore, for some reaches, the criteria used to determine model accuracy might be imposing narrower limits of variability on simulated ground-water levels and stream-aquifer fluxes than would occur in actuality. An analysis of flow-system sensitivity to changes in ground-water level and stream stage is discussed in following sections.

Calibration of the model using stream-aquifer fluxes proceeded by comparing computed fluxes with corresponding target ranges. Reasonable adjustments were made to hydraulic properties, and simulations were performed until computed stream-aquifer fluxes were within the target range for the corresponding reach, and ground-water residuals were at or below the acceptability criterion.

Ground-Water-Level Residuals

Ground-water-level residuals (computed minus measured water levels, or head) were calculated for calibration at 284 well locations in the Upper Floridan model and at 19 well locations in the Intermediate model (pl. 10). Residuals from the calibrated models (listed in tables 7 and 8 at the end of this report, p. 91–94), indicate that, on average, the acceptance criterion of 7 ft was met, and that calibration of the Upper Floridan and Intermediate models to October 1986 conditions was successful. Values of computed head for well locations used in calibration were obtained by applying the finite-element concept of linear variation (of head) in an element (Zienkiewicz, 1977, p. 93–95) to those elements containing wells. Thus, simulated heads at nodes were used to compute the head at locations in an element corresponding to the measured water levels in wells used for comparison during calibration.

Acceptance of ground-water-level residuals with regard to the established criterion of 7 ft was determined by computing the root-mean-square error of residuals, or *RMSE* (Torak and others, 1993) as

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(h_{i\,model} - h_{i\,obs}\right)^2\right]^{1/2}, \qquad (13)$$

where N is the number of residuals (284 for the Upper Floridan model, 19 for the Intermediate model), and $h_{i\,model}$ and $h_{i\,obs}$ are, respectively, the computed and observed hydraulic head for the i^{th} residual. Values of *RMSE* that satisfied the acceptability criterion were calculated according to equation 13 as 7 ft for the Upper Floridan model and 4.4 ft for the Intermediate model. The arithmetic average of residuals was computed as 0.4 ft for the Upper Floridan model and minus 0.6 ft for the Intermediate model, and the standard deviation of residuals in each model was equal to the corresponding value of *RMSE* (table 9).

Frequency distributions of ground-water-level residuals in the calibrated models (fig. 20; table 9) indicate a measure of accuracy in computed ground-water levels that cannot be derived from evaluating the *RMSE* values alone. Of the 284 residuals in the Upper Floridan model, 162 values were within 5 ft of zero, 23 values deviated from zero by more than 10 ft, and the largest residual was 20.2 ft (table 7). Of the 19 water-level residuals in the Intermediate system area, 15 values were within 5 ft, and no residual was larger than 10 ft (table 8).

Statistics of sum of squares, *RMSE*, and standard deviation of ground-water-level residuals were computed and plotted after each simulation so that progress of the models toward achieving calibration could be charted (fig. 21). Statistics calculated after each simulation indicated incremental improvement in numerical accuracy of the models to represent ground-water levels of October 1986, thus achieving calibration. An acceptable computed solution was obtained after a sequence of 83 trial-and-error changes followed by corresponding simulations with

Table 9. Statistics for ground-water-level residuals from the calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin

[ft^2, feet squared; ft, feet; RMSE, root-mean-square error of residuals]

	Upper Floridan model	Intermediate model
Number of terms	284	19
Sum of squares (ft^2)	13,728	360
RMSE (ft)	6.95	4.35
Standard deviation (ft)	6.95	4.43
Average residual (ft)	0.40	–0.59
Percentage of residuals within standard deviations		
1 standard deviation	70.1	63.2
2 standard deviations	93.3	94.7
3 standard deviations	100	100
Water-level residuals by class		
Class interval (feet)	**Number of occurrences**	**Number of occurrences**
–25 to –20	0	0
–20 to –15	7	0
–15 to –10	9	0
–10 to –5	42	2
–5 to 0	81	10
0 to 5	81	5
5 to 10	41	2
10 to 15	14	0
15 to 20	8	0
20 to 25	1	0

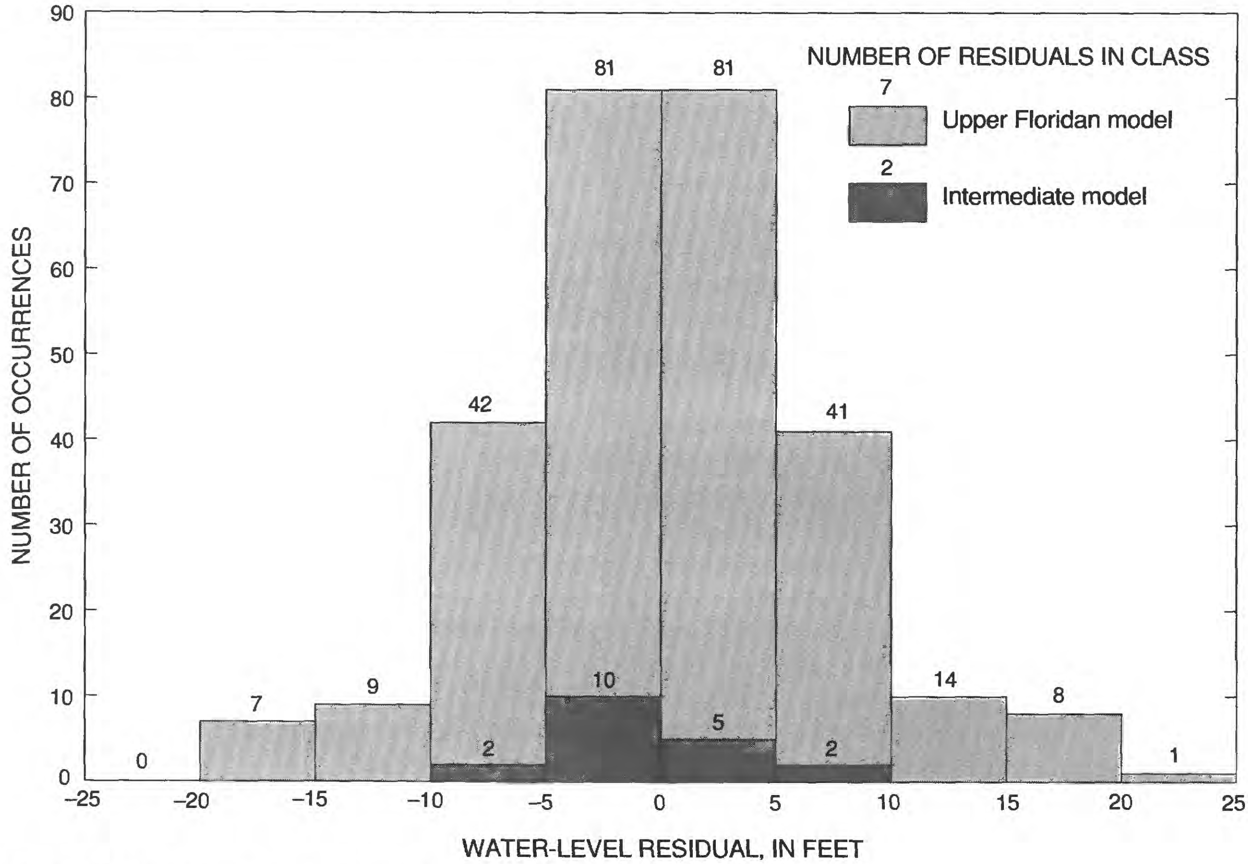


Figure 20. Frequency of ground-water-level residuals from model calibration.

the Upper Floridan model. For the Intermediate model, 14 trial-and-error changes were made to the data inputs before obtaining an acceptable computed solution. Values for the sum of squares decreased from the first to the last simulation from 156,517 to 13,728 ft^2 for the Upper Floridan model, and from 1,031 to 360 ft^2 for the Intermediate model. Values for the *RMSE* decreased from 21.6 to 7 ft for the Upper Floridan model, and from 7.6 to 4.4 ft for the Intermediate model.

Plots of statistical measures used to determine the adequacy of calibration (fig. 21) not only indicate progress made toward achieving calibration but the degree of subjectivity involved in determining which simulation truly represents a calibrated model. Because statistics provide an objective, or unbiased, view of the calibration process, it could be argued solely on the basis of the statistics presented in figure 21 that the Intermediate model required only 7 simulations to achieve calibration, instead of 14, and that the Upper Floridan model was calibrated after 44 simulations instead of 83. No significant improvement in statistics was accomplished by performing additional simulations beyond 7 and 44 for the corresponding models. However, subjective evaluation of model results, such as the location of accurate computed ground-water levels, water-budget components, and stream-aquifer fluxes, made after calibration seemingly was achieved, indicated that additional adjustments to hydraulic properties beyond that needed to satisfy statistical criteria for each model were necessary to adequately define stream-aquifer relations and meet study objectives.

Use of additional simulations beyond those required to satisfy statistical criteria is part of a "fine-tuning" process designed to improve overall-model performance, even though statistical improvement of simulation results is marginal. This fine-tuning process presents a dilemma in that hydraulic properties can be assigned values other than those used for the simulation in which the model was first deemed "calibrated" and still meet statistical criteria for calibration. Use of values for hydraulic properties that are different from those decided upon for calibration can be evaluated by performing a sensitivity analysis on the models. In this analysis, the amount of change to hydraulic properties that will significantly affect calibrated-model results is quantified. Hence,

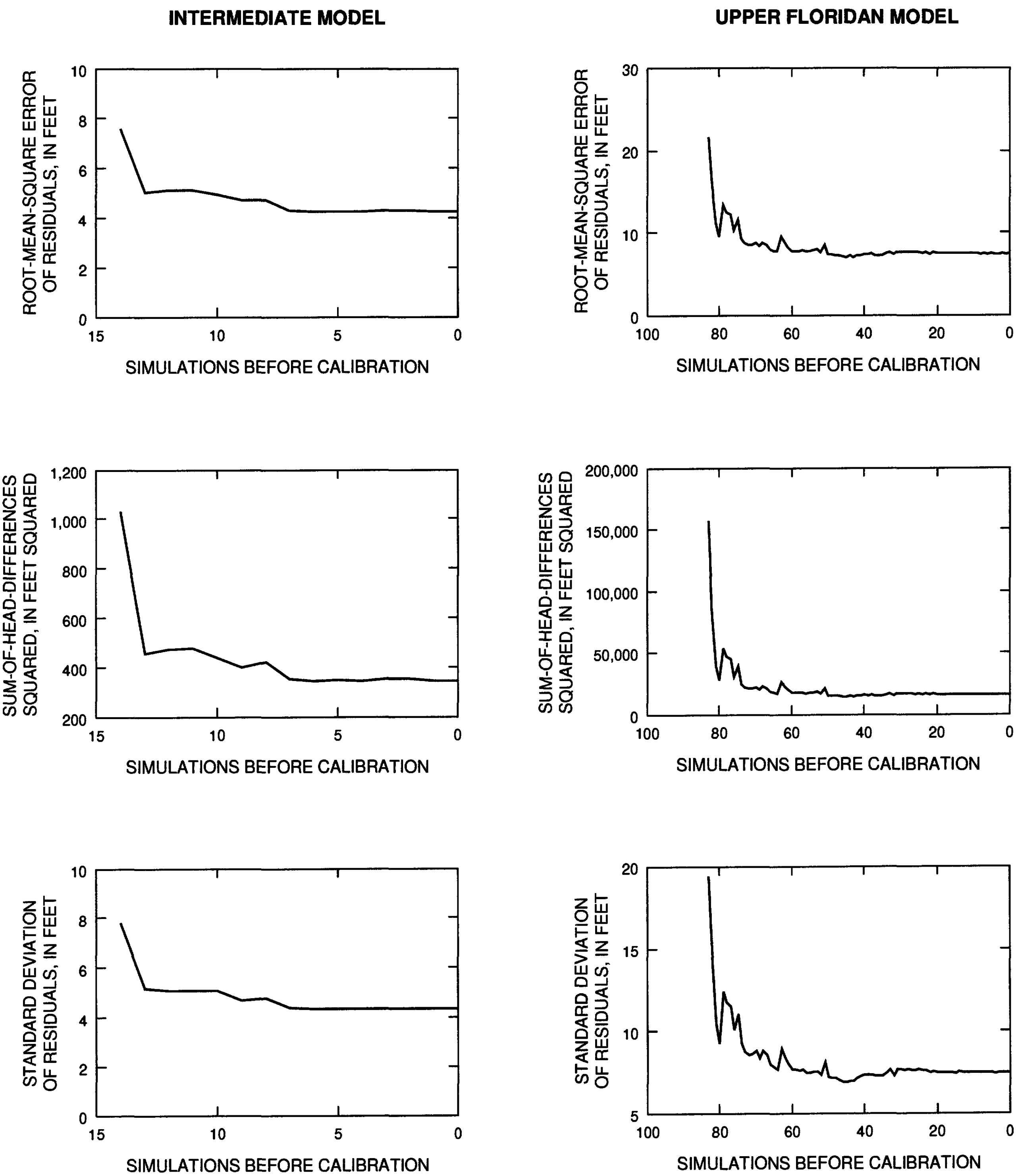


Figure 21. Root-mean-square residual, sum-of-head-differences squared, and standard deviation of ground-water-level residuals by simulation during calibration of Intermediate and Upper Floridan models.

different sets of values for hydraulic properties than the set used for calibration can be shown to exist, and give an equally plausible numerical solution, by analyzing model sensitivity to flow-system parameters. In addition, the analysis also gives an indication of true flow-system sensitivity to hydrologic features that operate in the basin. Results of a sensitivity analysis of the flow system to changes in hydraulic properties used in the Upper Floridan and Intermediate models is given in a later section.

A plot of ground-water-level residuals in the study area (pl. 10) shows that the distribution of residuals in sign and magnitude is nearly random—a desired quality of residuals from calibrated models—with only a few exceptions. In northern Decatur County, near Eldorendo, Ga., a cluster of about 10 negative residuals exists (computed water levels less than measured values) having values that range from minus 0.1 to minus 11.5 ft. These values are located in the interstream region between the Flint River and Spring Creek. East of the Chatta-hoochee River in southern Early and western Miller Counties, Ga., about 12 negative residuals exist, having values ranging from minus 0.3 to minus 13.8 ft. Like the first cluster of negative residuals, this region also is located in an interstream area (between Spring Creek and the Chattahoochee River).

Although possible explanations for clusters of negative residuals described above would be speculative, they indicate a need for additional hydrologic data to fully understand the ground-water-flow system in these areas. One possible explanation for negative residuals in these areas is the general manner in which hydraulic conductivity is represented with one value in the Upper Floridan model. The lack of detailed hydraulic-conductivity data precluded representing this aquifer property by more than one zone (pl. 6; table 6). Another possible explanation involves using one zone for vertical hydraulic conductance of the the overlying semiconfining unit (p. 5; table 4). As with aquifer-hydraulic conductivity, sparse data for hydraulic properties in this unit precluded detailed representation of vertical hydraulic conductance in the digital model.

Three other areas in the lower ACF River Basin contain water-level residuals that exhibit a nonrandom distribution in sign and/or magnitude. In southeastern Early and northern Miller Counties, Ga., about 8 positive residuals, ranging in value from 8.7 to 20.2 ft, are located near Spring Creek (pl. 10). A possible explanation for the positive residuals is the presence of springs in the vicinity of the creek and springflow in the creekbed, causing a lower potentiometric surface in the Upper Floridan aquifer than what was simulated. Northeast of this location, in eastern Early and western Baker Counties, Ga., a cluster of 5 negative residuals exists, having values ranging from minus 4 to minus 16.7 ft. This location is within the interstream region between Spring and Ichawaynochaway Creeks. Immediately east of this location, near Ichawaynochaway Creek, residuals are positive, ranging from 4.2 to 16.4 ft. In central Worth County, Ga., 12 negative residuals (ranging from minus 1.1 to minus 10.5 ft) are located in the upland area drained by Mill and Abrams Creeks.

Reasonable changes to hydraulic properties that affect ground-water flow in areas described above were not able to achieve a random distribution of residual values, nor were residuals able to be decreased to meet the acceptability criterion. One explanation for the clustered values of residuals is the lack of detail in the hydrologic characterization of the flow system in these areas. Relatively sparse data defining hydraulic properties of the flow system, springflow, and stream-aquifer relations (particularly in upland areas of the Upper Floridan aquifer) were insufficient for simulating details of the potentiometric surface, such as water-level variations, in small interstream areas. In an attempt to evaluate the uncertainty in values of hydraulic properties used in the model, a sensitivity analysis was performed on the hydrologic factors assumed to govern flow in the stream-aquifer system, the results of which are presented in a later section.

Despite areas of the Upper Floridan and Intermediate models where ground-water-level residuals violate either randomness or minimization criteria, comparison of contours of the computed potentiometric surfaces with ground-water-level measurements (pl. 11) indicates an overall goodness of fit that demonstrates success in the ability of the models to simulate ground-water levels. Contours of computed ground-water levels generally are located between appropriate values of water-level measurements, with the few exceptions being where ground-water-level residuals are larger than the acceptability criterion, as discussed previously. One notable exception is at the county line between Lee and Worth Counties, Ga., at the confluence of Mill Creek and the Flint River. The computed potentiometric surface at this location is represented with a closed 220-foot contour; however, ground-water-level measurements seem to indicate a broad region in this vicinity where water levels generally range from about 215 to 230 ft above sea level. Thus, a closed, 230-foot contour of water-level measurements could be drawn along the Flint River slightly northwest of the 220-foot contour of computed water levels. A small cluster of negative ground-water-level residuals in this area indicates that the computed potentiometric surface is lower than the surface represented by measurements.

Stream-Aquifer Flux

The flow rate across streambeds into and out of aquifers, termed stream-aquifer flux, was estimated for 37 reaches in the lower ACF River Basin (pl. 9; table 10) by using streamflow data collected during late October 1986. Positive values of stream-aquifer flux indicate that, within the reach, the stream is gaining water from the aquifer (ground-water discharges to streams); negative values indicate that the stream is losing water to the aquifer (stream recharges the aquifer). Average streamflow was computed as the arithmetic mean of upstream and downstream flow measurements. A target range and average stream-aquifer flux was established at each of the 37 reaches, according to the procedure described previously. Model-derived (computed) fluxes were compared with corresponding target ranges and measurement-based (average) fluxes to evaluate model acceptance.

Stream reaches listed in table 10 were grouped into 4 classes according to magnitude of average streamflow to facilitate interpretation of model results and to determine if acceptability criteria for stream-aquifer flux are satisfied on the basis of streamflow magnitude. The streamflow classes and corresponding reach numbers are as follows:

- 17 reaches, 1–17: less than 25 ft^3/s ("small streams")
- 10 reaches, 18–27: 5 to 250 ft^3/s ("major tributaries")
- 7 reaches, 28–34: 250 to 2,500 ft^3/s (Chipola and Flint Rivers)
- 3 reaches, 35–37: greater than 2,500 ft^3/s (Apalachicola River)

For the calibrated models, 27 of 37 reaches had computed stream-aquifer fluxes within their target ranges (table 10). The number and percentage of reaches satisfying the acceptability criteria are as follows, listed in order of the streamflow classes given above:

- 8 reaches, 47 percent
- 9 reaches, 90 percent
- 7 reaches, 100 percent
- 3 reaches, 100 percent

The apparent lack of agreement between computed stream-aquifer fluxes and target ranges for streams in the first class can be attributed to several factors. Where computed fluxes were less than their target ranges (reaches 1, 3, 5, 6, 19, table 10), one factor might be that the reach received water from the overlying semiconfining unit, which was assumed desaturated for October 1986 conditions. Small amounts of water from the overlying semiconfining unit to the Upper Floridan aquifer might have contributed to streamflow for these reaches if the unit is thick in these areas and not completely desaturated by drought conditions. Where computed stream-aquifer fluxes were larger than their target ranges (reaches 9, 11–14), simulated ground-water levels were higher than measured values in the vicinity of the reach. This can cause larger hydraulic gradients to streams and more simulated streamflow than was measured. Underlying each of these possible explanations for lack of agreement between computed and estimated stream-aquifer fluxes is the sparse distribution of hydrologic data in these areas. A sparse data distribution allows only a general characterization of hydrologic conditions to be made and limits simulation capability.

Two error terms associated with stream-aquifer flux were computed to evaluate the accuracy of model-derived (computed) stream-aquifer fluxes and to measure the relative significance of discrepancies in measurement-based (average) values. One error term, EQ, normalizes the difference between computed and average stream-aquifer fluxes as a percentage of average streamflow for the reach and is computed as

$$EQ=[(q_{ci}-q_{ei})/Q]\times 100, \quad (14)$$

where q_{ci} and q_{ei} are the computed and average fluxes, respectively, for reach i, listed in table 10 and shown on plate 9. Therefore, EQ represents the magnitude of error in computed stream-aquifer flux relative to average streamflow, Q, in the reach.

Another error term, $EqeTOT$, normalizes the difference in computed and average stream-aquifer flux as a percentage of the total stream-aquifer flux for all reaches in the study area. This term is computed as

$$EqeTOT=\left[(q_{ci}-q_{ei})/\sum_{i=1}^{37}|q_{ei}|\right]\times 100, \quad (15)$$

where all terms have been defined previously. Values of $EqeTOT$ are listed by reach in table 10. This term attempts to assess the significance of discrepancies between computed and average stream-aquifer flux relative to the total stream-aquifer flux in the flow system of the study area.

The largest percent deviation of computed stream-aquifer flux from average flux exists for

Table 10. Stream-aquifer flows from the calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin

[Reach numbers shown on plate 9; streamflow, average flux, target range, and computed flux, in cubic feet per second]

Reach number	Stream	Streamflow, Q	Average flux[1], qe_i	Target range		Computed flux[4], qc_i	Error, in percent	
				Fluxmin[2]	Fluxmax[3]		EQ[5]	EqeTOT[6]
[7]1	Gum Creek	5.5	10.9	9.8	12	3.6	−133	0.2
[7]2	Cedar Creek	.7	1.3	1.2	1.4	1.3	0	0
[7]3	Swift Creek	4.6	9.2	8.3	10.1	3.8	−117	.1
[7]4	Jones Creek	1.2	2.3	2.1	2.5	2.3	0	0
[7]5	Abrams Creek	4.6	9.1	8.2	10	2.6	−141	.2
[7]6	Mill Creek	6.0	11.9	10.7	13.1	6.9	83.3	.1
7	Cooleewahee Creek	.3	.5	.5	.6	.5	0	0
8	Chickasawhatchee Creek	12.2	4.2	1.8	6.6	4.1	−0.8	<.1
[7]9	do.	7.2	−14.3	−15.7	-12.9	.3	203	.3
[7]10	do.	1.3	2.5	2.3	2.8	2.8	23.1	<.1
11	Dry Creek (Ga.)	4.3	−1.6	−2.4	−.7	2.8	102	.1
[7]12	Spring Creek	.8	1.5	1.4	1.7	3.5	250	<.1
13	do.	9.2	15.4	13.6	17.2	19.5	44.6	.1
14	do.	14.8	−4.2	−7.2	−1.2	1.1	35.8	.1
[7]15	Sawhatchee Creek	4.9	9.7	8.8	10.7	9.6	−2.0	<.1
[7]16	Cowarts Creek	9.4	18.7	16.8	20.6	19.9	12.8	<.1
[7]17	Marshall Creek	16.4	32.7	29.4	36.	31.6	−6.7	<.1
18	Spring Creek	36.3	47.2	39.9	54.5	42.2	−13.8	.1
[7]19	Dry Creek (Fla.)	44.3	88.6	79.7	97.5	42.1	−105	1.1
20	Ichawaynochaway Creek	162	83	50.7	115	52.6	−18.8	.7
21	do.	203	0	−40.6	40.6	23.7	11.7	.6
22	Muckalee Creek	91.7	16.7	1.6	35	17.8	1.2	<.1
23	do.	98	−4.0	−23.6	15.6	3.9	8.1	.2
24	do.	106	19	−2.1	40.1	14.2	−4.5	.1
25	Kinchafoonee Creek	157	−12	−43.4	19.4	−2.3	6.2	.2
26	do.	154	5.0	−25.7	35.7	5.9	.6	<.1
27	Chipola River	115	114	91.1	137	115	.5	<.1
28	do.	344	343	309	377	340	−1.0	.1
29	do.	344	343	309	377	359	4.7	.4
30	Flint River	795	−49	−129	30.5	6.3	7.0	1.3
31	do.	1,256	549	424	675	604	4.4	1.3
32	do.	1,795	530	351	710	537	.4	.2
33	do.	2,140	160	−54	374	364	9.5	4.8
34	do.	2,400	360	120	600	352	−.3	.2
35	Apalachicola River	6,042	127	−477	731	282	2.6	3.7
36	do.	6,219	227	−395	849	166	−1.0	1.5
37	do.	6,829	994	311	1,677	523	−6.9	11.2
	Total		**4,222**			**3,963**		

[1] $qe_i = \dfrac{Fluxmin + Fluxmax}{2}, i = 1, 37.$

[2] $Fluxmin = (Q_d - EF \times Q_d) - (Q_u + EF \times Q_u), ft^3/s.$

[3] $Fluxmax = (Q_d + EF \times Q_d) - (Q_u - EF \times Q_u), ft^3/s.$ Q_u and Q_d are streamflows at the upstream and downstream ends of a reach, respectively, and EF is an error factor equal to 0.1 for reaches 1–27 and 0.05 for reaches 28–37.

