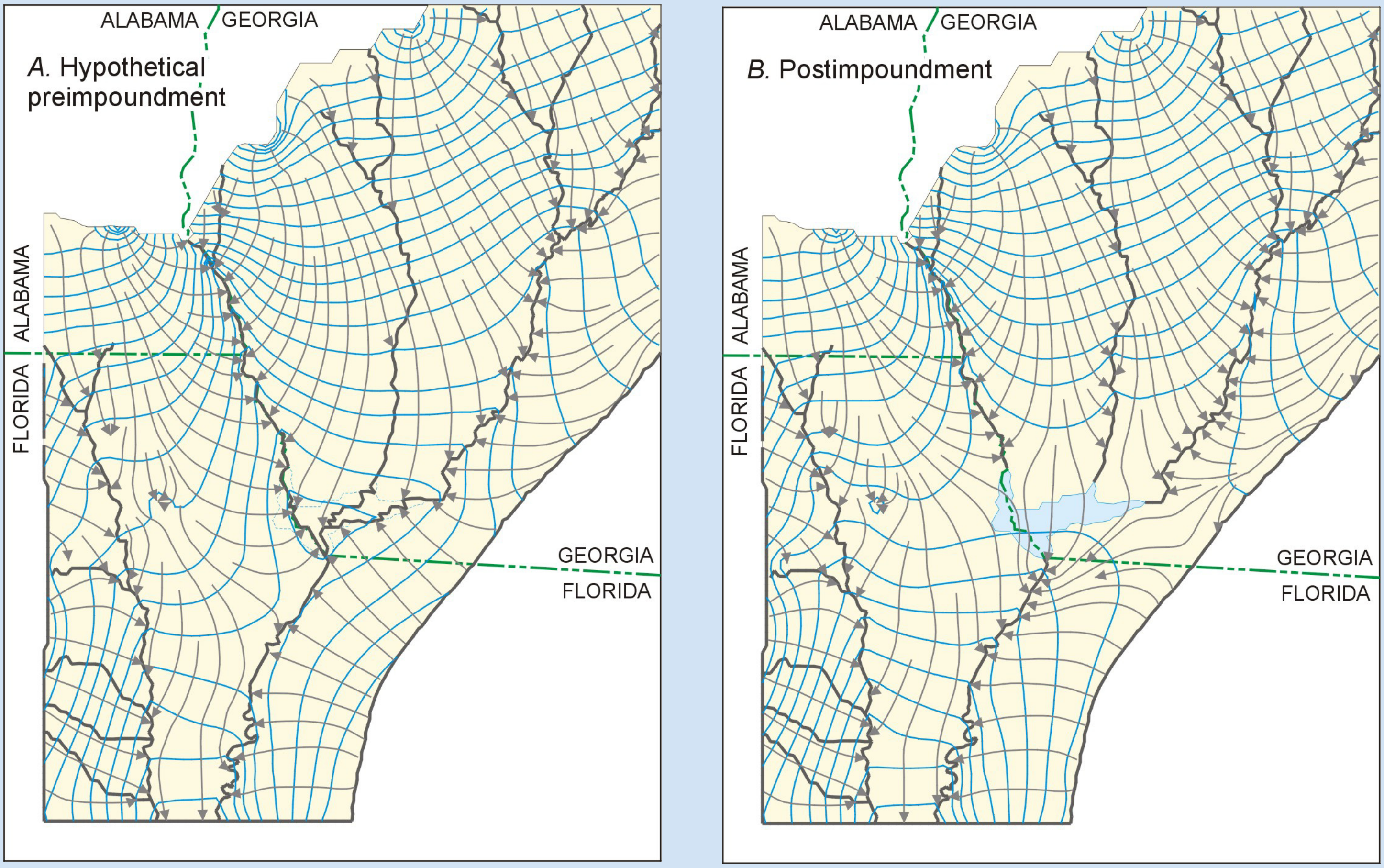
Simulated Effects of Impoundment of Lake Seminole on Ground-Water Flow in the Upper Floridan Aquifer in Southwestern Georgia and Adjacent Parts of Alabama and Florida



Prepared in cooperation with the
Georgia Department of Natural Resources
Environmental Protection Division
Georgia Geologic Survey

Scientific Investigations Report 2004-5077

U.S. Department of the Interior
U.S. Geological Survey

Cover: Northern view of Jim Woodruff Lock and Dam from the west bank of the Apalachicola River. Photo by Dianna M. Crilley, U.S. Geological Survey.

A. Map showing simulated flow net of the Upper Floridan aquifer in the lower Apalachicola-Chattahoochee-Flint River basin under hypothetical preimpoundment Lake Seminole conditions.

B. Map showing simulated flow net of the Upper Floridan aquifer in the lower Apalachicola-Chattahoochee-Flint River basin under postimpoundment Lake Seminole conditions.

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U.S. Department of the Interior
Gale A. Norton, Secretary

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Conversion Factors and Datum

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

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Historical data collected and stored as National Geodetic Vertical Datum of 1929 have been converted to NAVD 88 for this publication.

Simulated Effects of Impoundment of Lake Seminole on Ground-Water Flow in the Upper Floridan Aquifer in Southwestern Georgia and Adjacent Parts of Alabama and Florida

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Abstract

Hydrologic implications of the impoundment of Lake Seminole in southwest Georgia and its effect on components of the surface- and ground-water flow systems of the lower Apalachicola–Chattahoochee–Flint (ACF) River Basin were investigated using a ground-water model. Comparison of simulation results of postimpoundment drought conditions (October 1986) with results of hypothetical preimpoundment conditions (a similar drought prior to 1955) provides a qualitative measure of the changes in hydraulic head and ground-water flow to and from streams and Lake Seminole, and across State lines caused by the impoundment.

Based on the simulation results, the impoundment of Lake Seminole changed ground-water flow directions within about 20–30 miles of the lake, reducing the amount of ground water flowing from Florida to Georgia southeast of the lake. Ground-water storage was increased by the impoundment, as indicated by a simulated increase of as much as 26 feet in the water level in the Upper Floridan aquifer. The impoundment of Lake Seminole caused changes to simulated components of the ground-water budget, including reduced discharge from the Upper Floridan aquifer to streams (315 million gallons per day); reduced recharge from or increased discharge to regional ground-water flow at external model boundaries (totaling 183 million gallons per day); and reduced recharge from or increased discharge to the undifferentiated overburden (totaling 129 million gallons per day).

Introduction

Lake Seminole is a 37,600-acre (58.8-square-mile [mi^2]) impoundment, located in extreme southwestern Georgia and northwestern Florida (fig. 1), that was formed from construction of Jim Woodruff Lock and Dam by the U.S. Army Corps of Engineers (USACE) from the late 1940s to mid-1950s. The dam is situated on the Apalachicola River about 1,000 feet (ft) downstream of where the Flint River and Chattahoochee River channels converge near the Georgia-Florida State line, approximately 107 miles (mi) upstream from Apalachicola Bay and the Gulf of Mexico. About 250 mi of lake shoreline are irregularly distributed along two major impoundment arms on the Chattahoochee and Flint Rivers and along two minor impoundment arms on Spring Creek and Fishpond Drain, both of which are tributary to the Flint River impoundment arm. Backwater conditions inundate natural courses and floodplains of these streams, extending about 47 mi from the dam up the Chattahoochee River and Flint River impoundment arms (U.S. Army Corps of Engineers and others, 1984), and extending lesser distances upstream of the dam along other tributaries.

Jim Woodruff Lock and Dam is a multiple-purpose structure operated by the USACE, the primary functions of which are to aid navigation in the Apalachicola River downstream of the dam and in the Chattahoochee and Flint Rivers upstream, and to generate hydroelectric power. Secondary benefits of the dam include public recreation, regulation of streamflow, and fish and wildlife conservation. Despite its size, Lake Seminole is a run-of-the-river impoundment, dependent on inflow from the Chattahoochee and Flint Rivers to maintain flow in the Apalachicola River downstream of the dam. No flood-control storage is available in Lake Seminole (U.S. Army Corps of Engineers and others, 1984).

Construction of the lock and dam began during September 1947; the lock was opened to navigation during May 1954; and full pool (77 ft) was attained on February 4, 1957, at which time the power plant began operation (U.S. Army Corps of Engineers and others, 1984). At extreme low flow, the dam provides a 33-ft pool differential between tail water in the Apalachicola River (44 ft) and normal lake stage (full pool).

Releases from the dam and the impounded water behind it have become important local resources for shipping, hydroelectric power, and recreation. Outflow from the lake has a direct influence on the water resources, ecology, and economy of the Apalachicola River, its floodplain and estuary, and the Apalachicola Bay region, affecting navigation, hydroelectric power generation, flow regulation, and the supply of nutrients and detritus that support diverse aquatic biota, including Apalachicola Bay's diverse shellfish population.

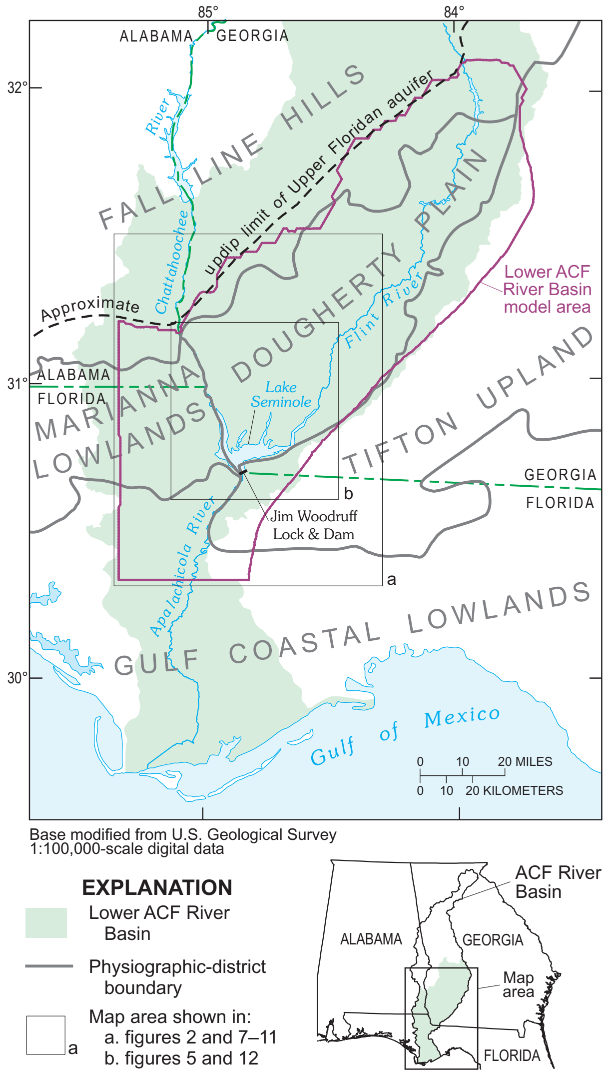

Figure 1. Location of study area, lower Apalachicola–Chattahoochee–Flint (ACF) River Basin area, lower ACF River Basin model area, and physiographic districts of the Coastal Plain Province (modified from Jones and Torak, 2003).

