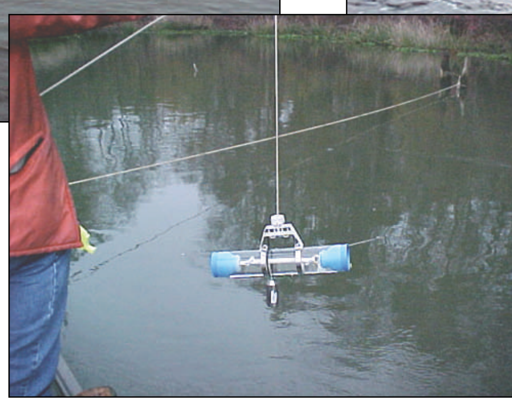
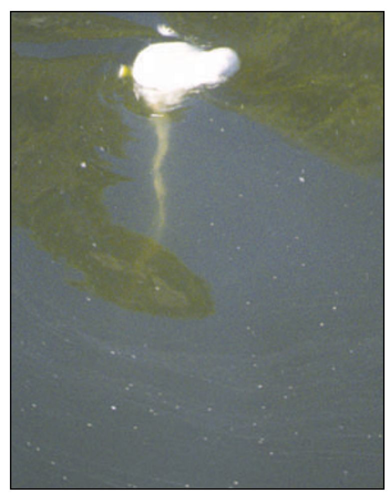
Physical and Hydrochemical Evidence of Lake Leakage near Jim Woodruff Lock and Dam and of Ground-Water Inflow to Lake Seminole, and an Assessment of Karst Features in and near the Lake, Southwestern Georgia and Northwestern Florida





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

Scientific Investigations Report 2005-5084

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

Cover photographs, clockwise from top left:

Boat-mounted acoustic Doppler current profiling apparatus in use near the River Boil; looking north from Apalachicola River toward Jim Woodruff Lock and Dam in background. Photograph by Lynn J. Torak, U.S. Geological Survey

River Boil on Apalachicola River, about 900 feet downstream of Jim Woodruff Lock and Dam, near Chattahoochee, Florida. Photograph by Lynn J. Torak, U.S. Geological Survey

Vortex flow entering sinkhole in the bottom on Lake Seminole at a depth from about 8 to 10 feet, located along the western shore of the lake about one-half mile from Jim Woodruff Lock and Dam near Sneads, Florida. Photograph by Harley Means, Florida Geological Survey

Nonisokinetic thief sampler (Van Dorn sampler) in use at State Dock Spring on Flint River impoundment arm of Lake Seminole, Bainbridge, Georgia. Photograph by Lynn J. Torak, U.S. Geological Survey

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U.S. Geological Survey

U.S. Department of the Interior
P. Lynn Scarlett, Acting Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

This report is a Web-only publication: ***pubs.usgs.gov/sir/2005/5084/***

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Suggested citation:
Torak, L.J., Crilley, D.M., and Painter, J.A., 2006, Physical and hydrochemical evidence of lake leakage near Jim Woodruff Lock and Dam and of ground-water inflow to Lake Seminole, and an assessment of karst features in and near the lake, southwestern Georgia and northwestern Florida: U.S. Geological Survey Scientific Investigations Report 2005-5084, 90 p.

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per hour (ft/hr)	0.3048	meter per hour (m/hr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Historical data collected and stored as North American Datum 1927 have been converted to NAD 83 for this publication.

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Milliequivalents (meq) is a means of expressing analytical results in units that recognize that ions of different species have different weights and electrical charges (Hem, 1992). Unit concentrations of all ions are chemically equivalent in an analysis expressed in milliequivalents per liter (see Hem, 1992, p. 55, 56 for details). If the formula weight of an ion is divided by the charge, the result is termed the "combining weight" or "equivalent weight." Ion concentrations in milligrams per liter are divided by the corresponding combining weight to obtain the chemical equivalence of that species (anions or cations), which is expressed in milligram equivalents, or milliequivalents, per liter. Conversion factors for chemical species occurring in natural water are listed in Hem (1992, table 9) and consist of the reciprocal of the corresponding combining weight. Thus, to convert ion concentration in milligrams per liter to milliequivalents, multiply the ion concentration by the reciprocal of the corresponding combining weight. The reciprocal of the combining weights for cations analyzed in this study are as follows—calcium (0.04990), magnesium (0.08229), potassium (0.02558), and sodium (0.04350) (Hem, 1992, table 9).

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Abstract

Hydrogeologic data and water-chemistry analyses indicate that Lake Seminole leaks into the Upper Floridan aquifer near Jim Woodruff Lock and Dam, southwestern Georgia and northwestern Florida, and that ground water enters Lake Seminole along upstream reaches of the lake's four impoundment arms (Chattahoochee and Flint Rivers, Spring Creek, and Fishpond Drain). Written accounts by U.S. Army Corps of Engineers geologists during dam construction in the late 1940s and early 1950s, and construction-era photographs, document karst-solution features in the limestone that comprise the lake bottom and foundation rock to the dam, and confirm the hydraulic connection of the lake and aquifer. More than 250 karst features having the potential to connect the lake and aquifer were identified from preimpoundment aerial photographs taken during construction. An interactive map containing a photomosaic of 53 photographic negatives was orthorectfied to digital images of 1:24,000-scale topographic maps to aid in identifying karst features that function or have the potential to function as locations of water exchange between Lake Seminole and the Upper Floridan aquifer. Some identified karst features coincide with locations of mapped springs, spring runs, and depressions that are consistent with sinkholes and sinkhole ponds.

Hydrographic surveys using a multibeam echosounder (sonar) with sidescan sonar identified sinkholes in the lake bottom along the western lakeshore and in front of the dam. Dye-tracing experiments indicate that lake water enters these sinkholes and is transported through the Upper Floridan aquifer around the west side of the dam at velocities of about 500 feet per hour to locations where water "boils up" on land (at Polk Lake Spring) and in the channel bottom of the Apalachicola River (at the "River Boil"). Water discharging from Polk Lake Spring joins flow from a spring-fed ground-water discharge zone located downstream of the dam; the combined flow disappears into a sinkhole located on the western floodplain of the river and is transmitted through the Upper Floridan aquifer, eventually discharging into the Apalachicola River at the River Boil. Acoustic Doppler current profiling yielded flow estimates from the River Boil in the range from about 140 to 220 cubic feet per second, which represents from about 1 to 3 percent of the average-daily flow in the river. Binary mixing-model analysis using naturally-occurring isotopes of oxygen and hydrogen (oxygen-18 and deuterium) indicates that discharge from the River Boil consists of a 13-to-1 ratio of lake water to ground water and that other sources of lake leakage and discharge to the boil probably exist.

Analyses of major ions, nutrients, radon-222, and stable isotopes of hydrogen and oxygen contained in water samples collected from 29 wells, 7 lake locations, and 5 springs in the Lake Seminole area during 2000 indicate distinct chemical signatures for ground water and surface water. Ground-water samples contained higher concentrations of calcium and magnesium, and higher alkalinity and specific conductance than surface-water samples, which contained relatively high concentrations of total organic carbon and sulfate. Solute and isotopic tracers indicate that, from May to October 2000, springflow exhibited more ground-water qualities (high specific conductance, low dissolved oxygen, and low temperature) than surface water; however, the ratio of ground water to surface water of the springs was difficult to quantify from November to April because of reduced springflow and rapid mixing of springflow and lake water during sampling. The saturation index of calcite in surface-water samples indicates that while surface water is predominately undersaturated with regard to calcite year-round, a higher potential for dissolution of the limestone matrix exists from late fall through early spring than during summer.

The relatively short residence time (5–7 hours) and rapid flow velocity (nearly 500 feet per hour) of lake water leaking into the Upper Floridan aquifer and exiting at the River Boil in the Apalachicola River implies that calcite-undersaturated water is in constant contact with the limestone, increasing the potential for limestone dissolution and enlargement of flow pathways by erosion. A relatively low potential exists, however, for limestone dissolution to cause sudden sinkhole collapse followed by catastrophic lake drainage because ground-water levels close to the lake, except near the dam, are nearly the same as lake stage, resulting in low vertical and lateral hydraulic gradients and low flow between the lake and aquifer. An increased potential for lake leakage and sinkhole formation and collapse exists near some in-lake springs during colder months of the year, as density differences and the hydraulic potential between lake water and ground water establish the conditions for calcite-undersaturated lake water to enter nonflowing springs and contact limestone.

Introduction

Lake Seminole is a 37,600-acre surface-water impoundment located at the junction of the Chattahoochee and Flint Rivers in southwestern Georgia and northwestern Florida (fig. 1). The lake is emplaced in the karstic plains of the lower Apalachicola–Chattahoochee–Flint (ACF) River Basin, occupying the old river courses and adjacent floodplains of the Chattahoochee and Flint Rivers, Spring Creek, and Fishpond Drain, where it is in hydraulic connection with the underlying Upper Floridan aquifer (Torak and others, 1996). Lake Seminole was formed during the mid-1950s following construction of Jim Woodruff Lock and Dam by the U.S. Army Corps of Engineers (Corps) on the Apalachicola River, about 107 miles (mi) upstream of its mouth in Apalachicola Bay and about 1,000 feet (ft) downstream of the confluence of the Chattahoochee and Flint Rivers. The lock and dam was constructed primarily to aid navigation in the Chattahoochee and Flint Rivers above the dam and in the Apalachicola River below the dam and to generate hydroelectric power. Secondary benefits include public recreation, regulation of streamflow, and fish and wildlife conservation; no flood-control storage is available in Lake Seminole (U.S. Army Corps of Engineers, 1984). The Chattahoochee and Flint Rivers, Spring Creek, and Fishpond Drain—which constitute the lake's four impoundment arms—provide inflow to Lake Seminole. 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.

The lake and its contributing rivers are important local resources for shipping, transport, hydroelectric power, and recreation. Outflow from the lake has regional importance to the water resources of the Apalachicola Bay and Apalachicola River floodplain and estuary. Lake outflow affects navigation, flow regulation, and the supply of nutrients and detritus to support various aquatic biota, including Apalachicola Bay's diverse shellfish population.

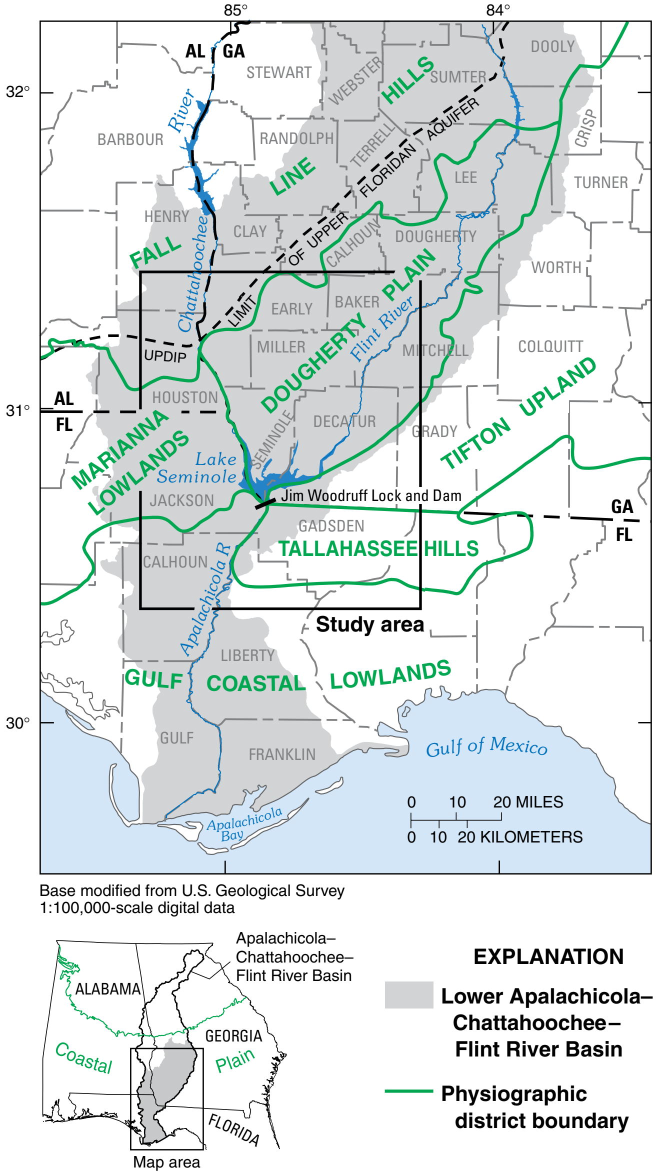


Figure 1. Location of study area, Lake Seminole, boundaries of the lower Apalachicola–Chattahoochee–Flint River Basin, and physiographic districts of the Coastal Plain province (modified from Torak and others, 1996).

Lake Seminole is underlain by the Upper Floridan aquifer, the most productive aquifer system in the southeastern United States, comprising 100,000 cubic miles (mi^3) of predominantly karst limestone in the Coastal Plain (Bush and Johnston, 1988). The Upper Floridan aquifer is the primary source of ground water for agricultural, industrial, and domestic uses in the study area. Irrigation, in particular, is the major ground-water withdrawal use in this heavily agricultural area. Nearly one-half million 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, Professor, National Environmentally Sound Production Agricultural Laboratory, The University of Georgia, Tifton, Ga., written commun., November 2002).

Hydraulic connection of the Upper Floridan aquifer with surface water occurs through numerous karst sinks and conduits that are present in the Lake Seminole area and lower ACF River Basin in Georgia. The hydraulic connection between Lake Seminole and the Upper Floridan aquifer is demonstrated by the occurrence of in-lake springs flowing from limestone located along the lake bottom and by features resembling sinkholes that permit lake water to leak into the aquifer; however, this connection is not well understood or easily quantified. Karstic landscape suggests surface- and ground-water connection, and some streams exhibit gaining and losing characteristics along specific reaches, including subterranean flow, where streams disappear from land surface and flow in caverns contained in the Upper Floridan aquifer. The lake receives ground water from springs that issue from the lake bottom and from diffuse ground-water inflow across the lake bed, and loses water to the aquifer through features resembling sinkholes and by diffuse leakage through the lake bottom.

Recently, Lake Seminole and the water released from it became major issues 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 major concerns for water-resource managers in the region, as the three States compete to acquire the basin's limited water resources to meet their conflicting demands. 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.

Essential to the State of Georgia's water-allocation plans was the necessity to undertake a technical study to develop a comprehensive water budget of the Lake Seminole area, to reasonably estimate the volume of water flowing into Florida before and after construction of the dam, and to monitor the effects of any sinkhole collapse within the lake (Harold F. Reheis, then-Director, Georgia Department of Natural Resources, Environmental Protection Division, written commun., 1997). The State of Georgia had requested that the U.S. Geological Survey (USGS) conduct a technical study to address these issues; during 1999, a 3-year study was initiated to address the following objectives:

- 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 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.

- 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 changes in pertinent hydrologic components that would indicate sudden draining of Lake Seminole, thereby providing a warning of its occurrence.

The 3-year study investigated features of the hydrologic system near Lake Seminole that contribute directly to the surface- and ground-water flow regime of the lake. The study focused on only 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 of water-chemistry, limnological, hydrogeological, and meteorological information, followed by analysis and interpretation of the resulting data and corresponding uncertainty.

Purpose and Scope

This report is one of three reports documenting a study to evaluate the effects of impoundment of Lake Seminole on water resources in the lower ACF River Basin. The other reports document differences in the pre- and postimpoundment ground-water flow regimes in the Upper Floridan aquifer for the area surrounding the lake (Jones and Torak, 2004) and present estimates of a lake water budget (Dalton and others, 2004). This report addresses the last two of the previously listed study objectives, namely, to 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 to 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.