[4] $qc_i = \alpha L (h_B - h)\,;\ \alpha = \dfrac{K_r W_r}{b_r},$ for reach, where estimates are used to define average streambed hydraulic conductivity (K_r), width (W_r), and thickness of streambed sediments (b_r); stream stage (h_B) and aquifer head (h) obtained from calibrated models; length of reach (L) computed from finite-element mesh.

[5] $EQ = \dfrac{qc_i - qe_i}{Q} \times 100, percent,\ i = 1, 37.$

[6] $EqeTOT = \dfrac{qc_i - qe_i}{Total,\ qc_i} \times 100,\ percent,\ i = 1, 37.$

[7] Reach originates within study area or discharge at one end of reach equals zero.

reach 12, located on Spring Creek (EQ=250 percent, table 10). Although the error in computed flux, given by EQ (eq. 14), seems large, the amount of streamflow through this reach is small (0.8 ft^3/s, table 10). Therefore, the relative error in computed flux, expressed by $EqeTOT$ (eq. 15), is insignificant compared with the total average stream-aquifer flux in the study area (4,222 ft^3/s, table 10). Similar interpretations of error terms as those made for reach 12 can be made for other reaches classed as "small" streams (reaches 1–11; 13–17). Most of the large values of EQ were associated with reaches having small average streamflows (table 10).

Negative values for the target range of steam-aquifer flux for reaches 9, 11, and 14 (table 10) were computed from streamflow measurements, indicating aquifer recharge or losing-stream conditions. However, the conceptualization and mathematical representation of these streams in the Upper Floridan model did not allow aquifer recharge from these reaches or from these streams in general. These streams were conceptualized as going dry when ground-water levels drop below the altitude of the bottom of streambed sediments, and were represented in the model using discharge-only functions. Because these reaches were not dry when measured during October 1986, two explanations are possible for the negative fluxes: (1) the negative fluxes are real; thus, the streams have the capacity to recharge the aquifer; and (2) the negative fluxes result from errors in streamflow measurements. Because the reaches are not deeply incised into the Upper Floridan aquifer, they drain, for the most part, the overlying semiconfining unit. Thus, it is not plausible that the reaches, or the streams, have the capacity to recharge the aquifer, as they probably would go dry as conceptualized when ground-water levels drop below the bottom of the streambed. Therefore, the negative fluxes probably are the result of errors associated with streamflow measurements.

Better agreement between computed and average stream-aquifer flux was obtained for the remaining reaches than is indicated by error terms associated with small streams (table 10). The larger average streamflows contained in the other 3 classes of reaches than in the first class cause relative errors in flux, expressed as $EqeTOT$, of about 5 percent for the remaining reaches except the last reach, which is the most downstream part the Apalachicola River ($EqeTOT$=11.2 percent). The discrepancy between computed and average stream-aquifer flux for this reach probably can be attributed to measurement error, as streamflow in this part of the Apalachicola River is affected by tides.

Evaluation of computed flux, target range, and error terms indicates that the acceptability criteria for stream-aquifer flux have been met in the Upper Floridan and Intermediate models. Errors in computed flux do not seem to be systematic; that is, they neither accumulate in the downstream direction for adjacent reaches nor increase with increasing magnitude of flux. Therefore, it seems that part of these discrepancies results from errors in streamflow measurements, upon which estimates of stream-aquifer flux are based. Other factors contributing to errors in computed flux are inaccurate computed ground-water levels and the sparse hydrologic data that was used to characterize flow-system details and generate model inputs in some parts of the study area.

Directions of Ground-Water Movement

Directions of ground-water movement in the Upper Floridan aquifer and Intermediate system can be inferred from contours of potentiometric surfaces that have been prepared using computed head from the calibrated models (pl. 11). These representations confirm the directions of ground-water movement that were described earlier during conceptualization of the flow system. In the Upper Floridan model, ground water flows into the northern and central parts of the lower ACF River Basin as regional flow across the eastern and western model boundaries and from outcrop areas along the northern model boundary. Ground-water discharge from the Upper Floridan aquifer occurs as stream-aquifer flux along surface-water features, primarily the Apalachicola, Chattahoochee, and Flint Rivers, and as regional flow along parts of the eastern and southern model boundaries.

In the Intermediate model, ground water enters across the northern model boundary along the outcrop of the Intermediate system and along the northern part of the western boundary, and exits by upward vertical leakage into the Apalachicola River and flood plain and Chipola River, and by regional flow across the southern model boundary, located in Apalachicola Bay. Movement of ground water within the study area is controlled by regional inflow from outcrop areas, parts of the Solution Escarpment (eastern boundary), and ground-water divides (western boundary), and by regional outflow across remaining parts of the eastern boundary (Solution Escarpment) and southern boundary, and discharge to surface-water features and swamps.

Local irregularities in the dominant directions of ground-water flow are caused by a combination of hydrologic influences on the regional-flow system, such as nonhomogeneity of hydraulic properties for aquifers and semiconfining units, vertical leakage, and stress. Relative flattening or slight depressions in the potentiometric surface are present in small areas due to stresses, such as ground-water pumpage and springflow, that have been applied to the Upper Floridan aquifer. However, these stresses seem to have an aggregate rather than individual effect on the potentiometric surface, as evidenced by the absence of distinct cones of depression from the potentiometric surface around points of stress, and by the strong influence of regional hydrologic boundaries on the flow system. Large irregularities in flow-directions can create closed water-level contours around locations of pumpage or springflow; however, these features are absent from the potentiometric surface (pl. 11), with one exception.

In the vicinity of Port St. Joe, Fla., pumpage from the Upper Floridan aquifer created a closed water-level contour in the potentiometric surface of the overlying Intermediate system (pl. 11). Effects of this pumpage from below the Intermediate system seem to extend about 5 mi eastward toward the Apalachicola River and have no apparent influence on stream-aquifer relations. Except for this local irregularity, effects of hydrologic stress on stream-aquifer relations and on the potentiometric surface of the aquifers are minimal.

Nonhomogeneities in horizontal hydraulic conductivity of the Upper Floridan aquifer and spatial variations in vertical leakage from the overlying semiconfining unit cause contours of the potentiometric surface to be irregularly spaced and to deviate from a uniform pattern depicting regional flow. Relatively steep hydraulic gradients in the northeastern part of the study area near the Dougherty-Worth County line are caused by the existence of a low hydraulic-conductivity zone situated among zones of higher hydraulic conductivity. To the west of this low hydraulic-conductivity zone, the hydraulic gradient is relatively flat, however, ground-water flow is high due to the relatively high hydraulic conductivity of the Upper Floridan aquifer in this area and drainage by the Flint River.

West of the area of high hydraulic conductivity, water-level contours of the potentiometric surface bend sharply upstream indicating that a large component of ground-water flow enters the Flint River (pl. 11). Solution cavities and near-conduit-flow conditions in the aquifer are intercepted by the Flint River near Radium Springs in Dougherty County, Ga. (Hicks and others, 1987). The distribution of solution openings and conduits in the aquifer northeast of Radium Springs (Torak and others, 1993, fig. 8) enables ground water to flow easily toward the Flint River, creating conditions of high horizontal ground-water flow and gentle hydraulic gradients. Similar sharp bending of water-level contours occurs along the Chattahoochee and Apalachicola Rivers, where the Upper Floridan aquifer is well drained by surface-water features and where aquifer hydraulic conductivity is relatively high.

Directions of ground-water movement that are influenced by vertical leakage through the overlying semiconfining unit are inferred from a comparison of maps showing the potentiometric surface of the Upper Floridan aquifer (pl. 11) and water-level differences between the aquifer and the undifferentiated overburden (pl. 12). About 5 mi southeast of the Dougherty-Worth County line near Gordy, Ga., water-level contours indicate an area of high aquifer water level and diverging ground-water flow. This area, located just southwest of Sylvester, Ga., contains higher land-surface altitude and greater thickness of undifferentiated overburden than surrounding areas and constitutes a recharge area to the aquifer. About 4 mi north of the Dougherty-Lee County line, between the Flint River and Muckalee Creek, contours of the potentiometric surface also indicate high aquifer water level and diverging ground-water flow. This interstream area is of higher land-surface altitude than its surroundings and contains several small ponds, indicating a shallow depth to the water table, which is present in the undifferentiated overburden. The shallow water-table depth creates high potential for downward vertical leakage of water through the semiconfining unit into the Upper Floridan aquifer. The appreciably large positive water-level differences between the overburden and Upper Floridan aquifer in these two areas indicate the potential for high rates of recharge by vertical leakage from the overburden into the aquifer to occur.

The influence of vertical leakage from the undifferentiated overburden on ground-water-flow directions is present in interstream areas between the

Chattahoochee and Chipola Rivers, Chattahoochee River and Spring Creek, Flint River and Spring Creek, and Spring and Ichawaynochaway Creeks. In these areas, the potentiometric surface has a scalloped shape that is characterized by sharp upstream bending of water-level contours at the streams, contrasted by pronounced downstream bending of contours in the interstream areas. This pattern of potentiometric contours is indicative of two flow conditions: downward leakage (aquifer recharge) from the overburden, and aquifer discharge to streams and in-channel springs.

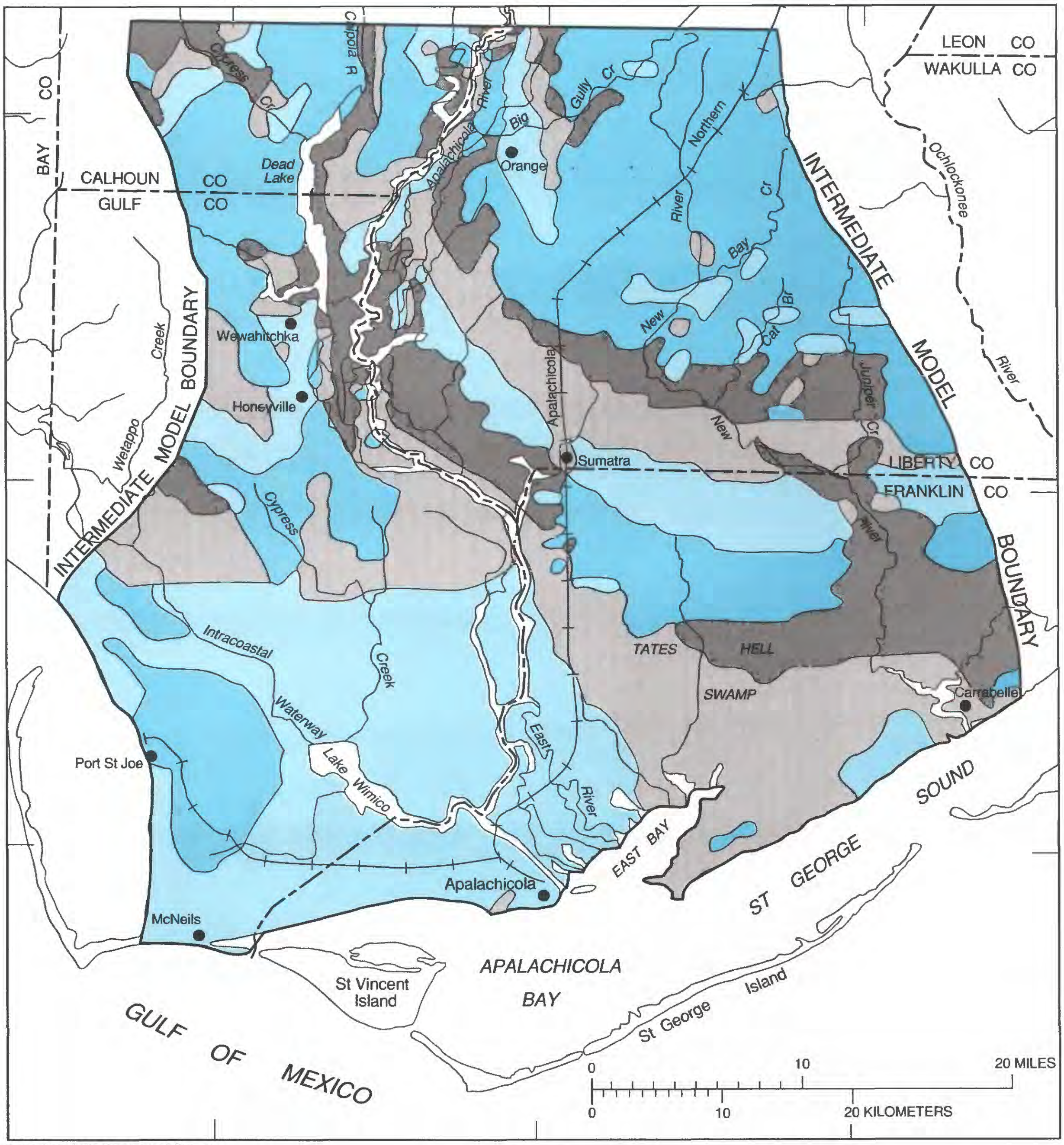
Throughout most of the lower ACF River Basin, ground water is moving vertically downward through overlying semiconfining units consisting of the undifferentiated overburden and terrace and undifferentiated (surficial) deposits to recharge the aquifers. Upward vertical movement exists only in the vicinity of stream channels, lakes, swamps, and springs (pl. 12; fig. 22). There are, however, exceptions to this general pattern of vertical ground-water movement. Along the Brothers and Apalachicola Rivers downstream of Sumatra, Fla., movement of ground water seems to be downward by vertical leakage into the Intermediate system from the surficial deposits. Northwest of this location, flow is reversed, as upward-vertical leakage from the Intermediate system enters flood-plain sediments of the Apalachicola River. Another exception exists in southern and eastern Franklin County, Fla., where upward-vertical leakage from the Intermediate system recharges surficial deposits beneath Tates Hell Swamp. Also, Lake Seminole functions as both a means of ground-water discharge from the Upper Floridan aquifer, in the northern part of the lake, and a ground-water source in the southern part, providing recharge to the aquifer.

Diverse vertical ground-water movement in the Intermediate model is indicated by differences between simulated head in the Intermediate system and head in the underlying Upper Floridan aquifer (fig. 23), which was not simulated by the Intermediate model but input as a vertical boundary condition. Upward vertical leakage (recharge) from the Upper Floridan aquifer to the Intermediate system exists along the Apalachicola, Chipola, and New Rivers, between Wilma and Sumatra, Fla, (Liberty and Franklin Counties, Fla.), and in Tates Hell Swamp along the coast of southern Franklin County. Downward vertical leakage (discharge) from the Intermediate system to the Upper Floridan aquifer exists in the northern and western parts of the Intermediate model, with the exception of the flood plain of the Apalachicola River and 3 small areas in central Gulf County near Wewhahitchka, Honeyville, and Overstreet, Fla.

Directions of vertical leakage indicate flow-through movement of ground water into and out of the Intermediate system in specific areas of Gulf and Franklin Counties, Fla. (figs. 22, 23). In eastern Gulf County, pumpage in the Upper Floridan aquifer at Port St. Joe, Fla., is partly responsible for inducing downward vertical leakage from the overlying semiconfining unit of surficial deposits, through the Intermediate system, and into the underlying pumped aquifer. A circular pattern of high head differences (greater than 5 feet) between the Intermediate system and overlying surficial deposits (fig. 22) seems to coincide with drawdown patterns that are centered around pumpage at Port St. Joe (pl. 10), indicating pumpage-induced recharge. In part of Tates Hell Swamp, northern Franklin County, ground water in surficial deposits recharges the Intermediate system which, in turn, discharges water to the underlying Upper Floridan aquifer (figs. 22, 23). Due to the absence of pumpage in the Upper Floridan aquifer at this location, this flow-through leakage seems to be a natural movement of ground water, with the swamp providing recharge to the underlying units. However, south of this location, the flow-through-vertical movement of ground water is reversed as upward flow from the Upper Floridan aquifer recharges the Intermediate system which, in turn, discharges upward to surficial deposits and the swamp. Vertical-flow directions are reversed again in a small area along St. George Sound, west of Carrabelle, Fla.

Surface-Water Influence on the Ground-Water-Flow System

The ground-water-flow system in the lower ACF River Basin is strongly influenced by rivers, streams, and lakes that occur either naturally or by man's intervention. As evidenced by the sharp bending of simulated potentiometric contours (pl. 11), discussed in the previous section, ground-water-flow directions for October 1986 were controlled by surface-water features, primarily the Flint River downstream of the Flint River Dam in Albany, Ga., Lake Seminole, and the Apalachicola, Chattahoochee, and Chipola Rivers.



Base from U.S. Geological Survey
State base map 1:500,000

EXPLANATION

SIMULATED VERTICAL LEAKAGE BETWEEN INTERMEDIATE SYSTEM AND OVERLYING SEMICONFINING UNIT—Patterns indicate recharge to or discharge from the Intermediate system as determined by head differences (H–h): h, is head in Intermediate system; H, is head in semiconfining unit

HEAD DIFFERENCE (H–h), IN FEET

DISCHARGE

h > H

Semiconfining unit

H

h

(Simulated aquifer)
Intermediate system

–5 to 0

Greater than –5

RECHARGE

0 to 5

Greater than 5

H > h

Semiconfining unit

H

h

(Simulated aquifer)
Intermediate system

Figure 22. Simulated vertical leakage between the Intermediate system and overlying semiconfining unit.

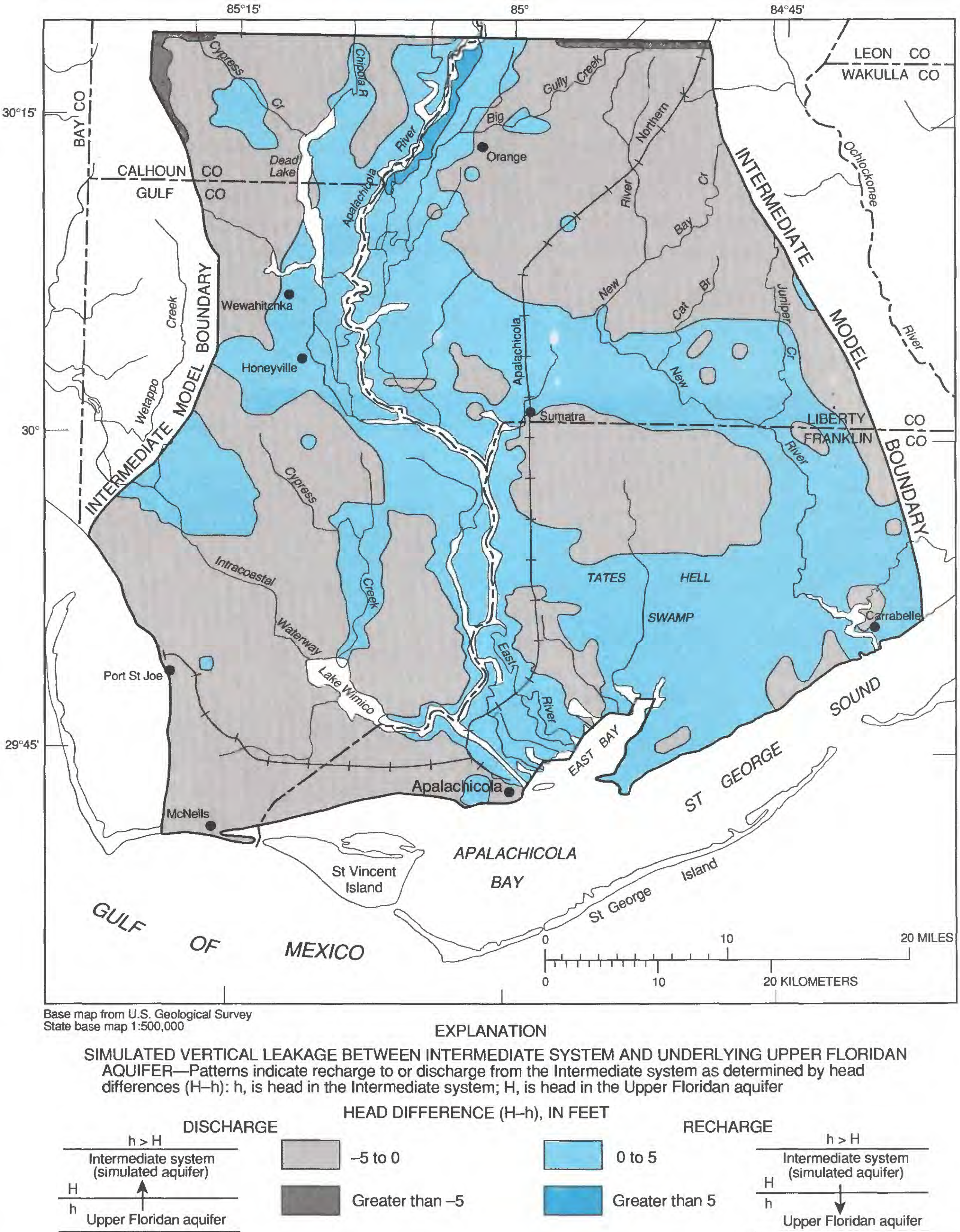


Figure 23. Simulated vertical leakage between the Intermediate system and underlying Upper Floridan aquifer.

The Flint and Chattahoochee Rivers drain the Upper Floridan aquifer and undifferentiated overburden of regional ground-water inflow from the west, north, and east. From the outcrop area to the northwest, potentiometric contours bend upstream to create a regional-flow regime characterized by ground-water discharge to the Flint and Chattahoochee Rivers. The general pattern of regional ground-water flow discharging to surface water is established along the entire course of these rivers in the lower ACF River Basin.

Functioning as a recharge and discharge mechanism for ground water, Lake Seminole is located within a broad, flat region of the potentiometric surface of the Upper Floridan aquifer at the confluence of Spring Creek and the Chattahoochee and Flint Rivers. Here the aquifer is characterized by relatively small hydraulic gradients (pl. 11), but, as described previously, large amounts of ground-water movement is possible due to relatively high aquifer transmissivity. Simulated potentiometric contours (pl. 11) bend sharply upstream to rivers that empty into the lake indicating high ground-water discharge, or stream-aquifer flux. Downstream of the lake, low aquifer hydraulic conductivity and gentle gradients indicate that ground-water discharge to rivers, hence, stream-aquifer flux, is less downstream of the lake than upstream.

Two hydraulic factors contribute to producing less stream-aquifer flux downstream of Lake Seminole than upstream. First, the outcrop area of the Upper Floridan aquifer in Houston County, Ala., which is drained by the Chipola River and its tributaries, is not as extensive as the area drained by the Flint and Chattahoochee Rivers, Spring Creek, and their tributaries. Hydraulic potential, or head, in the aquifer is reduced by ground water drainage to surface water upstream of the lake. This reduces hydraulic gradients and discharge to rivers that are located far from the ground-water source (outcrop area), such as downstream of the lake. Second, changes in land-surface altitude along the outcrop of the Upper Floridan aquifer cause ground-water levels in the relatively small area drained by the Chipola River and its tributaries to be 80 to 100 ft lower than levels in areas drained by the Flint River. This low land-surface altitude for the outcrop area drained by the Chipola River creates a small hydraulic potential to drive stream-aquifer flux from the aquifer to the river, in comparison with the larger hydraulic potential in outcrop areas drained by the Flint River and, to a lesser extent, by the Chattahoochee River. As a result, there is less ground-water discharge to rivers (stream-aquifer flux) along reaches located downstream of Lake Seminole than upstream.