The Apalachicola–Chattahoochee–Flint (ACF) River Basin encompasses a long, narrow area of about 19,200 mi^2, mostly in western and southwestern Georgia and partly in southeastern Alabama and northwestern Florida (fig. 1). About 17,200 mi^2 of the drainage basin are tributary to Lake Seminole, being nearly equally divided between the Chattahoochee and Flint Rivers, which provide headwater to the Apalachicola River downstream of the dam. The remaining 2,000-mi^2 area is tributary directly to the Apalachicola River (U.S. Army Corps of Engineers, 1973).

Of local and regional importance is the roughly 5,000 mi^2 of drainage area proximate to Lake Seminole within the Dougherty Plain and Marianna Lowlands divisions of the Coastal Plain physiographic province (fig. 1). This region is underlain by karst limestone of Eocene and Oligocene age that comprises the Upper Floridan aquifer. The lake interacts hydraulically with the limestone by direct leakage through sinkholes, cavities, and other dissolution features that were once exposed in the karstic floodplains of the Chattahoochee and Flint Rivers, but since impoundment are part of the lake bed. A relatively thin mantle of chemically weathered limestone residuum and alluvium, collectively termed *undifferentiated overburden*, overlies the aquifer and allows indirect leakage to and from Lake Seminole where these sediments are present in the lake bed. Many springs originating in the limestone discharge into Lake Seminole along the lake bottom or adjacent to the impoundment arms, flowing into the lake from small channels or spring runs.

The Upper Floridan aquifer is one of the most productive aquifers in the United States, and in the Lake Seminole area is the primary source of ground water for agriculture, industry, and public supply. Agricultural irrigation is the major ground-water use in this heavily agricultural region of southwestern Georgia and northwestern Florida. Nearly 500,000 acres are irrigated with ground water from about 4,000 wells completed in the Upper Floridan aquifer in the lower ACF River Basin (James E. Hook, National Environmentally Sound Production Agricultural Laboratory, the University of Georgia, Tifton, Georgia, written commun., November 2002).

In recent years, Lake Seminole and the water released from it have become focal points in water-allocation negotiations between Georgia, Florida, and Alabama that resulted from the ACF River Basin Compact.[1] Increases in population, agriculture, and industry and the drought of 1998–2002 have made water supply and use in the lower ACF River Basin a major concern for water-resource managers in the region, as the three States' conflicting demands have created competition for the basin's limited water resources. These concerns led the States to sign an interstate water compact during 1997, intended to ensure the equitable use and availability of water resources in the region while protecting river ecology.

To acquire information and increase the understanding needed by water-resource managers, the U.S. Geological Survey (USGS) and the State of Georgia agreed to conduct jointly a technical study of Lake Seminole and the surrounding area. The 3-year study, which began in 1999, had the following four objectives:

[1]As adopted by: the Alabama Legislature on February 18, 1997, and signed by the Governor of Alabama on February 25, 1997, as Alabama Acts 97-67, Alabama Code, Title 33-19-1 *et seq*.; the Florida Legislature on April 14, 1997, and signed by the Governor of Florida on April 24, 1997, as Chapter 97-25, Laws of Florida, Section 373.71, Florida Statutes (1997); the Georgia Legislature on February 11, 1997, as Georgia Acts No. 7, and signed by the Governor of Georgia on February 25, 1997, as Georgia Code Annual Section 12-10-100 *et seq*., and passed by the United States Congress on November 7, 1997, and signed by the President of the United States on November 20, 1997, as Public Law Number 105-104, 111 Statute 2219; *http://www.acfcompact.alabama.gov/pdfs/ACFCompact.pdf*, accessed August 1, 2003.

- Develop a water budget for Lake Seminole that will promote a reasonable understanding of the effect of the lake on the overall flow system in the lower ACF River Basin, and that can be used to guide water allocations between Alabama, Florida, and Georgia;

- Compare current and pre-Lake Seminole ground- and surface-water flow regimes to determine whether the volume of water flowing out of Georgia has changed substantially after construction of Jim Woodruff Lock and Dam and filling of the lake;

- Evaluate the possibility of a substantial amount of water entering the ground-water regime from Lake Seminole, flowing beneath Jim Woodruff Lock and Dam, and entering Florida downstream of the dam; and

- Assess the likelihood of failure of dissolution features in the karst limestone of the lake bottom, such as sinkhole collapse, and the likelihood of sudden partial or complete draining of the lake. If such an occurrence is likely, then propose a data-collection system to monitor pertinent hydrologic features that could cause sudden draining of Lake Seminole, and to provide data that could warn of such an occurrence.

The three-year study investigated features of the hydrologic system near Lake Seminole that contribute directly to the ground- and surface-water flow regime of the lake. The study focused only on those elements of the hydrologic cycle, surface-water features, and hydrogeologic units that are in hydraulic connection with the lake. A multidiscipline investigative approach was used that involved acquisition, analysis, and interpretation of chemical, limnologic, hydrogeologic, and meteorologic information, quantification of uncertainty, and numerical simulation.

Purpose and Scope

This report is one of a series of reports documenting the 3-year study to evaluate the effects of impoundment of Lake Seminole on water resources in the lower ACF River Basin. The second of four study objectives listed previously is addressed in this report, namely, to compare current and pre-Lake Seminole ground- and surface-water flow regimes to determine whether the volume of water flowing out of Georgia has changed substantially since construction of Jim Woodruff Lock and Dam and filling of the lake. The following technical tasks were performed to achieve this objective:

- Evaluate existing information on ground-water levels, hydraulic properties, and streambed characteristics to define current (postimpoundment) and pre-Lake Seminole (preimpoundment) ground- and surface-water flow conditions;

- Modify an existing numerical model of stream-lake-aquifer interaction developed by Torak and others (1996) near Lake Seminole, and simulate pre- and postimpoundment flow conditions; and

- Compare results of simulations representing pre- and postimpoundment conditions to evaluate changes in ground-water flow directions in the Lake Seminole area.

This study uses results from a modified version of a numerical model for the lower ACF River Basin (Torak and others, 1996) to evaluate pre- and postimpoundment conditions of the stream-lake-aquifer flow system near Lake Seminole. Descriptions of the geohydrology, conceptualization of the stream-lake-aquifer flow system, and of model implementation and calibration given for that study also apply to this study. Therefore, for brevity, full descriptions of these aspects of the study are not repeated herein, but can be found in the earlier report (Torak and others, 1996); only those details that are pertinent to the vicinity of Lake Seminole and to study results are presented and discussed herein.

Study Area and Physiography

The study area is located in the Coastal Plain physiographic province and consists of about 2,000 mi^2 surrounding Lake Seminole in extreme southwestern Georgia and northwestern Florida, and about 250 mi^2 located in the extreme southeastern corner of Alabama (fig. 2). In the study area, the Coastal Plain Province is subdivided into physiographic districts: the Fall Line Hills, Dougherty Plain, Marianna Lowlands, Tifton Upland, and Gulf Coastal Lowlands (figs. 1 and 2). Descriptions of these physiographic provinces are summarized from Cooke (1925), Puri and Vernon (1964), Sapp and Emplaincourt (1975), Clark and Zisa (1976), Brooks (1981), Wagner and Allen (1984), and Torak and others (1996).

The northern extent of the study area is in the Fall Line Hills district at the updip limit of the Ocala Limestone, which is the principal water-bearing unit of the Upper Floridan aquifer in the study area. The district is a highly dissected series of ridges and valleys that diminish in relief to the south and east (fig. 2) and has little level land except for marshy floodplains and adjacent better-drained, narrow stream terraces. Stream valleys range from 50 to 250 ft below adjacent ridges. In the study area, the southern boundary of the Fall Line Hills approximates the 250-ft elevation that separates the district from the Dougherty Plain.

Lake Seminole lies within the Dougherty Plain, an inner lowland having an irregular and undulating surface characterized by heterogeneous stream-channel development and karst topography. Many shallow sinks and depressions, ranging in size from a few tens of square feet to several hundred acres and some containing water year-round, speckle the landscape and provide evidence of active dissolution that is occurring at or below land surface in the limestone aquifer. Dissolution of the Ocala and Suwannee Limestones in the Dougherty Plain has created a subsurface, internal drainage (fig. 2), typical of karst topography; main-stem streams flow in terraced valleys and cut shallow channels across the Dougherty Plain, however, small tributary streams are scarce.

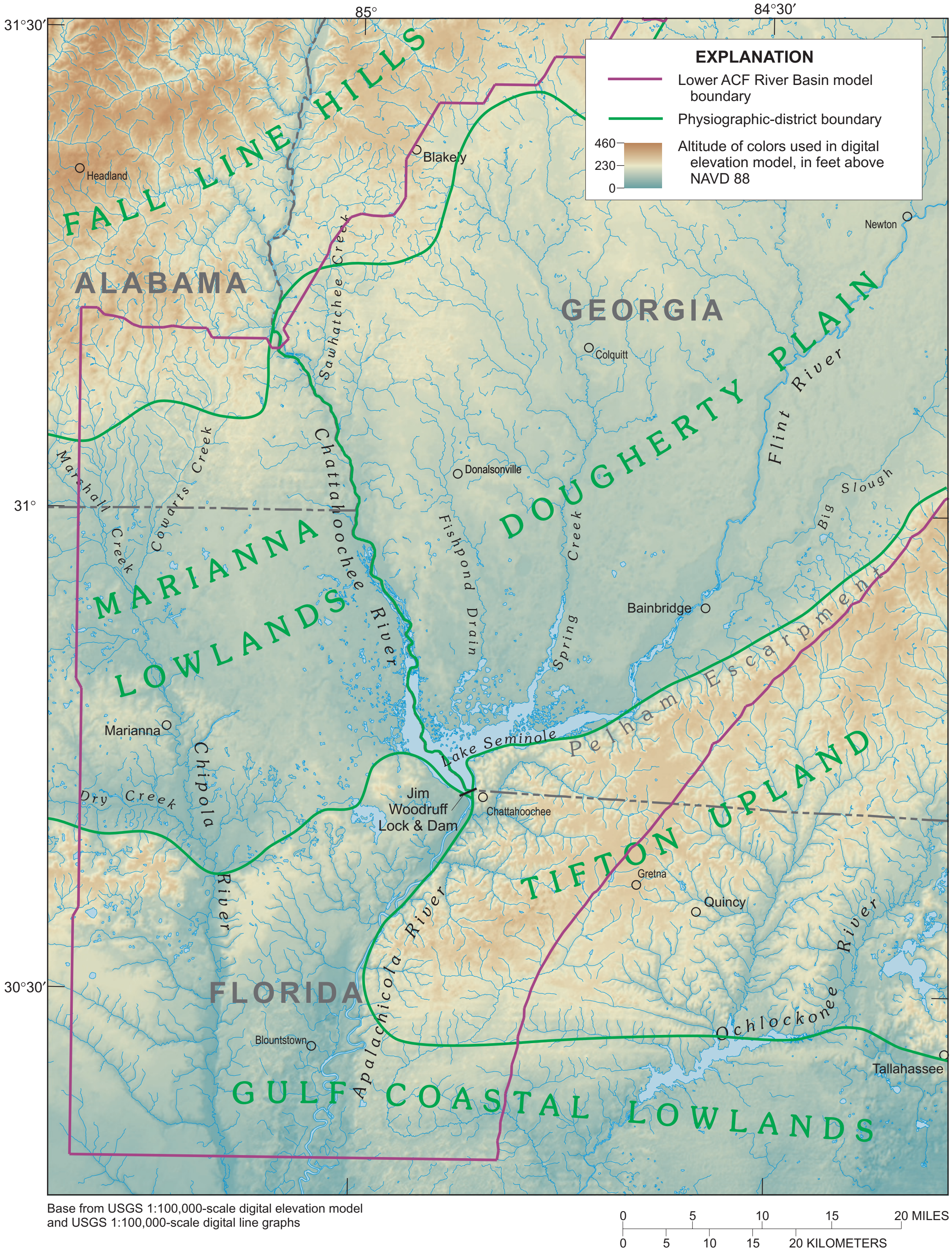

Figure 2. Southern part of the lower Apalachicola–Chattahoochee–Flint River Basin model area, showing physiographic districts, topography, major streams, lakes, and cities. (See figure 1 for map area.)