This report describes the physical and hydrochemical evidence of mixing ground water and surface water in the interconnected stream-lake-aquifer flow system of the Lake

[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.

Seminole area and provides an assessment of karst features around and beneath the lake. Physical evidence of stream-lake-aquifer interaction was investigated using several sources of hydrogeologic information. Ground-water levels were compared with stream and lake stage to determine the hydraulic potential for ground-water inflow to Lake Seminole and for lake leakage into the Upper Floridan aquifer. A detailed survey of streamflow gain along Spring Creek was conducted to identify point and diffuse sources of ground-water inflow to Lake Seminole. Written accounts by Corps geologists during dam construction during the late 1940s and early 1950s, Corps reports written prior to construction, and photographs taken during dam construction were used to identify locations in the present-day lake bed where surface water and ground water can mix by various inflow and outflow mechanisms that connect Lake Seminole with the karst limestone of the Upper Floridan aquifer. Participation in dye-tracing experiments performed by the Corps during this study near Jim Woodruff Lock and Dam confirmed the hydraulic connection of the lake with the Upper Floridan aquifer, and acoustic Doppler current profiling of upwelling (a boil) in the Apalachicola River provided additional field evidence of the aquifer-stream-lake hydraulic connection. Seasonal-temperature variations of in-lake springflow and flow from the boil were compared with water temperature at possible origins for this water to identify sources and mixing processes in the stream-lake-aquifer flow system.

Physical, chemical, and isotopic constituents of ground water, surface water, and springflow were analyzed from samples that were collected in the Lake Seminole study area to identify the origin of sampled water, to describe seasonal variations in water chemistry, and to infer mixing processes as they relate to the karst environment. Conservative-solute tracers, and naturally-occurring stable isotopes of oxygen and hydrogen (oxygen-18 and deuterium, respectively), were used to investigate the occurrence of lake leakage into the Apalachicola River at a river boil located just downstream of Jim Woodruff Lock and Dam. Geochemical analyses were performed on water sampled from the boil, possible end-member locations at nearby wells, and Lake Seminole to evaluate the stability of karst conduits connecting the lake with the Upper Floridan aquifer. The calcite-dissolution capacity of lake water and flow rates out of the boil also were used to evaluate the stability of conduits to the boil and to assess the potential for karstic dissolution of the limestone matrix of the Upper Floridan aquifer.

The assessment of karst features in the limestone of the Upper Floridan aquifer consisted of analysis of preimpoundment aerial photographs of the Lake Seminole area that were orthorectified to digital raster graphic images of 1:24,000-scale topographic quadrangle maps and of preconstruction maps of the geology and dam foundation, which were prepared by the Corps (U.S. Army Corps of Engineers, 1948). The photographs and maps were compared with current maps showing topography, bathymetry, and navigation features to identify locations where sinkholes and other karst features and springs existed in the lake area and stream channels prior to impoundment.

Previous Studies

Numerous investigators have studied the regional geology, physiography, hydrogeology, and ground-water resources of the Upper Floridan aquifer in the Lake Seminole area since the 1890s. A study by McCallie (1898) first described the general geology and ground-water resources of the Coastal Plain. Stephenson and Veatch (1915), Cooke (1943), and Herrick (1961) followed with additional descriptions. Wait (1963), Sever (1965a,b), Pollard and others (1978), Hicks and others (1981, 1987), Hayes and others (1983), Torak and others (1993, 1996), and Torak and McDowell (1996) described the geohydrology of southwestern Georgia. Moore (1955), Kwader and Schmidt (1978), Schmidt (1978, 1979, 1984), Schmidt and Coe (1978), Schmidt and Clark (1980), and Schmidt and others (1980) investigated the geology of parts of the Lake Seminole area and lower ACF River Basin in Florida. Arthur and Rupert (1989) investigated details of basin physiography. The Corps documented preconstruction details of the geology, hydrogeology, and structural integrity of foundation material to Jim Woodruff Lock and Dam (U.S. Army Corps of Engineers, 1948), and Mosner (2002) recently studied the hydrogeology of the region. Torak and others (1996) and Torak and McDowell (1996) used simulation techniques to evaluate the ground-water resources and stream-aquifer interaction in the Upper Floridan aquifer in the lower ACF River Basin.

McConnell and Hacke (1993) and Plummer and others (1998a,b) performed hydrologic studies of the water chemistry of a karstic area to the east of Lake Seminole in the Upper Floridan aquifer at Valdosta, Ga. Crandall and others (1999), Katz (1998), and Katz and others (1995a,b and 1997) studied hydrochemical investigations of stream-lake-aquifer interaction in karstic regions of northern Florida. Studies describing the geochemistry and ground-water quality of the Upper Floridan aquifer include Katz (1992), Sprinkle (1989), and Sever (1965a). Water-quality management studies of Lake Seminole by the U.S. Army Corps of Engineers (1982) provided important background information for the study area.

Acknowledgments

Sincere appreciation is extended to the residents of Decatur and Seminole Counties, Ga., and Jackson and Gadsden Counties, Fla., who volunteered the use of their wells for this study. Special thanks are extended to the U.S. Army Corps of Engineers, Mobile District Office, Mobile, Ala., for providing preimpoundment aerial photographs and other historical documents concerning construction of Jim Woodruff Lock and Dam, and for supplying assorted manpower, materiel, and guidance during various phases of this study. Dye-tracing experiments were performed under the direction of Nicolas C. Crawford, Ph.D., Crawford Hydrology Laboratory, Center for Cave and Karst Studies, Western Kentucky University, Bowling Green, Ky., whose expertise is appreciated greatly.

Study Area

The study area is located in the lower ACF River Basin of the Coastal Plain physiographic province in parts of southwestern Georgia, southeastern Alabama, and northwestern Florida (fig. 2) and includes Lake Seminole and the land area of the basin that contributes ground- and surface-water flow into and out of the lake, about 2,300 square miles (mi^2). In Georgia, the study area encompasses all or parts of Baker, Decatur, Early, Grady, Miller, Mitchell, and Seminole Counties; in Florida, the study area comprises parts of Calhoun, Gadsden, Jackson, and Liberty Counties; in Alabama, the study area comprises the southeastern part of Houston County.

Climate

Lake Seminole is located in a subtropical climate region characterized by long summers and mild winters. The coldest months, December and January, average about 51.4 degrees Fahrenheit (°F) (table 1); occasional freezing temperatures occur during this time. The warmest months, July and August, have an average temperature of about 80.7°F; however, temperatures near 100°F are not uncommon. The mean-annual air temperature for a 47-year period, 1957–2003, at Colquitt, Ga., is about 66.4°F (table 1).

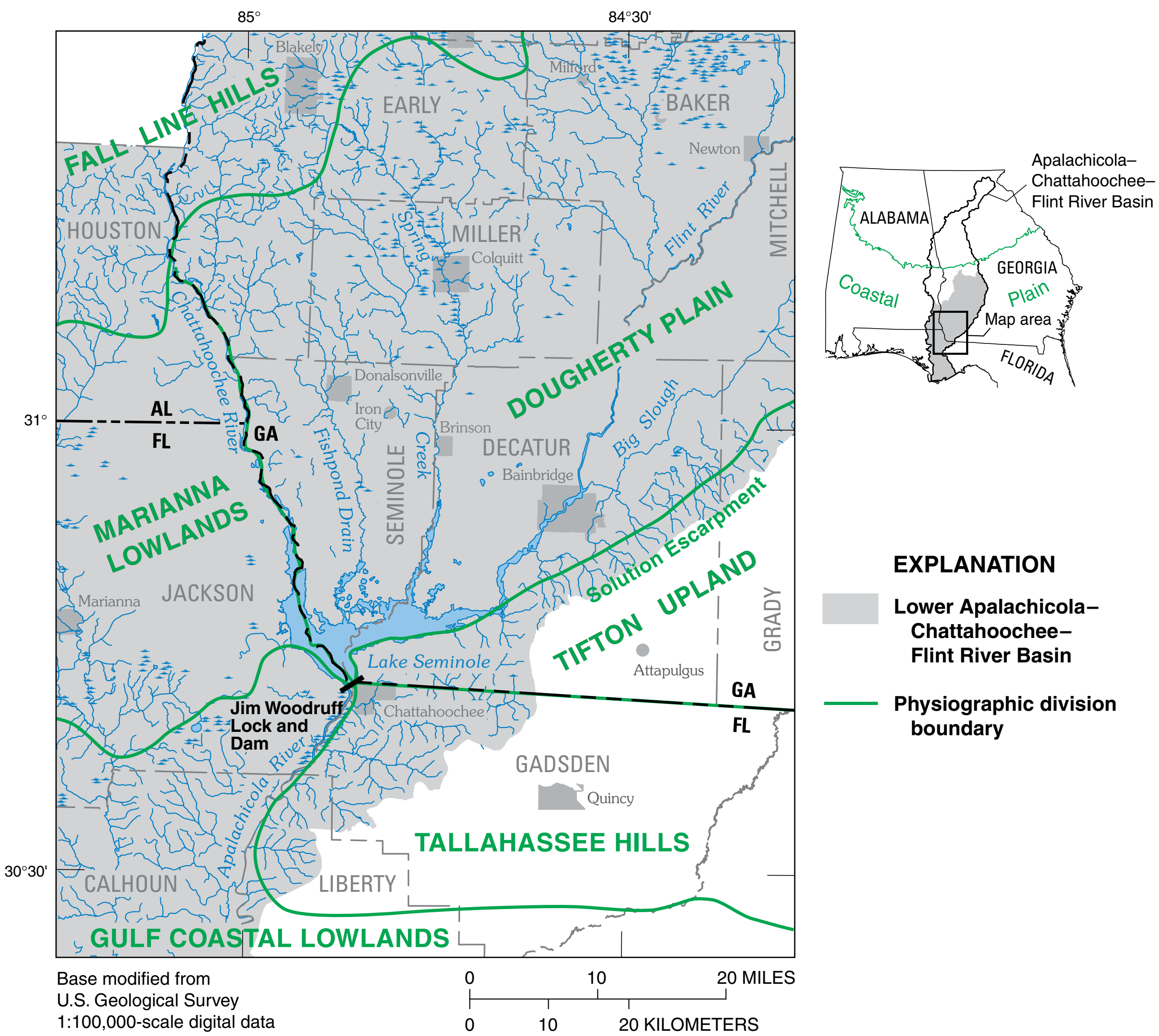


Figure 2. Physiographic divisions and drainage features of the Lake Seminole study area.

Table 1. Climate data for Colquitt, Georgia[1].

[°F, degree Fahrenheit]

Month	Average maximum temperature (°F)	Average minimum temperature (°F)	Average precipitation (inches)
January	61.2	38.1	5.29
February	65.3	41	4.7
March	72.1	46.9	6.14
April	79.7	53.4	3.83
May	85.6	60.4	3.58
June	90.1	67.3	5.36
July	91.9	70	5.41
August	91.2	69.6	4.96
September	88	65.7	4.44
October	80.1	54.5	2.6
November	71.8	46	3.38
December	64	39.9	4.23
Average	**78.4**	**54.4**	**Total = 53.92**

Mean-annual air temperature =	66.4°F
Average air temperature	
July and August =	80.7°F
December and January =	51.4°F

[1]Data for this climatological station are from National Oceanic and Atmospheric Administration weather station 2W, Colquitt, Ga. (see figure 2 for location), latitude 31°10'01"N, longitude 84°46'01"W (North American Datum of 1983), for the period 1957–2003. Source: Georgia Automated Environmental Monitoring Network, University of Georgia, College of Agriculture and Environmental Sciences, Griffin Experiment Station, Griffin, Ga., accessed September 1, 2004, at *http://georgiaweather.net*

Mean-annual rainfall for the region during the 47-year period, 1957–2003, was 53.92 inches, recorded at Colquitt, Ga. (table 1). The highest average monthly rainfall occurred during this period during March (6.14 inches); the lowest rainfall occurred during October (2.6 inches). Although precipitation is distributed fairly uniformly throughout the year (fig. 3), the majority of recharge to the aquifer occurs from December through March, when storms associated with frontal passages bring relatively long-duration (2–3 days), low-intensity rainfall to the study area, and evapotranspiration rates are low. Rainfall events of this type are conducive to high infiltration and low runoff, in contrast with summer rainfall, which is usually of short duration and high intensity, and is derived from convective-type thunderstorms that cause high runoff and low infiltration.

Total-annual precipitation in the Lake Seminole region during 2000 was consistently below the 47-year average of about 53.92 inches for the period 1957–2003 (table 1). Annual precipitation totaled about 35.46 inches to the east at Attapulgus, Ga.; 37.06 inches at Jim Woodruff Lock and Dam; and 48.51 inches at Newton, Ga., to the north of the lake (table 2). Monthly precipitation totals were well below average, except for higher than average rainfall during September (compare tables 1 and 2).

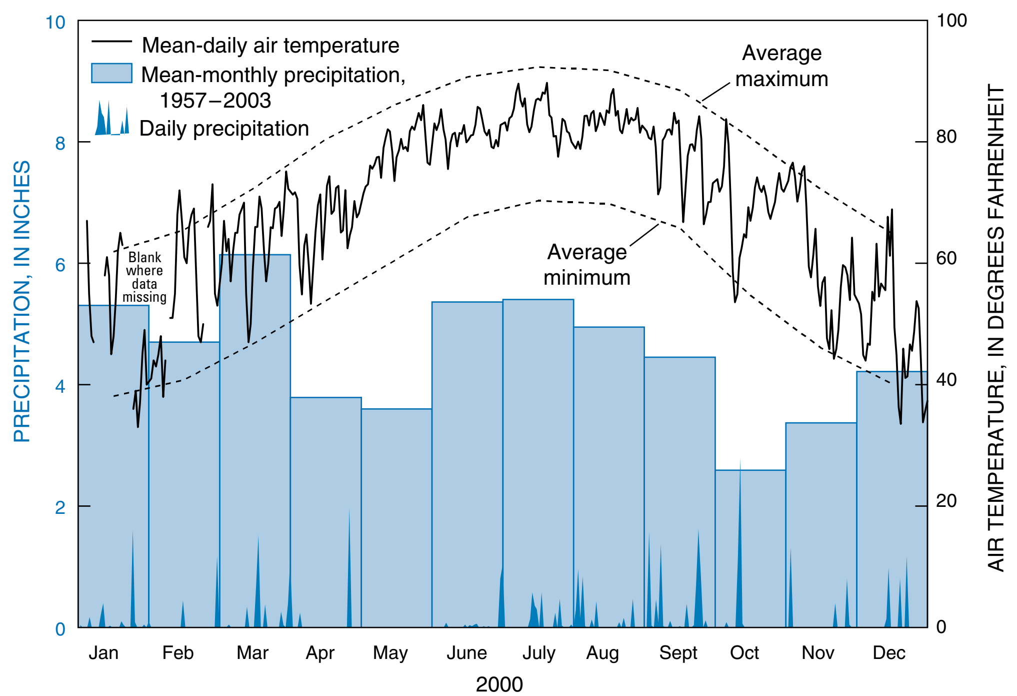


Figure 3. Precipitation and air temperature for Colquitt, Georgia. Data for this station are from National Oceanic and Atmospheric Administration weather station 2W, Colquitt, Ga., latitude 31°10'01"N, longitude 84°46'01"W (North American Datum of 1983), for the period 1957–2003; Georgia Automated Environmental Monitoring Network, University of Georgia, College of Agriculture and Environmental Sciences, Griffin Experiment Station, Griffin, Ga., accessed September 1, 2004, at *http://georgiaweather.net*

Table 2. Monthly precipitation data for 2000 at Attapulgus and Newton, Georgia, and at Jim Woodruff Lock and Dam, Lake Seminole, near Chattahoochee, Florida.