Approximately 8 mi downstream of Blountstown, Fla., the Apalachicola and Chipola Rivers begin to drain outcrop areas of the southward dipping Intermediate system. A high degree of hydraulic connection between the Intermediate system and these surface-water features is indicated by sharp upstream bending of simulated potentiometric contours at the rivers (pl. 11). However, the relatively short distance and low topographic relief between the outcrop area and the rivers, compared with that of the Upper Floridan aquifer, cause the Intermediate system to drain over a relatively short distance downstream of its outcrop area. Most of the potential for ground-water flow and stream-aquifer interaction (that is, most of the hydraulic head) has dissipated from the Intermediate system within 30 mi of the outcrop area. As a result, the potentiometric surface in the region located south of Sumatra, Fla., in the southern half of Franklin and Gulf Counties, is broad and flat, nearly identical to river stage, and generally less than 10 ft above sea level.

The influence of small creeks and other surface-water features on the ground-water-flow system of the Upper Floridan aquifer and Intermediate system seems to be less than the influence of the Apalachicola, Chattahoochee, Chipola, and Flint Rivers, and Lake Seminole. East of the Flint River, small creeks and streams drain the Solution Escarpment and exhibit a better hydraulic connection to water-bearing units of the undifferentiated overburden than to the Upper Floridan aquifer (Hicks and others, 1987). Similar conditions such as this exist west of the Chipola River in Jackson County near Marianna, Fla., where surface-water features drain thick terrace and undifferentiated deposits along ground- and surface-water divides that form the western study-area boundary.

Water-Budget Components for October 1986

Water budgets were prepared for October 1986 conditions and for conditions of increased pumpage on the basis of simulated inflows and outflows to the stream-aquifer system in the lower ACF River Basin. One budget, termed a general assessment, represents a quantitative account of the overall hydrologic features assumed to control ground-water flow in the stream-aquifer system. Another budget, termed a stream-aquifer budget, gives a detailed analysis of the ground-water component of streamflow for streams that were simulated in the study area. Water-budget components were used to assess the importance of each hydrologic feature on controlling flow in the stream-aquifer system by comparing their relative influence on water-budget rates and volumes. In the Upper Floridan model, flow rates were normalized as percentages of flow relative to the total withdrawal rate from wells for October 1986. Percentages were obtained by comparing results from a simulation having no pumpage with results of simulating October 1986 pumpage. In the Intermediate model, where pumpage was not simulated, water- budget components were normalized with regard to total discharge to streams, and percentages similar to those obtained for the Upper Floridan model were computed.

General Assessment

Volumetric flow rates and percentages of flow relative to either the October 1986 well-pumping rates (Upper Floridan model) or total discharge to streams (Intermediate model) (table 11) were computed from simulation results to give a general assessment of the overall water-budget components pertinent to the lower ACF River Basin. Rates and percentages for the Upper Floridan model indicate that simulated ground-water discharge from the Upper Floridan aquifer to streams was about 5 times larger than the total rate of withdrawal by pumping. Discharge from the aquifer by springflow was slightly larger than regional outflow across model boundaries (70 and 65 percent of the pumping rate, respectively), and discharge to the undifferentiated overburden was about 11 percent of the withdrawal rate from wells. Recharge to the aquifer by vertical leakage from the undifferentiated overburden was about 5.2 times larger than the withdrawal rate from wells, and regional inflow from the north, west, and east, not including the outcrop area, was nearly twice the pumping rate. Recharge from the outcrop area of the Upper Floridan aquifer was slightly more than one-quarter of the pumping rate from wells, and recharge from streams, primarily the Flint River, was about 5 percent of the pumping rate.

Volumetric flow rates and percentages of water-budget components in the Intermediate model indicate that the largest components of ground-water discharge from the Intermediate system are from streams and downward vertical leakage to the Upper Floridan aquifer, each yielding about 43 Mgal/d (table 11). Discharge by vertical leakage to overlying terrace and undifferentiated (surficial) deposits, listed as discharge to the undifferentiated overburden in table 11, is nearly one-quarter of the total discharge rate to streams in the Intermediate model, and discharge by regional outflow across lateral boundaries is about 7 percent of stream discharge.

The largest recharge component to the Intermediate system and largest water-budget component of the Intermediate model is upward vertical leakage from the Upper Floridan aquifer, which is about 10 percent larger than the total discharge to streams (table 11). As discussed previously, this leakage occurs along the Chipola and Apalachicola Rivers and flood plain, beneath Tates Hell Swamp in southern Franklin County, Fla., and in 3 small areas in Gulf County, Fla. (fig. 23). Comparison of vertical leakage patterns for the surficial deposits (fig. 22) and Upper Floridan aquifer (fig. 23) indicates that most of the recharge to the Intermediate system from the underlying Upper Floridan aquifer represents flow-through leakage to land surface and to surface water through overlying terrace and undifferentiated (surficial) deposits.

Volumetric rates and percentages for the remaining water-budget components of the Intermediate system represent smaller amounts of ground-water recharge than the amount of upward vertical leakage from the Upper Floridan aquifer. Recharge from overlying terrace and surficial deposits was slightly larger than regional inflow from outcrop areas—59 and 55 percent of discharge to streams, respectively (table 11)—and recharge from streams was about 1 percent of stream discharge.

The influence of hydrologic features on stream-aquifer relations in the Upper Floridan aquifer and Intermediate system is reflected by the relative magnitude and percentage that each water-budget component attained in the general assessment (table 11). The most influential hydrologic features on ground-water flow in the stream-aquifer system for October 1986 were those that had the largest values for water-budget components. For the Upper Floridan model, ground-water discharge to streams and in-channel springs and recharge by vertical leakage from the undifferentiated overburden were the largest water-budget components. For the Intermediate system, the largest components were ground-water

Table 11. Water-budget components from the calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin for October 1986 conditions
[Volumetric flow rate in million gallons per day; –, water-budget component not simulated in model]

Budget component	Upper Floridan model		Intermediate model		Total volumetric flow rate
	Volumetric flow rate	Percentage of pumping rate	Volumetric flow rate	Percentage of discharge rate to streams	
Discharge, by budget component					
Streams and in-channel springs[1]	2,381	502	43.4	100	2,424.4
Wells	475	100	–	–	475
Off-channel springs[2]	333	70	–	–	333
Regional flow	309	63	3.0	7.0	312
Undifferentiated overburden	51	11	9.8	23	60.8
Upper Floridan aquifer	–	–	43.6	100	43.6
Total	**3,549**		**99.8**		**3,648.8**
Recharge, by budget component					
Undifferentiated overburden	2,476	522	25.6	59	2,502
Regional flow	920	194	23.8	55	944
Upper Floridan outcrop	129	27	–	–	129
Upper Floridan aquifer	–	–	48.1	111	48.1
Streams	22.7	5.0	.5	1.0	23.2
Total	**3,547.7**		**98**		**3,646.3**

[1]In-channel springs discharge in or near streams and contribute to streamflow in the Upper Floridan model.
[2]Off-channel springs are located away from streams and do not contribute to streamflow (Upper Floridan model only).

discharge to streams and to the Upper Floridan aquifer, and recharge by vertical leakage from the Upper Floridan aquifer and from terrace and undifferentiated (surficial) deposits.

Stream-Aquifer Budget

A detailed analysis of stream-aquifer relations for October 1986 was made by compiling simulated stream-aquifer fluxes for all streams in the lower ACF River Basin (table 12). Aquifer-discharge components listed as "minor streams" and "other streams" in table 12 represent the accumulation of volumetric flow rates and percentages that are associated with tributary or distributary streams of major rivers (Apalachicola, Chattahoochee, Chipola, and Flint Rivers) in the basin. Minor streams include 18 streams listed in table 3 that were represented in the Upper Floridan model by using discharge-only functions; having the ability to only discharge water from the aquifer and to go dry. Minor streams flow from model boundaries, located either to the east (from the Solution Escarpment), northwest (outcrop of the Upper Floridan aquifer), or west (ground- and surface-water divide), to the major rivers.

The budget component in table 12 termed "Other streams" consists of the 10 streams listed in table 2, not including major rivers. From table 2, the Brothers, St. Marks, East, and Jackson Rivers are distributaries of the Apalachicola River; the remaining streams are tributaries to major rivers. These streams were represented in the Upper Floridan and Intermediate models by using a mathematical function that allows recharge to and discharge from the aquifers without the stream going dry.

Volumetric flow rates and percentages for components of the stream-aquifer budget for the Upper Floridan model indicate that about 2.4 times more ground water discharges to the Flint River than was withdrawn by pumpage from the lower ACF River Basin in October 1986 (table 12). Flow in the Flint River constitutes almost half of the total discharge to streams and in-channel springs in the study area. The rate of ground water discharge to the Chipola River is about two-thirds of the total rate withdrawn by wells, and ground-water discharge to the Apalachicola and Chattahoochee Rivers, and to minor streams occurs at about one-half of the total withdrawal rate. Ground-water discharge to other streams is about 37 percent of the withdrawal rate

Table 12. Components of stream-aquifer budget from the calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin for October 1986 conditions

[Volumetric flow rate in million gallons per day; –, component not simulated in model]

Budget component	Upper Floridan model		Intermediate model		Total volumetric flow rate
	Volumetric flow rate	Percentage of pumping rate	Volumetric flow rate	Percentage of discharge rate to streams	
Discharge to streams, by budget component					
Flint River	1,140	240	–	–	1,140
Chipola River	321	68	7.6	18	328
Apalachicola River	265	56	31.4	72	296
Minor streams[1]	244	52	–	–	244
Chattahoochee River	236	50	–	–	236
Other streams[2]	174	37	4.4	10	179
Total	**2,380**	**503**	**43.4**	**100**	**2,423**
Recharge from streams, by budget component					
Flint River	14.4	3	–	–	14.4
Other streams[2]	8.3	2	0.5	1	8.8
Apalachicola River	0	0	.01	.02	.01
Chattahoochee River	0	0	–	–	0
Chipola River	0	0	0	0	0
Minor streams[1]	0	0	–	–	0
Total	**22.7**	**5**	**0.51**	**1.02**	**23.21**

[1]Minor streams include 18 streams from Upper Floridan model, listed in table 3. Streams are simulated as discharge-only functions that drain the aquifer.

[2]Other streams include five streams from Upper Floridan model and five streams from Intermediate model, listed in table 2. Streams are simulated as sources or sinks to aquifer.

from wells. Recharge to the aquifer from the Flint River is about 3 percent of the withdrawal rate from wells, and recharge from other streams is about 2 percent of the withdrawal rate.

One possible explanation for the relatively large rate of ground-water discharge to the Flint River from the Upper Floridan aquifer (table 12) is that this river traverses the longest distance, about 130 mi, of all rivers in the study area; thus, it has the potential to receive the most ground-water discharge. The Flint River drains exclusively the Upper Floridan aquifer, and receives only small amounts of water as discharge from the undifferentiated overburden. Besides flowing the longest distance within the study area, the Flint River flows over the region of the Upper Floridan aquifer that contains the highest transmissivity in the basin. Ground water discharges easily to the river in the vicinity of Albany, Ga., where, as previously discussed, the aquifer contains numerous fractures and solution features, and exhibits conditions of near-conduit flow.

About 64 percent of ground-water discharge to the Flint River occurs along about a 30-mi reach between Albany and Newton, Ga. (pl. 1). For this reach, discharge to the river was computed by the Upper Floridan model as about 735 Mgal/d. Streamflow measurements indicated that between these locations the Flint River received about 697 Mgal/d of ground-water discharge, primarily from the Upper Floridan aquifer. The excess discharge that was computed by the model can be attributed to water withdrawn from the river for industrial use (22 Mgal/d), non-reported use, and channel evaporation. Measurement error associated with streamflows and ground-water levels also can account for the difference between computed and measured streamflow gain from the aquifer, as discussed earlier.

Ground-water discharge to the Chattahoochee River in the lower ACF River Basin represents about one-tenth of the total discharge to streams and in-channel springs and about one-fifth of the amount of ground water that discharges to the Flint River (table 12). This is partly because the course of the

Chattahoochee River within the study area is less than 40 mi, compared with about 130 mi for the Flint River. In addition, the Chattahoochee River drains parts of the Upper Floridan aquifer that contain lower transmissivity than the area drained by the Flint River.

Although the Apalachicola River receives combined surface-water flow from the Chattahoochee and Flint Rivers at Lake Seminole, ground-water discharge to the Apalachicola River from the Upper Floridan aquifer and Intermediate system is third among stream-aquifer-budget components for the Upper Floridan model, ranking behind the Flint and Chipola Rivers (table 12). The Chipola River receives more ground-water discharge than the Apalachicola River because it drains a more transmissive part of the Upper Floridan aquifer, the New Hope Ridge and Grand Ridge regions, than the Apalachicola River, which only partially drains the Grand Ridge, in addition to draining the Tallahassee Hills region (fig. 2). Also, the Chipola River is closer to the outcrop/recharge area of the Upper Floridan aquifer than the Apalachicola River.

In the Intermediate model, nearly three-fourths of the ground-water discharge to streams enters the Apalachicola River, the remaining discharge is taken up by the Chipola River (18 percent) and by other streams (10 percent, table 12). The dominance of the Apalachicola River to receive ground-water in the Intermediate model is attributed to the location of the river in the basin and its relative length in the model area, compared with the Chipola River and other streams.

Despite receiving most of its ground-water discharge from the Intermediate system, stream-aquifer flux to the Apalachicola River represents only about 12 percent of total discharge to streams in the lower ACF River Basin (table 12). Ground-water discharge to the Apalachicola River in this area is low because surface water reduces the hydraulic potential of the Upper Floridan aquifer by draining its highly transmissive units that are located upstream of Lake Seminole. In addition, the Upper Floridan aquifer is not connected hydraulically to the Apalachicola River along the downstream half of its length; the hydraulic connection is made by less transmissive units of the Intermediate system.

Ground-water recharge from streams is a minor component of the stream-aquifer budget. About 3 percent of the pumping rate, or 14.4 Mgal/d, recharges the Upper Floridan aquifer from the Flint River. This is the largest of 3 recharge components from streams (table 12). The second largest recharge component is the combined effect of 10 streams, termed "other streams" in table 12, which supply about 8 Mgal/d to the Upper Floridan aquifer and about 0.5 Mgal/d to the Intermediate system. Recharge to the Intermediate system from the Apalachicola River is relatively inconsequential to the stream-aquifer budget, amounting to about 0.01 Mgal/d, or about 0.02 percent of the total discharge rate to streams in the Intermediate model (table 12).

Sources and Effects of Error

During simulation, errors are introduced into the computed solution of hydraulic head that need to be evaluated with regard to their effect on results and conclusions about the flow system. Some errors are unavoidable and, through the advancement of simulation techniques, are very small, being contained within the physical or mathematical limitations of representing the physics of ground-water flow and boundary conditions. Other, larger errors can result from improper conceptualization of the flow system and from misuse of boundary conditions and/or models. These errors can be minimized with proper conceptualization of the flow system and application of digital models that sufficiently address the conceptual scheme. Still other, larger errors than those previously mentioned are associated with measuring and reporting physical phenomenon such as hydraulic head, hydrologic characteristics, well pumping rates, and stream stage and discharge. These measurement errors need to be identified and minimized as they could obscure true-flow-system behavior and lead to erroneous conceptualizations or conclusions about the response of the flow system to stress, such as pumpage or drought.

Discrepancies (errors) exist between computed results from calibrated models and the measurements used to verify their accuracy. Errors in computed results are compounded and sometimes undetected due to the imprecision at which land-surface altitude of well locations and gaging stations are known and due to measurement error. Computation of stream-aquifer flux depends on accurate measurements of ground- and surface-water levels and streamflow. A calibrated model can give a false impression of accuracy by providing a close "match" of computed water levels and fluxes to a set of observed conditions that are, themselves, in error. Because water-level measurements in the lower ACF River Basin can contain up to 5 ft of error, water-level differences between, for example, the Upper Floridan aquifer and Flint River can differ by at least 5 ft from values that are derived from the measurements. The effects of these deviations on measured and simulated stream-aquifer fluxes need to be identified and understood before evaluating model accuracy or attempting to explain flow-system behavior by using model results.

Two simulations were performed that change the water-level difference between the Upper Floridan aquifer and Flint River for the reach between the Flint River Dam and Lake Seminole (pl. 1) to account for possible errors in water-level measurements. Ground- and surface-water levels were adjusted alternately for each simulation to values that were 5 ft higher and 5 ft lower than those used in the calibrated model. The resulting simulated 10-foot water-level fluctuation represents the maximum deviation, or error, in water-level differences that can be caused by inaccurate water-level measurements. This technique was used successfully by Torak and others (1993) in a previous study of part of the lower ACF River Basin in the area of Albany, Ga. These changes in river stage caused a 136-Mgal/d fluctuation in ground-water discharge to the Flint River along the reach between Albany and Newton, Ga. (pl. 9), exceeding the 38-Mgal/d difference between computed and measured discharge that existed after calibration. In comparison, compounded errors of 5-percent in measured streamflow at the upstream (5-percent increase) and downstream (5-percent decrease) gaging stations can cause a 394-Mgal/d fluctuation in estimated streamflow gain due to ground water discharge (or, stream-aquifer flux) along this reach. This is about an order of magnitude larger than the apparent excess ground-water discharge to the Flint River computed by the calibrated model. Measurement error, therefore, can more than account for the difference between computed and measured ground-water discharge to the Flint River along this reach. Because other water-budget components contribute much less to the ground-water-flow system of the Upper Floridan aquifer than discharge to streams, they are affected less by measurement error than stream-aquifer flux.

Effects of Ground-Water Pumpage on the Stream-Aquifer System

Effects of ground-water pumpage on the stream-aquifer system were evaluated by comparing water-budget components for the simulated October 1986 conditions with components derived from a simulation of the Upper Floridan model containing zero pumpage. The zero-pumpage simulation used lateral and vertical boundary conditions of October 1986, and involved only the Upper Floridan model because no pumpage was simulated in the Intermediate model. The evaluation was designed to quantify the amount of ground water that would have discharged from the Upper Floridan aquifer to surface-water features in the absence of pumpage. The zero-pumpage simulation can be viewed as representing a predevelopment condition that could have existed in the lower ACF River Basin for climatic conditions that are similar to those of October 1986. This realization of predevelopment conditions, although possible, is not entirely accurate because surface-water-control structures, such as Jim Woodruff Lock and Dam and the Flint River Dam at Albany, Ga., post date the beginning of ground-water withdrawal from the Upper Floridan aquifer. For true predevelopment conditions to be represented by the simulation, the control structures would be removed.

Comparison of water-budget components from both simulations indicates changes to the flow regime of the stream-aquifer system caused by pumpage in the Upper Floridan aquifer and identifies the flow-system components that contributed water to the pumped wells (table 13). Volumetric-flow rates and percentages of the October 1986 pumping rate contributed by each water-budget component (table 13) indicate that about 61 percent of the pumped water was regional flow that would have discharged from the Upper Floridan aquifer to streams in the basin under conditions of no pumping. This source of pumped water is listed in table 13 as reduced discharge to streams and in-channel springs. Nearly 25 percent of ground water that was pumped from the Upper Floridan aquifer for October 1986 was derived from induced recharge by vertical leakage from the undifferentiated overburden. Induced recharge from regional flow, not including the outcrop area, and reduced discharge to regional flow exiting the study area across model boundaries to the east and south, constituted about 4 and 6 percent of the October 1986 pumping rate, respectively. About 3 percent of the pumping rate was derived from reduced discharge to the undifferentiated overburden, that is, from the capture by wells of ground water that would have leaked upward into the overburden from the aquifer. Only about 2 percent of

Table 13. Water-budget components that comprise October 1986 pumping rates, from calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin
[Volumetric flow rate in million gallons per day]

Budget component	Volumetric flow rate	Percentage of pumping rate
Discharge to wells	475	100
Reduced discharge, by budget component		
Streams and in-channel springs[1]	290	61
Regional flow	27.1	5.7
Undifferentiated overburden	15.5	3.3
Induced recharge, by budget component		
Undifferentiated overburden	114	24
Regional flow	18.9	4.0
Outcrop of Upper Floridan aquifer	8.8	1.9
Streams	0.7	0.1

[1]In-channel springs discharge in or near streams and contribute to streamflow (off-channel springs are located away from streams and are assumed to be unaffected by well pumpage).

the pumped water was derived from the outcrop (recharge) area, and about 0.1 percent was derived from induced recharge from streams.

The volumetric-flow rate and percentage of flow that each surface-water feature contributed to the October 1986 withdrawal rate from wells indicate that intercepted regional-ground-water flow to the Flint River accounted for about 37 percent of the pumping rate (table 14). This is comprehensible because the Flint River flows through the most productive part of the Upper Floridan aquifer—the Dougherty Plain—where most of the ground-water withdrawals are located. About 7 percent of the October 1986 pumpage was derived from intercepted regional ground-water flow to the Chattahoochee River. These percentages and volumetric flow rates are listed in table 14 as reduced discharge to the respective rivers. Reduced discharge to "minor streams," which have the potential to go dry, constitutes about 11 percent of the October 1986 pumping rate, and reduced discharge to "other streams" comprises about 6 percent of the pumping rate. Reduced ground-water discharge to the Chipola and Apalachicola Rivers contributes about 0.2 percent each to the October 1986 pumping rate.

Induced recharge from surface water caused by October 1986 pumping was negligible (table 14). The total amount of induced recharge was associated only with the Flint River and "other streams," and amounts to about 0.1 percent of the October 1986 pumping rate. However, only small amounts of induced recharge from streams is possible because of the establishment of large positive hydraulic gradients in the aquifer that extend from the recharge area and regional-flow boundaries to the streams. This flow pattern is minimally affected by ground-water withdrawal in the basin.

Table 14. Components of stream-aquifer budget that comprise October 1986 pumping rates, from calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin
[Volumetric flow rate in million gallons per day]

Budget component	Volumetric flow rates	Percentage of pumping rate
Discharge to wells	475	100
Reduced discharge to streams, by component		
Flint River	176	37
Minor streams[1]	51	10.8
Chattahoochee River	34.2	7.2
Other streams[2]	26.4	5.6
Chipola River	1.2	.2
Apalachicola River	1.1	.2
Total	**289.9**	**61**
Induced recharge from streams, by component		
Flint River	0.5	0.1
Other streams[2]	.1	.03
Minor streams[1]	0	0
Chipola River	0	0
Chattahoochee River	0	0
Apalachicola River	0	0
Total	**0.6**	**0.13**

[1]Minor streams include 18 streams from the Upper Floridan model, listed in table 3. Streams are simulated as discharge-only functions that drain the aquifer.

[2]Other streams include five streams from the Upper Floridan model and five streams from Intermediate model, listed in table 2. Streams are simulated as sources or sinks to the aquifer. The Intermediate model does not contribute to budget components.

Sensitivity Analysis

Effects on computed ground-water levels of independently changing values for hydrologic factors of the flow system were determined in a sensitivity analysis involving data inputs for the calibrated models. The objective of the analysis was to identify which hydrologic factors, when changed from values used in the calibrated models, caused the most change in computed ground-water levels and invoked the most change in computed stream-aquifer fluxes. Presumably, the stream-aquifer system would be most sensitive to those hydrologic factors that effected the most change in simulated stream-aquifer fluxes and ground-water levels.

Procedure

Values for the 49 hydrologic factors (table 15) that were conceptualized as having an influence on simulated ground-water levels and stream-aquifer fluxes were changed independently and systematically from those used in calibration, and corresponding simulations were performed. Changes were made using either a multiplier or an additive constant for the appropriate hydrologic factor. Multipliers ranged from 0 to 10 and additive constants ranged from minus 30 to 30. A multiplier of one (1) or an additive constant of 0 corresponds to the value of the hydrologic factor used in the calibrated model. After each simulation, the sum of squares of water-level residuals was computed. Aquifer hydraulic conductivity, withdrawal rates from wells, vertical-leakage coefficients, and head in source layers that provide steady vertical leakage to the simulated aquifers each were regarded as single hydrologic factors whose values were changed over the entire model area. No changes were made to values of individual zones or nodes corresponding to these factors. The remaining hydrologic factors represented components of the flow system that were defined as segments (zones) of head-dependent (Cauchy-type) boundaries. Coefficients and external (or boundary) heads for these factors were considered to be distinct parameters to which individual changes were made to a zone or group of zones.

Significance to the Ground-Water-Flow System

Analysis of hydrologic factors comprising the ground-water-flow system indicated that some factors influence simulated ground-water levels more than others. Factors that were shown to have the most influence on ground-water levels would be instrumental in shaping the potentiometric surface of the aquifer and also might influence stream-aquifer flux. Therefore, these influential hydrologic factors need to be represented accurately in models that are constructed to evaluate stream-aquifer relations.