A prominent, steeply sloping karst area termed the *Pelham Escarpment*[1] (Clark and Zisa, 1976) bounds the Dougherty Plain along the southern side of the Flint River impoundment arm of Lake Seminole (fig. 2). The Pelham Escarpment produces local relief as great as 125 ft, forming a topographic and surface-water divide in the study area between the Flint River Basin to the northwest and the Ochlockonee River Basin to the southeast (Torak and others, 1996). Many small streams flow northwestward down the Pelham Escarpment and into caves and sinkholes along the eastern edge of the Dougherty Plain (Sever, 1965).

In northwestern Florida and extreme southeastern Alabama, the Coastal Plain Province in the study area has been subdivided by Vernon (1951) into a minor geomorphic unit termed the *Marianna River Valley Lowlands*, or, as proposed by Cooke (1939), the *Marianna Lowlands* (fig. 2). Like the Dougherty Plain, the Marianna Lowlands consists of low, generally flat or rolling topography that resulted from a complicated sequence of stream erosion, deposition, and capture by several streams, including the Apalachicola, Chattahoochee and Chipola Rivers. The lowland has existed since the early Pleistocene, being formed by removal and dissection of Miocene clastic sediments, which expose underlying limestone units at the surface. As a result of this erosion, the normal topography of a coastal plain has been formed, rather than karst topography (Moore, 1955). The Chattahoochee River forms the eastern boundary of the Marianna Lowlands (fig. 2), separating it from the physiographically similar Dougherty Plain. Small streams that are tributary to the Chipola River and extend to the east and northeast have produced a north-facing escarpment, which forms the southern boundary of the Marianna Lowlands.

The Tifton Upland is a region of relatively high hills composed largely of resistant clayey sands, silts, and clays, located to the southeast of the Pelham Escarpment (Arthur and Rupert, 1989). A dendritic drainage pattern dissects the hills, forming V-shaped valleys. In northwestern Florida, the Tifton Upland is termed the *Tallahassee Hills* (Puri and Vernon, 1964). The Tifton Upland ends abruptly at the Apalachicola River in steep bluffs having relief of about 150–200 ft above the floodplain that exposes Miocene to Holocene sediments. Torak and others (1996) described additional details about the Tifton Upland and a similar series of remnant hills and sand-hill ridges located to the west of the Apalachicola River and southwest of Lake Seminole.

In northwestern Florida, south of the Tifton Upland and Marianna Lowlands is the Gulf Coastal Lowlands, a sandy, flat, seaward-sloping physiographic district. In the northern part of the Gulf Coastal Lowlands are weathered and partially eroded relics of deltaic deposits in late Miocene to Pliocene sandy and silty soils. South of these paleodelta features are river terrace deposits that have eroded alluvial plains. These features were shaped mostly by wave and current activity from high sea-level stands during the Pleistocene Epoch (Arthur and Rupert, 1989).

Geohydrology

Geologic units of the stream-lake-aquifer flow system in the Lake Seminole area consist of Coastal Plain sediments of middle Eocene to Holocene age; these sediments typically are cross-bedded clayey sands, sands, and gravels; clay; limestone; dolomite; and limestone residuum, occurring in an offlapping sequence that dips gently and thickens gradually to the southeast. These units are, in ascending order, Lisbon Formation; Clinchfield Sand; Ocala, Suwannee, and Tampa Limestones; Hawthorn Group; undifferentiated overburden (residuum); and terrace and undifferentiated (surficial) deposits (fig. 3).

The Lisbon Formation of middle Eocene age is thick and dense throughout most of the study area and functions as a nearly impermeable base to the Upper Floridan aquifer. The surface of the Lisbon Formation crops out in the Fall Line Hills physiographic district in the northwestern part of the study area, dips to the southeast and south, and is nearly 1,000 ft below NAVD 88 at the southern boundary of the lower ACF River Basin model area (Miller, 1986).

The Clinchfield Sand of late Eocene age overlies the Lisbon Formation (fig. 3) and crops out less than 1 mi beyond the updip limit of the overlying Ocala Limestone (Herrick, 1972). Downdip the sand grades into the Ocala Limestone (Herrick, 1972).

The Ocala Limestone of late Eocene age overlies the Lisbon Formation and the Clinchfield Sand (fig. 3), where it is present in the Dougherty Plain, and consists of a “white bioclastic limestone that is honeycombed with solution cavities” (Sever, 1965). Locally, the surface of the Ocala Limestone is irregular as a result of dissolution of limestone and development of karst topography. In some areas, the upper few feet of the limestone in the subsurface consists of soft, clayey residuum (Miller, 1986). In extreme southeastern Alabama, the Ocala Limestone thickens to about 300 ft (Torak and others, 1996, pl. 3). The Ocala Limestone is about 250 ft thick at Bainbridge, Ga., thins to about 100 ft to the northwest near Donalsonville, Ga., and is absent farther to the northwest at the Chattahoochee River. Beneath the Tifton Upland, the Ocala Limestone thickens to about 750 ft and becomes a brown saccharoidal dolomitic limestone containing gypsum (Sever, 1965). The Ocala limestone in the study area has been subdivided into units that have distinct geohydrologic characteristics, as described by Moore (1955), Sever (1965), and Miller (1986).

[1]The Pelham Escarpment also has been called the Solution Escarpment by (MacNeil, 1947), Sever (1965), Hicks and others (1987), and Torak and others (1996).

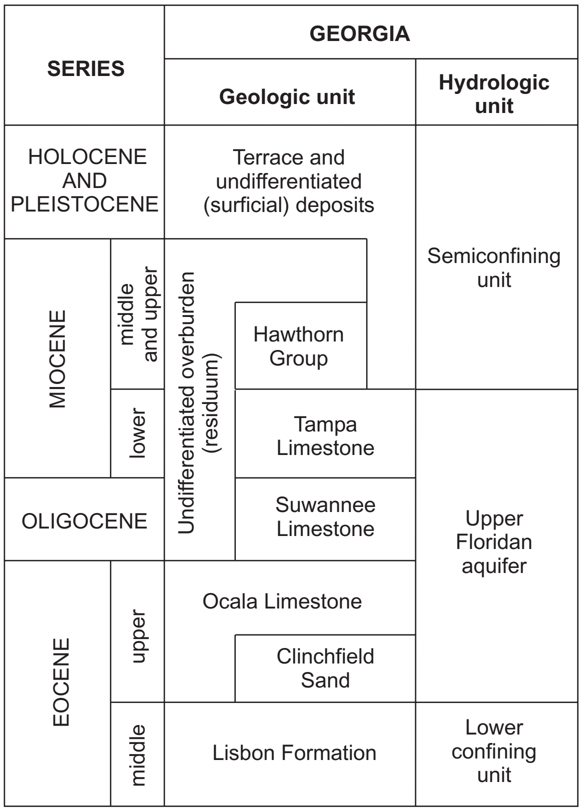

Figure 3. Correlation chart of geologic and hydrologic units comprising the stream-lake-aquifer flow system near Lake Seminole (modified from Torak and others, 1996).

The Suwannee Limestone of Oligocene age overlies the Ocala Limestone in the southern part of the study area. The Suwannee Limestone crops out at the base of the Pelham Escarpment but is absent from most of the Dougherty Plain (Sever, 1965). In northwestern Florida, the Suwannee Limestone crops out west of Lake Seminole. The limestone forms part of the bed of Lake Seminole, extending from the dam about 9 mi up the Chattahoochee River impoundment arm and 16 mi up the Flint River impoundment arm, bordering the Pelham Escarpment (Sever, 1965, pl. 2). Thickness of the Suwannee Limestone varies from about 10 ft in the western part of the study area in Florida, to about 115 ft in Florida to the west of Lake Seminole near the dam, to about 210 ft south of the lake (Moore, 1955). The cavernous nature of the Suwannee Limestone results in abundant water yields to wells that are completed in this unit and provides good hydraulic connection with streams and the lake.

The Tampa Limestone consists of early Miocene sediments that overlie the Suwannee Limestone and, in turn, are overlain by either clayey sands and gravels of terrace and undifferentiated deposits or the Hawthorn Group (fig. 3). The Tampa Limestone is absent from the Dougherty Plain and crops out in a narrow band around the southern margin of the Marianna Lowlands, where it is from about 20 to 40 ft thick (Sever, 1965). The Tampa Limestone underlies the high-relief region of the Tifton Upland and southern part of the study area in Florida. South of the Tifton Upland and east of the study area in Georgia, the Tampa Limestone is nearly 250 ft in thickness. On the Tifton Upland, most domestic and some industrial wells are completed in the Tampa Limestone because the depth to older, more productive water-bearing limestones of the Upper Floridan aquifer is greater than 400 ft (Sever, 1965). The foundation of Jim Woodruff Lock and Dam is emplaced in the Tampa Limestone, which is about 170 ft thick and thins to about 100 ft in the western part of the study area in Florida (Reves, 1961). The valley walls near the dam are composed of Tampa Limestone, although the lithology is chalky (U.S. Army Corps of Engineers, 1948). The limestone also is exposed in large streams that dissect the Tifton Upland (Sever, 1965).

The Hawthorn Group of middle to late Miocene age consists of sediments that overlie the Tampa Limestone in part of the study area (fig. 3). Near Jim Woodruff Lock and Dam, the Hawthorn Group is about 40 ft thick and consists of sandy clay and fine- to medium-grained sand. The Hawthorn Group crops out in the valleys of large streams in the Tifton Upland. Sands in the upper part of the formation yield water to dug and bored wells (Sever, 1965).

Undifferentiated overburden (residuum) consisting of late Miocene alluvial deposits and chemically weathered limestone remnants overlies the Hawthorn Group and limestone units of the Upper Floridan aquifer (fig. 3). The residuum ranges in thickness from a few feet to as much as 100 ft. Although the thickness of the residuum is quite variable, in areas where it overlies the calcareous parts of the Suwannee and Tampa Limestones, the irregular topographic surface conforms to the surface of the underlying limestone, a result of the dissolution of the underlying soluble limestone (Reves, 1961, p. 42). Hayes and others (1983) and Hicks and others (1987) noted that approximately the lower half of the residuum is more clayey than the sandy upper part, perhaps due to its origin as a weathering product of the underlying limestone. The clayey lower part of the residuum is a semiconfining unit to the underlying Upper Floridan aquifer; and, where present, the upper sandy part can contain a water table. Hydraulic connection of the Upper Floridan aquifer with the water table in the sandy upper part of the overburden, or with terrace and undifferentiated deposits, is indirect by vertical leakage through the clayey residuum overlying the limestone.