[NAD 83, North American Datum of 1983]

Month	Precipitation (inches)		
	Attapulgus, Georgia[1]	Newton, Georgia[2]	Jim Woodruff Lock and Dam,[3] Lake Seminole
January	1.99	2.91	2.84
February	1.73	2.82	1.63
March	2.87	3.89	4.74
April	2.27	0.81	2.22
May	0.01	.21	0
June	4.37	4.44	2.19
July	3.44	8.87	2.75
August	4.14	2.54	5.13
September	7.68	10.57	5.80
October	0.85	1.43	4.09
November	2.97	6.42	2.57
December	3.14	3.60	3.10
Total	**35.46**	**48.51**	**37.06**

[1]Data for this climatological station are from Attapulgus Research Farm, University of Georgia, Attapulgus, Decatur County, Ga. (see figure 2 for location), latitude 30°45'40"N, longitude 84°29'07"W (NAD 83) (Georgia Automated Environmental Monitoring Network, University of Georgia, College of Agriculture and Environmental Sciences, Griffin Experiment Station, Griffin, Ga., accessed September 1, 2004, at *http://georgiaweather.net*; and Eddie Edenfield, University of Georgia, College of Agriculture and Environmental Sciences, Griffin Experiment Station, Griffin, Ga., written commun., September 2004).

[2]Data for this climatological station are from Joseph W. Jones Ecological Research Center, Ichauway, Newton, Baker County, Ga. (see figure 2 for location), latitude 31°13'26"N, longitude 84°28'40"W (NAD 83) (Georgia Automated Environmental Monitoring Network, University of Georgia, College of Agriculture and Environmental Sciences, Griffin Experiment Station, Griffin, Ga., accessed September 3, 2004, at *http://georgiaweather.net*).

[3]Data for this climatological station are from Jim Woodruff Lock and Dam, Lake Seminole, near Chattahoochee, Gadsden County, Fla. (see figure 2 for location), latitude 30°42'33"N, longitude 84°51'45"W (NAD 83) (U.S. Army Corps of Engineers, Mobile District, Mobile, Ala., accessed September 3, 2004, at *http://water.sam.usace.army.mil/gage/jwrain.htm*).

Physiography and Drainage

The study area is in the Coastal Plain physiographic province and can be divided into three distinctive regions: a low-lying karstic region; a region of dissected remnant hills and sand-hill ridges; and a flat, low-lying, coastal-sediment region. The karstic region includes the Dougherty Plain, Marianna Lowlands, and Tifton Upland physiographic districts (fig. 2). Karst topography is present where Eocene limestone is present at the surface, the dissolution of which exerts the greatest influence on water quality and stream-lake-aquifer interaction in the Lake Seminole area. In the Florida panhandle, the Dougherty Plain District is called the Marianna Lowlands District, and the Tifton Upland District is called the Tallahassee Hills District (fig. 2) (Puri and Vernon, 1964). The boundary between the Tifton Upland and the Dougherty Plain is a regionally prominent northwest-facing escarpment called the Solution Escarpment (MacNeil, 1947) or the Pelham Escarpment (Hayes and others, 1983).

The Dougherty Plain and Marianna Lowlands are relatively flat, internally drained, inner-lowland regions characterized by numerous karst-dissolution features, such as sinkholes and cavities. These districts are the major recharge area for the Upper Floridan aquifer, and include surface outcroppings of the Ocala and Suwannee Limestones. Active solutioning of limestone has produced sinkholes, sinkhole ponds, marshes, and underground channels that capture surface drainage. Practically all direct runoff from rainfall flows into numerous sinkholes, and small tributary streams are scarce (Sever, 1965a).

Between the Dougherty Plain and Tifton Upland Districts lies the Solution Escarpment, a steeply-sloping escarpment along the southeastern shore of the Flint River impoundment arm that continues northeastward across Decatur, Grady, and Mitchell Counties, Ga. (fig. 2). The ridge of the escarpment forms a topographic and surface-water divide between the Flint River Basin and the Ochlockonee and Withlacoochee River Basins to the east. The slope of the Solution Escarpment faces west-to-northwest (as much as 125 ft of local relief), and small streams flow northwestward down the escarpment into caves and sinkholes along the eastern edge of the Dougherty Plain (Sever, 1965a). The base of the escarpment contains some cavities and sinkholes, but solution features are more narrow and deeper than those features of the Dougherty Plain (Hicks and others, 1987). The Tifton Upland and Tallahassee Hills are hilly regions between the low-lying Dougherty Plain and Gulf Coastal Lowlands, consisting of narrow, rounded plateaus and well-developed drainage. These regions have high hills composed largely of resistant clayey sands, silts, and clays (Arthur and Rupert, 1989). Dendritic streams dissect the hills, forming V-shaped valleys. The Tifton Upland ends abruptly at the Flint River, and the Tallahassee Hills region ends abruptly at the Apalachicola River, both in steep bluffs that provide relief from about 150 to 200 ft above the floodplain (Torak and others, 1996).

Geologic Framework

The study area is underlain by Coastal Plain deposits of pre-Cretaceous to Quaternary; however, the geologic framework discussed herein is limited to geologic units of late-middle Eocene and younger that are in hydraulic connection with surface water or that otherwise contribute to the stream-lake-aquifer flow system containing Lake Seminole. These water-bearing units typically consist of cross-bedded clayey sands, sands, gravels, and clay, limestone, dolomite, and limestone residuum in an off-lapping sequence that dips gently and thickens gradually to the southeast. In ascending order, these units are the Lisbon Formation; Clinchfield Sand; Ocala, Suwannee, and Tampa Limestones; Hawthorn Group; terrace and undifferentiated deposits (residuum); and terrace and undifferentiated (surficial) deposits (fig. 4).

SERIES	FLORIDA AND GEORGIA NORTHWEST OF LAKE SEMINOLE			GEORGIA AND FLORIDA SOUTHEAST OF LAKE SEMINOLE		
	Geologic unit	Hydrologic unit	Ground-water quality	Geologic unit	Hydrologic unit	Ground-water quality
Holocene and Pleistocene	Terrace and undifferentiated (surficial) deposits	Surficial aquifer system / Upper semiconfining unit	Not determined	Terrace and undifferentiated (surficial) deposits	Surficial aquifer system / Upper semiconfining unit	Not determined
Miocene	Undifferentiated overburden (residuum)	Upper semiconfining unit	Not determined	Hawthorn Group	Upper semiconfining unit	Corrosive
Miocene	Undifferentiated overburden (residuum)	Upper semiconfining unit	Not determined	Tampa Limestone; Chattahoochee Formation; St. Marks Formation	Upper semiconfining unit / Upper Floridan aquifer	Moderately soft to moderately hard, high magnesium
Oligocene	Suwannee Limestone	Upper Floridan aquifer	Moderately hard	Suwannee Limestone; Marianna Limestone	Upper Floridan aquifer	Moderately hard to hard, high magnesium and sulfate
Eocene	Ocala Limestone; Clinchfield Sand	Upper Floridan aquifer	Moderately hard, good quality	Ocala Limestone	Upper Floridan aquifer	Hard to very hard, high magnesium and sulfate; high iron along Solution Escarpment
Eocene	Lisbon Formation	Lower confining unit	Moderately hard, fair quality but sulphurous	Lisbon Formation	Lower confining unit	Moderately hard, sulphurous

Figure 4. Geologic and hydrologic units in the Lake Seminole study area and general description of ground-water chemistry of water-bearing units (modified from Sever, 1965a; and Torak and others, 1996).

The study area is underlain by the Lisbon Formation, an argillaceous to dolomitic, clastic limestone of late-middle Eocene that is interspersed with fine-grained calcareous glauconitic sand layers (Miller, 1986). The Lisbon Formation crops out north of the study area in southeastern Alabama and southwestern Georgia. Downdip, the Lisbon Formation grades into calcareous, glauconitic clay that contains thin to thick beds of fine, 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.

The Clinchfield Sand overlies the Lisbon Formation (fig. 4) and crops out less than 1 mi beyond the updip limit of the overlying Ocala Limestone (Herrick, 1972). The Clinchfield Sand is an ancient beach deposit that generally consists of medium to coarse, fossiliferous, calcareous quartz sand. Downdip, the sand grades into the Ocala Limestone (Herrick, 1972).

The late Eocene Ocala Limestone overlies the Lisbon Formation and Clinchfield Sand (fig. 4), where it is present in the Dougherty Plain, and consists of a "white-to-cream-colored-bioclastic limestone ... [that] is honeycombed with solution cavities" (Sever, 1965a). The surface of the Ocala Limestone locally is irregular from limestone dissolution and development of karst topography. Locally, the upper few feet of the limestone in the subsurface consist 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 and boundary of the Dougherty Plain District (fig. 2). Beneath the Tifton Upland, the Ocala Limestone thickens to about 750 ft and grades to a brown saccharoidal dolomitic limestone containing gypsum (Sever, 1965a).

In Georgia, the Ocala Limestone contains two distinct ground-water flow regimes defined by equally distinct lithologic characteristics; the ground-water flow pattern corresponding to the different rock units constitutes a unique flow regime. One flow regime exists in the upper unit of the Ocala Limestone, which contains a white, soft, friable, porous coquina composed of large foraminifera, bryozoan fragments, and whole to broken echinoid remains, all loosely bound by a matrix of micritic limestone. In the northern part of the study area, the upper unit of the Ocala Limestone is dense and supplies ground water to the lower unit of the Ocala Limestone through vertical flow. Near Lake Seminole, the upper 10–20 ft of Ocala Limestone yield abundant water to uncased wells.

A second flow regime is present in the lower unit of the Ocala Limestone and consists of fine-grained, soft to semi-indurated, micritic limestone (Miller, 1986). In the northern part of the study area, the lower unit contains recrystallized dolomitic limestone that is very hard, but fractured (David W. Hicks, U.S. Geological Survey, written commun., 1994); thus, the limestone can transmit ground water horizontally as well as vertically. Southeast of the study area on the Tifton Upland, however, wells have penetrated the entire thickness of Ocala Limestone and reported yields are less than 30 gallons per minute (gal/min) (Sever, 1965a).

In northwestern Florida adjacent to Lake Seminole, the Ocala Limestone contains lithological and paleontological variations that can affect ground-water flow. These differences in lithology and paleontology have led to a local naming of the Ocala Limestone, which is not discussed herein, but Moore (1955) described it in detail. In this area, the Ocala Limestone consists of a white to cream-colored, generally soft, granular, permeable, fossiliferous pure limestone, composed almost wholly of the tests of foraminifera and bryozoa (Moore, 1955). In some places, the Ocala Limestone has been recrystallized into a hard, dense limestone with local silicification that might cause it to transmit ground water less readily than the soft, granular variety. A local member of the Ocala Limestone is softer and whiter than the surrounding limestone and slightly glauconitic (Moore, 1955), and also may impede ground-water flow.

Another member of the Ocala Limestone, described by Moore (1955), is buff to white in color, soft, porous, and fine-grained, and differs paleontologically from the Ocala Limestone in Georgia by the scarcity of large foraminifera. A zone of dense, brown chert is present near the top of the limestone along with selenite, all of which may impede ground-water movement. The Ocala Limestone is overlain by undifferentiated overburden in the central to northern part of the study area and by the Suwannee Limestone in the southern part of the study area.

The Suwannee Limestone is a cavernous cream-colored fossiliferous Oligocene limestone (fig. 4) that crops out at the base of the Solution Escarpment and east of the study area in Georgia, but is absent from most of the Dougherty Plain (Sever, 1965a). The limestone forms part of the bed of Lake Seminole, extending from the dam to about 9 mi up the Chattahoochee impoundment arm and about 16 mi up the Flint River impoundment arm, where it borders the Solution Escarpment (fig. 2) (Sever, 1965a, pl. 2). In northwestern Florida, the Suwannee Limestone crops out to the west of Lake Seminole and consists of tan to buff-colored limestone, dolomitic limestone, and dolomitic to calcareous clay. It is overlain by early Miocene sandy clays, clays, and marls or, where present, the Tampa Limestone (Moore, 1955). 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 enables it to yield abundant water to wells that are completed in this unit and provides good hydraulic connection with streams and the lake.

> At the Jim Woodruff Dam site, the "only consistently … impervious strata of rock at the site below foundation grade" that was encountered in exploratory core borings, was a 5-foot thick ... sandy limestone zone, referred to as the "D" zone. This zone comprises the top of the Suwannee Limestone at the site, and acts as a semiconfining layer for the more pervious beds below, everywhere except immediately east of the powerhouse, where a NNW-SSE [north-northwest to south-southeast trending] solution … [channel] has cut through the D zone. During excavation, exploratory holes drilled through the D zone in the western part of the spillway recorded pressures up to 30 psi [pounds per square inch], and many flowed at a rate of 300 to 500 gpm [gal/min].
>
> *James H. Sanders, Jr.,*
> *U.S. Army Corps of Engineers, Mobile District,*
> *written commun., February 2005*

The Tampa Limestone consists of early Miocene sediments that overlie the Suwannee Limestone and are overlain by either clayey sands and gravels of terrace and undifferentiated deposits or the Hawthorn Group (fig. 4). The Tampa Limestone is absent from the Dougherty Plain and crops out in a narrow band around the southern margin of the Marianna Lowlands at the Solution Escarpment, where the limestone ranges in thickness from about 20 to 40 ft. The Tampa Limestone underlies the high-relief region of the Tifton Upland and southern part of the study area in Florida and approaches 250 ft in thickness south of the Tifton Upland and to the east of the study area in Georgia. On the Tifton Upland, most domestic and some industrial wells are completed in the Tampa Limestone because the depth to other limestone units of the Upper Floridan aquifer is greater than 400 ft (Sever, 1965a). 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 appearance is chalky (U.S. Army Corps of Engineers, 1948). The limestone also is exposed in large streams that dissect the Tifton Upland (Sever, 1965a).

The Tampa Limestone contains two distinct, areally segregated facies that affect the water-bearing properties of the formation and stream-lake-aquifer interaction. Puri (1953) called these facies formations in the Florida Panhandle, where a calcareous downdip facies is termed the *St. Marks Formation*, and an updip silty facies is termed the *Chattahoochee Formation*. The Tampa Limestone generally consists of white to light gray, sandy, hard to soft, locally clayey, fossiliferous limestone (Miller, 1986), containing white, gray, and green clays that commonly are calcareous (Moore, 1955). Near Jim Woodruff Lock and Dam, the Tampa Limestone consists of white, arenaceous, and argillaceous limestone, with beds of green "plastic" clay, finely sandy to clayey marl, and fine beds of scattered quartz sand interbedded within the upper 110 ft of thickness (Moore, 1955). The upper 130 ft of Tampa Limestone lies above the stage of the Apalachicola River at the dam (about 44 ft), and about 97 ft of clay in the Tampa Limestone lies above the stage of Lake Seminole (about 77 ft). Ground-water levels in limestone layers interspersed with the clays in the Tampa Limestone on the Solution Escarpment are higher than the stages of either Lake Seminole or the Apalachicola River, because the clay impedes vertical ground-water movement from land surface to the limestone below.