The sensitivity of each hydrologic factor to the ground-water-flow system was determined by computing and plotting the sum of squares of ground-water-level residuals for the corresponding change in value of the hydrologic factor and by analyzing the shape of the resulting "sensitivity curves," as described in Torak (1991). Each plot yielded one of three general shapes, or sensitivity curves (fig. 24). Hydrologic factors that are most influential on the flow system yielded sensitivity curves that resemble a parabola having a deep trough and steeply dipping sides (fig. 24*A*). This shape indicated that small changes to the value of the hydrologic factor produced large changes in computed water levels. Hence, a hydrologic factor that yielded this type of sensitivity curve had a greater influence on ground-water levels and the flow system than other hydrologic factors which produced a broad, gently dipping curve (fig. 24*B*). Hydrologic factors to which the flow system was least sensitive produced a relatively flat sensitivity curve (fig. 24*C*).

Sensitivity curves for each hydrologic factor were categorized according to the shapes shown in figure 24. Results of the sensitivity analysis indicated that computed ground-water levels were influenced most by (exhibited high sensitivity to) the following hydrologic factors:

- Hydraulic conductivity of the Upper Floridan aquifer
- Vertical leakage coefficient of semiconfining unit overlying the Upper Floridan aquifer
- Source-layer head of semiconfining unit overlying the Upper Floridan aquifer
- Source-layer head of Upper Floridan aquifer underlying the Intermediate system
- Stage of the Flint River downstream of the Flint River Dam to Lake Seminole

Sensitivity curves for these hydrologic factors had a shape similar to that of figure 24*A*, indicating that relatively small changes in calibrated values caused large changes in the sum of squares of ground-water-level residuals. All factors listed, except stage of the Flint River, apply to the entire model area.

Although not an areally extensive hydrologic factor, the sensitivity analysis indicated that the Flint River has a major influence on ground-water flow in the Upper Floridan aquifer. In addition to the shape of its sensitivity curve, influence of the Flint River on ground-water flow is demonstrated by the area affected by changes in stage (fig. 25). Lines of equal change in ground-water levels corresponding to a 30-foot change in the stage of the Flint River downstream of the Flint River Dam show that ground-water levels are changed by at

Table 15. Hydrologic factors used in sensitivity analysis of Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin
[Linear and nonlinear Cauchy-type-boundary zones shown on plate 4]

	Aquifer and confining-bed factors
	Upper Floridan aquifer and Intermediate system: hydraulic conductivity
	Overlying semiconfining unit: vertical leakage coefficient and source-layer head
	Upper Floridan aquifer underlying Intermediate system: source layer head
	Semiconfining unit underlying Intermediate system: vertical leakage coefficient
	Withdrawal rates for wells (Upper Floridan model)
	Spring discharge (Upper Floridan model)
	Specified-head-boundary factor (Upper Floridan model)
	Outcrop area along northwest model boundary
	Linear Cauchy-type-boundary factors by model
	Upper Floridan model
Zone(s)	
1–4	Flint River downstream of Warwick Dam to Flint River Dam: boundary coefficient and river stage.
5–17	Flint River downstream of Flint River Dam to Lake Seminole: boundary coefficient and river stage.
18–36	Other streams: boundary coefficient and stream stage.
37–40	Chattahoochee River to Lake Seminole: boundary coefficient and river stage.
41–46	Chipola River: boundary coefficient and river stage.
47–50	Apalachicola River downstream of Lake Seminole: boundary coefficient and river stage.
51	Regional flow across southwestern model boundary: boundary coefficient and external head.
52	Regional flow across southern model boundary: boundary coefficient and external head.
53	Regional flow across southeastern model boundary: boundary coefficient and external head.
54, 55	Regional flow across eastern model boundary (Solution Escarpment): boundary coefficient and external head.
56–58	Regional flow across northeastern model boundary: boundary coefficient and external head.
	Intermediate model
Zone(s)	
59–61	Apalachicola River: boundary coefficient and river stage.
62, 63	Chipola River, including Dead Lake, downstream to confluence with Apalachicola River: boundary coefficient and river stage.
64–68	Other streams: boundary coefficient and river stage.
69	Regional flow across northern model boundary: boundary coefficient and external head.
70	Regional flow across northwestern model boundary: boundary coefficient and external head.
71	Regional flow across southwestern model boundary: boundary coefficient and external head.
72	Regional flow across southern model boundary: boundary coefficient and external head.
	Nonlinear Cauchy-type-boundary factors (Upper Floridan model) by zone
Zone(s)	
1–56	Minor streams: boundary coefficient and stream stage.

least 1 foot over about 60 percent of the area of the Upper Floridan model.

Other hydrologic factors listed in table 15 yielded sensitivity curves that indicated less of an influence on the ground-water-flow system than factors having curves that are similar to figure 24*A*. Hence, the following hydrologic factors exhibited moderate sensitivity to ground-water levels in the stream-aquifer system:

- Boundary heads along the eastern boundary of the Upper Floridan model
- Stage of major streams in Upper Floridan and Intermediate models
- Stage of the Chattahoochee River

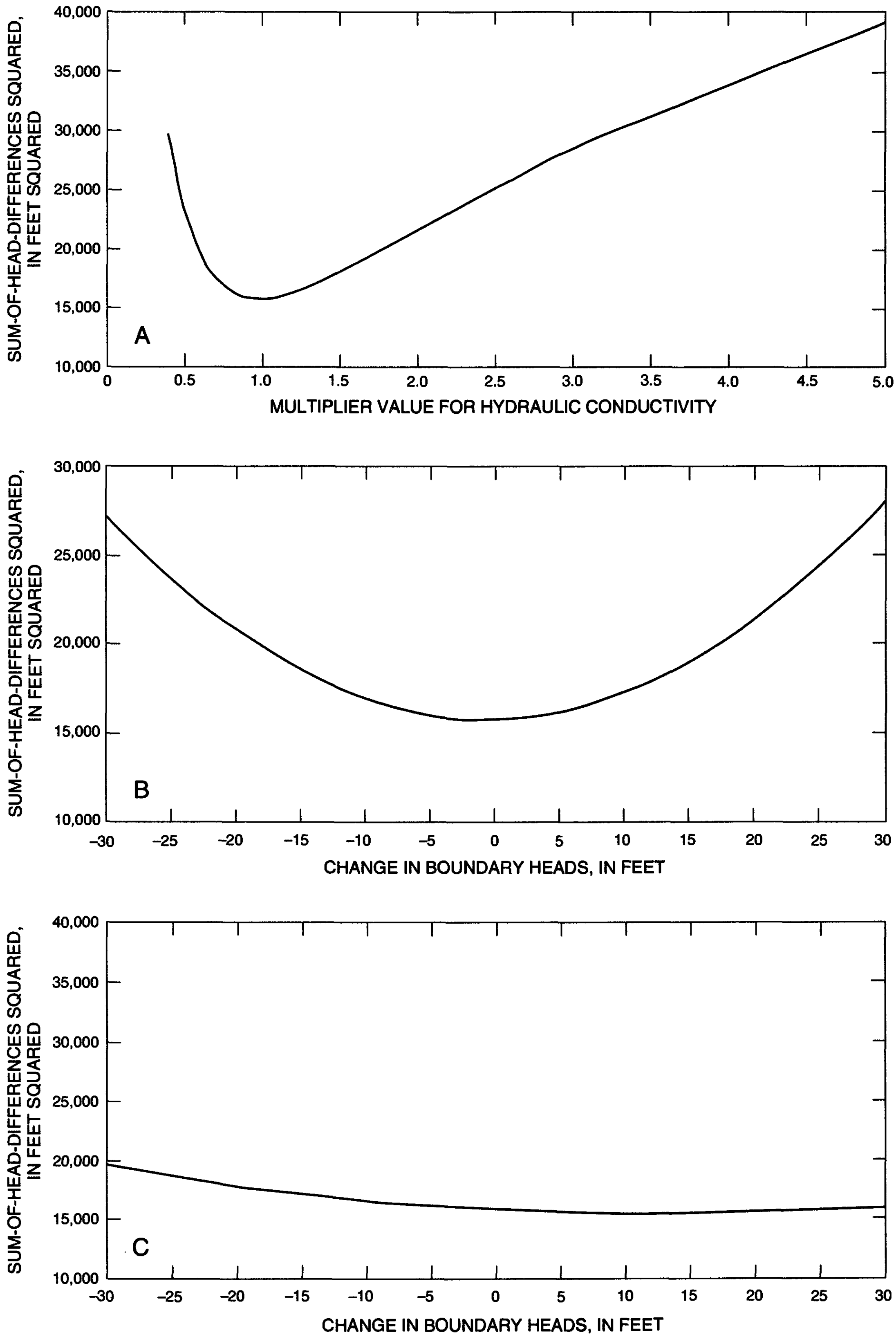


Figure 24. Changes in sum-of-head-differences squared with respect to simulated changes in parameters of the Upper Floridan model. (*A*) Aquifer hydraulic conductivity; (*B*) Heads along eastern model boundary; and (*C*) Heads along northeastern model boundary.

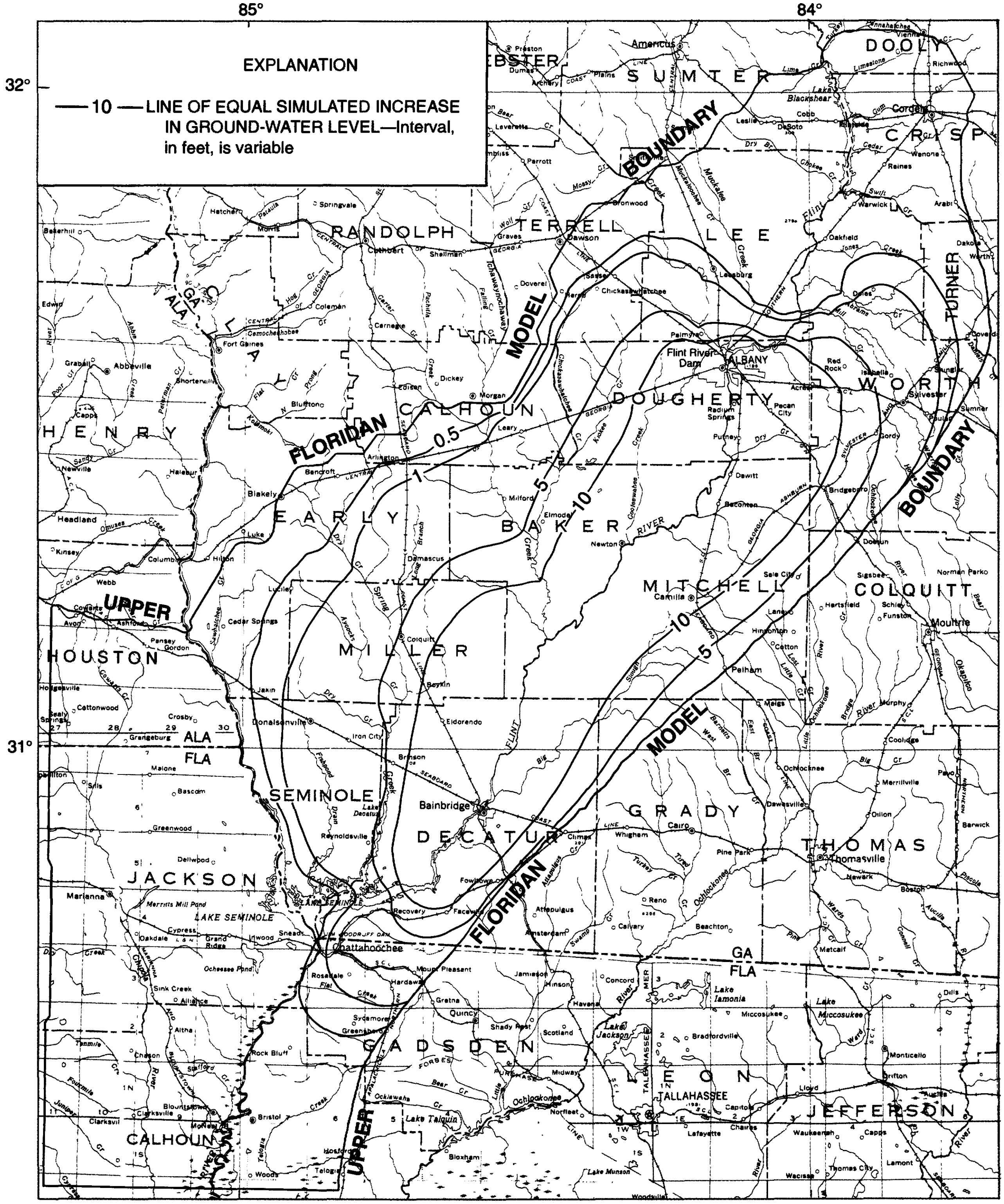


Figure 25. Lines of equal simulated increase in ground-water levels from October 1986 conditions caused by a simulated 30-foot increase in stage of the Flint River downstream from the Flint River Dam.

- Stage of minor streams in Upper Floridan model
- Spring discharge
- Well pumping rates
- Boundary heads along southern boundary of the Intermediate model

Sensitivity curves for these hydrologic factors have shapes similar to the curve shown in figure 24*B*, indicating that changes in values for these factors cause moderate changes to the sum of squares of ground-water-level residuals. Although only small areas are contained by the eastern boundary of the Upper Floridan model, the Chattahoochee River, and the southern boundary of the Intermediate model, their affect on ground-water levels was demonstrated by the broad, gently dipping sensitivity curves that these factors produced.

Simulated ground-water levels in the Upper Floridan model were affected very little by changes in well-pumping rates that were less than about twice the rates for October 1986 (fig. 26). In particular, the sum of squares of ground-water-level residuals computed from a simulation of zero pumpage was only slightly different than the sum of squares corresponding to the calibrated model, which contained pumpage; a multiplier value of zero in figure 26 represents the zero-pumpage condition. The change in sum of squares of ground-water-level residuals resulting from other simulated pumping rates indicate that pumpage from the Upper Floridan aquifer has only a moderate effect on ground-water levels and on the shape of the potentiometric surface for October 1986.

Spring discharge, although not areally extensive, exhibited moderate sensitivity to the ground-water-flow system, as the shape of the sensitivity curve is similar to the shape generated by ground-water pumpage (fig. 26). This indicates that the ground-water-flow system is sensitive to increases in spring discharge of more than about 3 times the discharge rates used in the calibrated model; decreases in spring discharge had only minimal effects on the sum of squares of ground-water-level residuals.

Sensitivity curves for other hydrologic factors listed in table 15 indicated only a small influence on ground-water flow in the lower ACF River Basin. Curves for these hydrologic factors were relatively flat (similar to fig. 24*C*), indicating that large changes in values used for these factors in the models produced only small changes in computed water levels.

The relative insensitivity of the ground-water-flow system to hydrologic factors that define the outcrop area of the Upper Floridan aquifer and that characterize stream-aquifer relations along the Apalachicola and Chipola Rivers is significant because these hydrologic factors initially were conceptualized as being important to the flow system (see earlier section on conceptualization of the flow system). Sensitivity curves indicate that boundary heads on the eastern and southern model boundaries of the lower ACF River Basin and surface-water levels influence ground-water flow more than the outcrop area of the Upper Floridan aquifer and boundary coefficients for the Apalachicola and Chipola Rivers. Greater sensitivity of computed water levels to boundary heads and surface-water levels than to boundary coefficients indicates that the ground-water-flow system responds to water-level changes along model boundaries and surface-water features in a manner similar to that in which the flow system would be influenced by specified-head boundaries, if such boundaries existed in the models at these locations. Therefore, accurate water-level measurements along model boundaries and surface-water features are necessary to provide accurate computed ground-water levels in the study area.

Flow-System Response to Increased Pumpage

Simulations of increased pumpage from October 1986 rates were made to evaluate the effects of ground-water pumpage on streamflow. Of particular importance was the effect of pumpage in the Upper Floridan aquifer on the northern and central parts of the basin; no pumpage was simulated in the southern part as it was negligible in the Intermediate system. Steady-state simulations of 5 pumpage scenarios were performed with the Upper Floridan model by increasing pumping rates by factors of 1.5, 2, 3, 5, and 7 from the values used in calibration. Flow-system response was evaluated by noting changes to water-budget components, stream-aquifer fluxes, and ground-water-level declines, and was interpreted for analysis of potential changes in water quality.

Changes to Water-Budget Components

Effects of increased pumpage on stream-aquifer relations in the lower ACF River Basin were evaluated by analyzing the changes to water-budget com-

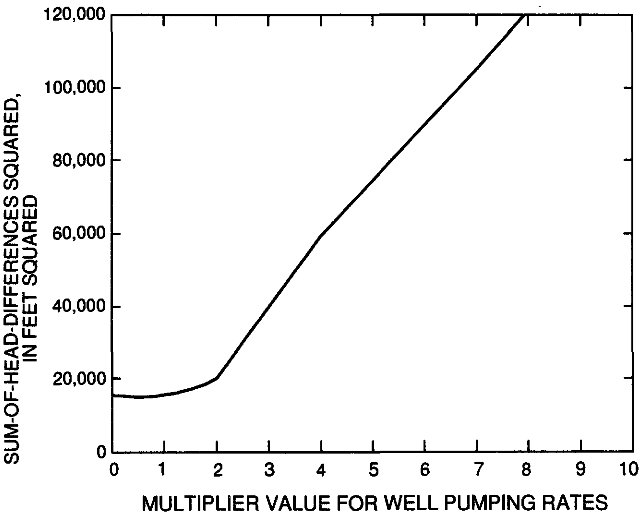


Figure 26. Changes in sum-of-head-differences squared in the Upper Floridan model with respect to simulated changes in well pumping rates for October 1986.

ponents caused by pumpage increases. Changes in volumetric flow rates and in relative percentages that each water-budget component contributed to the increased pumpage (table 16) were evaluated by comparing water-budget components from the calibrated model with similar components from the 5 pumpage scenarios. Volumetric-flow rates for water-budget components obtained from these scenarios were subtracted from values of corresponding components obtained from the calibrated model. The resulting differences in rates were expressed as a percentage that each component contributed to increased pumpage for the scenario.

The water-budget component that contributed most to increased pumpage is reduced discharge to streams and in-channel springs (table 16). This component represents the amount of regional ground-water flow that would have discharged to streams but was intercepted by pumpage. About 63 percent of the additional water pumped for the scneario in which pumpage was increased by a factor of 1.5, or, about 149 Mgal/d, was derived from reduced discharge to streams and in-channel springs. This percentage holds, approximately, for pumpage increases by factors of 2 and 3, but decreases to 53 and 45 percent, respectively, for pumpage increases by factors of 5 and 7.

The water-budget component that exhibited the most change in response to increased pumpage was induced recharge from streams (table 16). The volumetric rate of induced recharge from streams increased about 31 times, from 0.7 percent for the scenario corresponding to a pumpage increase by a factor of 1.5, to 21.5 percent for increased pumpage by a factor of 7. Other water-budget components exhibited changes of about an order of magnitude or less for the scenarios of increased pumpage.

Although some induced recharge across streambeds is possible for all pumpage scenarios, actual rates of induced recharge associated with the larger pumpage increases (factors of 5 and 7 times the October 1986 rates) would be less than those presented in table 16. Streamflow reductions would cause decreases in stream stage that, in turn, decrease vertical hydraulic gradients and induced ground-water recharge to the aquifer across streambeds. Because the digital models did not simulate decreases in stream stage as streamflow was reduced, induced recharge was allowed to be computed at artificially high rates; that is, at rates corresponding to stages that do not reflect pumpage-induced-streamflow reductions. Ultimate streamflow reduction would cause the stream to dry up, which was simulated in streams (listed in table 3) that were conceptualized as being unable to provide recharge to the aquifer. However, the models did not simulate lowering of stream stages in conjunction with decreased ground-water levels for streams that could provide ground-water recharge. Therefore, if a stream, or reach, had gone dry unexpectedly, then the "dry" stream reach would continue to yield water to the aquifer at rates corresponding to the difference between stream stage and aquifer water level. Some of this "extra" recharge could be eliminated by representing these potentially dry reaches as discharge-only boundaries, as was done for streams listed in table 3. Another possible unaccounted source of water is created when reaches convey water downstream to dry reaches that might recharge the aquifer with the conveyed water. Simulation of flow routing, not provided in the models, would be necessary in order to make the conveyed water available to the dry reach for possible recharge to the aquifer.

Commensurate with pumpage-induced reduction of ground-water discharge to streams and in-channel springs are increases to volumetric recharge rates from regional flow and vertical leakage from the undifferentiated overburden (table 16). Changes to these water-budget components represent increases to lateral and vertical flow of ground water into the Upper Floridan aquifer to meet simulated pumpage demand. However, like induced recharge from streams, the ability of the flow system to supply

Table 16. Water-budget components for scenarios of increased pumpage from the Upper Floridan aquifer in the lower Apalachicola-Chattahoochee-Flint River Basin

[Volumetric rates, in million gallons per day, and percentages were rounded slightly]

Component	Multiplier for October 1986 pumping rates				
	1.5	2	3	5	7
Volumetric rate by component					
Increased well discharge	237	475	949	1,864	2,657
Reduced discharge component					
Streams and in-channel springs[1]	149	301	587	987	1,187
Regional flow	12.8	25.3	49.4	90.4	119
Undifferentiated overburden	6.8	12.5	20.6	28.3	30.9
Induced recharge component					
Undifferentiated overburden	52.4	99.6	195	379	525
Regional flow	10.5	21.3	45.5	104	172
Outcrop, Upper Floridan model	4.5	9.0	18.4	36.4	51.7
Streams	1.6	5.7	32.5	239	570
Percentage of increased pumping rates, by component					
Increased well discharge	100	100	100	100	100
Reduced discharge component					
Streams and in-channel springs[1]	62.7	63.5	61.9	53	44.7
Regional flow	5.4	5.3	5.2	4.9	4.5
Undifferentiated overburden	2.9	2.6	2.2	1.5	1.2
Induced recharge component					
Undifferentiated overburden	22.1	21	20.6	20.3	19.8
Regional flow	4.4	4.5	4.8	5.6	6.5
Outcrop, Upper Floridan model	1.9	1.9	1.9	2.0	2.0
Streams	.7	1.2	3.4	12.9	21.5

[1]In-channel springs discharge in or near streams and contribute to streamflow (off channel springs are located away from streams and are assumed to be unaffected by well pumpage).

water to the aquifer at the rates indicated in table 16 for lateral and vertical flow for the long-term is problematic because these flow rates are dependent on head differences that exist between the aquifer and undifferentiated overburden (for vertical leakage), and across model or basin boundaries (for regional flow). It is unrealistic to assume that hydraulic head in the overburden or in the aquifer region external to the model area would not decline in response to increased pumpage or prolonged drought. Ground-water levels in aquifer material adjacent to the model area and in the overburden likely would be lower than the levels of October 1986 for conditions of more severe drought and increased pumpage than experienced during that time. Therefore, corresponding flow rates across lateral and vertical boundaries most likely would be lower than the rates simulated and listed in table 16.

However, lower volumetric recharge rates to the Upper Floridan aquifer than was simulated for lateral boundary flow and for vertical leakage each affect the water budget of the stream-aquifer system differently. Because the amount that regional flow contributes to pumpage-induced recharge to the aquifer is small for all pumpage scenarios—less than 7 percent for the largest increase to pumping rates (table 16)—it seems unlikely that changes in head outside the study area would have a significant affect on water-budget components and water levels in the study area. Conversely, induced recharge from the undifferentiated overburden constitutes about 20 percent of the volumetric flow rate that comprises the increased pumpage (table 16). Therefore, it is likely that clayey sediment in the overburden eventually would dewater under conditions of increased pumpage or prolonged drought, thereby reducing vertical-leakage rates from those listed in table 16. If normal seasonal precipitation does not resume following drought conditions, then recharge through the overburden by infiltration of precipitation might be eliminated completely as a source of water to the Upper Floridan aquifer.

The slight decrease in the percentage of induced recharge to the Upper Floridan aquifer from the undifferentiated overburden (from about 22 to 20 percent, table 16) that contributed to the increased pumpage is probably due to parts of the aquifer becoming unconfined and hydraulically detached from the overburden. For unconfined conditions, the vertical hydraulic gradient that controls the leakage rate is constant despite additional ground-water-level declines and increased pumpage.