Terrace and undifferentiated deposits of Holocene and Pleistocene age (fig. 3) consist of marine terrace deposits in the Marianna Lowlands to the south and west of Lake Seminole, and lowland terraces and floodplains along the principal streams, namely the Apalachicola and Chattahoochee Rivers. These deposits directly overlie the residuum and limestone units of the Upper Floridan aquifer, which are exposed in river valleys as a result of dissection and removal of the Miocene clastic formations (Moore, 1955). Thickness of terrace deposits ranges from 30 to 50 ft (Moore, 1955); however, near

Jim Woodruff Lock and Dam, erosion and dissolution of the Tampa Limestone have deeply incised former channels of the Apalachicola River, and these ancient incisions have been filled with alluvium that varies in thickness from at least 30 ft to nearly 80 ft in some places (U.S. Army Corps of Engineers, 1948). Terrace and undifferentiated deposits can contain a water table that, depending on the amount of clay or residuum that is present, either fluctuates with the adjacent river stage or underlying aquifer, or creates a perched water-table condition that fluctuates independently of the river or aquifer. Hydraulic connection of the terrace and undifferentiated deposits with the underlying Upper Floridan aquifer can be direct where sandy deposits overlie the limestone units, or indirect where fluvial deposits overlie clayey limestone residuum.

Geologic units contributing to the stream-lake-aquifer flow system around Lake Seminole are grouped into hydrologic units according to their hydraulic characteristics and are termed *semiconfining unit*, *Upper Floridan aquifer*, and *lower confining unit* (figs. 3 and 4). Karst processes, hydraulic properties, and stratigraphic relations limit stream-lake-aquifer interaction to geologic units that include and are younger than the late Eocene-age Ocala Limestone (fig. 3). Descriptions of the hydraulic properties of the semiconfining unit, Upper Floridan aquifer, and lower confining unit are given in Torak and others (1996).

Stream erosion and dissolution of carbonate sediments in the study area have produced a flow system in the Upper Floridan aquifer that can be characterized as having: (1) high rates of direct recharge through sinkholes, swallow holes, or similar depressions; (2) indirect recharge by vertical leakage through and/or from overlying terrace and undifferentiated deposits, Hawthorn Group sediments, and residuum; and (3) channel leakage to or from the aquifer across the streambed or lake bed (fig. 4). A lower confining unit consisting of the Lisbon Formation forms an impermeable base to the stream-lake-aquifer flow system.

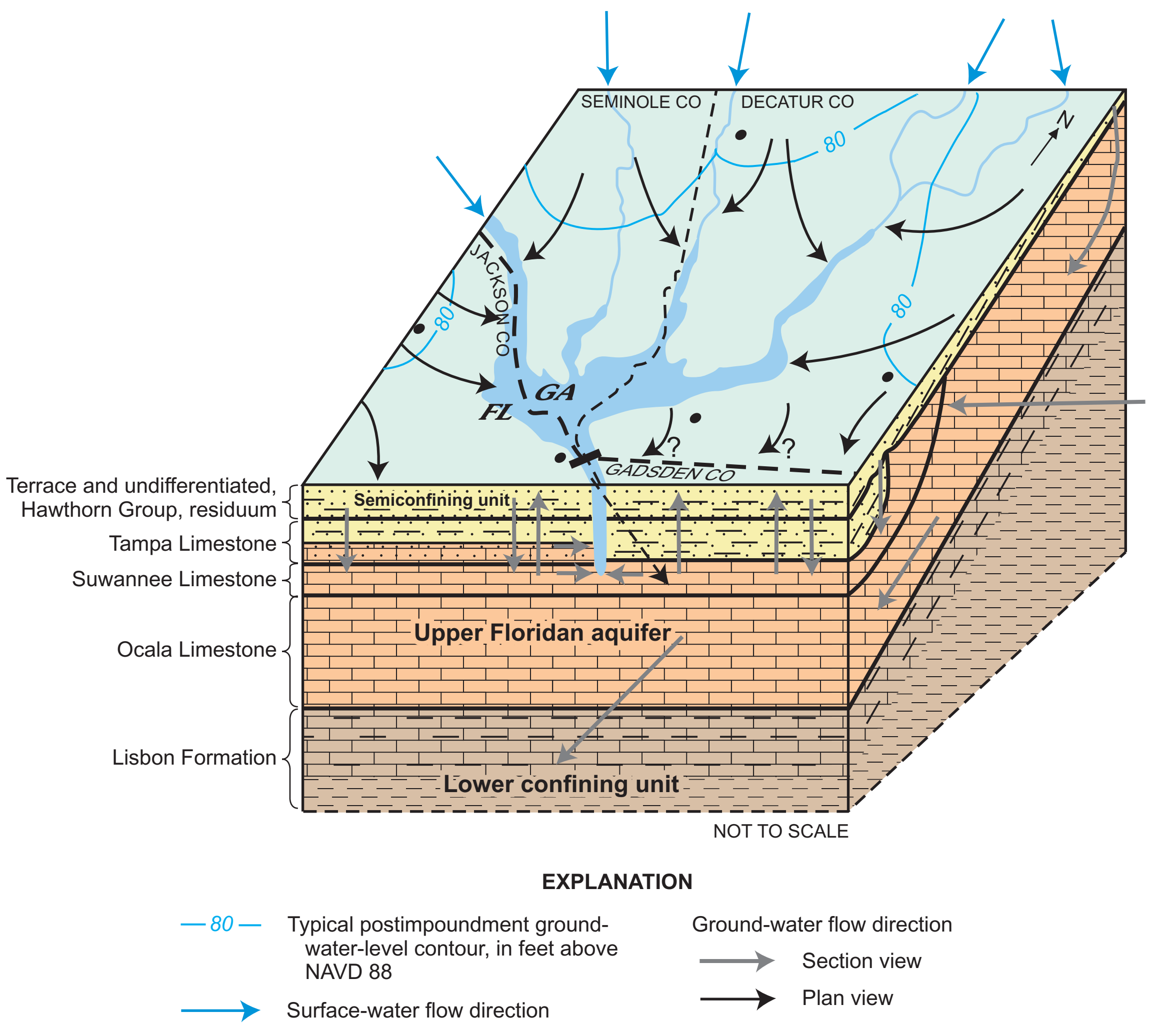

Figure 4. Diagram of hydrogeologic units and conceptualization of ground-water and surface-water flow in the vicinity of Lake Seminole (modified from Torak and others, 1996).

The Upper Floridan aquifer is a stepped sequence of carbonate sediments consisting of the Ocala, Suwannee, and Tampa Limestones and, locally, the Clinchfield Sand. The older sediments extend to the surface as the northernmost outcrop area of the sequence; younger sediments crop out successively to the south. Where limestone units of the Upper Floridan aquifer are near land surface, they are semiconfined by the overlying terrace and undifferentiated deposits, residuum, and Hawthorn Group. This occurs in extreme southeastern Alabama and southwestern Georgia, and in the western and central parts of the study area in Florida. In the Dougherty Plain, the Upper Floridan aquifer primarily consists of the Ocala Limestone, but includes the Suwannee Limestone along the Pelham Escarpment and on the Tifton Upland, and the Clinchfield Sand, where present. The Tampa Limestone is included in the aquifer south of the Florida-Georgia State line, where it overlies the Suwannee Limestone.

The function of the Tampa Limestone in transmitting ground water in the stream-lake-aquifer system varies, depending on juxtaposition of the limestone with the Apalachicola River and other surface-water drainage, and on areal extent and lithology of the limestone. West of the river, the combination of incomplete areal extent, sandy lithology, and well-developed surface-water drainage results in the Tampa Limestone being hydrologically similar to the underlying limestone of the Upper Floridan aquifer; thus, the limestone is included in the Upper Floridan aquifer in this area. West of the river, the semiconfining unit to the Upper Floridan aquifer consists of, where present, residuum, Hawthorn Group sediments, and terrace and undifferentiated deposits. By comparison, east of the Apalachicola River, the Tampa Limestone has a large areal extent and thickness, a dense, clayey lithology, and less-developed surface-water drainage. The Tampa Limestone east of the river also contains a higher hydraulic head than underlying limestone units of the Upper Floridan aquifer. This higher head, combined with less-transmissive hydraulic characteristics than the deeper units, results in the Tampa Limestone east of the Apalachicola River functioning as a semiconfining unit, providing a mechanism for indirect downward vertical leakage to the Upper Floridan aquifer from the overlying residuum, Hawthorn Group, or terrace and undifferentiated deposits.

Numerical Methods

A previously published, calibrated numerical ground-water model of the lower ACF River Basin (Torak and others, 1996) was used to evaluate the effects that the impoundment of Lake Seminole had on ground-water flow and stream-aquifer interaction. The vertical hydraulic conductance of the semiconfining unit overlying the Upper Floridan aquifer was modified slightly from the calibrated ground-water model to reflect changes in current understanding of the occurrence and thickness of the overburden and to represent the absence of Lake Seminole from the hydrologic system. Model boundaries were added to represent the Chattahoochee and Flint Rivers and Spring Creek, as these streams existed prior to the impoundment of Lake Seminole. Simulation results representing both pre- and postimpoundment conditions were analyzed to provide estimates of the change in volume of ground-water flow along the Georgia-Alabama and Georgia-Florida State lines.

Model Background and Assumptions

The numerical model code used to simulate ground-water flow with stream-lake interaction in the lower ACF River Basin was the USGS MODular Finite-Element model, MODFE (Cooley, 1992; Torak, 1993a,b). Torak and others (1996) applied MODFE to a conceptualization of the stream-lake-aquifer flow system in the lower ACF River Basin to define better stream-aquifer relations and to evaluate the effects of ground-water pumping on streamflow. Details of MODFE formulation, simulation approach, conceptualization of the stream-lake-aquifer flow system, and application of MODFE to the study area are contained in these references. The resulting numerical model of the lower ACF River Basin (Torak and others, 1996) simulated ground-water flow in the Upper Floridan aquifer, linearly distributed flows to or from streams and external boundaries, and areally distributed vertical leakage to or from the overlying undifferentiated overburden and the bed of Lake Seminole. The model was calibrated using drought conditions of October 1986.

Linearly distributed ground-water flows to or from streams and external boundaries are represented in the existing numerical model using head-dependent Cauchy-type boundaries (Torak and others, 1996). Major and minor streams were discretized linearly as element sides, which were grouped into zones of Cauchy-type boundaries. These boundaries relate the flow rate across the streambed to the difference in head between the aquifer and stream and to hydraulic characteristics of the streambed (Torak and others, 1996, p. 38–40). Each end node was assigned a head value based on stream stage during drought conditions of October 1986. Element sides along the northeast, southeast, and southwest external boundaries of the model were grouped into zones of Cauchy-type boundaries, and each end node was assigned a head value based on the October 1986 potentiometric-surface map. In the bed of Lake Seminole, Cauchy-type boundaries were added along the impoundment arms of the Chattahoochee and Flint Rivers and Spring Creek to Lake Seminole to simulate these streams under hypothetical preimpoundment conditions.