East of the Apalachicola River and downdip of the Solution Escarpment, the Tampa Limestone consists predominantly of clay layers interspersed with limestone. The clay is quite resistant, blocky and tough, and is effectively eroded only by stream abrasion (Moore, 1955). Land surface in this area has more relief than in areas underlain by pure limestone. The clayey units of the Tampa Limestone do not transmit water readily between the overlying Hawthorn Group sediments and the underlying limestone of the Upper Floridan aquifer, and limestone layers within the clay contain water levels that are higher than water levels measured in the underlying limestone. West of the Apalachicola River, the Tampa Limestone is calcareous and well dissected by streams, and water levels in the Tampa Limestone are similar to those in the underlying limestone of the Upper Floridan aquifer.

The Hawthorn Group consists of middle Miocene sediments that overlie the Tampa Limestone (fig. 4), and consists of a series of interbedded varicolored clay, clayey sand, and sandy clay in the upper part, and thin beds of calcareous sand and sandy limestone in the lower part (Sever, 1965a). Near Jim Woodruff Lock and Dam, the Hawthorn Group is about 40 ft thick and consists of sandy clay and fine to medium sand. In northern Florida, the Hawthorn Group contains lenses of green to gray fuller's earth (U.S. Army Corps of Engineers, 1948, p. 2-1). The Hawthorn Group crops out in the valleys of large streams in the Tifton Upland, and sand in the upper part of the formation yields water to dug and bored wells (Sever, 1965a).

An unnamed sand and gravel deltaic deposit of late Miocene overlies the Hawthorn Group to the east of Lake Seminole on the Tifton Upland, and contains as much as 100 ft of red clayey sand and gravel with hematite concretions (Sever, 1965a). This deposit consists of a series of cross-bedded, coarse sand and gravel that is visible at the surface on the tops of hills in the Tifton Upland. Although this deposit can supply water to dug and drilled wells, the water is corrosive and contains high iron concentrations (Sever, 1965a).

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. 4). The residuum consists of unsorted to interbedded sand, silt, and clay with local inclusions of silicified limestone boulders, and 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 Tampa and Suwannee Limestones, the irregular topographic surface conforms to the surface of the underlying limestone, a result of the solution of the underlying soluble limestone (Reves, 1961). Hayes and others (1983) and Hicks and others (1987) noted that approximately the lower half thickness of residuum is more clayey than the sandy, upper part, perhaps as a result of its origin as a weathering product of the underlying limestone. The clayey lower part of the residuum semiconfines the underlying Upper Floridan aquifer; 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 Pleistocene and Holocene (fig. 4) 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 have been exposed in river valleys by dissection and removal of the Miocene clastic formations (Moore, 1955). The terrace and undifferentiated deposits consist of clayey sand, sand, and gravel that change lithology and texture laterally and vertically within short distances. Most deposits are cross-bedded, and locally "limonite" cements the sand and gravel into a hard, dense, ferruginous sandstone (Moore, 1955). The formation contains residual boulders where stream terraces have dissected the underlying limestone. Thickness of terrace deposits range 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 clay or residuum content, either fluctuates with the adjacent river stage or underlying aquifer, or creates a perched water-table condition that fluctuates independent 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.

Hydrogeologic Framework

Stratigraphic relations and distinguishing hydraulic characteristics of limestone and other geologic units differentiate the complex lithology into the upper semiconfining unit, the Upper Floridan aquifer, and the lower confining unit (figs. 4 and 5), which form the subsurface components of the stream-lake-aquifer flow system in the Lake Seminole area. Torak and others (1996) give descriptions of the hydraulic properties of the semiconfining unit, Upper Floridan aquifer, and lower confining unit and additional hydrologic characteristics of these units. Karst processes, hydraulic properties, and stratigraphic relations limit stream-lake-aquifer interaction to these hydrologic units. Stream erosion and dissolution of carbonate sediments have created a flow system in the Upper Floridan aquifer that contains high rates of direct recharge through sinkholes, swallow holes, or similar depressions; indirect recharge by vertical leakage through and/or from overlying terrace and undifferentiated deposits (residuum) and Hawthorn Group sediments; and channel leakage to or from the aquifer across streambeds or the lake bed (fig. 6).

In parts of Alabama and Georgia and to the west of Lake Seminole in Florida, the semiconfining unit overlying the Upper Floridan aquifer consists of alternating layers of sand, silt, and clay that compose the Hawthorn Group sediments, residuum, and terrace and undifferentiated deposits (figs. 4 and 5). In most places, however, these deposits contain enough sand to produce a water table that is connected hydraulically to the Upper Floridan aquifer by vertical leakage (fig. 6). Although most layers of similar lithology are laterally discontinuous, a layer of clay persists in the lower half of the residuum that confines the Upper Floridan aquifer. Residuum thickness ranges from about 20 to about 200 ft; although locally, it can be absent along streams or in the lake bed.

On the Tifton Upland to the south and east of Lake Seminole, the semiconfining unit overlying the Upper Floridan aquifer is defined as the clayey lower part of the Tampa Limestone. Thickness of this clayey part of the Tampa Limestone is about 50 ft.

Locally, the substantial thickness and relatively low vertical hydraulic conductivity of the clay layers overlying the Upper Floridan aquifer impede vertical leakage into or out of the Upper Floridan aquifer across its upper boundary. Perched ground water can occur above the clay in sandy and silty zones of the residuum and in the Tampa Limestone and Hawthorn Group sediments for a short time. The clay layer impedes ground-water recharge from infiltration of precipitation and also controls the rate of infiltration of surface-applied chemicals that might contaminate the ground-water resource (Torak and others, 1996). Limestone units of the Upper Floridan aquifer that are at shallow depths below land surface are semiconfined by overlying terrace and undifferentiated deposits, residuum, Hawthorn Group sediments, and, in places, the Tampa Limestone, as described previously.

In the Dougherty Plain, the Upper Floridan aquifer primarily consists of the Ocala Limestone, but includes the Suwannee Limestone at the Solution Escarpment and on the Tifton Upland, and the Clinchfield Sand, where present. The Tampa Limestone is included in the aquifer west of the Apalachicola River and south of the Florida–Georgia State line, where it overlies the Suwannee Limestone.

Aquifer tests indicate that the transmissivity of the Upper Floridan aquifer ranges from 1,000 to 1,000,000 feet squared per day (ft^2/d) (Hayes and others, 1983; Wagner and Allen, 1984; Bush and Johnston, 1988), and varies regionally depending on the extent and interconnectivity of solution features in the limestone (Torak and others, 1993). Dissolution that occurs along fractures and solution features near Lake Seminole improves stream-lake-aquifer connectivity and integrates the ground-water and surface-water flow system (fig. 6).

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 limited areal extent, sandy lithology, and well-developed surface-water drainage causes the Tampa Limestone to be hydrologically similar to the underlying limestone of the Upper Floridan aquifer. Consequently, the Tampa Limestone is regarded as part of the Upper Floridan aquifer in this area. 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. Ground water in the Tampa Limestone east of the river also has a higher hydraulic head than underlying limestone units of the Upper Floridan aquifer. This hydraulic head, combined with lower-transmissive hydraulic characteristics than the deeper units, causes the Tampa Limestone east of the Apalachicola River to function as a semiconfining unit, providing a mechanism for indirect downward vertical leakage to the Upper Floridan aquifer from either overlying residuum, Hawthorn Group, or terrace and undifferentiated deposits.

The lower confining unit consists of the Lisbon Formation, a hard, well-cemented, and clayey limestone unit having a distinct lower water-yielding capability than the overlying Upper Floridan aquifer. In the Dougherty Plain, wells yield only a few gallons per minute from this unit although to the southeast, adequate water supply for domestic use has been obtained (Hayes and others, 1983). Thus, leakage across the vertical boundary between the Upper Floridan aquifer and the Lisbon Formation is negligible, and the Upper Floridan aquifer is considered to have an impermeable base.

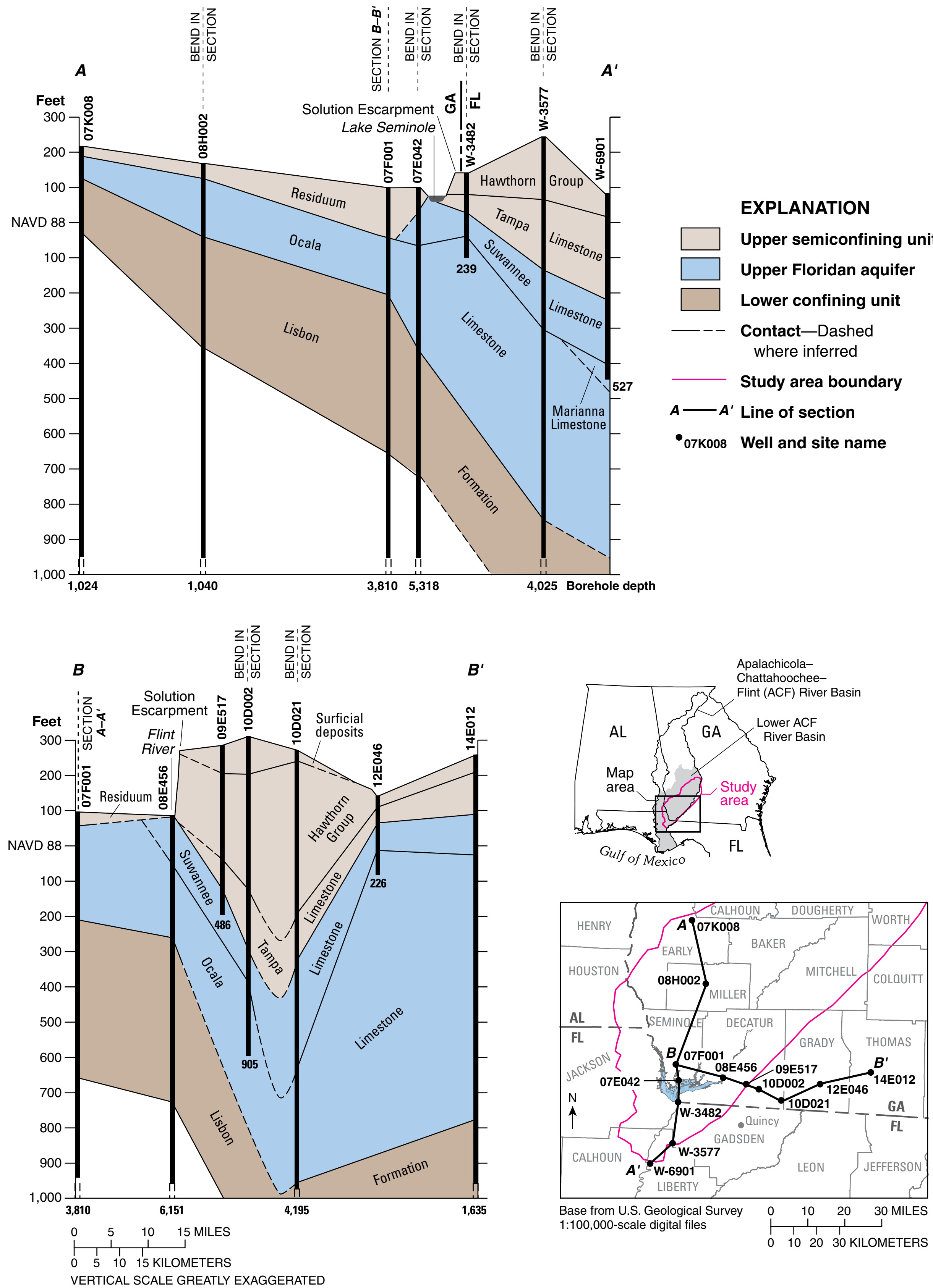


Figure 5. Hydrostratigraphic sections *A–A′* and *B–B′* and locations of wells used to construct sections through the Lake Seminole study area.

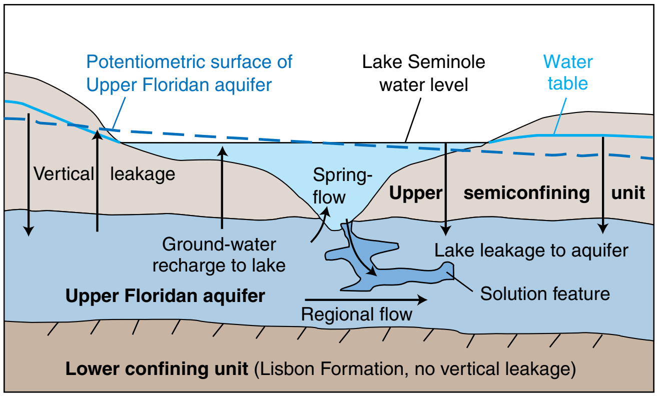


Figure 6. Conceptual diagram of ground-water and surface-water flow in the interconnected stream-lake-aquifer flow system for Lake Seminole.

Hydrochemistry

The concentration of chemical constituents in ground water, surface water, and springflow in the Lake Seminole area is controlled primarily by precipitation and dissolution of minerals by water percolating through overlying residuum into the Upper Floridan aquifer. Ground water in the Upper Floridan aquifer is partially confined, making it open to gas exchange with atmospheric oxygen and carbon dioxide (Katz, 1992). Limestone, dolomite, and gypsum are present in abundance in the Upper Floridan aquifer, and can supply ground water with ions derived from dissolution of calcium carbonate, magnesium carbonate and calcium sulfate, respectively. Other minerals present in sediments composing the residuum and Upper Floridan aquifer are glauconite and pyrite, which through dissolution, can supply ground water with potassium, iron silica, and sulfate ions. Precipitation generally is dilute with respect to ions; the highest specific conductance and lowest pH were measured during March and April 2000 (table 3).

Ground water in the Upper Floridan aquifer in the Dougherty Plain is generally a hard, calcium-magnesium-bicarbonate type. In the Tifton Upland, however, the water is very hard and contains sulfate in places. A 100-mi^2 region of high iron concentration trends roughly parallel with the Solution Escarpment and Flint River impoundment arm of the lake, southeast of Bainbridge, Ga. (Sever, 1965a, fig. 2).

A multiphase investigation of water quality in Lake Seminole, performed by the Corps from April to November 1978, indicated that water in the impoundment arms tends to be well mixed and exhibits no substantial lateral or vertical stratification of temperature, dissolved oxygen, or pH (U.S. Army Corps of Engineers, 1981). Water temperature throughout the lake was highest during July 1978, when average temperatures during the sampling cycle (July 17–20, 1978) were 29.6°C and 28.3°C for the Chattahoochee and Flint River impoundment arms, respectively. The wide, shallow, and relatively stagnant water in the Fishpond Drain impoundment arm had a high temperature of 30°C; the mostly spring-fed water in the Spring Creek impoundment arm had a high temperature of 28.5°C. Immediately upstream of the dam, lake-water temperature was 29.3°C for July, and the Apalachicola River had a temperature of 29°C (U.S. Army Corps of Engineers, 1981, appendix D). Minimum lake temperatures of 18–19°C occurred during November 1978. The Spring Creek impoundment arm contained higher concentrations of dissolved calcium and total hardness than the other impoundment arms, owing to a large ground-water component from springflow and diffuse inflow across the channel bottom.

Table 3. Monthly weighted-mean concentrations of selected chemical constituents in precipitation at Quincy, Florida, for 2000[1].