Other water-budget components collectively contributed about 8 percent to the water budget for the scenario involving a pumpage factor of 7 (table 16), and thus, individually, had only a minor influence on supplying water to meet the increased-pumpage demand. Reduced discharge to regional ground-water flow supplied about 5 percent of the increased discharge to wells; induced recharge from outcrop areas of the Upper Floridan aquifer supplied about 2 percent. About 1 percent of the pumpage increase by a factor of 7 was derived from induced recharge from the undifferentiated overburden. This is a decrease from about 3 percent for the scenario of increased pumpage by a factor of 1.5; the result of an increasingly larger aquifer area becoming unconfined and detached hydraulically from the overburden as pumpage increases, thus subject to a constant vertical-leakage rate from the overburden.

Decrease in Base Flow of Streams

Decreased base flow of streams due to pumpage is the combined effect of reduced discharge to and induced recharge from streams. The effects of individual streams on stream-aquifer relations are represented in base-flow reductions, and are expressed for each stream by using volumetric flow rates and percentages of increased pumpage for the 5 scenarios (table 17). Decreases in base flow were calculated by subtracting values of net stream-aquifer flux, derived from each pumpage scenario, from corresponding values in the calibrated model. Net stream-aquifer flux is defined as the overall gain (or loss) in base flow of a stream over its total length in the study area, and is computed by subtracting the volumetric rate of ground-water recharge to the aquifer from the stream from the volumetric rate of discharge to the stream.

The largest pumpage-induced base-flow reduction was exhibited by the Flint River (table 17). For simulated pumpage up to about 3 times the October 1986 rates, base-flow reductions represent about 38 percent of the increased well discharge. The percentage of base-flow reduction decreased to about 29 percent for the largest pumpage increase, which probably was due to prominent aquifer dewatering near the river and to river reaches changing from gaining- to losing-stream conditions. Volumetric rates corresponding to these percentages represent combined effects of increased pumpage on decreased base flow of (or, on decreased ground-water discharge to) the Flint River and on induced recharge to the aquifer from the river. The percentage that induced recharge from the Flint River contributes to reduced baseflow increased with increased pumpage, from less than 1 percent (pumpage multiplier of 1.5) to about 17 percent (pumpage multiplier of 7). This increase is caused by reversing the direction of the hydraulic gradient from a condition of ground-water flow toward the river to that of ground-water flow away from the river as pumpage increases.

Decreases in streamflow (not only base flow) of the Flint River are larger than indicated by values listed in table 17 because of decreases in tributary flows. From tables 2 and 3, there are 5 "other streams" (table 2) and 9 "minor streams" (table 3) that are tributaries to the Flint River; therefore, changes in flow to these streams affect streamflow in the Flint River. Some reaches of minor streams had gone dry for scenarios of the 2 largest pumpage increases, thus partially eliminating a source of tributary flow to the Flint River. This is indicated by decreased percentages of reduced discharge to minor streams, listed in table 17, for scenarios of increased pumpage by multipliers of 5 and 7. For each scenario of increased pumpage, the total streamflow reduction in the Flint River can be obtained by combining decreases in base flow of the minor and other streams that are tributaries of the Flint River with similar decreases in the river itself. These computations indicate that decreases in streamflow of the Flint River constitute about 56 percent of the increased pumpage for each scenario. For increased pumpage by a multiplier of 7, this percentage represents about a 1,482 Mgal/d decrease in streamflow for the Flint River, and also represents a decrease in base flow for the Flint River and its tributaries of the same amount. In comparison, measured flow of the Flint River upstream of Bainbridge, Ga., during October 23 to 28, 1986 was about 1,667 Mgal/d (table 1). Therefore, simulated pumpage in the study area at 7 times the October 1986 rates under dry conditions caused about an 89-percent decrease in streamflow in the Flint River from measured values.

Decreased base flow of the Chattahoochee River constitutes about 7 to 9 percent of the increased

Table 17. Components of stream-aquifer budget for scenarios of increased pumpage from the Upper Floridan aquifer in the lower Apalachicola-Chattahoochee-Flint River Basin
[Volumetric rates, in million gallons per day, and percentages were rounded slightly]

Component	Multiplier for October 1986 pumping rates				
	1.5	2	3	5	7
Volumetric rate by component					
Increased well discharge	237	475	949	1,864	2,657
	Reduced discharge to streams, by component				
Flint River	90	182	368	645	781
Minor streams[1]	25.7	53	82.2	93.7	99.8
Other streams[2]	13.6	26	47.5	87.5	118
Chipola River	.6	1.2	2.5	5.3	7.9
Chattahoochee River	18.3	38.4	85.2	151	174
Apalachicola River	.5	1.1	2.3	4.8	7.2
	Induced recharge from streams, by component				
Flint River	1.5	4.0	23.3	183	449
Other streams[2]	.1	1.7	9.2	21.3	33.5
Minor streams[1]	0	0	0	0	0
Chipola River	0	0	0	0	0
Chattahoochee River	0	0	0	34.8	87.2
Apalachicola River	0	0	0	0	0
Percentage of increased pumping rates, by component					
Increased well discharge	100	100	100	100	100
	Reduced discharge to streams, by component				
Flint River	38	38.3	38.7	34.6	29.4
Minor streams[1]	10.8	11.2	8.7	5.0	3.8
Other streams[2]	5.7	5.5	5.0	4.7	4.4
Chipola River	.3	.3	.3	.3	.3
Chattahoochee River	7.7	8.1	9.0	8.1	6.6
Apalachicola River	.2	.2	.2	.3	.3
	Induced recharge from streams, by component				
Flint River	.6	.9	2.5	9.8	16.9
Other streams[2]	.1	.4	1.0	1.1	1.3
Minor streams[1]	0	0	0	0	0
Chipola River	0	0	0	0	0
Chattahoochee River	0	0	0	1.9	3.3
Apalachicola River	0	0	0	0	0

[1]Minor streams include 18 streams from Upper Floridan model (table 3). Streams are simulated as discharge-only functions that drain the aquifer.
[2]Other streams include five streams from Upper Floridan model (table 2). Streams are simulated as sources or sinks to the aquifer.

pumping rates for scenarios listed in table 17. Because the Chattahoochee River neither extends far into the lower ACF River Basin nor contains as large a base-flow component as the Flint River, the contribution to increased pumpage by decreased base flow of the Chattahoochee River is not as large as similar contributions corresponding to the Flint River. Even the combined effects of reduced discharge to and induced recharge from the Chattahoochee River constitute only about 10 percent of the increased pumpage for the scenario having the largest pumping rate (table 17).

Although base-flow reductions of the Apalachicola and Chipola Rivers seem to be minimal (table 17), streamflow in the Apalachicola River will be reduced greatly by decreased base flow of streams

Table 18. Net stream-aquifer flux for scenarios of increased pumpage from the Upper Floridan aquifer in the lower Apalachicola-Chattahoochee-Flint River Basin

[Flux, in cubic feet per second, is positive for aquifer discharge to a gaining stream]

Stream	Net stream-aquifer flux, by multiplier of October 1986 pumping rates					
	1	1.5	2	3	5	7
Flint River	1,742	1,601	1,455	1,137	461	−161
Chipola River	497	496	495	493	488	484
Apalachicola River	410	409	408	407	403	399
Chattahoochee River	365	337	305	233	77.8	−40
Ichawaynochaway Creek	199	188	177	153	102	55.8
Spring Creek	102	68.9	33.9	2.5	1.2	.8
Dry Creek (Fla.)	86.6	86.4	86.3	85.9	85.2	84.5
Marshall Creek	38.1	38.1	38.0	37.7	37.3	36.9
Muckalee Creek	32.4	24.2	15.9	−.7	−22.6	−35.3
Cowarts Creek	29.6	29.4	29.3	29.0	28.3	27.7
Chickasawhatchee Creek	25.8	25.2	24.7	23.6	21.4	19.5
Kinchafoonee Creek	25.8	23.6	21.4	16.9	8.9	2.8
Juniper Creek	21	20.9	20.9	20.9	20.9	20.8
Sawhatchee Creek	13.9	13.5	13.1	12.3	10.6	9.5
Tenmile Creek	10.8	10.8	10.8	10.7	10.7	10.6
Mill Creek	10.2	9.6	9.0	7.7	5.3	3.5
Fourmile Creek	7.8	7.8	7.8	7.8	7.7	7.7
Dry Creek (Ga.)	7.5	6.2	4.8	2.0	.7	.5
Swift Creek	7.2	6.4	5.6	4.0	2.3	1.3
Abrams Creek	6.2	5.4	4.6	3.0	.9	.3
Gum Creek	5.0	3.9	2.7	1.0	0	0
Cedar Creek	3.3	3.0	2.6	1.8	.5	0
Jones Creek	2.9	2.4	1.9	.9	.1	.1
Cooleewahee Creek	.7	.5	.3	.1	0	0
Limestone Creek	.1	.1	0	0	0	0

that contribute to the headwaters of the Apalachicola River at Lake Seminole. Because flow in the Apalachicola River depends on flows in the Chattahoochee and Flint Rivers and on flow in Spring Creek, base-flow reductions of these surface waters due to increased ground-water pumpage will cause reduced flow in the Apalachicola River. These base-flow reductions also affect the ability to maintain surface-water levels of lakes in the basin, principally Lake Seminole, and to a lesser extent, Lakes Worth and Blackshear.

The effects of pumpage on flow in the Apalachicola River can be estimated by summing values of all stream-budget components listed in table 17. This sum represents streamflow that once was available to enter Lake Seminole and flow ultimately to the Apalachicola River prior to pumping at the simulated rates. For example, a 7-fold increase in pumpage would amount to a total base-flow reduction of about 1,760 Mgal/d for streams listed in table 17. This represents about a 37-percent decrease in flow in the Apalachicola River as measured near Sumatra, Fla., during the low-flow conditions of October 1986 (table 1).

Pumpage-induced reductions in base flow of every stream simulated in the Upper Floridan and Intermediate models were computed by using changes in net stream-aquifer fluxes for the 5 pumpage scenarios (table 18). On 4 small tributaries to the Flint River—Limestone, Gum, Cedar, and Cooleewahee Creeks—net fluxes were zero for simulations of some pumpage scenarios, indicating that they had gone dry. The Flint River exhibited the most change in net stream-aquifer flux of all simulated streams, decreasing by about 1,903 ft^3/s over the entire range of simulated pumpage, and changing from gaining- to losing-stream conditions (negative net stream-aquifer flux) for the simulation of the largest pumpage increase. The Chattahoochee River and Muckalee Creek also changed from gaining to losing in response to simulated-pumpage increases.

Note that recharge to the aquifer by the Flint River for losing-stream conditions is larger than the ground-water discharge that contributes to the base flow of tributary streams (table 18). Streams that exhibit the least change in net stream-aquifer flux generally were located away from pumped wells. Therefore, it is unrealistic to assume that simulated stream-aquifer fluxes for the largest pumpage scenario will ever be attained, even if pumpage does increase to 7 times the October 1986 rates for extremely dry climatic conditions. More realistic results for this pumpage scenario than indicated by simulation results and table 18 would include lower positive stream-aquifer fluxes, more dry streams, and consequently, lower ground-water levels.

Pumpage-induced decreases in simulated net stream-aquifer flux for the Apalachicola and Chipola Rivers were minimal, totaling about 24 ft^3/s for the 5 scenarios listed in table 18. This represents about a 3-percent reduction in total ground-water discharge to these rivers (about 900 ft^3/s). One factor that can be used to explain the relatively small influence of pumpage on stream-aquifer flux for these rivers is the lack of significant pumpage in the Upper Floridan aquifer that has been reported in Florida and Alabama for October 1986. The distribution of pumped wells in Florida and Alabama is disproportionately less than in Georgia, considering that there are no significant changes in the geohydrology, physiography and land-use practices in the vicinity of the state lines and these rivers.

Ground-Water-Level Decline

Ground-water-level decline (drawdown) in the Upper Floridan aquifer in response to increased pumpage was determined by comparing simulated water levels from the 5 pumpage scenarios of the Upper Floridan model with results obtained from calibration. Drawdown was computed at all nodes by subtracting simulated water levels for each scenario from corresponding values obtained from the calibrated model. The nodal drawdown represents point values that can be compared with actual drawdown in wells located at nodes for the simulated pumpage conditions.

Lines of equal simulated drawdown for the Upper Floridan model (figs. 27–31) illustrate the spatial variability in the effects of increased pumpage on ground-water levels resulting from each scenario. Drawdown seems to be concentrated in 5 general areas, all within the northern part of the lower ACF River Basin. The largest of these areas is centered about Miller County, Ga., where simulated pumpage at 1.5 times the October 1986 rate created at least 2 feet of drawdown in the county (fig. 28). The next largest area of drawdown is located between Muckalee Creek and the Flint River in eastern Lee County, Ga. Increased pumpage by a factor of 1.5 generated about 10 ft of maximum drawdown between these surface-water features. Directly northeast and southwest of this area are 2 small areas containing enclosed lines of equal drawdown of 2 and 5 ft, respectively. Another small but distinct drawdown pattern exists in western Mitchell County between the Flint River and Big Slough.

With the exception of the previously mentioned drawdown pattern in Lee County, the Upper Floridan aquifer responds to increased pumpage by creating large areas of somewhat uniform water-level decline. For simulated pumpage at 1.5 times the October 1986 rate, about 91 percent of the 12,113 nodes in the Upper Floridan model exhibited water-level declines of 3 ft or less, with a mean (arithmetic average) drawdown of about 0.83 ft (table 19). Simulated pumpage at twice the October 1986 rate yielded water-level declines up to 5 ft at about 88 percent of the nodes (mean of about 1.7 ft); at 3 times the October 1986 pumpage, about 89 percent of the nodes had simulated water-level declines of less than 11.5 ft (mean of about 3.8 ft); at 5 times the October 1986 pumpage, about 84 percent of the nodes had water-level declines up to 17 ft (mean of about 8.3 ft). Simulated pumpage at 7 times the October 1986 rate generated water-level declines that were 21 ft or less for about 83 percent of the nodes, and a mean drawdown of about 11.4 ft.

For all scenarios except the one using the largest simulated pumping rate, maximum drawdown in the Upper Floridan model occurred in the same area of the lower ACF River Basin. In Lee County, Ga., between Muckalee Creek and the Flint River, the maximum drawdown ranged from about 12 ft to

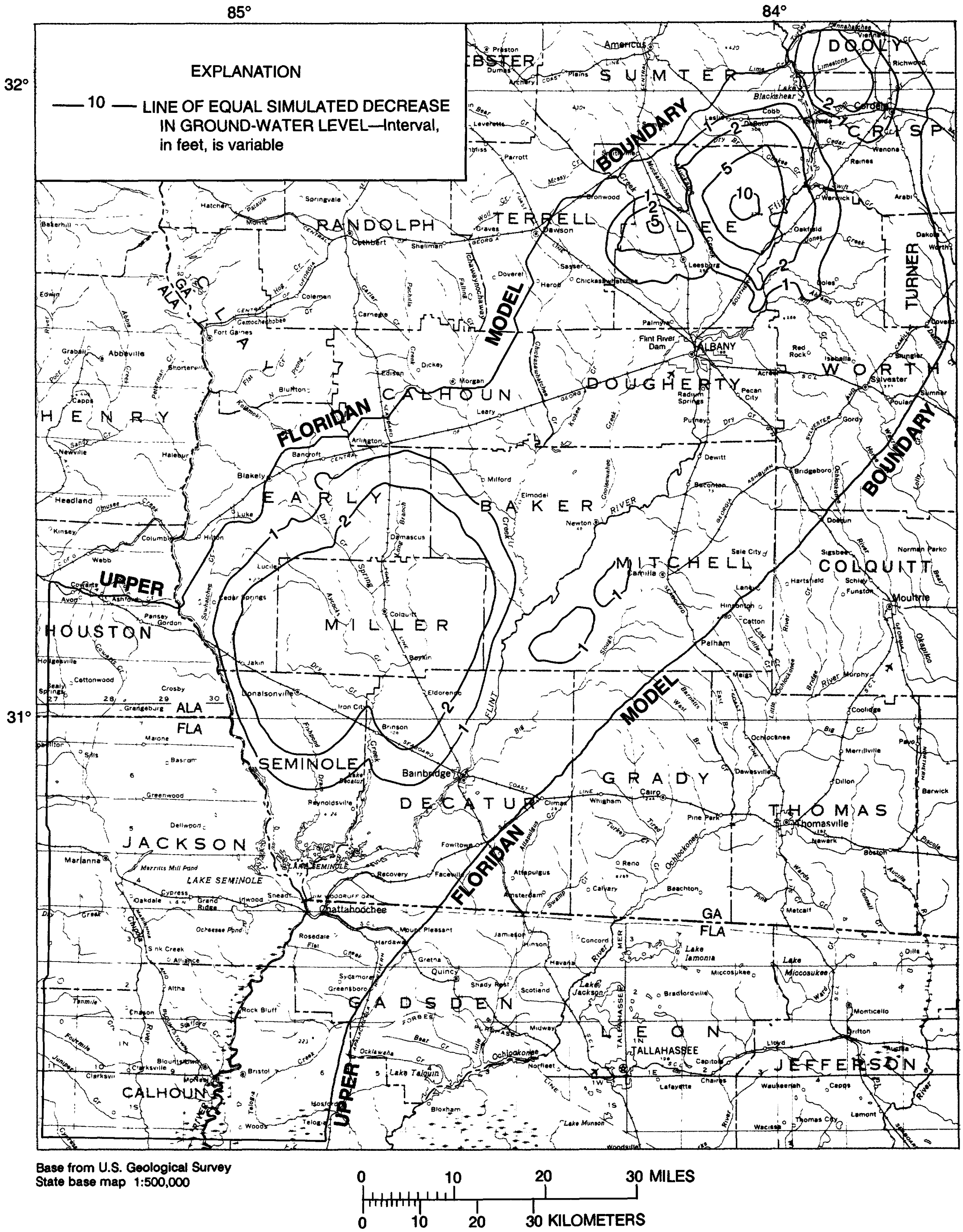
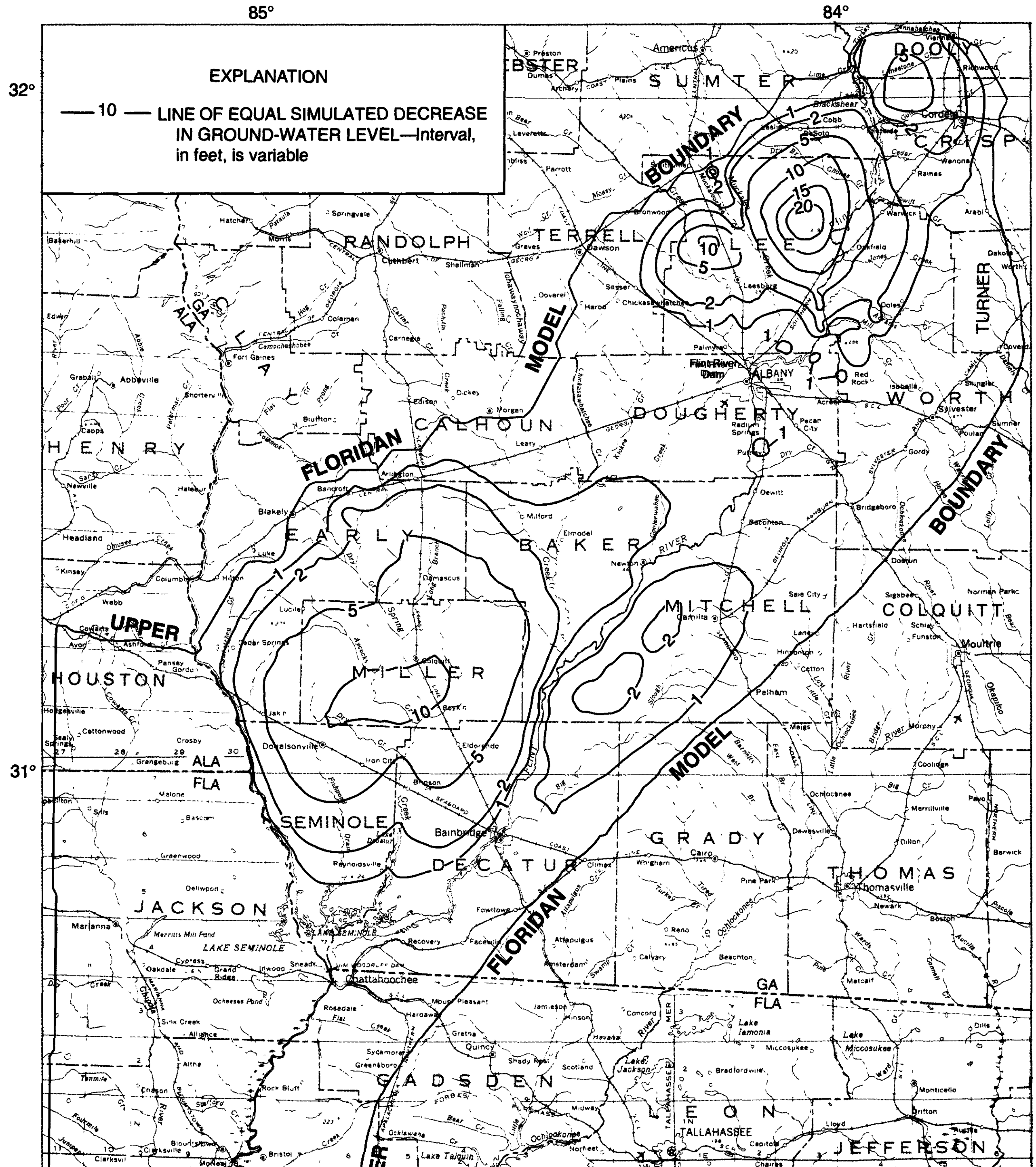


Figure 27. Lines of equal computed drawdown in the Upper Floridan aquifer from simulation of increase in October 1986 pumping rate by a factor of 1.5.



Base from U.S. Geological Survey
State base map 1:500,000

0 10 20 30 MILES

0 10 20 30 KILOMETERS

Figure 28. Lines of equal computed drawdown in the Upper Floridan aquifer from simulation of increase in October 1986 pumping rate by a factor of 2.

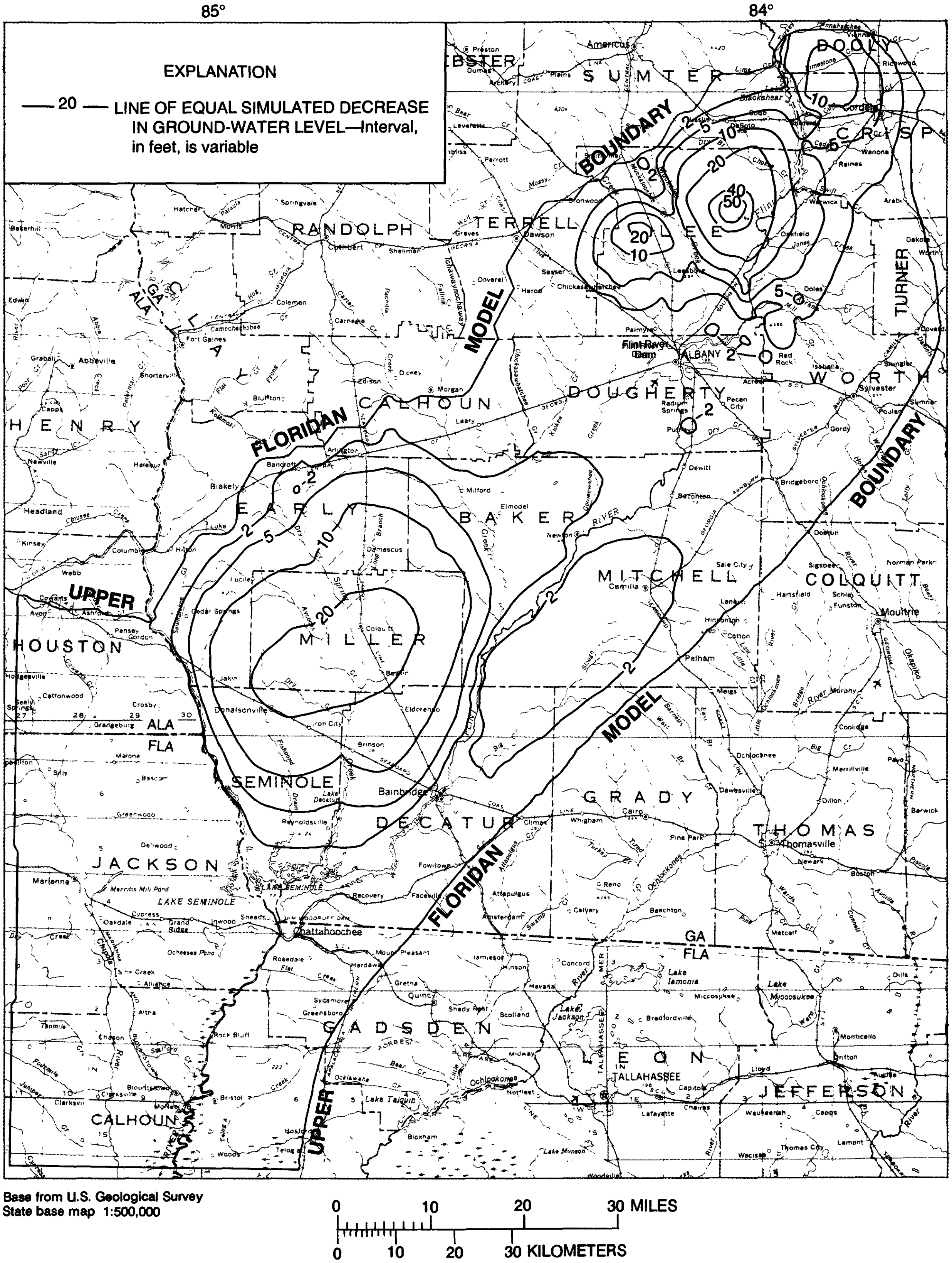


Figure 29. Lines of equal computed drawdown in the Upper Floridan aquifer from simulation of increase in October 1986 pumping rate by a factor of 3.