Areally distributed vertical leakage to or from the overburden and Lake Seminole both are represented in the numerical model by a steady, nonlinear, head-dependent vertical-leakage boundary. The vertical-leakage boundary is distributed areally based on estimated vertical hydraulic conductance (vertical hydraulic conductivity divided by thickness) of the overburden or lake bed. In the postimpoundment simulation, vertical hydraulic conductance: (1) was zero where overburden is absent, (2) ranged from 8.4×10^{-10} to 9.8×10^{-4} feet per day per foot (ft/d/ft) in areas where undifferentiated overburden is present, and (3) was $8.0x10^{-3}$ ft/d/ft for the bed of Lake Seminole (Torak and others, 1996, table 4, pl. 5). In areas where overburden is present, head in the overburden was estimated from water levels in wells. For the area representing Lake Seminole, head was set equal to the pool elevation of Lake Seminole during October 1986 (75.66 ft) for the postimpoundment simulation and in the hypothetical preimpoundment simulation; vertical hydraulic conductance was zero, representing the absence of overburden.

Because the purpose of this study was to investigate only the effects of the impoundment of Lake Seminole on ground- and surface-water flow, other model stresses unrelated to the impoundment were not changed. Between the postimpoundment and hypothetical preimpoundment simulations, the only input changes were the conditions of hydrologic boundaries to the Upper Floridan aquifer that represented: (1) vertical leakage from the bed of Lake Seminole (postimpoundment) or overburden sediments (hypothetical preimpoundment), (2) flows to preimpoundment streams (hypothetical preimpoundment), and (3) flow at external boundaries (hypothetical preimpoundment). Pumpage for the hypothetical preimpoundment simulation was input at the same rate as that used in the calibrated model of October 1986 conditions (Torak and others, 1996, p. 43–44), even though irrigation pumpage is known to have increased considerably during the period 1957–86. Considering these basic assumptions, results of these simulations should be viewed as hypothetical, for purposes of hydrologic evaluation, and might not represent any real flow condition.

Vertical Hydraulic Conductance

Minor modifications to values of vertical hydraulic conductance from those used in the existing numerical model (Torak and others, 1996) were made to reflect current understanding of the occurrence of undifferentiated overburden in the Lake Seminole area. Well records compiled for this study and recent field reconnaissance indicate that the undifferentiated overburden probably is absent near the channels of the Flint River, Spring Creek, and Fishpond Drain north of Lake Seminole. To reflect the absence of overburden in the numerical model, vertical hydraulic conductance in selected elements along these stream reaches was set to zero (fig. 5); whereas, vertical hydraulic conductance in element zones north of Lake Seminole had been nonzero and nearly uniform in the original numerical model. The effect of this change on simulated head in the Upper Floridan aquifer was minimal—the maximum simulated change from the calibrated model was 0.04 ft (Jones and Torak, 2003). For preimpoundment conditions, the undifferentiated overburden also was assumed to be absent beneath Lake Seminole; in the numerical model, the vertical hydraulic conductance in the area representing Lake Seminole was set to zero (fig. 5).

Cauchy-Type Boundaries

Upstream of Lake Seminole, the Chattahoochee and Flint Rivers and Spring Creek are represented in the model by head-dependent Cauchy-type boundaries. Near Lake Seminole, for the postimpoundment simulation, values of head at these boundaries were set to estimates of stage in these streams during October 1986, which were influenced by the impoundment. To represent preimpoundment conditions, historic streamflow data and associated stage-discharge rating curves from the Chattahoochee, Flint, and Apalachicola Rivers prior to 1955 (U.S. Geological Survey, unpublished records, Georgia District, Atlanta, Georgia) were used to estimate the stage that corresponds to streamflow along these three streams during a drought similar to that of October 1986. In the numerical model, head values assigned to each node of the Cauchy-type boundaries representing these streams were lowered accordingly (fig. 6). Head-dependent Cauchy-type boundaries representing the preimpoundment channels of these streams in the area of Lake Seminole, downstream to the site of Jim Woodruff Lock and Dam, also were added (fig. 5) and assigned head values in a similar manner (fig. 6). Simulated head change, due to the impoundment of Lake Seminole, near external Cauchy-type boundaries was examined to determine the appropriateness of assigning the same head values for both simulations.

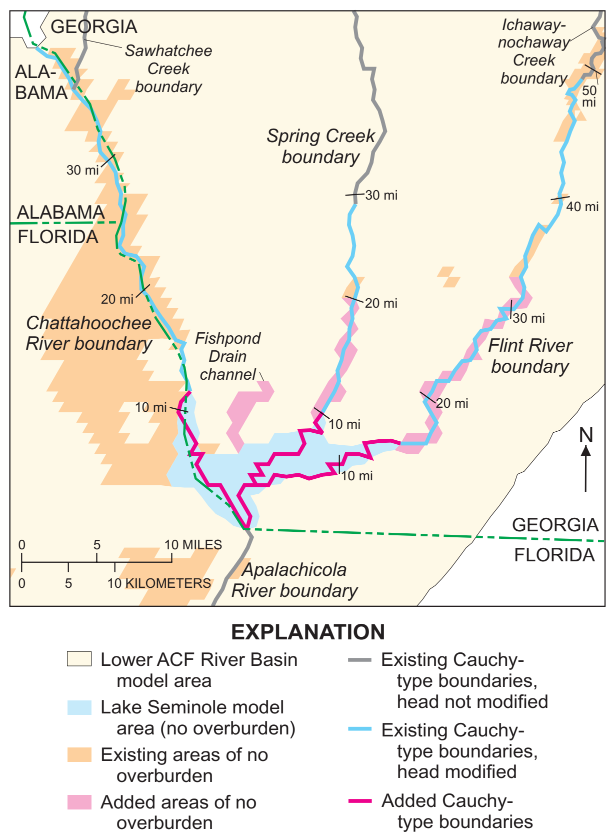

Figure 5. Boundary conditions of the lower Apalachicola–Chattahoochee–Flint River Basin model in the Lake Seminole area, showing modifications for simulating hypothetical preimpoundment conditions. (See figure 1 for map area.)

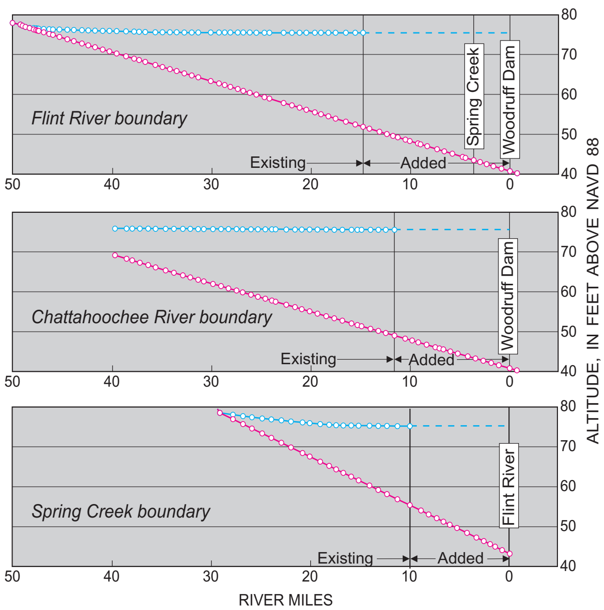

Figure 6. Model-input river stage for Cauchy-type boundaries representing the Chattahoochee and Flint Rivers and Spring Creek, hypothetical preimpoundment conditions (red) and postimpoundment conditions (blue). (See figure 5 for locations of streams in model.)

State-Line Flow

To assess change in interstate ground-water flow under simulated postimpoundment and hypothetical preimpoundment conditions, model element sides closest to the Georgia-Alabama and Georgia-Florida State lines were selected and separated into six zones based on the neighboring State, hydrologic boundaries, and simulated ground-water flow directions. Details of the zonation are discussed in the next section. To quantify ground-water flow on each side of these State-line element sides, MODFE was modified to calculate specific-discharge vectors (equivalent to Darcy velocity) at the centroid of the elements containing the State-line element sides, each side having one element in Georgia and one in the neighboring State (Alabama or Florida). The component of an elemental specific-discharge vector that is normal to a State-line element side (equivalent to a boundary flux) was assumed to represent the flow of ground water that is either moving toward or away from the State line on that side, depending on the direction of the normal component. The product of this normal component, average thickness of the aquifer along a State-line element side, and length of the element side yields a volumetric ground-water flow rate. For each element containing a State-line element side, this volumetric rate is either an inflow into Georgia or an outflow from Georgia. Inflows and outflows were summed by State-line zone for elements located in Georgia and for elements located in the neighboring States. Where State-line element sides correspond to Cauchy-type boundaries, model-boundary outflows (discharge to streams) also were summed.

Simulation Results

Initially, the only differences in model input data between the postimpoundment and the hypothetical preimpoundment simulations, were: (1) the elimination of leakage from the bed of Lake Seminole, which was replaced by an area without overburden; (2) the addition of Cauchy-type boundaries to represent the preimpoundment (channel) conditions of the Chattahoochee and Flint Rivers and Spring Creek; and (3) the reduction of input-head values at Cauchy-type boundaries representing the lowest reaches of these streams, which had input-head values that were increased due to the impoundment. The preliminary simulated increase in ground-water level in the Upper Floridan aquifer due to the impoundment, based on these initial preimpoundment conditions (fig. 7), was examined to determine whether or not this result was reasonable. In an aquifer of nearly uniform thickness and transmissivity, the increase in ground-water level due to an impoundment such as Lake Seminole would be expected to be nearly symmetric at points located the same radial distance from the impoundment. In other words, the contours of simu-

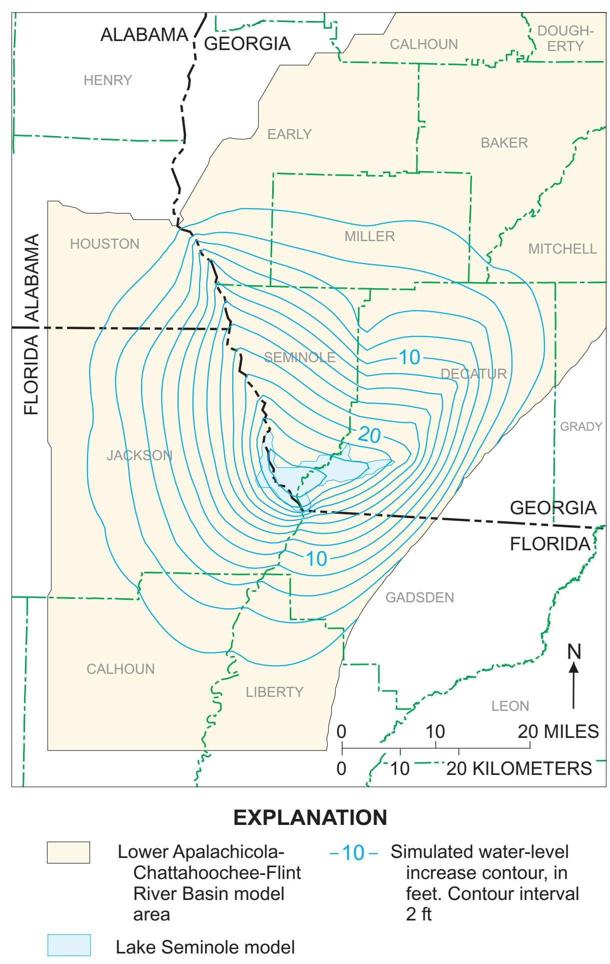

Figure 7. Preliminary simulated increase in ground-water level in the Upper Floridan aquifer due to the impoundment of Lake Seminole based on initial preimpoundment conditions. (See figure 1 for map area.)

lated increase in ground-water level would be roughly circular. The contours of ground-water level increase in figure 7; however, they are flattened near the external Cauchy-type boundary southeast of Lake Seminole. Flattened contours of ground-water level increase could be the result of input-head values that are too high along the external Cauchy-type boundary under hypothetical preimpoundment conditions. It is reasonable to expect that the impoundment of Lake Seminole would have raised water levels along this boundary, which at the closest point is only about 6 mi from the Flint River impoundment arm of the lake.