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; Ca, calcium; Mg, magnesium; K, potassium; Na, sodium; NH_4, ammonia; NO_3, nitrate; Cl, chloride; SO_4, sulfate]

Month	pH, field (standard units)	Specific conductance, field (µS/cm)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	NH_4 (mg/L)	NO_3 (mg/L)	Cl (mg/L)	SO_4 (mg/L)
January	4.81	14.0	0.06	0.06	0.03	0.55	0.08	0.58	0.92	0.89
February	4.82	12.6	.11	.09	.09	.77	.1	.68	1.33	1.17
March	4.91	19.2	.11	.05	.06	.4	.18	.59	.7	1.11
April	4.9	11.5	.16	.04	.04	.28	.23	.88	.49	1.02
May	4.57	18.6	.16	.06	.06	.53	.21	1.44	.9	1.39
June	4.92	8.9	.08	.03	.02	.23	.05	.54	.41	.57
July	4.51	19.5	.12	.02	.02	.14	.23	1.23	.24	1.56
August	4.69	11.9	.04	.02	.01	.17	.04	.64	.32	.69
September	4.79	9.1	.03	.01	.01	.06	.05	.54	.12	.56
October	5.56	4.3	.03	.03	.05	.2	.06	.12	.38	.23
November	4.99	7.3	.04	.02	.01	.17	.06	.4	.29	.41
December	4.91	17.5	.09	.13	.05	1.16	.09	.67	2.12	.88
Average	**4.87**	**12.9**	**1.03**	**.05**	**.04**	**.39**	**.12**	**.69**	**.69**	**.87**

[1]Data for this station are from Quincy, Fla. (see figure 2 for location), latitude 30°32'53"N, longitude 84°36'3"W (North American Datum of 1983), for 2001 (U.S. Geological Survey National Atmospheric Depositional Program/National Trends Network, accessed April 19, 2005, at *http://nadp.sws.uiuc.edu*).

Work performed in this study (fig. 7) indicates that during late spring through late fall, ground-water at temperatures from 19° to 20°C discharges into the lake from springs located in the lake bottom. This relatively cold ground-water fraction is denser than the surrounding lake water; therefore, the ground water mixes minimally with lake water and is confined to the depths of the in-lake springs—from about 20 to 45 ft—and along the lake bottom in spring runs (channels leading from the spring), causing local temperature stratification. Although the lake surface warms in the summer months, a thermocline does not develop because of the lake's shallow depths (except near in-lake springs) and wind-generated mixing. Lake temperatures were highest during August, nearing 34°C close to the surface, and lowest during winter, about 5°C throughout the water column, except near in-lake springs.

Results from a subsequent phase of the Corps study during 1979 and 1980 showed that the Chattahoochee River generally was from about two to three times as turbid as the Flint River but had lower specific conductance, total dissolved solids, alkalinity, dissolved calcium and total hardness than the Flint River (U.S. Army Corps of Engineers, 1982). During spring and early summer, total iron concentrations in Lake Seminole exceeded the 1-milligram-per-liter (mg/L) standard established by the U.S. Environmental Protection Agency for freshwater aquatic health (U.S. Environmental Protection Agency, 1986).

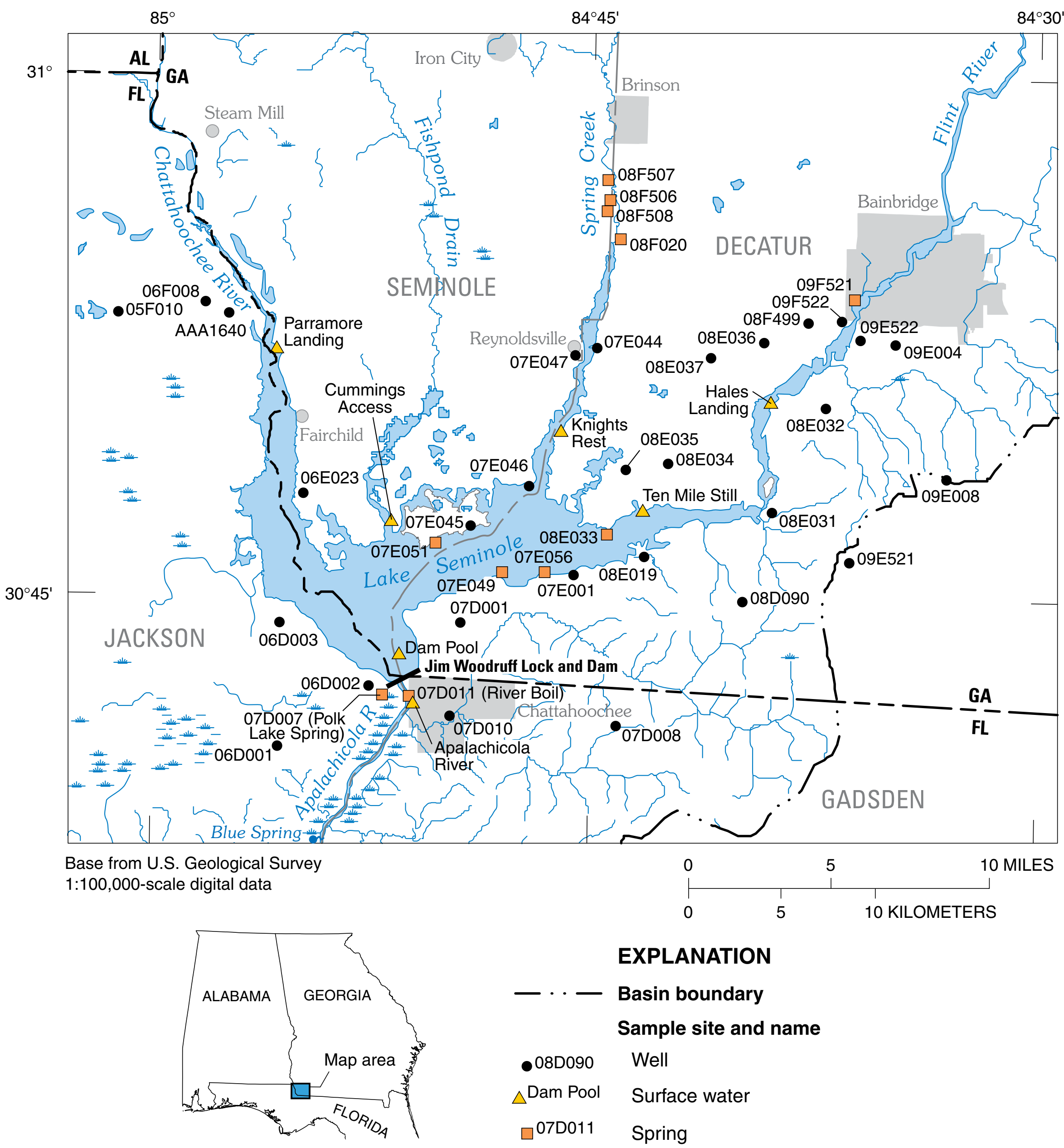


Figure 7. Sampling locations for water-chemistry and springflow-temperature analyses in the Lake Seminole area, 2000 and 2001.

Lake water is well oxygenated above aquatic vegetation, and high dissolved carbon-dioxide levels were reported during December 1979 (U.S. Army Corps of Engineers, 1982). Aquatic vegetation, mostly hydrilla, occupies about half of the lake's 37,600 acres at depths less than about 10 ft, oxygenating the water during daylight hours, and depleting the oxygen in water at night and in areas of thick decomposing vegetation.

Physical Evidence of Lake Leakage near Jim Woodruff Lock and Dam and of Ground-Water Inflow to the Lake

Physical evidence of lake leakage near Jim Woodruff Lock and Dam, and of ground-water inflow to Lake Seminole, was collected during the study using several means of hydrogeologic investigation. The hydraulic potential for lake leakage into the Upper Floridan aquifer and for ground-water inflow to Lake Seminole was evaluated by comparing lake stage with ground-water levels in wells located adjacent to the lake. Lake leakage was documented using results of dye-tracing experiments performed by the Corps (Roger A. Burke, Plan Formulation Branch, U.S. Army Corps of Engineers, written commun., April 2003), and by streamflow (current) profiling downstream of the dam. Ground-water inflow to Lake Seminole was measured at springs located along the Spring Creek impoundment arm and was inferred from surface-water discharge and water-temperature measurements taken along the lake bottom, at springs, and in spring runs. Written accounts by Corps geologists during pre- and post-construction phases of the dam, accompanied by photographs, describe the structural integrity of the limestone units that now comprise the dam foundation and lake bottom, and provide evidence of the potential for lake leakage.

Comparison of Ground-Water Levels with Lake and Stream Stage

Ground-water levels in wells completed in the Upper Floridan aquifer were measured near Lake Seminole during April and August 2000, and the resulting potentiometric surfaces were compared with lake and stream stage. For April 2000, ground-water levels were consistently higher than lake stage (about 77 ft, table 4) near the upper reaches of the four impoundment arms, as indicated by the location of the 80- and 90-ft water-level contours and water-level measurements from wells located in this area (fig. 8; table 5). The occurrence of ground-water levels higher than lake stage in areas adjacent to the impoundment arms has the potential to cause ground-water inflow to Lake Seminole. Along Fishpond Drain, ground-water levels in wells 07F002, 07F006, and 07E006 were higher than lake stage (fig. 9; table 5). Near well 06E023, which is a few miles south and west of these wells and just east of the lower part of the Chattahoochee River impoundment arm (fig. 9), the ground-water level was lower than lake stage, indicating the potential for lake leakage.

Along the west side of the Spring Creek impoundment arm, ground-water levels in wells 07E007, 07E046, and 07E047 were lower than lake stage, indicating the potential for lake leakage (fig. 9; tables 4 and 5). On the east side of the Spring Creek impoundment arm, the ground-water level in well 07E044 was lower than lake stage; about 1 mi to the east, however, the ground-water level in well 08F018 was higher than lake stage. Between the Spring Creek and Flint River impoundment arms, downstream of Bainbridge, Ga., ground-water levels in wells 08E003, 08E034, and 08E037 were lower than lake stage, indicating the potential for lake leakage into the Upper Floridan aquifer in this area. Across the lake from these wells, however, on the east side of the Flint River impoundment arm, ground-water levels in wells 09E003, 09E004, and 09E005 were higher than lake stage, indicating ground-water flow into Lake Seminole and possibly across it, into the previously mentioned area to the west of the Flint River impoundment arm.

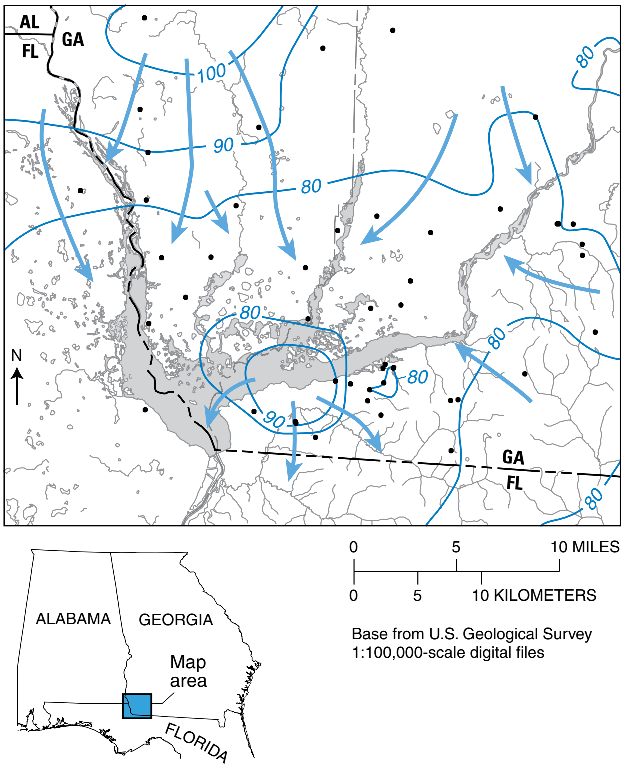
Table 4. Precipitation and stage data for Lake Seminole, measured at Jim Woodruff Lock and Dam[1].

[NAVD 88 , North American Vertical Datum of 1988; —, not applicable]

Month	Precipitation (inches)[2]		Mean-daily lake stage (feet, NAVD 88)	
	2000	1985–2001	2000	1957–2001
January	2.84	5.63	77.06	77.30
February	1.63	4.03	76.49	77.34
March	4.74	6.03	77.05	77.36
April	2.22	2.73	77.08	77.34
May	0	3.19	75.59	77.22
June	2.19	6.52	75.7	77.15
July	2.75	5.29	75.93	77.05
August	5.13	5.27	75.73	77.02
September	5.8	3.52	75.96	76.91
October	4.09	3.05	76.39	76.78
November	2.57	4.24	76.47	76.85
December	3.1	2.59	76.49	77.11
Total	**37.06**	**52.1**	**—**	**—**

[1]Data for this station are from Jim Woodruff Lock and Dam, Lake Seminole, near Chattahoochee, Gadsden County, Fla. (see figure 7 for location), latitude 30°42'33"N, longitude 84°51'45"W (North American Datum of 1983) (U.S. Army Corps of Engineers, Mobile District, Mobile, Ala., accessed September 3, 2004, at *http://water.sam.usace.army.mil/gage/jwrain.htm*).

[2]Total precipitation listed for 2000 by month; monthly average precipitation listed for period 1985–2001.



EXPLANATION

—80— **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells in the Upper Floridan aquifer during April 2000. Contour interval 10 feet. Datum is NAVD 88

General direction of ground-water flow

• **Well**

Figure 8. Potentiometric surface of the Upper Floridan aquifer in the Lake Seminole area, April 2000 (modified from Torak, 2001).

Table 5. Ground-water levels and other data for wells completed in the Upper Floridan aquifer and measured during April 2000, near Lake Seminole.

[NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; °, degree; ', minute; ", second; —, no data]

Well name (see fig. 9)	Latitude (North, NAD 83)	Longitude (West, NAD 83)	Land-surface altitude (feet)	Well depth (feet)	Water-level altitude (feet, above NAVD 88)	Date
06E023	30°47'58"	84°55'13"	80	220	72.5	April 27
06F001	30°53'49"	84°53'55"	110	99	82.7	April 26
07D006	30°43'16"	84°46'59"	273	340	76.5	April 25
07E001	30°45'39"	84°46'03"	170	154	69.4	April 25
07E006	30°50'47"	84°52'13"	91	170	80	April 26
07E007	30°50'24"	84°47'35"	105	130	75.5	April 26
07E009	30°45'32"	84°45'08"	158	320	75.9	April 25
07E044	30°52'10"	84°45'19"	89	83	71.2	April 27
07E046	30°48'15"	84°47'26"	90	44	74.6	April 27
07E047	30°51'59"	84°46'02"	110	123	72.7	April 27
07F002	30°56'16"	84°49'58"	118	160	92.2	April 26
07F006	30°52'58"	84°51'02"	100	—	78.8	April 26
08D001	30°44'50"	84°44'27"	252	300	73.5	April 25
08D003	30°44'08"	84°44'47"	250	300	67.4	April 25
08E003	30°49'54"	84°42'26"	100	207	74.5	April 27
08E019	30°46'13"	84°43'43"	90	147	82.2	April 25
08E020	30°46'23"	84°43'38"	82	88	78.3	April 25
08E021	30°46'16"	84°43'12"	85	125	69	April 25
08E022	30°46'14"	84°43'14"	85	85	67.5	April 25
08E023	30°45'17"	84°43'32"	241	280	63.1	April 25
08E024	30°45'37"	84°43'41"	165	216	89.7	April 25
08E025	30°45'33"	84°48'32"	135	300	58.5	April 25
08E034	30°48'58"	84°42'47"	107	—	76.2	April 25
08E037	30°51'57"	84°41'29"	126	97	75.1	April 29
08F018	30°52'36"	84°44'07"	118	125	78	April 27
09E003	30°52'23"	84°35'17"	115	75	79.5	April 25
09E004	30°52'23"	84°35'13"	115	75	80	April 25
09E005	30°52'22"	84°34'30"	120	80	82.8	April 25
09F520	30°57'42"	84°35'46"	128	251	79.9	April 25

To the south of the Flint River impoundment arm in the area along the Solution Escarpment (fig. 2), leakage dynamics of the lake and aquifer become more complex than across the lake to the north, because of the variation in hydraulic properties within the Tampa Limestone and Hawthorn Group sediments that overlie the Upper Floridan aquifer in this area (fig. 4, as discussed previously). Increased land-surface altitude and topographic relief as much as 200 ft above lake stage provide the hydraulic potential for local water-bearing zones contained in the units overlying the Upper Floridan aquifer to leak ground water vertically into the aquifer, and for subsequent leakage northward and westward into Lake Seminole. This is evidenced by ground-water levels in the Upper Floridan aquifer that were higher than lake stage in wells 08E019, 08E020, and 08E024 (table 5) and perhaps by the occurrence of in-lake springs (fig. 7). Other wells south of the lake, however, had ground-water levels that were lower than lake stage, such as wells 07D006, 07E001, 07E009, 08D001, 08D003, 08E023, and 08E025, located on the Solution Escarpment, and wells 08E021 and 08E022, located between the escarpment and the lake (fig. 9). Areas south of Lake Seminole where ground-water levels are lower than lake stage contain the potential for lake water to leak into the Upper Floridan aquifer and to join regional ground-water flow from the northwest as it flows to the south and east.