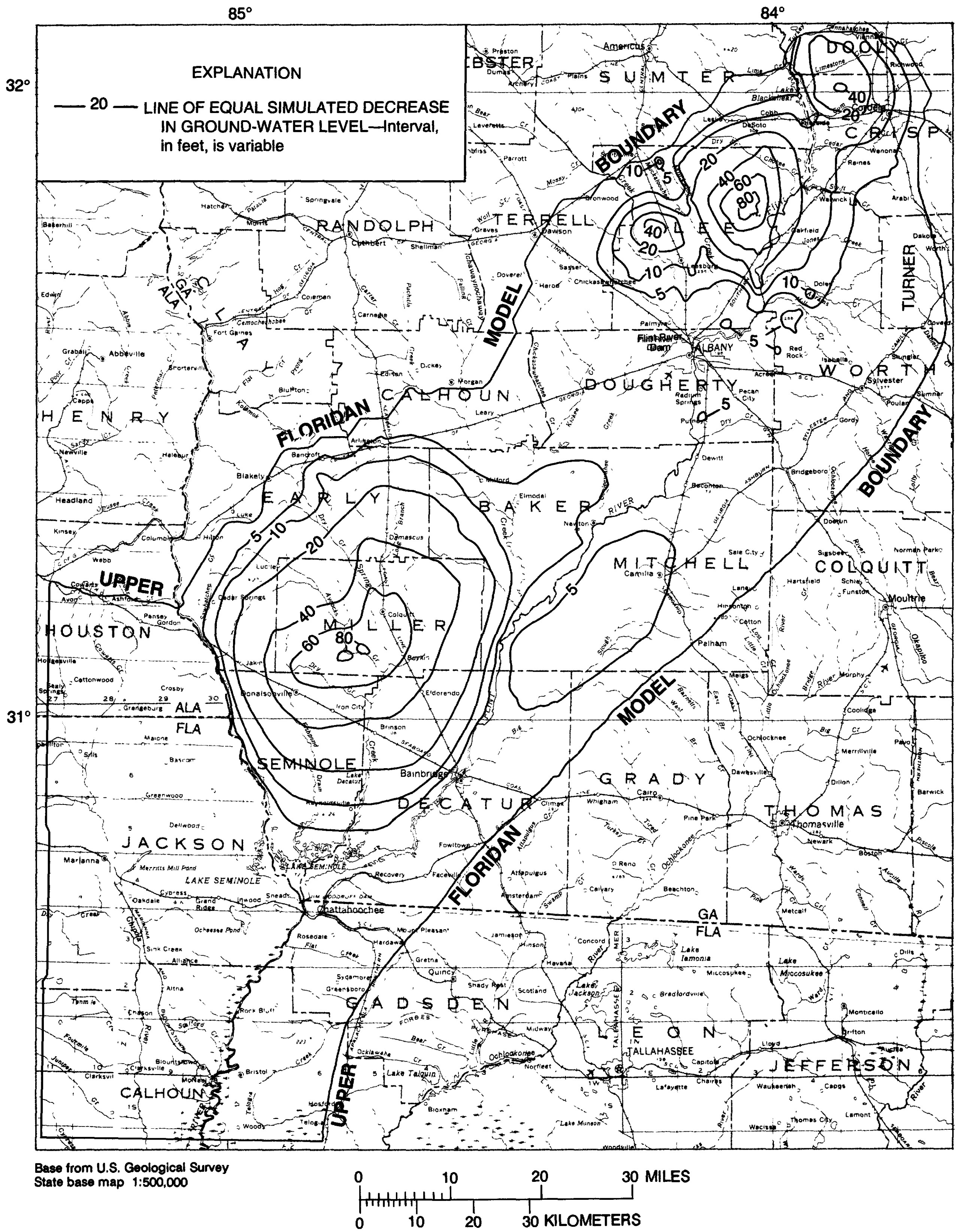
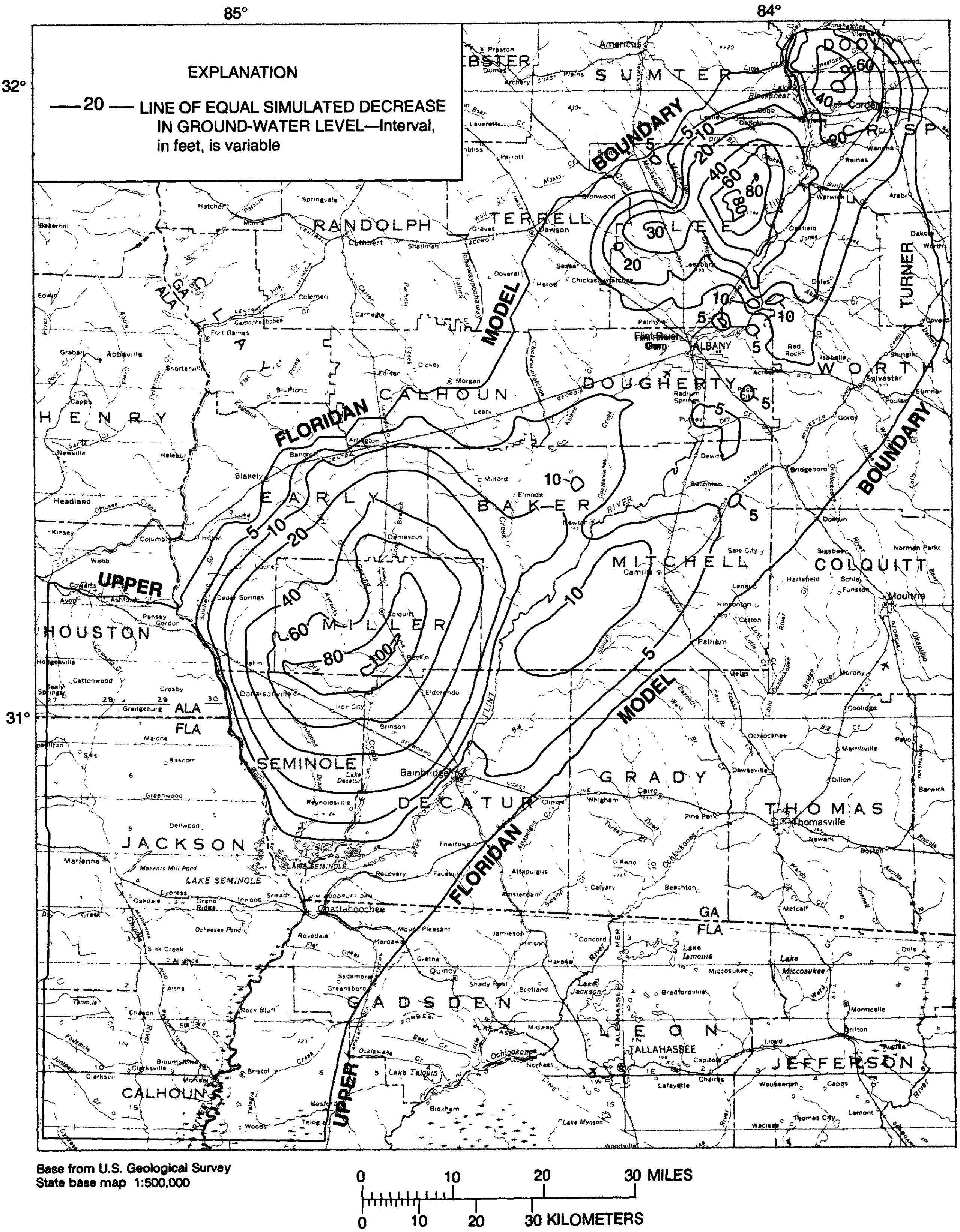


Figure 30. Lines of equal computed drawdown in the Upper Floridan aquifer from simulation of increase in October 1986 pumping rate by a factor of 5.



Base from U.S. Geological Survey
State base map 1:500,000

Figure 31. Lines of equal computed drawdown in the Upper Floridan aquifer from simulation of increase in October 1986 pumping rate by a factor of 7.

Table 19. Mean and maximum drawdown by pumping scenario in Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin
[Mean and maximum drawdown, in feet, computed from 12,113 nodal values; pumpage in million gallons per day]

Multiplier for October 1986 pumping rates	Total pumpage	Mean drawdown	Maximum drawdown
1.5	712	0.83	11.6
2	949	1.73	24.5
3	1,424	3.84	57.3
5	2,338	8.3	84.7
7	3,131	11.4	105.4

about 85 feet (figs. 27–30) for the first 4 pumpage scenarios in table 19. Aquifer drying precluded this area from attaining the maximum drawdown for the fifth scenario, which simulated pumpage at 7 times the October 1986 rate. For this simulation, a maximum drawdown of about 105 feet was located in Miller County, Ga. (fig. 31).

The susceptibility of parts of the Upper Floridan aquifer to go dry in response to increased pumpage can be inferred from maps of aquifer thickness (pl. 3) and simulated drawdown from each pumpage scenario (figs. 27–31). Comparison of these maps indicate that pumpage at 7 times the October 1986 rate might cause drying of the Upper Floridan aquifer in the following areas in Georgia:

- Crisp and Dooly Counties, Ga., east of Lake Blackshear and northwest of Cordele, Ga.
- Lee County, Ga., between Muckalee Creek and the Flint River
- Miller County, Ga., between Dry and Spring Creeks and west of Boykin, Ga.
- Early and Seminole Counties, Ga., north of Donalsonville, Ga.

For pumpage at 5 times the October 1986 rate, the Upper Floridan aquifer might go dry over smaller areas within the areas listed above. For example, in Lee County, Ga., only a small area along the Flint River east of Leesburg, Ga., is expected to go dry for pumpage at 5 times the October 1986 rate (fig. 30), whereas a larger area in this vicinity is expected to go dry for pumpage at 7 times the October 1986 rate (fig. 31). Drawdown from simulated pumpage increases of less than 5 times the October 1986 rate did not produce dry conditions in the Upper Floridan aquifer.

Values of mean and maximum drawdown in the Upper Floridan aquifer for scenarios of increased pumpage (table 18) indicate a nonlinear flow-system response; that is, pumpage at twice the rate did not produce twice the mean or maximum drawdown. A possible cause of nonlinear flow-system behavior due to increased pumpage is the decrease in thickness and transmissivity of the Upper Floridan aquifer as water levels decline in unconfined, or water-table, parts of the aquifer. Nonlinear flow-system behavior also can be attributed to conversion from confined (artesian) to water-table conditions, as increased pumpage lowers water levels below the top of the aquifer and below the base of the undifferentiated overburden. For this case, parts of the aquifer that once exhibited the linear flow characteristics of confined conditions have become unconfined due to increased drawdown, responding in a nonlinear manner as a water-table aquifer and receiving a constant rate of (nonlinear) vertical leakage from the overburden, as described previously. A third possible cause of nonlinear conditions is aquifer drying due to excessive drawdown. At the dry locations, directions of ground-water movement and flow paths are altered from that of saturated or confined conditions, and maximum drawdown is limited to the available, previously saturated, aquifer thickness.

Potential for Changes to Water Quality

Possible changes in the chemical quality of water in the stream-aquifer system of the lower ACF River Basin were evaluated by defining the hydraulic mechanisms that affect ground-water flow in the aquifers. These mechanisms are vertical leakage from underlying and overlying hydrologic units, leakage across streambeds and lakebeds, regional inflow across study-area boundaries, and recharge from the outcrop area. Changes in the hydrologic factors controlling these mechanisms, namely, hydraulic head in the aquifer and in overlying and underlying hydrologic units, surface-water levels, and pumping rates in the Upper Floridan aquifer, have the potential to cause changes in water quality in the basin.

Potential water-quality changes are inferred from changes in recharge rates to aquifers or to surface-water features in relation to changes in the hydraulic mechanisms listed above. Water-budget components for calibration and for scenarios of increased pumpage indicate that the greatest potential for changing the water quality of the Upper Floridan aquifer and Intermediate system can be associated with recharge by vertical leakage from overlying and underlying hydrologic units. For the calibration conditions of October 1986, recharge from the undifferentiated overburden to the Upper Floridan aquifer by vertical leakage is more than 5 times the pumping rate (table 11); increased pumpage induces additional vertical leakage (recharge) at a rate equal to about one-fifth of the pumpage increase (table 16). Recharge to the Intermediate system from terrace and undifferentiated (surficial) deposits is nearly 60 percent of the total aquifer discharge to streams, and similar recharge from the underlying Upper Floridan aquifer is about 1.1 times larger than aquifer discharge to streams (table 10). Therefore, the potential is high for changes in water quality in the Upper Floridan aquifer and Intermediate system to be caused by vertical leakage from the undifferentiated overburden, surficial deposits, and Upper Floridan aquifer (underlying the Intermediate system in the Intermediate model).

Ground-water discharge from the Upper Floridan aquifer and Intermediate system to surface water has the potential to change the water quality of streams, lakes, and Apalachicola Bay. Ground-water discharge to streams, including in-channel springflow, exceeds 5 times the withdrawal rate from wells (table 10) for October 1986 conditions. Because surface water depends on ground-water discharge to sustain levels and flows, changes in ground-water quality can affect the quality of streamflow that eventually enters Apalachicola Bay.

Changes in pumpage can cause changes to the hydraulic mechanisms that control water quality. Increased pumpage causes an increase in ground-water recharge by induced vertical leakage through semiconfining units and across streambeds and lakebeds, and has the potential to change water-quality. Pumpage also can induce lateral flow across regional boundaries, thus increasing the aquifer area that supplies water to wells. Along outcrop areas, chemical or biological constituents can enter the aquifer from surface or near-surface sources and change the quality of water that recharges the flow system.

Although hydraulic mechanisms can be evaluated to determine the potential of each one to change water quality, the most influential element for causing water-quality change in the lower ACF River Basin is the continued intervention by man. Surface-applied chemicals, either by design or accident, leaking underground-storage tanks, discharge of treated or untreated effluent and industrial waste into surface and ground waters, and anthropogenic sources of acid deposition have the potential for causing large and irreversible water-quality changes that can alter specific elements of the basin's water resources and render it unusable. Areas where semiconfining units are thin or absent (pl. 2) and (or) where high rates of vertical leakage to the aquifers are possible (pl. 12; figs. 22, 23) can be regarded as areas of high potential for change in ground-water quality, given man's intervention on the water resources of the basin. The proximity of industry to surface water poses a potential for change in ground- and surface-water quality. Introduction of these factors locally into the stream-aquifer system will increase the potential for large-scale change in water quality as flow-system elements function according to the hydrodynamics of the basin.

CONCLUSIONS

The geohydrology pertinent to stream-aquifer relations in the lower Apalachicola-Chattahoochee-Flint River Basin is contained in Coastal Plain sediments of pre-Cretaceous to Quaternary age, and is comprised of sand, clay, sandstone, dolomite, and limestone that alternate, gradually thicken, and dip gently to the southeast. Geologic units in these sediments control the nature of stream-aquifer relations in the study area. These are, in ascending order, the Lisbon Formation, Clinchfield Sand, Ocala Limestone, Marianna Formation, Suwannee Limestone, Tampa Limestone, undifferentiated overburden, Intracoastal Formation, Chipola Formation, Jackson Bluff Formation, Citronelle Formation, and terrace and undifferentiated (surficial) deposits. Stream-aquifer systems comprised of semiconfining units, the Intermediate system, Upper Floridan aquifer, lower confining unit, and sub-Floridan confining unit are defined by these geologic units according to their hydraulic properties and degree of connection with surface water.

Conceptually, the hydrologic processes controlling stream-aquifer relations allow division of the lower ACF River Basin into 3 parts according to the hydrologic units that were connected hydraulically with surface-water during the drought conditions of October 1986. In the northern part, the Upper Floridan aquifer is the hydrologic unit in primary contact with surface water; negligible amounts of water were supplied by terrace and surficial deposits and by the undifferentiated overburden. The aquifer consists mostly of the Ocala Limestone, with small thicknesses of overlying carbonate sediments of the

Suwannee and Tampa Limestones and the Marianna Formation. Fractures, bedding planes, and dissolution of carbonate rocks by circulating ground water permit the Ocala Limestone to store large quantities of water and to transmit ground water easily to surface water. Solution conduits, some in direct connection with surface water, shape the potentiometric surface and facilitate movement of large quantities of ground water in the stream-aquifer system by establishing preferential-flow paths and high contrasts in hydraulic conductivity between the conduit system and adjacent aquifer materal. The Upper Floridan aquifer is semiconfined from above by terrace and undifferentiated (surficial) deposits, and confined effectively from below by the Lisbon Formation, which forms the lower confining unit in Alabama and Georgia, and the sub-Floridan confining unit in Florida.

In the central part, variations in the hydraulic properties of geologic units in the Upper Floridan aquifer and differences in surface-water drainage create distinct ground-water-flow regimes to the east and west of the Apalachicola River. East of the Apalachicola River, the Tampa Limestone is incised below its base and is not in hydraulic connection with surface water. Poor surface-water drainage and low water-transmitting ability of the Tampa Limestone east of the Apalachicola River cause it to function as an overlying semiconfining unit to the deeper limestones of the Upper Floridan aquifer. West of the Apalachicola River, the Tampa Limestone and deeper units are cut by well-developed drainage to the Chipola and Apalachicola Rivers. The sandy lithology of the Tampa Limestone west of the Apalachicola River allows it to drain easily, and all limestone units of the Upper Floridan aquifer are connected hydraulically to surface water. West of the Apalachicola River, the Upper Floridan aquifer is semiconfined from above by fine-grained or clayey sediments consisting of terrace and undifferentiated (surficial) deposits. The Upper Floridan aquifer is confined from below by the Lisbon Formation, as in the northern part of the study area.

In the southern part of the lower ACF River Basin, stream-aquifer relations involve hydraulic connection of the Intermediate system with surface water. Here the Intermediate system overlies and replaces, stratigraphically, the Upper Floridan aquifer as the hydrologic unit in contact with surface water. The Intermediate system contains locally sandy or carbonate beds from the Jackson Bluff, Intracoastal, and Chipola Formations, and yields small amounts of water mostly to domestic wells. It serves as the middle unit for "flow-through" vertical leakage of ground water between overlying surficial deposits and the underlying Upper Floridan aquifer, although functioning primarily as an overlying semiconfining unit to the Upper Floridan aquifer. Hydraulic connection of the Intermediate system with surface water is indirect, through contact with flood-plain alluvium, riverbeds and lakebeds. Head differences in these units drive vertical leakage upward from the Upper Floridan aquifer to the rivers, and both upward and downward in areas away from the rivers.

Ground-water levels in the stream-aquifer system of the lower ACF River Basin fluctuate seasonally in response to precipitation, evapotranspiration, and pumpage. Maximum ground-water levels in the Upper Floridan aquifer and undifferentiated overburden occur in late winter and early spring as a result of recharge by infiltration of precipitation coupled with low evapotranspiration and pumpage. By late summer, seasonal increases in pumpage and evapotranspiration and decreased recharge cause ground-water levels to be at or near minimum values, and low water levels are maintained through the fall. Water levels in the Intermediate system respond to fluctuations in river stage that are transmitted through, although damped by, overlying surficial deposits. Seasonal water-level fluctuations in the Intermediate system are less than in the Upper Floridan aquifer and undifferentiated overburden, due to the rural setting, small water-supply needs, surface-water connection, and low water-transmitting properties of this unit in the study area.

Two finite-element, digital-computer models of two-dimensional, steady-state, ground-water flow successfully simulated stream-aquifer relations as defined by the 3-part conceptualization of the flow system. The northern and central parts constituted the Upper Floridan model, and the southern part constituted the Intermediate model. The mesh for the Upper Floridan model consisted of 12,295 elements and 12,113 nodes; the mesh for the Intermediate model contained 4,024 elements and 3,963 nodes. Physical or hydrologic boundaries consisting of either ground- or surface-water divides were used as limits for the finite-element mesh in each model.

In the Upper Floridan model, the ground-water component of stream-aquifer relations was represented with a model layer that simulated flow in the Upper Floridan aquifer. The simulated aquifer exchanged ground water by steady vertical leakage with the overlying semiconfining unit consisting of terrace and undifferentiated (surficial) deposits and undifferentiated overburden. The lower confining unit, or sub-Floridan confining unit, provided an impermeable base to the simulated aquifer. Wells and off-channel springs were simulated as constant-flow, point boundaries at nodes in the finite-element mesh that approximately located these features. Stream-aquifer relations were simulated by stream reaches represented with element sides of the finite-element mesh. Stream-aquifer flux was computed as the volumetric flow rate across streambed material in response to differences between stream stage and aquifer head by using linear and nonlinear functions that account for streambed dimensions and hydraulic characteristics. Lateral flow across model boundaries was simulated to represent regional ground-water movement into and out of the study area.

In the Intermediate model, the Intermediate system was simulated as a model layer in contact with surface water. Steady vertical leakage through overlying and underlying semiconfining units and lakebeds was simulated to provide recharge to, and discharge from, the Intermediate system. The hydraulic potential for this leakage was provided by input of appropriate values of source-layer head representing the overlying semiconfining unit, underlying Upper Floridan aquifer, and lakes. Stream-aquifer interaction was simulated in the Intermediate model as vertical flow across streambed sediments in the identical manner as that used in the Upper Floridan model. Wells and springflow were not simulated because they were either nonexistent or assumed negligible for the Intermediate system.

Calibration of the Upper Floridan and Intermediate models to steady-state, low-flow conditions of October 1986 was achieved according to error criteria established for computed head and stream-aquifer flux. Successful calibration validated the conceptualization of the stream-aquifer system as described for each of the 3 parts of the lower ACF River Basin and ensured the reliability of the models to simulate actual, worst-case, drought conditions.

Water budgets prepared using simulation results of October 1986 conditions provided a general, or overall, assessment of the ground- and surface-water components that function in the study area and indicated the relative importance of specific components of the flow system during worst-case, drought conditions. Results indicated that stream-aquifer interaction is dominated by ground-water discharge from the aquifer to streams and in-channel springs. About 99 percent of stream-aquifer interaction consists of ground-water discharge to streams and in-channel springs, as measured by rates of ground-water discharge to, or recharge from, these features. About 98 percent occurs in the northern and central parts of the lower ACF River Basin, where the Upper Floridan aquifer is connected hydraulically with surface water. This supports the concept that the Upper Floridan aquifer is the primary hydrologic component for transmitting ground water to streams.

The largest and most influential water-budget components of the stream-aquifer system were those associated with the Upper Floridan aquifer. Ground-water discharge to streams and in-channel springs and recharge from the undifferentiated overburden were the largest water-budget components in the stream-aquifer system; both occurred at about 5 times the October 1986 pumping rate. Recharge to the Upper Floridan aquifer by regional flow across lateral boundaries, excluding flow from outcrop areas, exerted less of an influence on the stream-aquifer system than discharge to streams and in-channel springs or recharge from the overburden, but, nonetheless, occurred at about twice the pumping rate. Outcrop areas had a slight influence on the water resources of the Upper Floridan aquifer, providing recharge at a rate that was about one-fourth of the pumping rate. Recharge from streams had a negligible effect on stream-aquifer relations.