To account for the probable raising of water levels in the area of the southeastern external boundary of the model due to the impoundment of Lake Seminole, model input-head values for the Cauchy-type boundaries representing this external boundary were lowered systematically in a subsequent hypothetical preimpoundment simulation. By extending the contours of water-level increase past the southeastern boundary in a roughly circular pattern, a hypothetical increase in ground-water level along the boundary, due to the impoundment of Lake Seminole, was estimated that ranged from 0 to about 10 ft (see fig. 8). Reducing input-head values along the Cauchy-type boundary in this area produced a more reasonable estimation of hypothetical preimpoundment conditions than using the higher boundary heads caused by the impoundment. The result of reducing input-head values along the external boundary by this amount in shown in figure 9, which is a map of simulated water-level increase similar to that shown in figure 7. Although Jones and Torak (2003) reported preliminary results using the initial hypothetical preimpoundment simulation in this report, the modified simulation accounting for lower water levels in the Upper Floridan aquifer in the area of the southeastern boundary is considered to be a more accurate estimate of hypothetical preimpoundment conditions than previously reported.

The difference in simulated ground-water levels from hypothetical preimpoundment to postimpoundment conditions (fig. 9) indicates an increase in ground-water level in the Upper Floridan aquifer by as much as 26 ft in extreme southern Seminole County due to the impoundment of Lake Seminole. Ground-water storage apparently increased in several counties in southwest Georgia and adjacent parts of Florida and Alabama due to the impoundment—simulated water levels in the Upper Floridan aquifer increased at least 10 ft in south- and central-western Decatur County and throughout Seminole County in Georgia, and in eastern Jackson County and northwestern Gadsden County in Florida. These results also indicate, however, that the effect of the impoundment of Lake Seminole on ground-water level is relatively localized. Simulated ground-water level increased by less than 2 ft beyond linear distances from Jim Woodruff Lock and Dam of about 35 mi along the Chattahoochee and Flint Rivers, and about 20 mi along the Apalachicola River.

Comparison of maps showing simulated water levels and directions of ground-water movement in the Upper Floridan aquifer for hypothetical preimpoundment and postimpoundment conditions (fig. 10*A* and *B*, respectively) indicates that the impoundment of Lake Seminole locally altered the direction of ground-water flow. The greatest change in ground-water flow directions due to the impoundment occurred southeast of Lake Seminole and east of the Apalachicola River (labeled “a” in fig. 10). In this area, under hypothetical preimpoundment conditions, ground water flowed northwestward from Florida and discharged to the Flint River. Under postimpoundment conditions, ground water flows southwestward from Georgia and discharges to the Apalachicola River. There is a smaller area southwest of Lake Seminole (labeled “b” in fig. 10) where, under hypothetical preimpoundment conditions, ground water diverged from the regional southeastward flow direction, flowed eastward and finally northeastward from Florida, and discharged to the Chattahoochee River near its confluence with the Flint River. Under postimpoundment conditions, ground water flows southeastward and then southward, bypasses or flows under Lake Seminole, and discharges to the Apalachicola River.

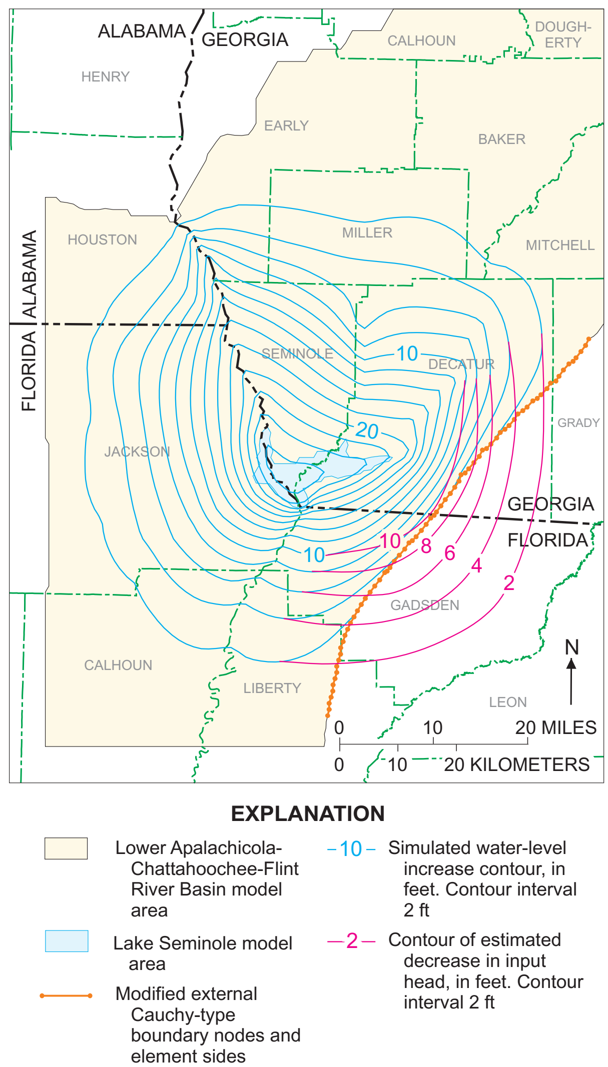

Figure 8. Estimated decrease in input-head values along the southeastern external Cauchy-type boundary to account for lower hypothetical preimpoundment water levels in the Upper Floridan aquifer. (See figure 1 for map area.)

Also, under hypothetical preimpoundment conditions, water levels in the Upper Floridan aquifer north of Lake Seminole near Spring Creek (labeled “c” in fig. 10) were below the streambed and very little ground water discharged to Spring Creek. Under postimpoundment conditions, water levels are higher than the streambed, and the aquifer discharges water to the creek, as indicated by the flow lines ending at Spring Creek and the bending of contours in the simulated potentiometric surface.

Regional effects of the impoundment of Lake Seminole are indicated by comparing water-budget components for the hypothetical preimpoundment and postimpoundment simulations (table 1). Recharge to the Upper Floridan aquifer was decreased by about 261 million gallons per day (Mgal/d), of which about 143 Mgal/d is decreased regional ground-water inflow across external model boundaries, about 115 Mgal/d is decreased downward leakage from the undifferentiated overburden, and about 3 Mgal/d is decreased infiltration near the updip limit of the aquifer, where it crops out. These recharge components mostly offset the decrease in discharge to streams and in-channel springs (about 314 Mgal/d). Other differences in discharge components due to the impoundment are an increase in regional ground-water outflow across external model boundaries (about 40 Mgal/d) and an increase in upward leakage to the undifferentiated overburden (about 13 Mgal/d).

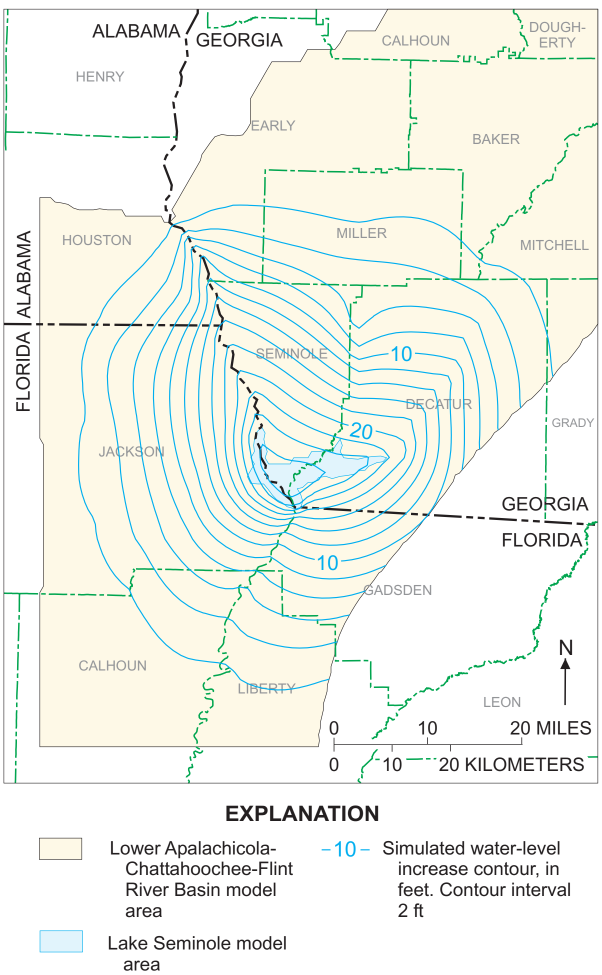

Figure 9. Simulated increase in ground-water level in the Upper Floridan aquifer due to the impoundment of Lake Seminole and accounting for lower preimpoundment water levels along the southeastern external Cauchy-type boundary. (See figure 1 for map area.)

Cauchy-type boundaries are used to represent the interaction of ground water and surface water along streams and in-channel springs, and were used to provide regional flow of ground-water in the Upper Floridan aquifer to and from (recharge and discharge) the model area at the external boundaries of the model. Among water-budget components in table 1, the largest differences between simulations of hypothetical preimpoundment and postimpoundment conditions involve Cauchy-type boundaries. The impoundment of Lake Seminole reduced discharge to streams and in-channel springs by about 314 Mgal/d, and reduced recharge from or increased discharge to regional flow at external model boundaries by about 143 Mgal/d and about 40 Mgal/d, respectively, or by a total of about 183 Mgal/d. To assess more precisely which streams and boundaries account for these large water-budget differences, recharge and discharge rates at Cauchy-type boundaries in the Lake Seminole area for both simulations were plotted in figure 11*A* and 11*B*. The rate of recharge or discharge per length (in Mgal/day/mile) along each element side of a Cauchy-type boundary is indicated by color; ground-water recharge is shown in shades of blue and discharge is shown in shades of red. For each major stream and for zones of external model boundaries, the recharge or discharge rates are totaled along the length of the element sides.

The effects of the impoundment of Lake Seminole on stream-aquifer flow rates are indicated by comparing simulated ground-water discharge rates to nine major streams in the Lake Seminole area for hypothetical preimpoundment and postimpoundment conditions (table 2; streams listed in order of the absolute difference of simulated discharges). The impoundment caused discharge from the Upper Floridan aquifer to the Flint and Chattahoochee Rivers to be reduced substantially (about 267 Mgal/d and about 202 Mgal/d, respectively) along the lower sections of these streams where the model-input river stage was lowered for the hypothetical preimpoundment simulation. Although model-input river stage for Spring Creek also was lowered for the hypothetical preimpoundment simulation, ground-water levels between the Flint and Chattahoochee Rivers were low enough prior to the impoundment that almost no water discharged to the lower reaches of Spring Creek. Higher ground-water levels after the impoundment than before caused increased discharge to the lower reaches of Spring Creek by about 28 Mgal/d. Discharge to other streams near Lake Seminole (Apalachicola and Chipola Rivers, and Dry, Cowarts, Marshall, and Sawhatchee Creeks) for which model-input river stage was unchanged, was less for preimpoundment conditions than for postimpoundment conditions because of low preimpoundment ground-water levels were lower. The total difference in discharge to these nine streams (about 319 Mgal/d) is within 2 percent of the total reduction in discharge to streams and in-channel springs, due to the impoundment of Lake Seminole, for the entire model area (about 314 Mgal/d, table 1).