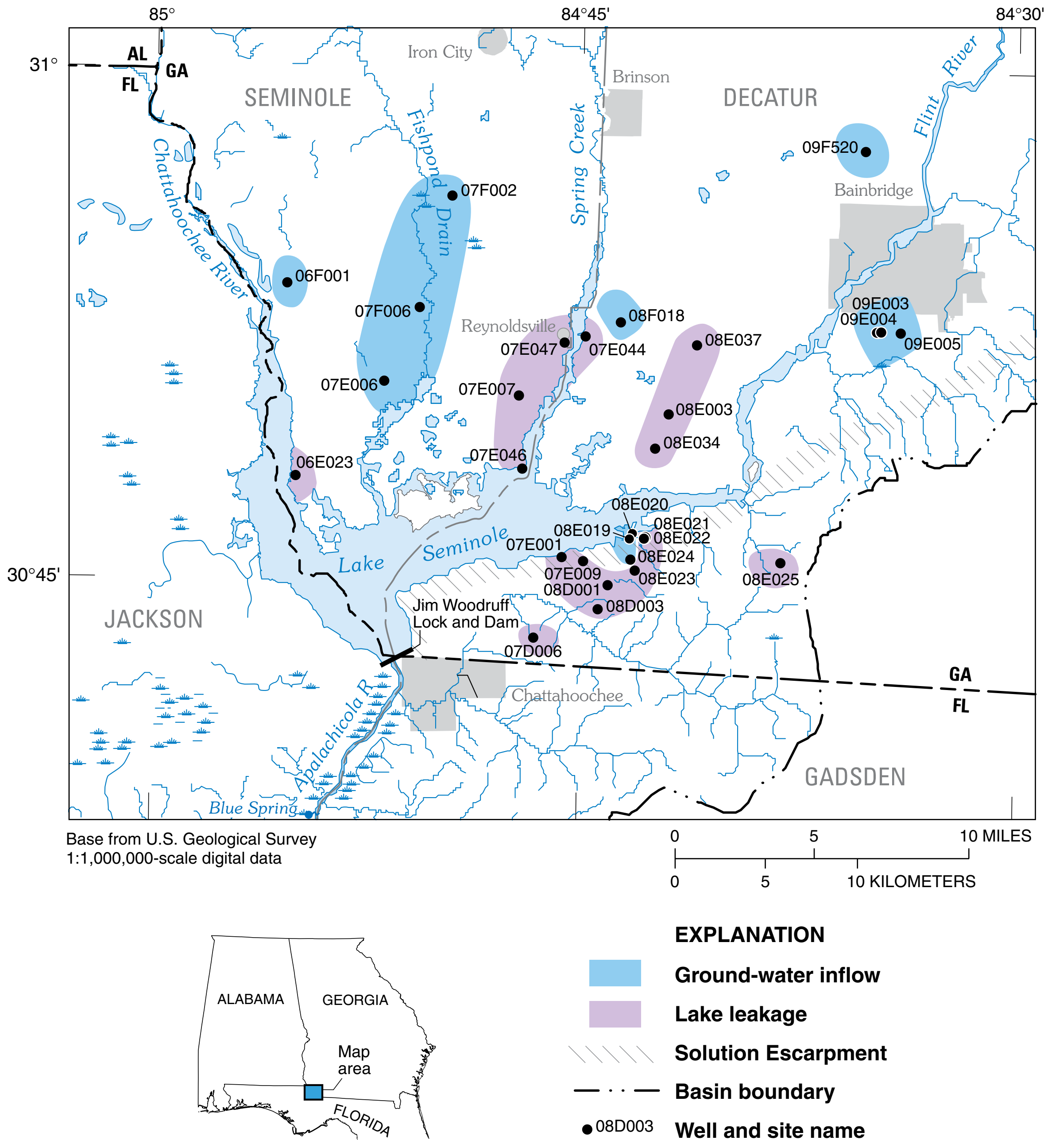


Figure 9. Selected wells completed in the Upper Floridan aquifer and used for ground-water-level measurements near Lake Seminole, April 2000, and areas of inferred lake leakage and ground-water inflow (modified from Mosner, 2002).

The potentiometric surface of the Upper Floridan aquifer for August 2000 generally is flat near Lake Seminole (fig. 10); a potential for ground-water inflow to the lake, however, is indicated by a slight upstream bending of the 80-ft water-level contour as the contour crosses the Chattahoochee River impoundment arm and lower reaches of the Flint River and Spring Creek. For August 2000, the average daily stage of Lake Seminole was about 75.7 ft (table 4); the stage of Spring Creek near Reynoldsville, Ga. (station 02357150), about 20 mi upstream from the dam, was about 76.1 ft; and, 10 mi farther upstream, near Iron City, Ga. (station 02357000), the stream stage was about 86.1 ft. For August 2000, the 80-ft water-level contour crosses Spring Creek downstream of the streamgage near Iron City, Ga., and upstream of the streamgage near Reynoldsville, Ga. Thus, ground water has the potential to flow into Lake Seminole and the lower reaches of Spring Creek during conditions, such as those during August 2000, when the lake or stream stage is lower than the adjacent ground-water level.

Leakage into the Upper Floridan aquifer from Lake Seminole and impoundment-arm streams may occur in areas where the ground-water level is lower than lake or stream stage, which can be inferred from water-level contours that bend downstream as streams are crossed. Ground-water inflow to Lake Seminole is indicated along the Solution Escarpment to the south and east of the Flint River impoundment arm, where 80-ft water-level contours are located adjacent to the Flint River and the lake (fig. 10). Within 10 mi of the dam, however, along the Flint River impoundment arm and west of the dam along the Chattahoochee River impoundment arm, the 70-ft water-level contour is located near the lake, indicating a potential for lake leakage into the Upper Floridan aquifer in these areas.

The potentiometric surfaces of the Upper Floridan aquifer during May 1998, at the onset of drought, and during October 1999, after the first full year of drought, indicate the potential for ground-water inflow to Lake Seminole and for lake leakage into the Upper Floridan aquifer. The 80-ft water-level contour of the May 1998 potentiometric surface of the Upper Floridan aquifer (fig. 11) bends upstream and is nearly parallel to the Chattahoochee River impoundment arm for about 15 mi in Florida before crossing the river, indicating the potential for ground-water inflow to Lake Seminole in this area. Similar upstream bending of the 80-ft water-level contour occurs along both sides of Spring Creek and the Spring Creek impoundment arm, with the contours drawn nearly parallel to the creek and impoundment arm for about 10 mi, before crossing the creek with a sharp bend.

During October 1999, the 80-ft water-level contour of the potentiometric surface of the Upper Floridan aquifer (fig. 12) bent gradually upstream as it crossed the Chattahoochee River impoundment arm and also bent across Spring Creek and the Flint River, but not as sharply as during May 1998. This change in geometry of the 80-ft water-level contour is an indication of less ground-water inflow to Lake Seminole during October 1999 than during May 1998, because of the persistence of drought conditions during 1999. The 80-ft water-level contour crossed the Flint River impoundment arm farther downstream during May 1998 than during October 1999, indicating higher ground-water levels adjacent to the lake and a higher potential for ground-water leakage during May 1998 than during October 1999. The 70-ft water-level contour of the Upper Floridan aquifer for May 1998 intersected Lake Seminole west of the dam, establishing the potential for lake leakage to the aquifer near the Dam Pool (the lake area directly behind the dam), because lake stage was about 5 ft higher than ground-water levels in this area at that time.

Lake leakage and ground-water inflow to Lake Seminole can occur at the same location at different times, as seasonal water-level fluctuations in the Upper Floridan aquifer cause hydraulic gradients to reverse between the lake and aquifer. Along the Chattahoochee River impoundment arm, the water level in well 06F001 fluctuated about 23 ft during 2000, from a high during mid-February of about 95 ft, to a record low of about 72 ft during July (fig. 13). Low recharge rates and high irrigation pumpage in late spring through summer usually cause water-level declines from 20 to 30 ft in this area. From near the end of January through mid-May 2000, the water level in well 06F001 was higher than lake stage (which was about 77 ft), creating favorable conditions for ground-water flow into Lake Seminole. From mid-May until the water-level record was interrupted during mid-August, the water level in well 06F001 was below lake stage, establishing conditions that were favorable for lake leakage into the Upper Floridan aquifer. During late September, the water level in the well was about 10 ft higher than lake stage, which is conducive to ground-water inflow to the lake; the water level remained higher than lake stage for the remainder of the year, except for a few days during mid-November 2000.

Ground-water inflow to Lake Seminole and lake leakage to the Upper Floridan aquifer are affected locally by cyclic patterns of irrigation pumpage. In central Decatur County, Ga., northwest of the Flint River impoundment arm, irrigation pumpage near well 09F520 from May through August 2000 caused a series of daily water-level declines in the Upper Floridan aquifer from about 10 to 15 ft, followed by periods of recovery lasting from several days to about 2 weeks (fig. 13). During irrigation pumping, ground-water levels occasionally were more than 5 ft below lake stage, which was at an altitude of about 77 ft, providing the potential for lake leakage into the Upper Floridan aquifer. During the nonpumping cycles, ground-water levels recovered to heights that ranged from about 2 to 3 ft above lake stage, establishing conditions that were favorable for ground-water inflow to the lake.

In the area between the Flint River and Spring Creek impoundment arms, ground-water levels in the Upper Floridan aquifer are lower than lake stage year-round, creating the potential for continuous lake leakage into the aquifer. Periodic ground-water level measurements in well 08E037 (fig. 13), and in other wells nearby in this area, indicate that ground-water levels are below lake stage and conditions are favorable for lake leakage into the Upper Floridan aquifer.

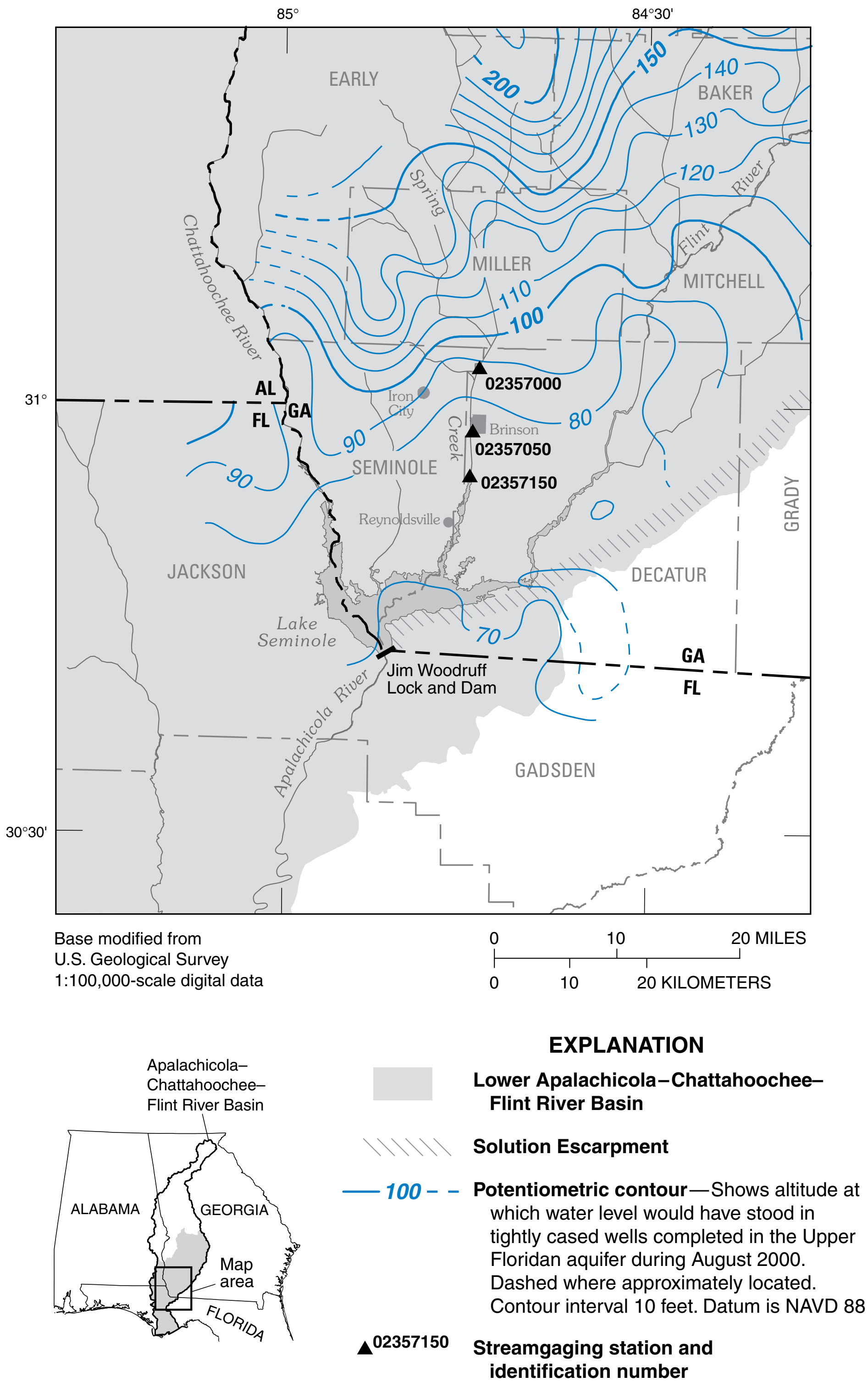


Figure 10. Generalized potentiometric surface of the Upper Floridan aquifer near Lake Seminole, August 2000 (modified from Mosner, 2002).