Effects of possible multiple-use scenarios on the water resources of the lower ACF River Basin can be evaluated by understanding how changes in stress, such as ground-water pumpage, applied to the stream-aquifer system might affect ground-water levels and specific components of the water budget during worst-case, drought conditions, such as October 1986. Ground-water-development plans that ultimately decrease ground-water discharge to streams and in-channel springs and that increase recharge by vertical leakage will have negative effects on the quantity and availability of water for multiple uses in a specific area and possibly basinwide. Water budgets developed from results of simulating worst-case conditions involving increased pumpage from the October 1986 rates indicated large reductions in ground-water discharge to streams and in-channel springs and increased recharge from the overburden. Pumpage-induced, water-level declines caused areas of the aquifer to partially dewater. Some areas became completely dry, indicating that a high potential for adverse hydrologic responses to ground-water development exists if care is not exercised when formulating alternative plans for resource development during drought conditions. How much pumpage-induced, streamflow reduction or ground-water-level decline is acceptable or can be tolerated is a question water managers can answer only after weighing the hydrologic and economic benefits and costs of existing plans against anticipated effects resulting from alternative or hypothetical multi-use scenarios.

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TABLES 7 AND 8

Table 7. Ground-water-level residuals from calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin

[Water-level altitude and residual, in feet above sea level]

Well number	$h_{i\,model}$[1] Computed water-level altitude	$h_{i\,obs.}$[1] Measured water-level altitude	Water-level residual	Well number	$h_{i\,model}$[1] Computed water-level altitude	$h_{i\,obs.}$[1] Measured water-level altitude	Water-level residual
CAL002	44.9	47.8	−2.9	06G012	91.1	99.9	−8.8
CAL001	51.7	57.8	−6.1	11G001	97.1	91.7	5.4
GAD003	71.1	57.4	13.7	10G001	95.4	96.6	−1.2
JAC001	72.7	70.6	2.1	ALA0V4	95.2	113.6	−18.4
JAC002	75.6	86.3	−10.7	08G005	89.0	94.1	−5.1
06E001	76.6	72.1	4.5	10G005	88.6	86.5	2.1
JAC006	76.8	87.2	−10.4	11G003	103.7	96.7	7.0
JAC009	79.1	72.4	6.7	ALA0S8	131.4	136.2	−4.8
08E005	75.9	73.8	2.1	09G007	82.0	81.8	.2
08E003	76.1	73.0	3.1	08G007	88.6	100.1	−11.5
06E020	76.8	80.4	−3.6	11G004	106.9	105.2	1.7
06E018	77.0	72.5	4.5	07G005	97.5	90.7	6.8
08E006	76.4	76.4	0.0	09G010	84.7	86.8	−2.1
07E007	77.1	72.4	4.7	ALA0U8	129.6	136.4	−6.8
06E019	77.0	74.1	2.9	ALAT10	136.1	124.4	11.7
07E006	77.3	77.7	−.4	06G008	95.0	92.1	2.9
08E002	76.5	78.8	−2.3	07G008	99.4	97.5	1.9
08E007	76.6	72.3	4.3	09G008	91.6	97.3	−5.7
07F005	78.3	75.9	2.4	06G006	95.9	90.3	5.6
07F006	79.1	73.2	5.9	11G002	103.7	104.0	−.3
06F007	77.7	77.5	.2	10G313	90.4	88.7	1.7
08F009	77.0	77.1	−.1	09G005	91.2	99.8	−8.6
06F004	79.5	78.7	.8	08G004	103.9	103.2	.7
06F001	79.1	74.9	4.2	09G004	82.9	78.6	4.3
08F017	77.6	79.4	−1.8	08G001	103.6	110.6	−7.0
06F005	79.6	85.6	−6.0	09G006	99.3	92.1	7.2
08F012	78.1	77.4	.7	12H009	121.9	120.2	1.7
07F002	82.7	85.0	−2.3	07G001	119.2	117.0	2.2
06F003	82.8	81.5	1.3	07H006	116.3	121.0	−4.7
08F010	79.4	77.9	1.5	06H007	119.7	124.1	−4.4
09F005	78.6	75.0	3.6	07H009	123.6	127.9	−4.3
09F520	79.4	78.7	.7	11H005	105.0	102.8	2.2
JAC003	106.5	101.5	5.0	07H005	114.4	122.5	−8.1
09F004	82.8	83.6	−.8	06H013	123.4	131.5	8.1
07F003	82.4	69.9	12.5	09H013	101.7	104.1	−2.4
10F004	88.3	89.2	−.9	10H006	91.5	94.5	−3.0
JAC005	95.6	97.4	−1.8	06H006	125.9	129.2	−3.3
08F006	82.9	78.0	4.9	07H008	124.6	126.4	−1.8
09F006	78.6	78.7	−.1	11H003	103.8	103.6	.2
08F011	83.8	87.0	−3.2	09H012	96.2	95.9	.3
07F004	86.7	79.9	6.8	09H001	89.6	108.0	−18.4
10F001	85.3	87.5	−2.2	06H005	130.6	141.8	−11.2
08F007	84.4	84.6	−.2	07H014	131.1	129.6	1.5
06F006	88.7	89.8	−1.1	08H011	121.7	116.2	5.5
07G007	90.5	98.5	−8.0	06H004	130.1	141.6	−11.5
ALA0X2	109.8	109.7	.1	08H010	116.9	118.4	−1.5
08G006	86.1	82.3	3.8	07H002	133.4	133.7	−.3
06G007	81.6	84.6	−3.0	ALAO12	189.0	193.1	−4.1

Footnote at end of table.

Table 7. Ground-water-level residuals from calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin—Continued

[Water-level altitude and residual, in feet above sea level]

Well number	$h_{i\ model}$[1] Computed water-level altitude	$h_{i\ obs.}$[1] Measured water-level altitude	Water-level residual	Well number	$h_{i\ model}$[1] Computed water-level altitude	$h_{i\ obs.}$[1] Measured water-level altitude	Water-level residual
09H006	106.3	112.1	−5.8	08J005	79.2	95.2	−16.0
06H009	141.2	142.8	−1.6	14J020	193.6	197.5	−3.9
07H012	131.7	133.1	−1.4	14J018	184.0	184.4	−.4
05H011	135.6	138.0	−2.4	13J004	147.9	145.3	2.6
07H010	144.6	148.0	−3.4	09J012	152.0	147.8	4.2
05H008	144.7	158.5	−13.8	11J020	133.3	123.9	9.4
08H008	133.8	117.1	16.7	12J003	129.1	131.8	−2.7
08H006	129.4	124.9	.5	11J004	141.7	137.7	4.0
08H003	136.5	125.6	10.9	14J019	204.4	201.7	2.7
10H004	100.5	110.3	−9.8	08K001	183.6	200.0	−16.4
07H011	149.7	144.9	4.8	14J022	193.4	196.9	−3.5
09H007	124.1	127.7	3.6	12K001	138.9	136.4	2.5
12H008	131.2	126.1	5.1	09K010	175.8	185.1	−9.3
11H008	115.5	119.6	−4.1	10K004	148.3	144.7	3.6
08H005	144.4	128.0	16.4	08K013	181.3	185.3	−4.0
09H008	128.9	130.2	−1.3	11K011	141.6	137.9	3.7
08H009	139.3	145.1	−5.8	14K007	189.4	185.3	4.1
09H009	120.8	126.6	−5.8	13K013	172.5	154.9	17.6
11H007	118.7	123.6	−4.9	14K008	190.6	191.3	−.7
13H007	153.2	146.3	6.9	12K009	142.2	135.3	6.9
08H007	144.3	135.6	8.7	12K014	41.9	35.2	6.7
07H015	149.4	129.2	20.2	13K017	164.4	157.4	7.0
05J007	173.4	167.0	6.4	13K018	177.6	182.9	−5.3
11J001	120.3	122.3	−2.0	08K008	219.2	220.1	−.9
09J009	135.9	136.3	−.4	12K013	141.0	148.0	−7.0
11J018	119.8	121.1	−1.3	15K010	216.5	215.8	.7
09J005	135.5	135.6	−.1	13K014	148.7	148.1	.6
11J006	115.4	116.4	−1.0	11K015	152.7	146.3	6.4
11J019	118.8	122.9	−4.1	12K016	144.5	150.8	−6.3
07J013	160.3	145.3	15.0	13K011	162.6	150.3	12.3
08J015	158.7	149.0	9.7	14K011	207.1	205.3	1.8
10J006	126.8	128.7	−1.9	08K007	218.7	218.8	−.1
10J005	130.0	136.4	−6.4	08K006	210.9	210.9	0.0
13J001	159.5	168.4	−8.9	10K005	177.9	166.4	11.5
09J010	139.2	122.8	16.4	13K019	148.4	143.9	4.5
11J012	116.9	115.4	1.5	14K012	221.6	220.7	.9
10J003	129.5	127.3	2.2	14K009	180.8	190.7	−9.9
09J004	143.4	130.6	12.8	11K003	157.1	158.6	−1.5
11J016	123.2	120.7	2.5	15K009	222.4	221.9	.5
11J005	124.4	120.9	3.5	14K006	207.9	212.4	−4.5
12J002	136.0	134.5	1.5	11L019	168.5	161.5	7.0
07J012	173.3	155.7	17.6	14L013	212.4	210.7	1.7
09J002	146.5	137.8	8.7	13L048	172.9	173.6	.7
09J008	144.4	134.0	10.4	13L028	167.5	165.7	1.8
09J003	153.5	138.4	15.1	13L033	164.5	157.4	7.1
14J021	186.3	184.6	1.7	16L019	220.5	212.5	8.0
11J014	132.2	136.1	−3.9	13L012	156.1	148.9	7.2
08J004	171.1	187.8	−16.7	11L014	181.0	176.5	4.5

Footnote at end of table.

Table 7. Ground-water-level residuals from calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin—Continued

[Water-level altitude and residual, in feet above sea level]

Well number	$h_{i\ model}$[1] Computed water-level altitude	$h_{i\ obs.}$[1] Measured water-level altitude	Water-level residual
12L030	153.4	151.0	2.4
15L020	228.2	217.3	10.9
13L032	164.8	154.9	9.9
12L023	159.0	145.8	13.2
11L020	185.2	183.9	1.3
12L028	164.9	159.6	5.3
14L012	221.2	222.9	-1.7
13L003	174.7	182.2	-7.5
13L057	166.9	151.4	15.5
12L029	155.3	139.1	16.2
11L022	196.3	182.6	13.7
14L009	225.9	233.1	-7.2
14L011	207.5	208.6	-1.1
13L049	162.3	164.2	-1.9
10L004	212.5	218.9	-6.4
11L003	204.8	199.7	5.1
15L022	237.7	241.6	-3.9
11L018	193.1	193.4	-.3
13L014	168.2	174.0	-5.8
11L021	197.2	188.4	8.8
12L044	158.4	166.7	-8.3
11L017	196.7	190.0	6.7
13L052	170.4	183.9	-13.5
13L047	203.5	195.1	8.4
13L054	181.1	176.0	5.1
12L045	172.9	178.4	-5.5
13L059	173.4	180.5	-7.1
13L055	191.2	183.6	7.6
12L043	177.0	182.4	-5.4
15L023	241.1	247.5	-6.4
14L014	230.2	234.8	-4.6
13M081	181.6	185.7	-4.1
13M013	186.6	202.3	-15.7
12M017	89.4	79.4	10.0
11M010	210.7	209.0	1.7
10M003	228.1	230.8	-2.7
13M083	199.2	212.1	-12.9
11M006	224.3	231.6	-7.3
13M061	209.6	207.8	1.8
13M063	214.7	212.0	2.7
15M005	250.4	251.7	-1.3
13M008	207.3	212.6	-5.3
11M007	228.3	245.3	-17.0
14M009	211.5	222.0	-10.5
12M010	202.7	193.6	9.1
12M025	197.7	183.0	14.7
13M057	210.1	215.6	-5.5
13M062	220.6	217.6	3.0
13M049	210.9	212.9	-2.0
13M080	229.9	230.3	-0.4
12M028	198.3	193.1	5.2
15M004	257.0	259.1	-2.1
13M004	224.5	226.0	-1.5
13M050	213.8	209.8	4.0
12M012	211.7	203.8	7.9
13M059	224.9	232.5	-7.6
12M004	208.4	204.6	3.8
12M011	202.9	194.7	8.2
13M079	230.5	227.7	2.8
13M051	221.5	221.1	.4
13M077	220.5	219.3	1.2
11M019	252.4	247.3	5.1
14M008	246.6	250.2	-3.6
13M006	217.0	219.7	-2.7
13M078	225.2	228.2	-3.0
14M006	227.0	230.5	-3.5
13M066	217.7	216.6	1.1
13M060	224.7	225.5	-.8
13M009	225.4	227.6	-2.2
10N013	292.5	293.6	-1.1
10N012	295.0	293.5	1.5
12N003	233.6	240.7	-7.1
12N005	223.9	223.8	.1
12N002	232.8	240.6	-7.8
13N003	231.6	237.9	-6.3
13N005	242.3	250.9	-8.6
13N004	241.7	242.6	-.9
13N009	255.4	264.2	-8.8
13N007	259.3	255.0	4.3
12N004	263.1	263.1	0.0
13P005	262.5	258.6	3.9
11P006	280.3	276.4	3.9
12P012	268.7	273.2	-4.5
13P004	266.0	273.0	-7.0
12P011	284.1	280.2	3.9
12P010	281.2	272.3	8.9
15P002	275.3	273.3	2.0
15P018	265.2	263.5	1.7
14P013	240.0	230.7	9.3
14P001	238.4	229.4	9.0
14P012	258.2	243.6	14.6
15Q011	277.5	284.0	-6.5

[1] $Average\ residual = \frac{1}{N}\sum_{i=1}^{N}\left(h_{i\ model} - h_{i\ obs}\right) = 0.4\ ft;\ N = 284.$

Table 8. Ground-water-level residuals from calibrated Intermediate model
[Water-level altitude and residual in feet above sea level]

Well number	$h_{i\ model}$[1] Computed water-level altitude	$h_{i\ obs.}$[1] Measured water-level altitude	Water-level residual
CAL003	26.5	29.0	−2.5
CAL004	25.5	30.0	−4.5
CAL005	32.4	34.0	−1.6
FRA001	7.4	3.0	4.4
FRA002	5.1	9.0	−3.9
FRA003	8.9	2.0	−3.1
FRA004	8.8	15.0	−6.2
GUL001	−0.8	−2.0	1.2
GUL002	7.8	10.0	−2.2
GUL003	8.0	−2.0	10.0
GUL004	11.0	7.0	−6.0
GUL005	16.3	18.0	−1.7
GUL006	16.4	21.0	−4.6
GUL008	15.3	15.0	0.3
GUL009	18.3	22.0	−3.7
LIB001	39.6	34.0	5.6
LIB002	37.9	34.0	3.9
LIB003	14.6	10.0	4.6
LIB004	29.9	31.0	−1.1

[1] $Average\ residual = \frac{1}{N}\sum_{i=1}^{N}\left(h_{i\ model} - h_{i\ obs}\right) = 0.6\ ft;\ N = 19.$

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
U.S. ARMY CORPS OF ENGINEERS, MOBILE DISTRICT
ALABAMA DEPARTMENT OF ECONOMIC AND COMMUNITY AFFAIRS
NORTHWEST FLORIDA WATER MANAGEMENT DISTRICT
GEORGIA DEPARTMENT OF NATURAL RESOURCES, ENVIRONMENTAL PROTECTION DIVISION

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Base from U.S. Geological Survey
State base maps, 1:500,000

0 10 20 30 MILES
0 10 20 30 KILOMETERS

MAP SHOWING LOCATION OF WATER-LEVEL MEASUREMENTS IN WELLS OPEN TO UPPER FLORIDAN AQUIFER AND WATER-BEARING UNITS OF INTERMEDIATE SYSTEM AND SURFACE-WATER MEASUREMENTS IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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WATER-SUPPLY PAPER 2460
Clayey sediment thickness in overlying semiconfining units—PLATE 2
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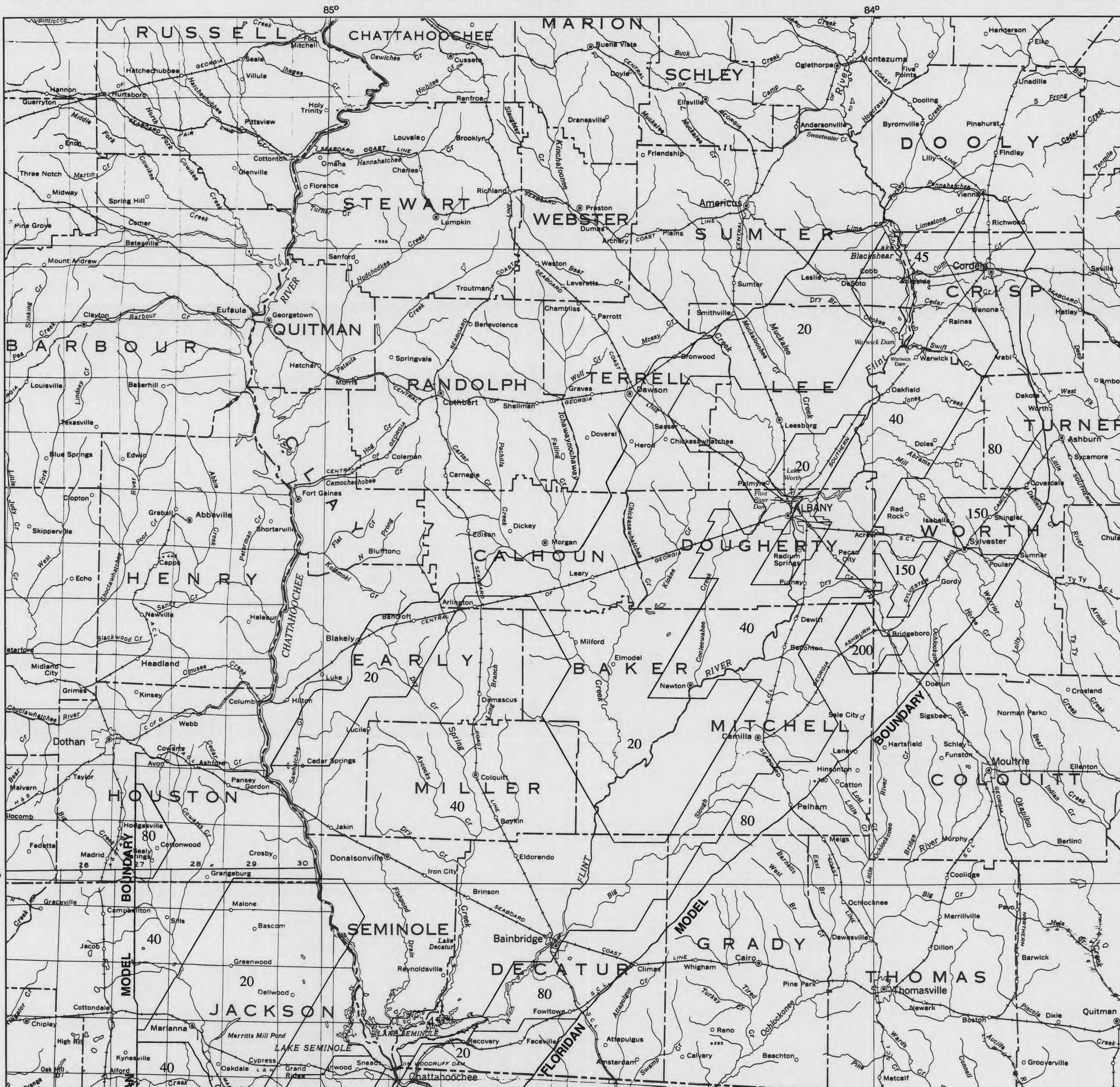

Base from U.S. Geological Survey
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0 10 20 30 MILES
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MAP SHOWING ZONES OF THICKNESS OF PREDOMINANTLY CLAYEY SEDIMENTS IN OVERLYING SEMICONFINING UNITS TO INTERMEDIATE SYSTEM AND UPPER FLORIDAN AQUIFER IN THE LOWER APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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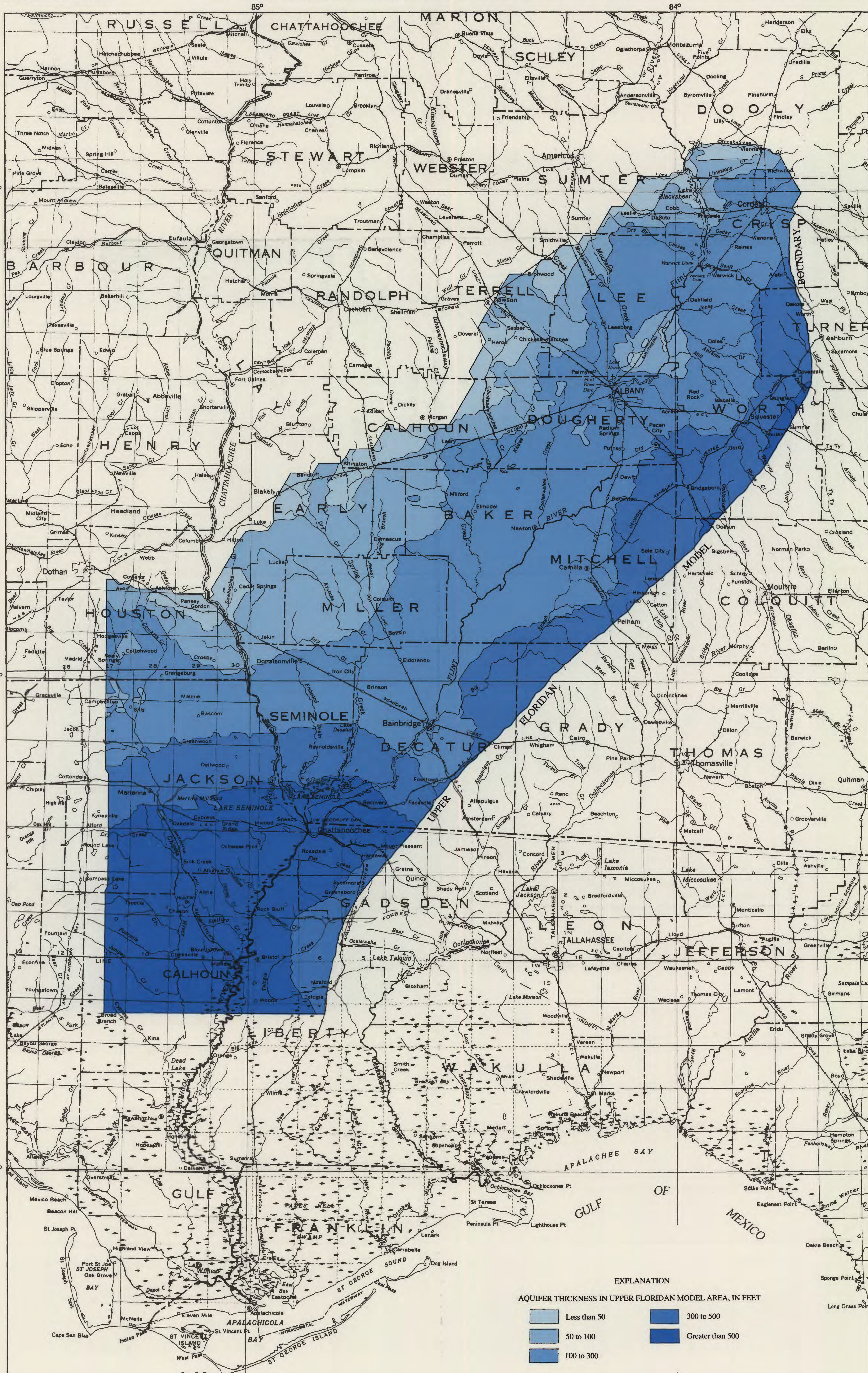