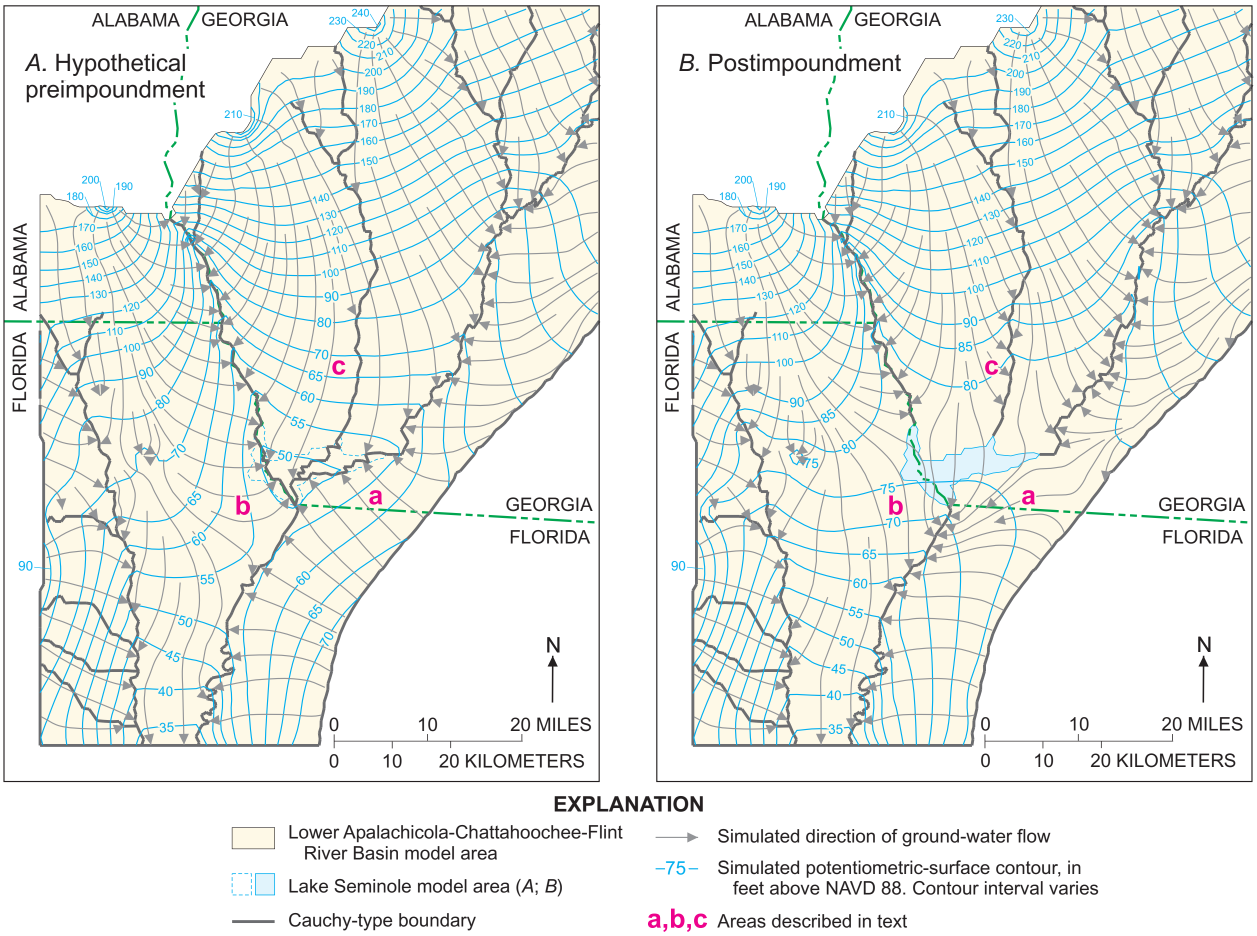

Figure 10. Simulated potentiometric surface and directions of ground-water flow in the Upper Floridan aquifer from simulation of (*A*) hypothetical preimpoundment conditions and (*B*) postimpoundment conditions. (See figure 1 for map area.)

Table 1. Simulated water-budget components for the lower Apalachicola–Chattahoochee–Flint River Basin model, hypothetical preimpoundment and postimpoundment conditions.

[All values are volumetric flow rates in million gallons per day. Difference indicates the simulated effect of the impoundment of Lake Seminole; decreases are negative, increases are positive. Due to rounding, differences and column totals may be inexact]

Water-budget component	Hypothetical preimpoundment	Postimpoundment	Difference
Discharge, by budget component			
Streams and in-channel springs	2,740	2,425	–314
Wells	475	475	0
Off-channel springs	333	333	0
Regional flow	263	304	+40
Undifferentiated overburden	36	49	+13
Total	**3,846**	**3,585**	**–261**
Recharge, by budget component			
Undifferentiated overburden	2,602	2,486	–115
Regional flow	1,075	933	–143
Upper Floridan aquifer outcrop	144	141	–3
Streams	25	25	–1
Total	**3,846**	**3,585**	**–261**

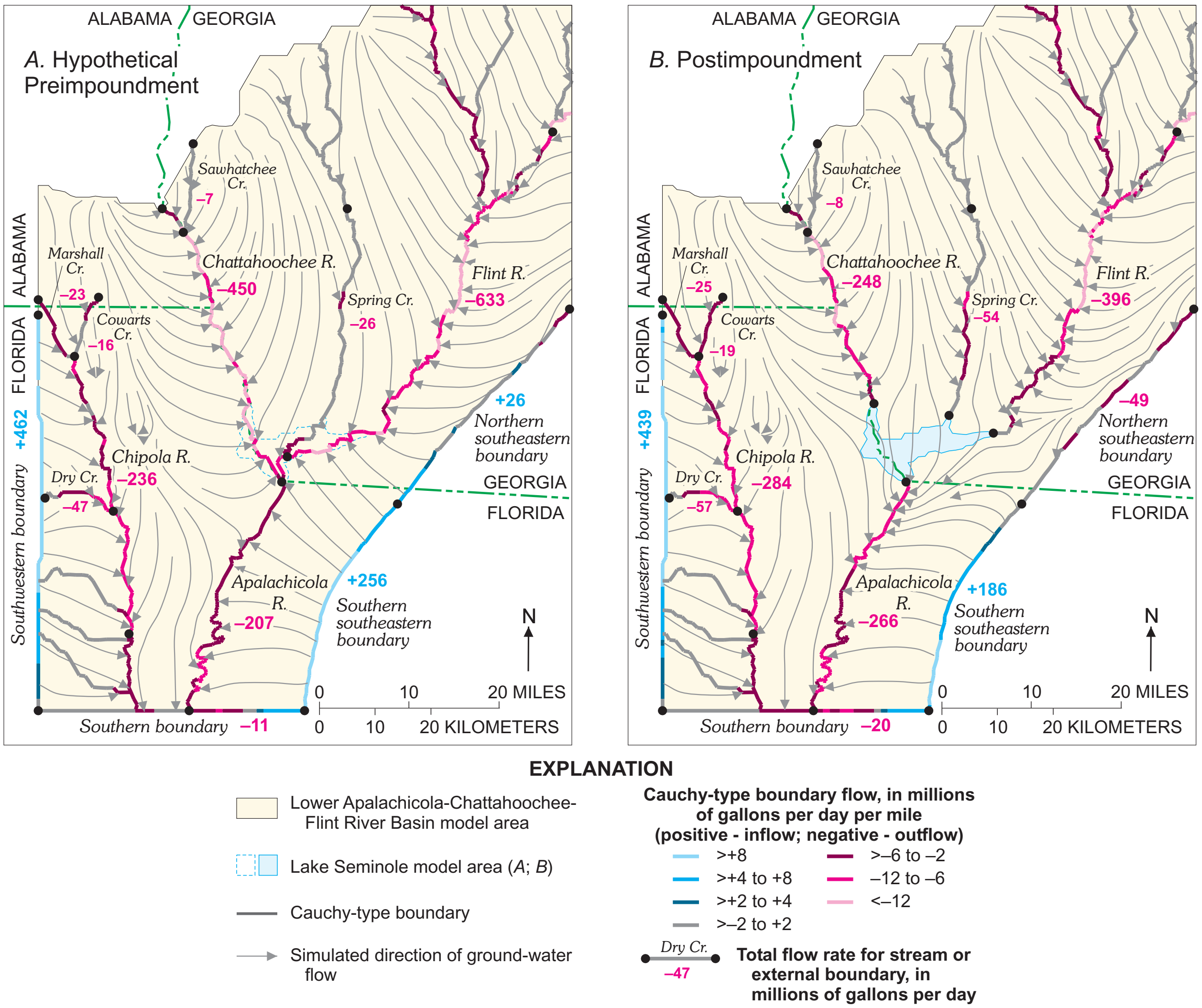

Figure 11. Simulated ground-water recharge (shades of blue) or discharge (shades of red) rates at Cauchy-type boundaries from simulation of (*A*) hypothetical preimpoundment conditions and (*B*) postimpoundment conditions. (See figure 1 for map area.)

Table 2. Simulated discharge to streams in the Lake Seminole area, hypothetical preimpoundment and postimpoundment conditions.

[All values are volumetric flow rates in million gallons per day. Difference indicates the simulated effect of the impoundment of Lake Seminole; decreases are negative, increases are positive. Due to rounding, differences and column totals may be inexact]

Streams	Hypothetical preimpoundment	Postimpoundment	Difference
Flint River	663	396	–267
Chattahoochee River	450	248	–202
Apalachicola River	207	266	+59
Chipola River	236	284	+48
Spring Creek	26	54	+28
Dry Creek (Florida)	47	57	+10
Cowarts Creek	16	19	+3
Marshall Creek	23	25	+2
Sawhatchee Creek	7	8	+1
Total	**1,675**	**1,356**	**–319**

The effects of the impoundment of Lake Seminole on external model-boundary zones shown in figure 11 are indicated by comparing simulated inflow and outflow rates from and to regional flow (table 3). The compass-point designations of the external model-boundary zones (southwestern, southern, and southeastern) are those used in Torak and others (1996), except that the southeastern boundary is divided into a southern section and a northern section. Most of the change in regional flow between the two simulations occurs along the two sections of the southeastern boundary. The northern section of the southeastern boundary is a recharge boundary under hypothetical preimpoundment conditions (totaling about 26 Mgal/d recharge), but it becomes a discharge boundary under postimpoundment conditions (totaling about 49 Mgal/d of discharge), a change of about 75 Mgal/d. The southern section is a recharge boundary in both simulations, but the total recharge rate decreases by about 70 Mgal/d (from about 256 Mgal/d to about 186 Mgal/d) from hypothetical preimpoundment to postimpoundment conditions. Adding to these changes the total decrease of about 32 Mgal/d due to the southwestern and southern boundaries results in a total decrease in recharge or increase in discharge of about 178 Mgal/d along these four external model-boundary zones from hypothetical preimpoundment to postimpoundment conditions. This approximate 178-Mgal/d change is within about 3 percent of the about 183 Mgal/d in decreased recharge or increased discharge due to the impoundment of Lake Seminole (table 1).