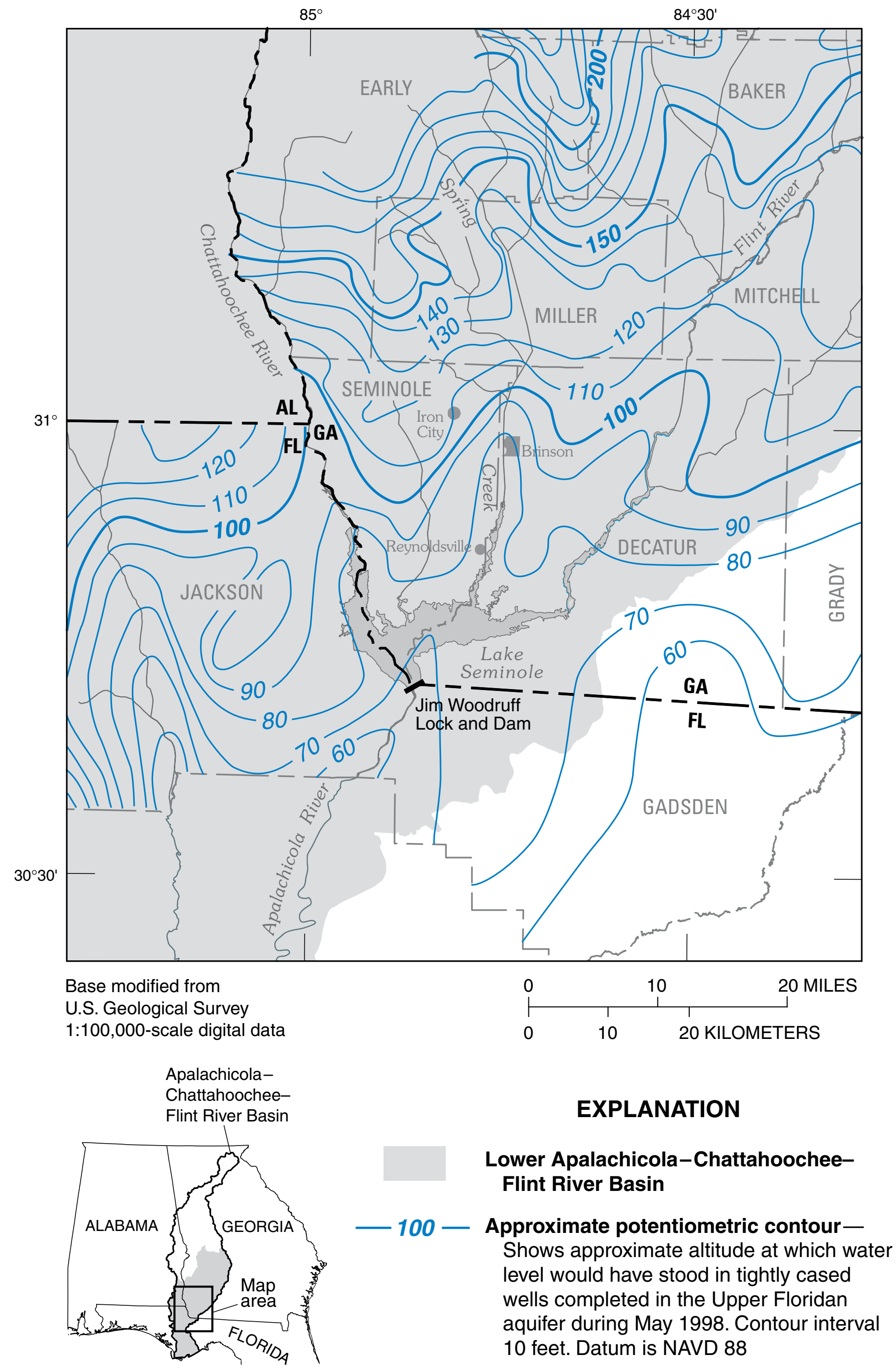


Figure 11. Generalized potentiometric surface of the Upper Floridan aquifer in the lower Apalachicola–Chattahoochee–Flint River Basin, May 1998 (modified from Peck and others, 1999).

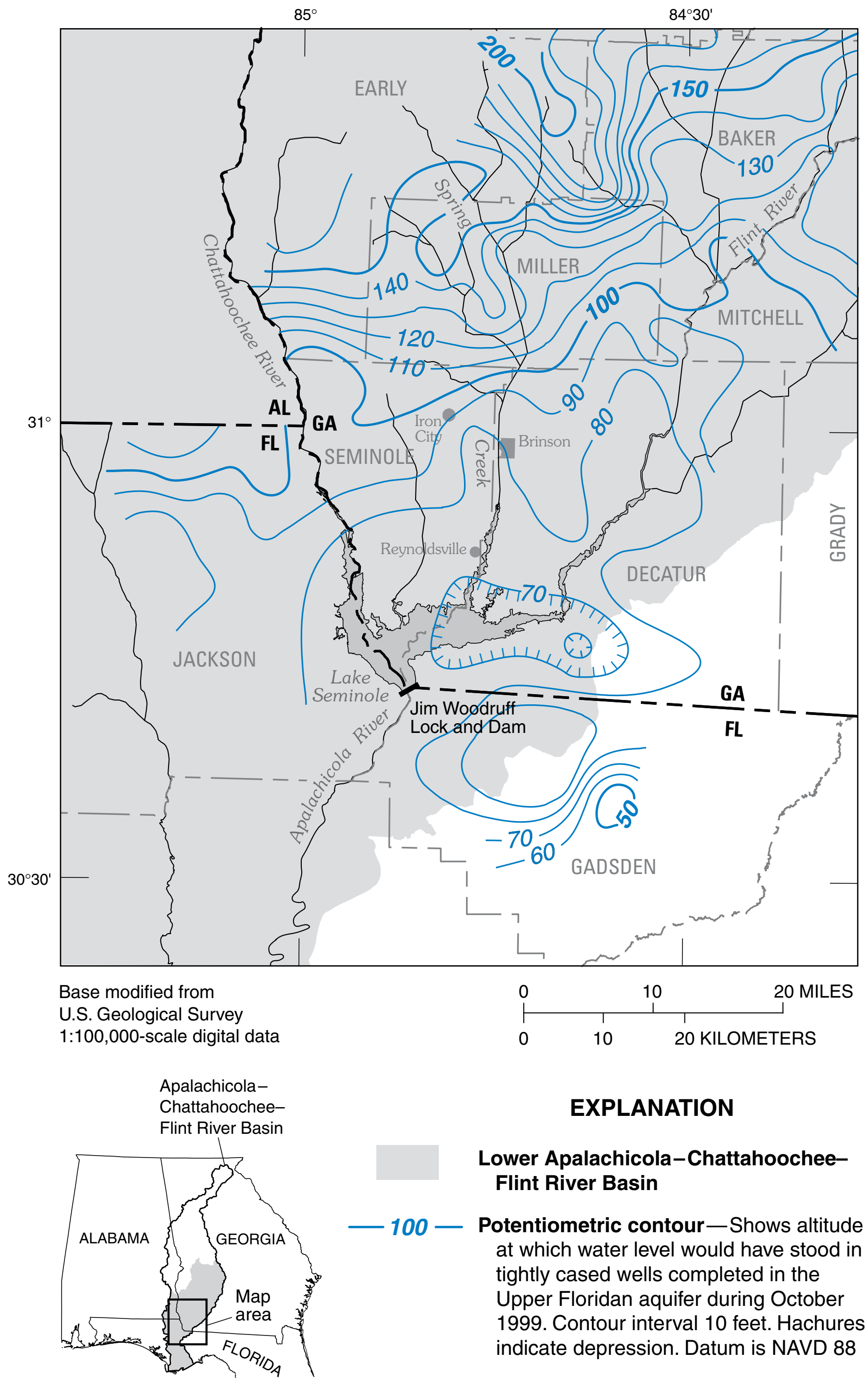


Figure 12. Generalized potentiometric surface of the Upper Floridan aquifer in the lower Apalachicola–Chattahoochee–Flint River Basin, October 1999 (modified from Mosner, 2002).

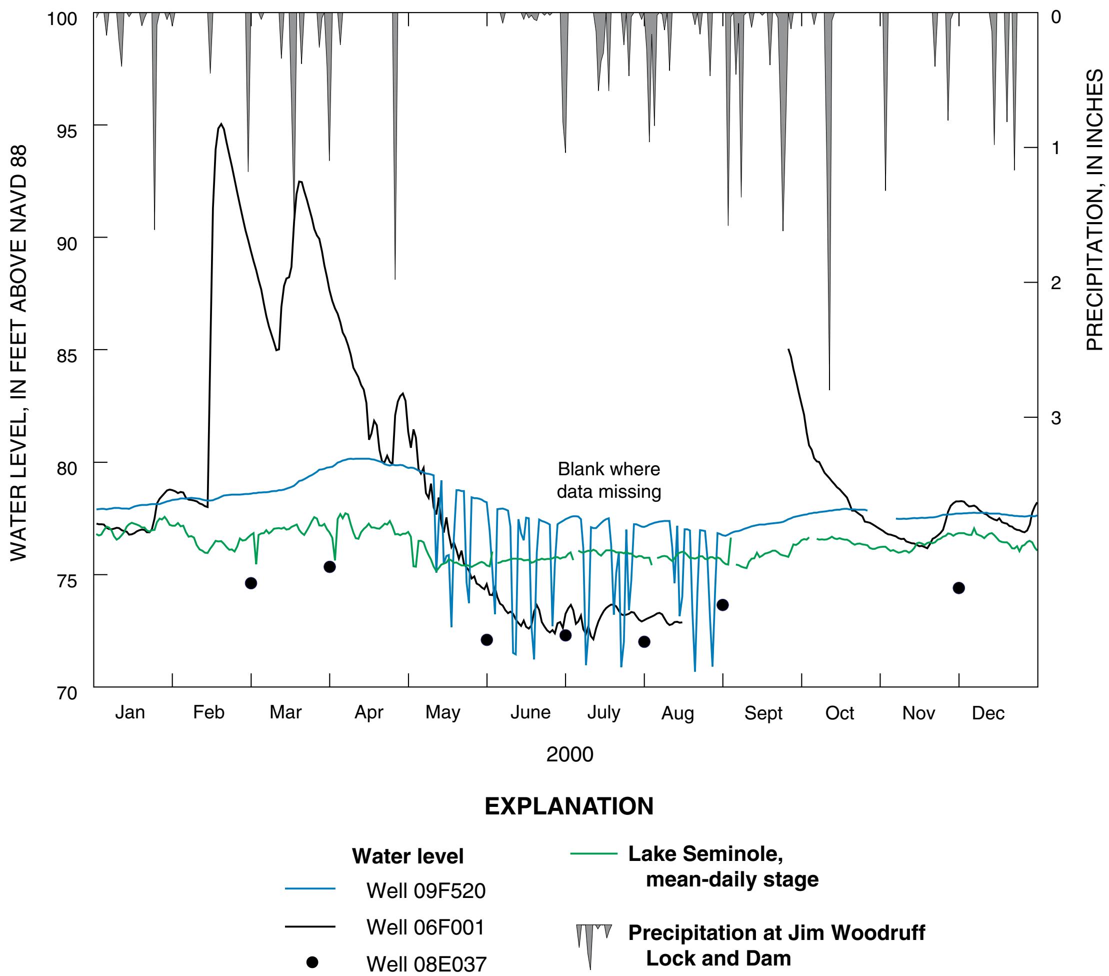


Figure 13. Mean-daily stage and daily precipitation for Lake Seminole, and water-level fluctuations in wells completed in the Upper Floridan aquifer near the lake during 2000 (see figure 9 for well locations).

Results of Dye-Tracing Experiments and Acoustic Doppler Current Profiling

The U.S. Army Corps of Engineers, Mobile District, Mobile, Ala., conducted two dye-tracing experiments during 2001 "to determine the fate of water entering small sinkholes along the western rim of Lake Seminole" (Roger A. Burke, Plan Formulation Branch, U.S. Army Corps of Engineers, Mobile District, written commun., April 2003). The dye-tracing experiments were part of investigations performed by the Corps "to characterize subsurface loss of flows from the lake" and "to ensure that the dam remains in a safe condition" (Roger A. Burke, Plan Formulation Branch, U.S. Army Corps of Engineers, Mobile, Ala., written commun., July 2001). Dye-tracing procedures are available online at *http://www.dyetracing.com* (accessed October 22, 2003). Other investigations performed by the Corps to characterize subsurface flow out of Lake Seminole consisted of hydrographic surveys of the lake bottom in the vicinity of the dam and along the western side of the lake within 1 mi of the dam (discussed later in this report).

The hydrographic surveys identified sinkholes in the lake bottom along the western shore and in front of the dam that function as reverse springs, leaking water directly to the limestone of the Upper Floridan aquifer (fig. 14). These sinkholes served as locations where dye was introduced for dye-tracing experiments performed by the Corps. About 800 ft downstream of Jim Woodruff Lock and Dam, Polk Lake Spring discharges in a swampy area adjacent to the western bank of the Apalachicola River. Water from Polk Lake Spring flows southward in a channel, or spring run, about 1,000 ft, where it converges with water flowing northward from a spring-fed area of diffuse ground-water discharge, located south of U.S. Highway 90. On May 10, 2004, discharge from Polk Lake Spring was measured at about 10 cubic feet per second (ft^3/s), and discharge in a channel containing the northward flowing water was measured at about 30 ft^3/s. Water from both of these sources enters a sinkhole on the western bank of the Apalachicola River and becomes subterranean flow in the limestone. About 900 ft downstream of the lock structure, water upwells, or "boils up," from the bottom of the channel of the Apalachicola River from a sinkhole or ledgelike structure in the limestone, termed the *River Boil* (fig. 14). Dye receptors were placed at Polk Lake Spring and in the River Boil to determine if the sinkholes in the lake provide water to these features.

The first dye-tracing experiment was performed on January 25, 2001, with the introduction of an optical brightener (dye) into two sinkholes located along the western lakeshore, about 2,500 and 3,000 ft upstream of a receptor placed at Polk Lake Spring (fig. 14). Within 5–7 hours, dye was detected at Polk Lake Spring, indicating that the sinkholes provided the hydraulic connection for lake water to leak into the Upper Floridan aquifer, where it mixed with ground water and subsequently was transported downstream of the dam to Polk Lake Spring. The following account, written by the Corps, summarizes the findings of the hydrographic survey and first dye-tracing experiment.

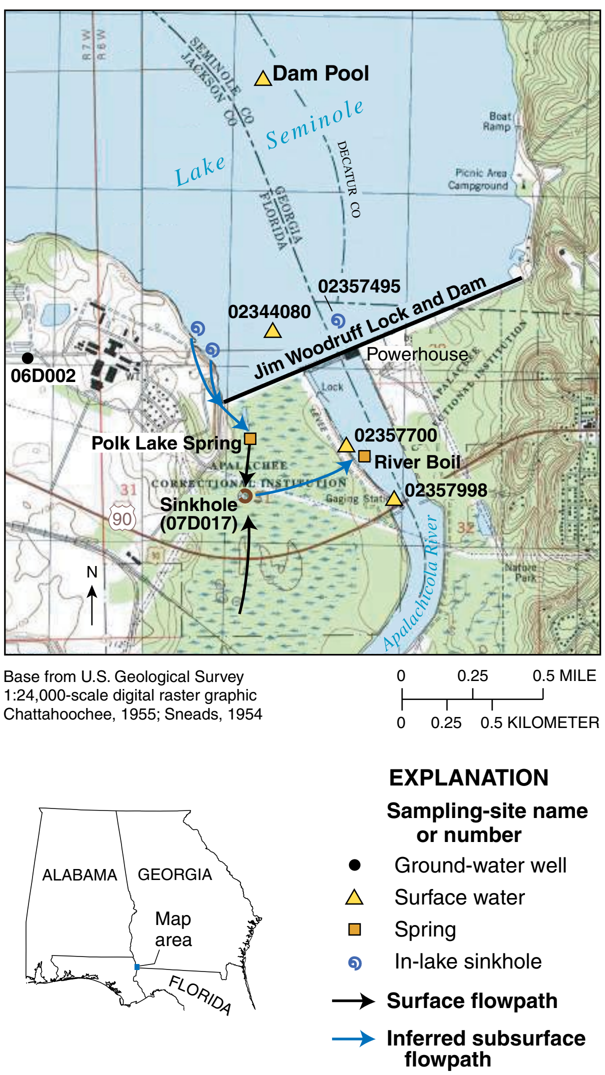


Figure 14. Hydrologic features in and around Lake Seminole evaluated during dye-tracing studies performed by the U.S. Army Corps of Engineers, 2001, and possible directions of lake leakage and subsurface flow to the River Boil on the Apalachicola River.