Base from U.S. Geological Survey
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0 10 20 30 MILES
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MAP SHOWING THICKNESS OF UPPER FLORIDAN AQUIFER IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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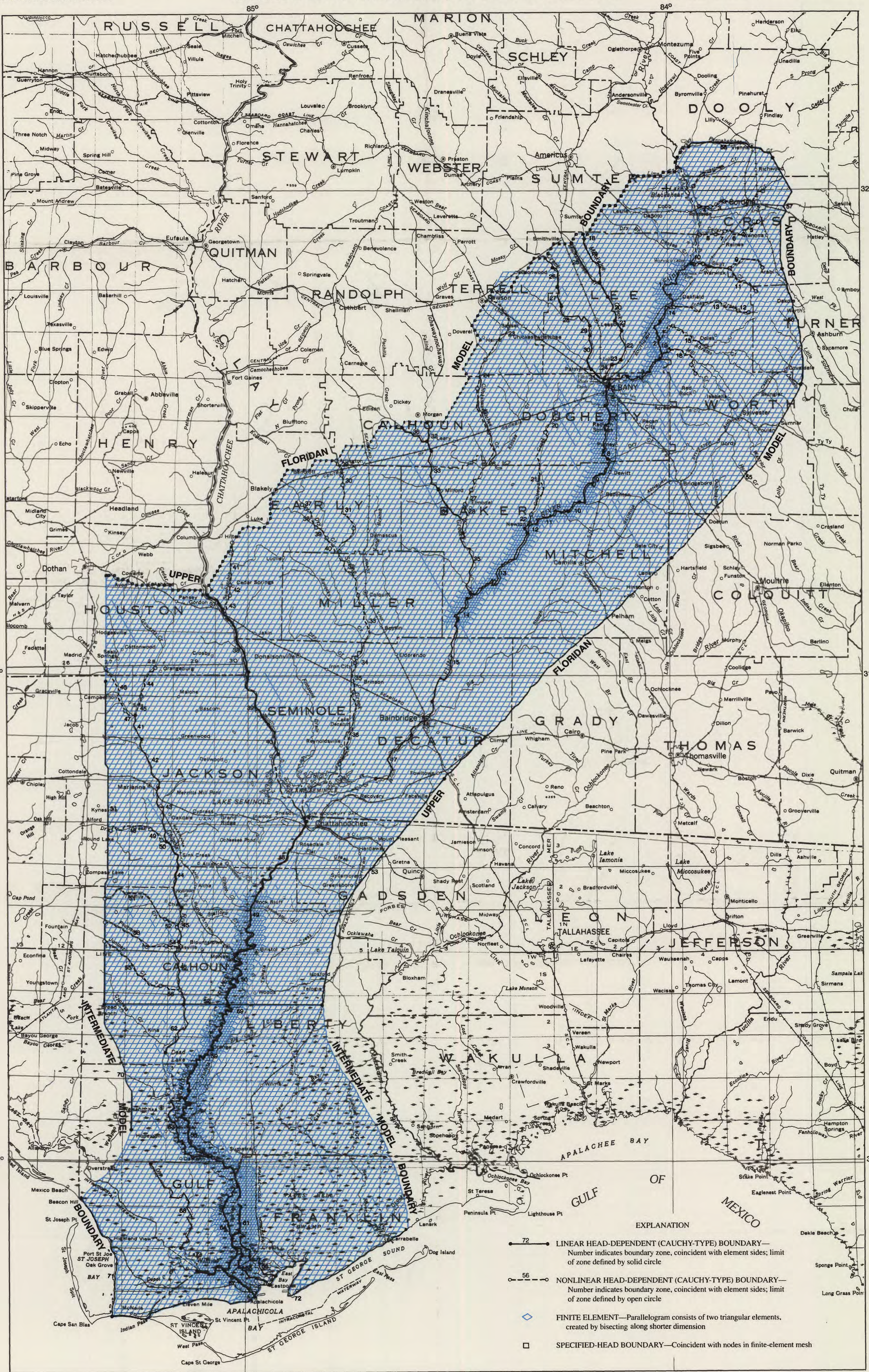

Base from U.S. Geological Survey
State base maps, 1:500,000

0 10 20 30 MILES
0 10 20 30 KILOMETERS

MAP SHOWING FINITE-ELEMENT MESH AND BOUNDARY CONDITIONS FOR MODELS OF THE UPPER FLORIDAN AQUIFER AND INTERMEDIATE SYSTEM IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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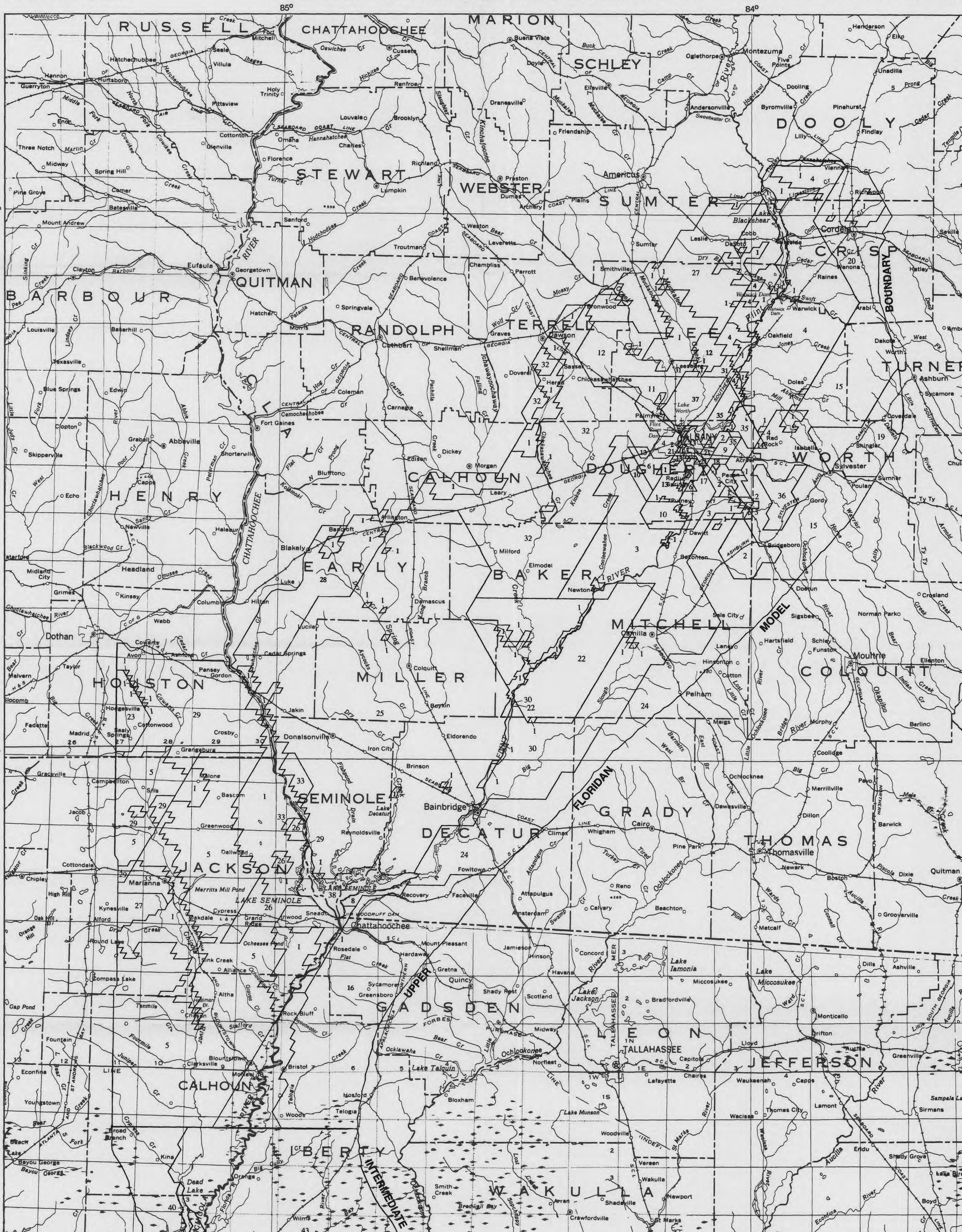

Base from U.S. Geological Survey
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0 10 20 30 MILES
0 10 20 30 KILOMETERS

MAP SHOWING ZONES OF VERTICAL HYDRAULIC CONDUCTANCE OF OVERLYING SEMICONFINING UNITS IN THE UPPER FLORIDAN AND INTERMEDIATE MODELS IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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MAP SHOWING DISTRIBUTION OF HYDRAULIC-PROPERTY ZONES FOR THE UPPER FLORIDAN AND INTERMEDIATE MODELS IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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WATER-SUPPLY PAPER 2460
Pumped wells, Oct. 1986—PLATE 7
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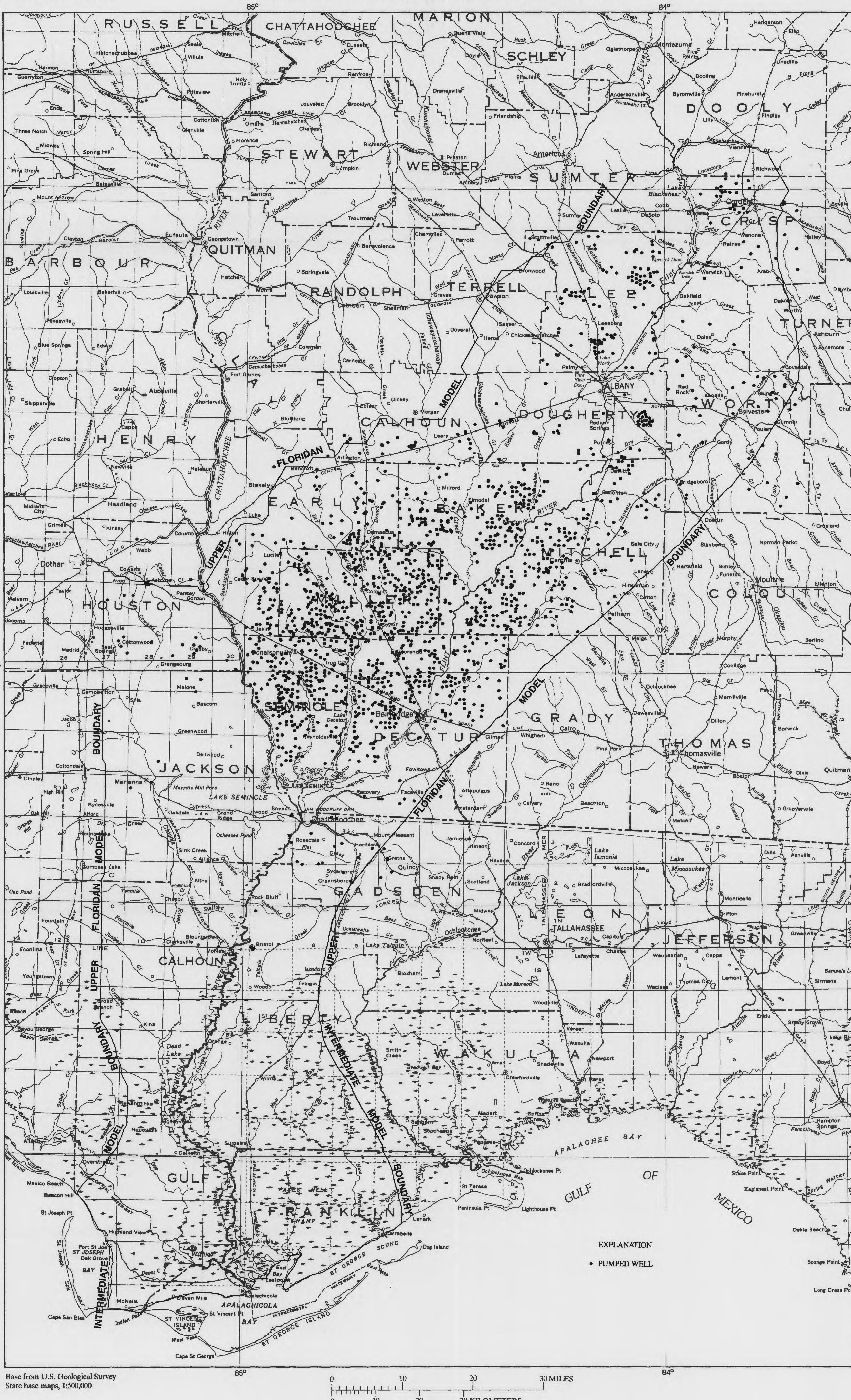

MAP SHOWING DISTRIBUTION OF PUMPED WELLS IN THE NORTHERN AND CENTRAL PARTS OF THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA, OCTOBER 1986

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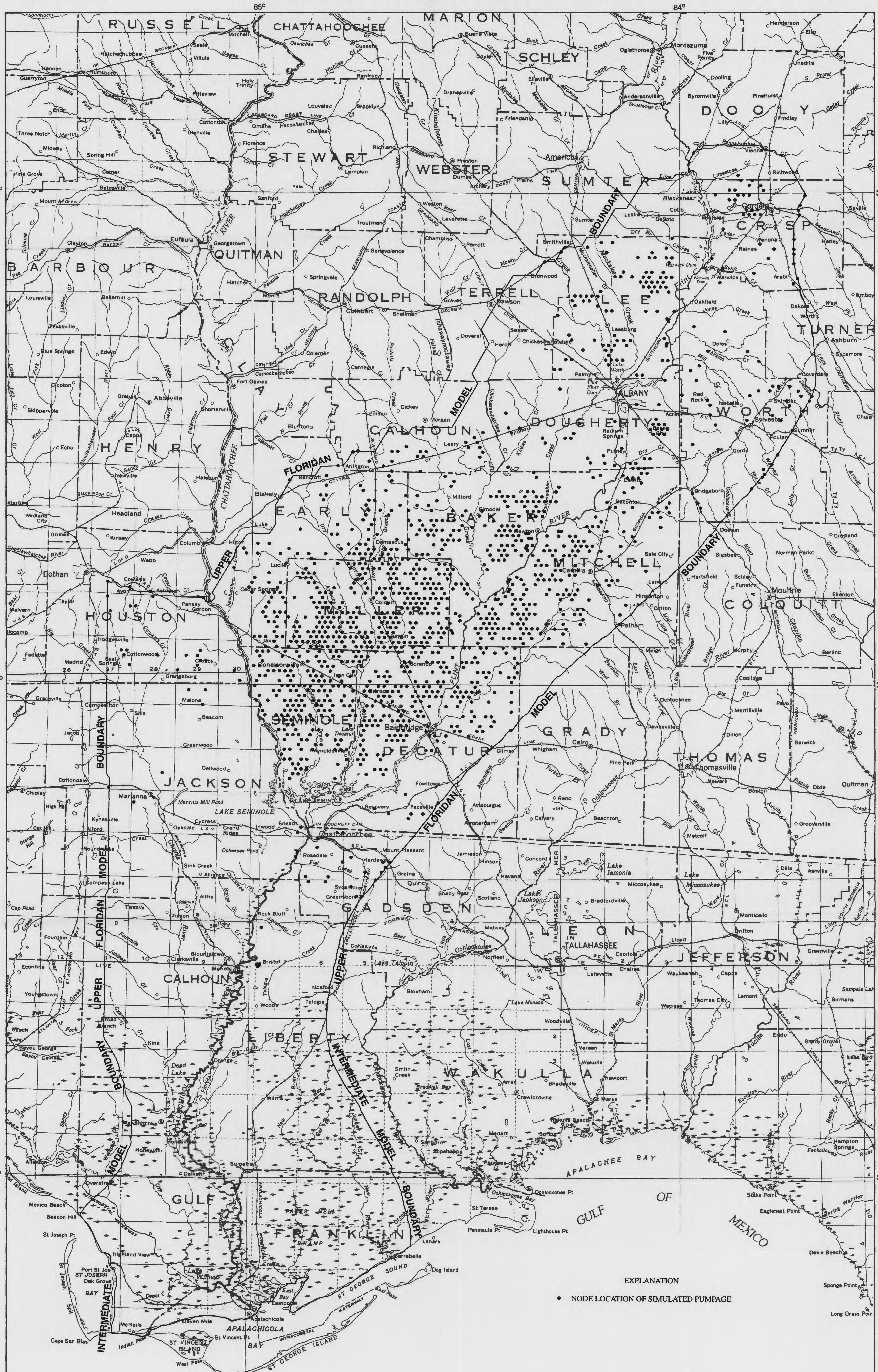

Base from U.S. Geological Survey
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0 10 20 30 MILES
0 10 20 30 KILOMETERS

MAP SHOWING DISTRIBUTION OF NODES SIMULATING PUMPAGE IN THE NORTHERN AND CENTRAL PARTS OF THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA, OCTOBER 1986

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MAP SHOWING STREAM REACHES SIMULATED WITH SIDES OF FINITE-ELEMENT MESH FOR UPPER FLORIDAN AND INTERMEDIATE MODELS IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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WATER-SUPPLY PAPER 2460
Water-level residuals Oct. 1986—PLATE 10
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MAP SHOWING LOCATIONS OF WATER-LEVEL MEASUREMENTS AND WATER-LEVEL RESIDUALS FOR THE CALIBRATED UPPER FLORIDAN AND INTERMEDIATE MODELS IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA, OCTOBER 1986

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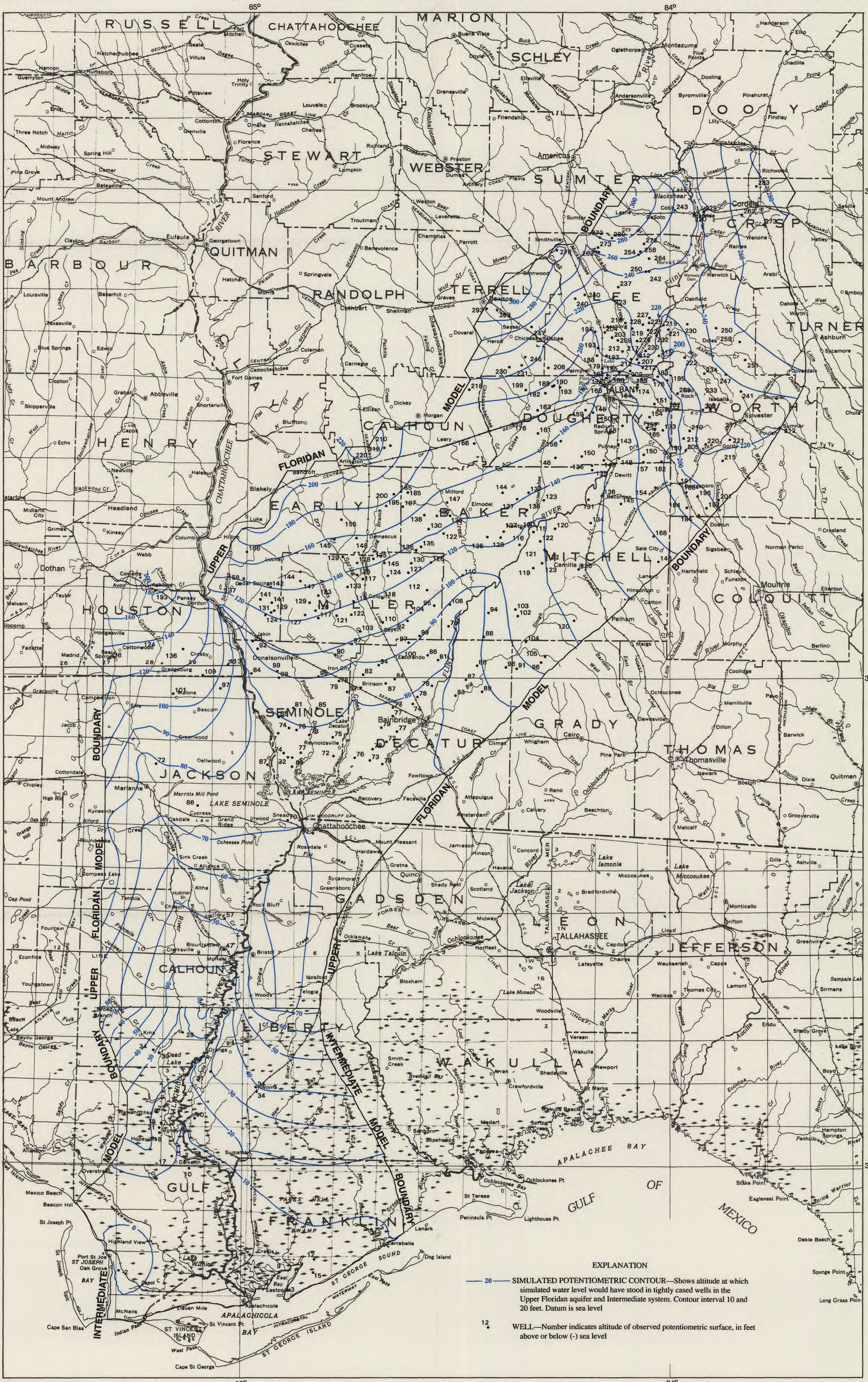

Base from U.S. Geological Survey
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MAP SHOWING SIMULATED POTENTIOMETRIC SURFACE AND MEASURED WATER LEVELS IN THE UPPER FLORIDAN AQUIFER AND INTERMEDIATE SYSTEM FOR CALIBRATION CONDITIONS IN THE LOWER APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA, OCTOBER 1986

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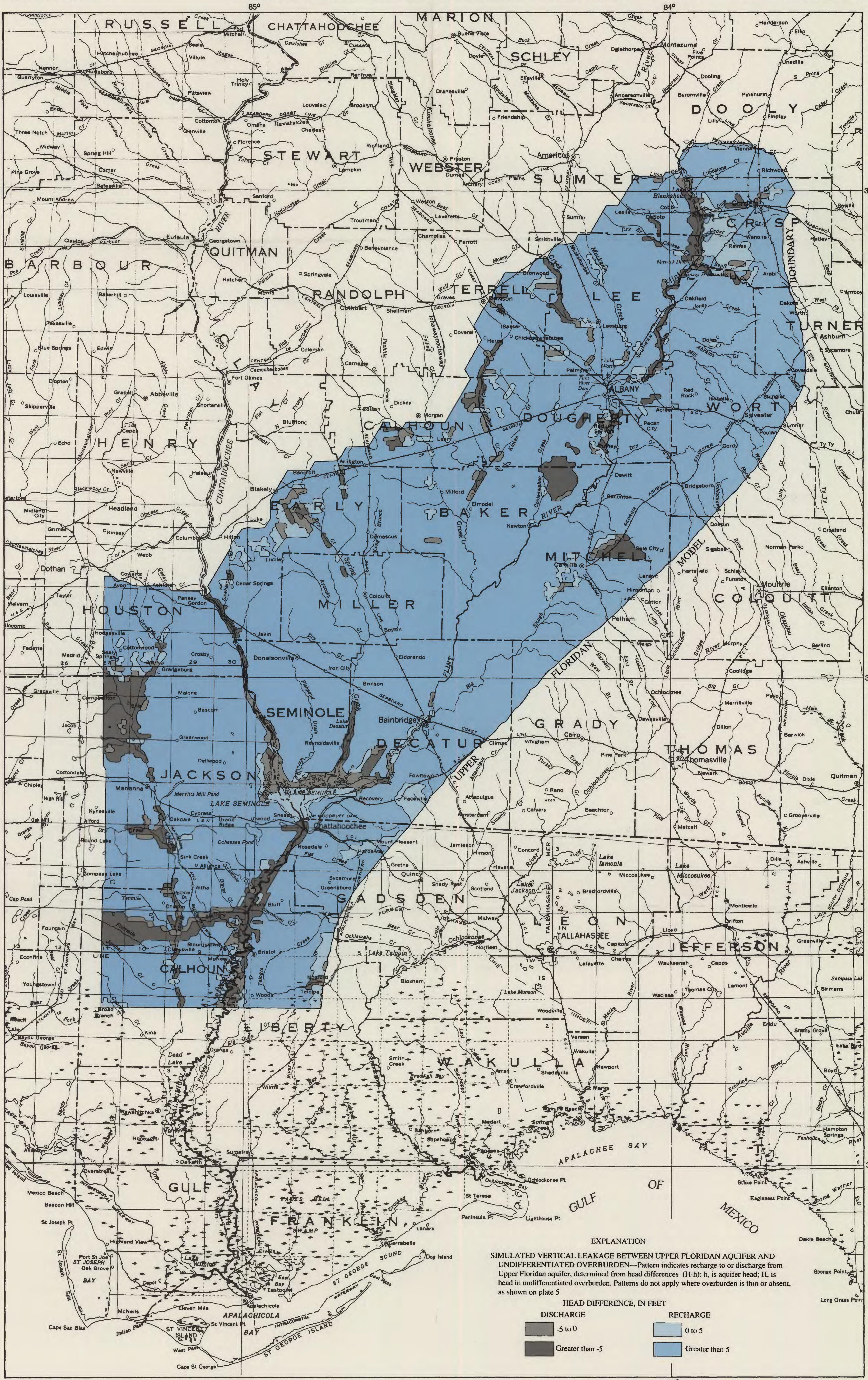

Base from U.S. Geological Survey
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MAP SHOWING VERTICAL LEAKAGE BETWEEN UPPER FLORIDAN AQUIFER AND UNDIFFERENTIATED OVERBURDEN IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN, SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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