For a discussion of across State-line flows, the Georgia-Alabama-Florida State line in the model area was divided into six zones (fig. 12). Zone 1 corresponds to the Georgia-Alabama State line along the Chattahoochee River from the external model boundary southward to the Alabama-Florida State line. Zone 2 corresponds to the Georgia-Florida State line along the Chattahoochee River from the Alabama-Florida State line southward to the Lake Seminole model area. Under both of the simulated conditions, zones 1 and 2 are Cauchy-type boundaries that permit ground-water discharge from the aquifer to the Chattahoochee River. Zones 3 and 4 correspond to the Georgia-Florida State line along the channel of the Chattahoochee River in the Lake Seminole model area downstream to Jim Woodruff Lock and Dam. In the postimpoundment simulation, zones 3 and 4 were in the bed of Lake Seminole, and no Cauchy-type boundary condition was assigned to element sides in these zones; but, in the hypothetical preimpoundment simulation, zones 3 and 4 are Cauchy-type boundaries that were added to permit ground-water discharge to the Chattahoochee River in the same manner as zones 1 and 2. Zones 5 and 6 correspond to the Georgia-Florida State line from Jim Woodruff Lock and Dam eastward to the model boundary; no hydrologic boundary condition is associated with element sides in these zones.

For both simulations that are compared in zones 1 and 2, ground-water flow converges at the Chattahoochee River (fig. 12*A*,*B*) and results in outflow to the Chattahoochee River, which is represented by a Cauchy-type boundary. For the hypothetical preimpoundment simulation (fig. 12*A*) in zones 3 and 4, ground-water flow converges and results in outflow to the Chattahoochee River at the added Cauchy-type boundary. For the postimpoundment simulation (fig. 12*B*) in zone 3, ground water flows under a low hydraulic gradient from Florida southeastward into Georgia; and in zone 4, ground water flows under a slightly higher gradient from Georgia southward back into Florida (hydraulic gradients can be inferred from contour spacing in figure 10B). Under hypothetical preimpoundment conditions (fig. 12*A*), in zones 5 and 6 ground water flows under a relatively high gradient northwestward from Florida into Georgia. Under postimpoundment conditions (fig. 12*B*) in zone 5, ground water flows under a low hydraulic gradient southwestward from Georgia into Florida; but in zone 6, ground-water flow generally is parallel to the Georgia-Florida State line, not across it.

Table 3. Simulated regional flow rates at external model-boundary zones in the Lake Seminole area, hypothetical preimpoundment and postimpoundment conditions.

[All values are volumetric flow rates in million gallons per day; positive values are inflow, negative values are outflow. Difference indicates the simulated effect of the impoundment of Lake Seminole; decreases are negative, increases are positive. Due to rounding, differences and column totals may be inexact]

Regional model boundaries	Hypothetical preimpoundment	Postimpoundment	Difference
Southwestern	+463	+439	–24
Southern	–11	–20	–9
Southeastern, lower	+256	+186	–70
Southeastern, upper	+26	–49	–75
Total	**+734**	**+556**	**–178**

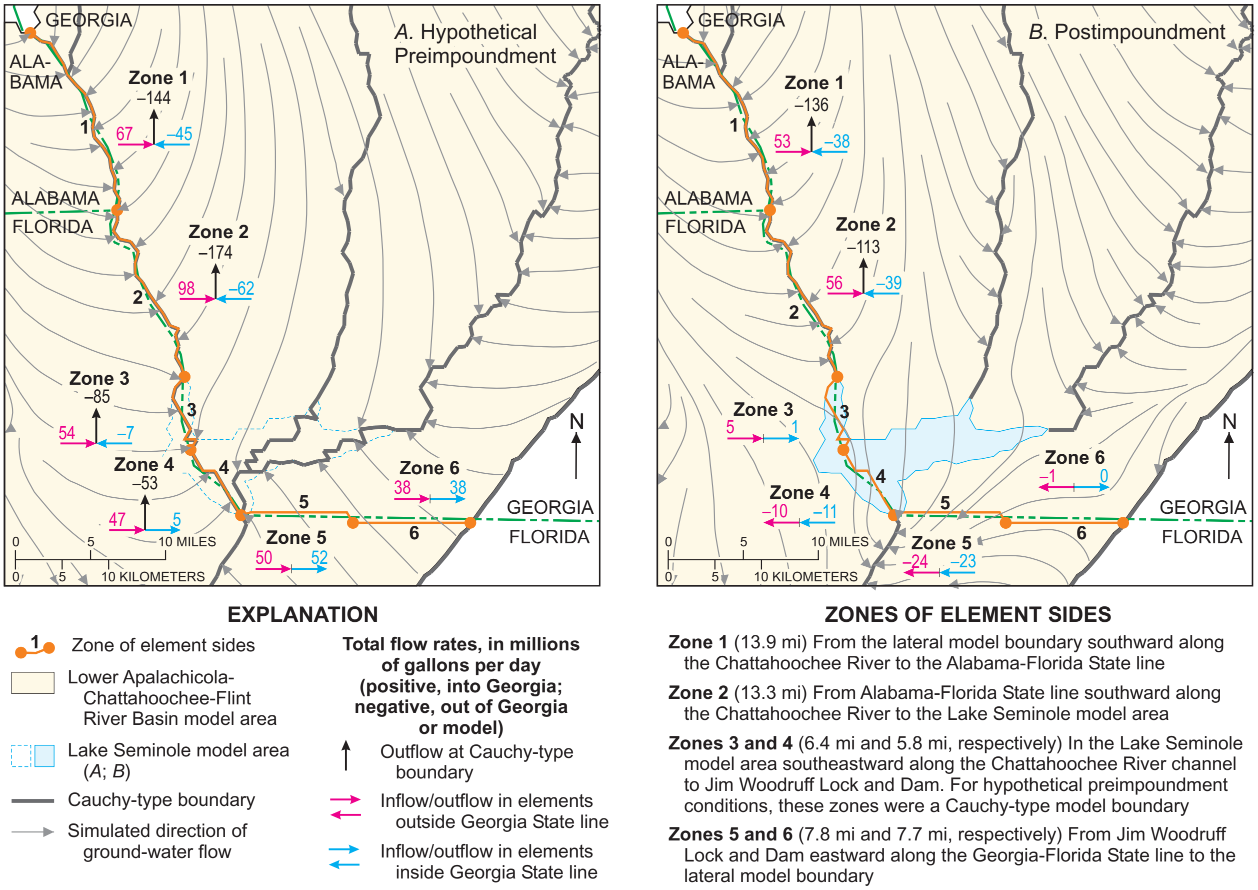

Figure 12. Simulated flow rates in the Upper Floridan aquifer adjacent to zones of element sides and at Cauchy-type boundaries along the Georgia-Alabama and Georgia-Florida State lines: (*A*) hypothetical preimpoundment conditions; and (*B*) postimpoundment conditions. Black arrows represent ground-water discharge to the Chattahoochee River, where it is a Cauchy-type boundary. Blue and red arrows indicate ground-water inflows to Georgia (pointing right) and outflows from Georgia (pointing left) for each zone of element sides. Flow rates are totaled for elements outside Georgia (red) and elements inside Georgia (blue). Due to other flow components not shown, flow rates do not balance. (See figure 1 for map area.)

Uncertainty and Variability of Parameters

Records of ground-water levels and pumpage for the Upper Floridan aquifer prior to the construction of Jim Woodruff Lock and Dam and the impoundment of Lake Seminole are scarce, particularly in the area south of Lake Seminole. Consequently, the accuracy of the hypothetical preimpoundment simulation cannot be verified through a calibration procedure that matches simulated and measured water levels and stream baseflows. Also, under hypothetical preimpoundment conditions, simulated recharge to the aquifer from regional flow is greater than the recharge simulated for October 1986 post-impoundment conditions (table 1). The increased simulated recharge under hypothetical preimpoundment conditions mostly occurs along the external head-dependent Cauchy-type boundary located to the southeast of Lake Seminole (fig. 9).

Head-dependent Cauchy-type boundaries usually are used where the aquifer extends beyond the boundary, but where storage effects in this external aquifer region can be ignored. Such boundaries are used where the contribution of flow across this mathematical boundary would not vary substantially from flow that would occur if the model were extended to include this external area. For the original numerical model, this boundary was placed at a ground-water divide that existed in that area during 1986. It is not known whether the divide existed in the same location prior to impoundment of Lake Seminole or whether preimpoundment water levels in this area were similar enough to those during postimpoundment to ensure that the hypothetical preimpoundment simulation does not violate any assumptions of the boundary. Results of a preliminary simulation of preimpoundment conditions, using the same input-head values as those used in the postimpoundment simulation, indicate that aquifer head along the southeast Cauchy-type boundary was probably lower prior to the impoundment of Lake Seminole. For the hypothetical preimpoundment simulation, input heads for the Cauchy-type boundary in this area were lowered to more accurately depict historical conditions.

Extremely low observed and simulated hydraulic gradients in the Lake Seminole area during postimpoundment conditions cause the potentiometric surface near the lake to be flat and almost horizontal. Slight differences in computed hydraulic head at nodes in elements in this area are responsible for the ground-water flow paths shown in figure 10*A*; therefore, ground-water flow paths in the Lake Seminole area can only be considered approximate, because neither the model nor the hydrologic data on which the model was developed contain sufficient detail to identify accurately ground-water flow directions. Because the potentiometric surface is relatively flat near the lake, small changes to model input data—such as updated pumping estimates or improved estimates of aquifer properties—would alter the direction and magnitude of simulated ground-water flow vectors described herein.

Summary

Based on simulation results, the impoundment of Lake Seminole changed ground-water flow directions in the Upper Floridan within about 20–30 mi of the lake. The largest change occurred southeast of the lake, where, prior to impoundment, ground water flowed from Florida into Georgia, discharging to the Flint River downstream of Bainbridge, Ga. This water then flowed into the Apalachicola River. Following impoundment, ground water southeast of the lake flows from Lake Seminole to the Apalachicola River; however, hydraulic gradients and flow volumes are small. Also, discharge to the Upper Floridan aquifer from Lake Seminole has created a mound in the potentiometric surface of the aquifer near the lake, thus increasing the amount of ground water that is stored in this area. Aquifer water levels were increased by as much as 26 ft near Jim Woodruff Lock and Dam; the area in which water levels were increased at least 10 ft extends nearly 20 mi upstream along the Chattahoochee and Flint Rivers, and several miles downstream along the Apalachicola River.

Simulation results indicate that the impoundment of Lake Seminole changed ground-water budget components, including reduction of ground-water discharge from the Upper Floridan aquifer to streams by about 400 Mgal/d; reduction of inflow of ground water into the Upper Floridan aquifer in the region simulated by about 240 Mgal/d; and a reduction of ground-water recharge from the undifferentiated overburden by about 110 Mgal/d. Most of the reduction of ground-water discharge to streams was along the lowest reaches of the Chattahoochee and Flint Rivers that are now part of the lake. Prior to impoundment, stage in these streams was as much as 40 ft lower than postimpoundment conditions. Most of the reduction in regional inflow of ground water to the modeled area occurs at the model boundary southeast of the lake.

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