> There are at least 5 locations less than one-half mile upstream of the dam, most located by the hydrographic survey, where water is leaking into the limestone of the western rim of the reservoir. All are relatively small sinkholes or joints, with irregular passageways generally measuring less than 6-inches in diameter. … [A] “four foot” dimension is at the top of a funnel shaped opening of one of the sinkholes. Dye introduced into this “four foot” sinkhole was detected at Polk Lake 7 hours after introduction. Dye introduced into the southernmost sinkhole in the area was detected at Polk Lake 5 hours after being introduced. Dye was not detected in the fixed crest gallery [located beneath the fixed-crest spillway on the western abutment of the dam] until 9 days after it was introduced, indicating that the seepage is around the western abutment, and not under the dam. Dye never was detected at either of the two wells located west of the lake on the property of the Apalachee … [Correctional] Institution. … Much more water exits at the … [River Boil] downstream of the lock than enters the sinkhole on the right bank, and an additional source of water feeding this spring is being searched for in the upper pool.
>
> *Roger A. Burke,*
> *Plan Formulation Branch,*
> *U.S. Army Corps of Engineers,*
> *written commun., July 2001*

A second dye-tracing experiment was conducted on August 15, 2001, to determine the hydraulic connection of the sinkhole located on the west bank of the Apalachicola River with the River Boil located in the channel downstream of the dam (fig. 14). Fluorescent dye (Rhodomine WT) was introduced to the sinkhole, which was receiving water from Polk Lake Spring and from the area of ground-water discharge to the south. The Corps measured travel time from this sinkhole to the River Boil to be less than 2 hours (Roger A. Burke, Plan Formulation Branch, U.S. Army Corps of Engineers, Mobile District, written commun., April 2003), confirming the hydraulic connection of the sinkhole with the river. As stated previously, however, the volume of water discharging from the aquifer at the River Boil is much greater than the flow of water entering the sinkhole on the right bank of the Apalachicola River (about 40 ft^3/s); thus, additional sources of water to the River Boil exist that have yet to be identified.

Acoustic Doppler current profiling (ADCP) (Lipscomb, 1995) was used to estimate discharge from the River Boil and from other springs or tributaries to the Apalachicola River in the study area. On October 21, 1999, discharge from the River Boil was estimated with ADCP at about 140 ft^3/s; on April 27, 2000, discharge was estimated at about 220 ft^3/s. The increased discharge during April 2000 compared with October 1999 cannot be explained by the hydraulic potential given by the difference in stage between Lake Seminole and the Apalachicola River. Lake stage was nearly identical during both ADCP measurements, at 76.8 ft (U.S. Army Corps of Engineers, Woodruff Elevation Data, accessed May 7, 2004, at *http://water.sam.usace.army.mil/acfframe.htm*), but the river stage was 6.7 ft higher during April than during October (stage data for Apalachicola River at Chattahoochee, Florida, station 02358000, on file at the USGS, Florida Integrated Science Center, Tallahassee, Florida). Inflows to the Apalachicola River from the River Boil represented less than 3 percent of the streamflow that occurred on the dates that the ADCP was performed; average daily flow in the Apalachicola River was about 5,800 ft^3/s on October 21, 1999, and about 20,000 ft^3/s on April 27, 2000 (U.S. Army Corps of Engineers, Woodruff Discharge Data, accessed May 7, 2004, at *http://water.sam.usace.army.mil/acfframe.htm*).

About 6 mi downstream of the River Boil, springflow from Blue Spring enters a small channel, or spring run, and discharges to the Apalachicola River along the right downstream bank (fig. 7). On October 21, 1999, discharge from Blue Spring was estimated using ADCP at 50.3 ft^3/s; on April 27, 2000, estimated discharge using ADCP was 17.2 ft^3/s. Like the River Boil, these discharge estimates indicate no relation between springflow and lake stage, which was virtually the same on both days. The lower discharge during April than during October, however, could be attributed to the stage of the Apalachicola River, which, as stated previously, was 6.7 ft higher during April 2000 than during October. The high river stage during April 2000 may have created backwater conditions in the spring run and above the spring opening, decreasing the hydraulic potential between the aquifer and the river from that which occurred during October, thus decreasing springflow. Other springs or tributaries either discharged negligible amounts of water to the Apalachicola River or showed no relation between discharge rate and river stage or lake stage.

Discharge estimates for the River Boil and Blue Spring, prepared using ADCP data, indicate that different hydrologic processes contribute to flow at each of these features. At the River Boil, higher discharge was estimated during April 2000 (220 ft^3/s) than during October 1999 (140 ft^3/s); at Blue Spring, the opposite discharge effects were estimated, with higher springflow occurring during October 1999 (about 50 ft^3/s) than during April 2000 (about 17 ft^3/s). Backwater conditions at Blue Spring, caused by the higher Apalachicola River stage during April 2000 compared with October 1999, could explain the lower estimated springflow during April 2000. The opposite effect, however, occurred at the River Boil, where discharge during April 2000 increased by about 50 percent compared with the October 1999 discharge. These relative increases and decreases in discharge from Blue Spring and the River Boil indicate that these sites are not controlled by the same hydrologic processes. Discharge from Blue Spring seems to be affected by changes in stream stage; discharge from the River Boil seems to be unaffected by changes in stream stage. Ground-water level data were unavailable near either Blue Spring or the River Boil, due to the lack of nearby wells; therefore, relations between discharges from Blue Spring and the River Boil, lake stage, and ground-water level could not be determined.

Streamflow Gain along Spring Creek

Measurements of stream discharge and springflow along the upper reach of the Spring Creek impoundment arm to Lake Seminole give a detailed account of streamflow gain from ground-water inflow (fig. 15; tables 6 and 7). Springflow and stream-discharge measurements were made on August 3 and September 15, 2000, during drought conditions, on a 6-mi reach of the Spring Creek impoundment arm, from the gaging station near Reynoldsville, Ga. (station 02357150), to just upstream of the lake at the gaging station at Brinson, Ga. (station 02357050) (fig. 10). Streamflow also was measured at the gaging station near Iron City, Ga. (station 02357000), about 5 mi upstream of the gaging station at Brinson, Ga. (fig. 10).

Streamflow on Spring Creek measured at the gaging station near Iron City, Ga. (station 02357000), was 0.4 ft^3/s on August 3, 2000, and 0.1 ft^3/s on September 15, 2000 (table 6), indicating nearly dry stream conditions owing to the drought.

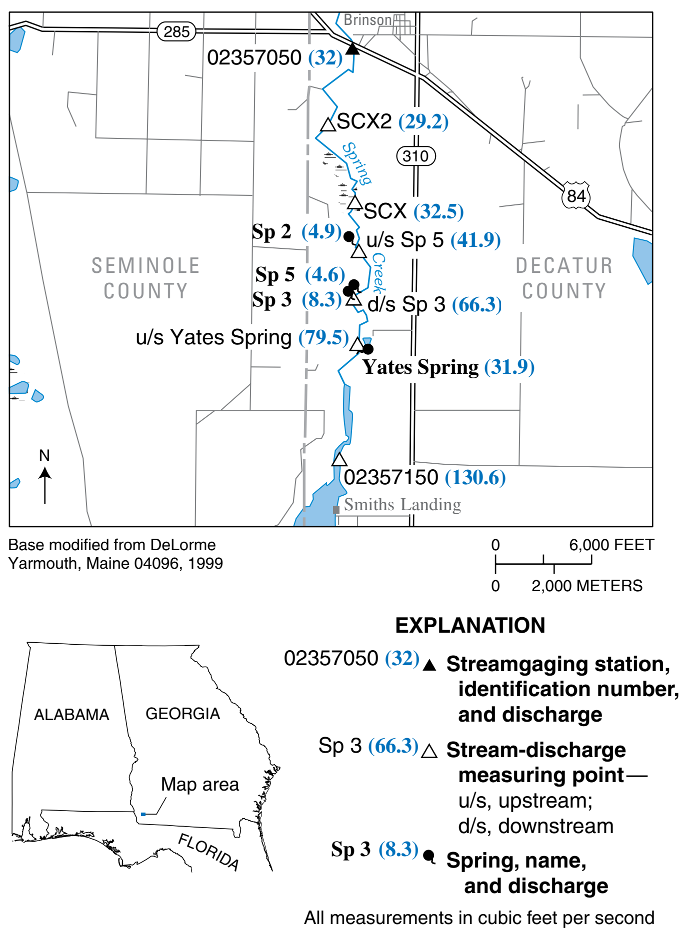


Figure 15. Upper reach of Spring Creek impoundment arm and locations of stream-discharge and springflow measurements, August 3 and September 15, 2000 (modified from Torak, 2001).

Table 6. Stream-discharge measurements for Spring Creek, August 3 and September 15, 2000.

[Stations shown on figure 15, except station 02357000, which is shown on figure 10; NAD 83, North American Datum of 1983; ft^3/s, cubic foot per second; °, degree; ', minute; ", second; SCX, SCX2, stream sections; Sp3, Sp5, springs; —, no data]

Station name and downstream-order number (if applicable)	Latitude (North, NAD 83)	Longitude (West, NAD 83)	Discharge (ft^3/s)	
			Aug. 3	Sept. 15
Spring Creek near Iron City, Ga., 02357000	31°02'23"	84°44'18"	[1]0.4	[1]0.1
Spring Creek (U.S. Hwy. 84) at Brinson, Ga., 02357050	30°54'14"	84°44'57"	[2]31.4	[2]31.6
SCX2	30°57'51"	84°44'58"	—	29.2
SCX	30°56'51"	84°44'45"	38.1	38.5
Upstream of Sp5	30°56'21"	84°44'38"	—	41.9
Downstream of Sp3	30°55'58"	84°44'40"	—	66.3
Upstream of Yates Spring	30°55'25"	84°44'41"	—	79.5
Spring Creek near Reynoldsville, Ga., 02357150	30°54'14"	84°44'57"	[3]105	130.6

[1]Daily mean streamflow available from USGS National Water Information System, accessed January 30, 2004, at *http://nwis.waterdata.usgs.gov/ga/nwis/discharge?site_no=02357000*

[2]Streamflow measurement at Brinson, Ga., contained a possible error of 2.5 ft^3/s, which makes resolving differences in streamflow of this magnitude between this station and either upstream or downstream measurements difficult (Mark S. Reynolds, U.S. Geological Survey, oral commun., September 2000).

[3]Daily mean streamflow available from USGS National Water Information System, accessed May 18, 2004, *http://nwis.waterdata.usgs.gov/ga/nwis/discharge?site_no=02357150*

Table 7. Springflow measurements for Spring Creek, August 3 and September 15, 2000.

[NAD 83, North American Datum of 1983; ft^3/s, cubic foot per second; °, degree; ', minute; ", second; Sp2, Sp3, Sp5, springs; —, no data]

Spring (see fig. 15)	Latitude (North, NAD 83)	Longitude (West, NAD 83)	Grid number	Discharge (ft^3/s)	
				Aug. 3	Sept. 15
Yates Spring	30°55'23"	84°44'40"	08F020	36.2	34.0
Sp2	30°56'29"	84°44'43"	08F507	4.7	4.9
Sp3	30°56'01"	84°44’39"	08F508	8.6	8.3
Sp5	30°56'07"	84°44'35"	08F506	—	4.6

During these same dates, diffuse ground-water inflow through the channel bottom, however, resulted in a streamflow gain of about 30 ft^3/s downstream along the 5-mi reach between the gaging station near Iron City and the gaging station at Brinson, Ga. (station 02357050, fig. 15; table 6). On September 15, 2000, the reach extending 0.8 mi downstream of the gaging station at Brinson, Ga., to stream-section SCX2 (fig. 15; table 6) exhibited no gain, and possibly a loss in streamflow of about 2 ft^3/s. The streamflow measurement at Brinson, Ga., contained a possible error of 2.5 ft^3/s, which makes it difficult to resolve differences in streamflow of this magnitude between Brinson, Ga., and either upstream or downstream measurements (Mark S. Reynolds, U.S. Geological Survey, oral commun.September 2000). A streamflow gain of about 8 ft^3/s was indicated by discharge measurements made along the 1.2-mi reach of Spring Creek at stream sections SCX2 and SCX (fig. 15; table 6).

Streamflow gains of as much as about 92 ft^3/s from diffuse ground-water inflow through the channel bottom and from the tributary inflow of four spring runs have been documented for August 3 and September 15, 2000, for the 4-mi reach of Spring Creek, defined by upstream measurements at stream-section SCX and downstream measurements at the gaging station near Reynoldsville, Ga. (station 02357150, fig. 15) (tables 6 and 7). The largest measurable inflow to Spring Creek was about 36 ft^3/s discharging from Yates Spring on August 3, 2000 (table 7). Between Yates Spring and the gaging station near Reynoldsville, Ga., a distance of about 1.3 mi (fig. 15), diffuse ground-water inflow through the channel bottom contributed about 17 ft^3/s to streamflow on September 15, 2000 (streamflow at station 02357150 near Reynoldsville, Ga., [130.6 ft^3/s] minus measured streamflow upstream of Yates Spring [79.5 ft^3/s] (from table 6), and flow into Spring Creek from Yates Spring, [34 ft^3/s], from table 7, yields a streamflow gain of 17.1 ft^3/s).

Water-Temperature Variation at In-Lake and Off-Channel Springs

Water-temperature variation at in-lake and off-channel springs indicates ground-water inflow to Lake Seminole. Vertical-temperature profiles at in-lake springs (fig. 16), and temperature measurements taken at locations of water-chemistry sampling (fig. 7) and during stream-discharge and springflow measurements (table 8) indicate that water along the lake bottom near springs has a temperature that is consistent with that of ground water. In general, the ground-water temperature at a depth of about 100 ft below land surface is about the same as mean-annual air temperature (Johnson Division, UOP, Inc., 1980). Mean-annual air temperature for Bainbridge, Ga. (fig. 7), located at the northern part of the Flint River impoundment arm, is 67.7°F or 19.8°C (Sever, 1965a). Ground-water temperatures measured during water-quality sampling at wells around Lake Seminole varied only slightly from a value of 20°C year-round (fig. 17).

Temperature measurements made along the bottom of Lake Seminole at State Dock Spring (09F521) and Wingate Spring (08E033) (fig. 7), also known as Little White Spring (Sever, 1965a, pl. 1), indicate water with a temperature of about 20°C existed near the spring from about early May through early November 2000 (fig. 16). Water at this temperature located along the bottom of Lake Seminole is consistent with the temperature of ground water; thus, it can be inferred that ground water enters Lake Seminole at these locations during these periods.

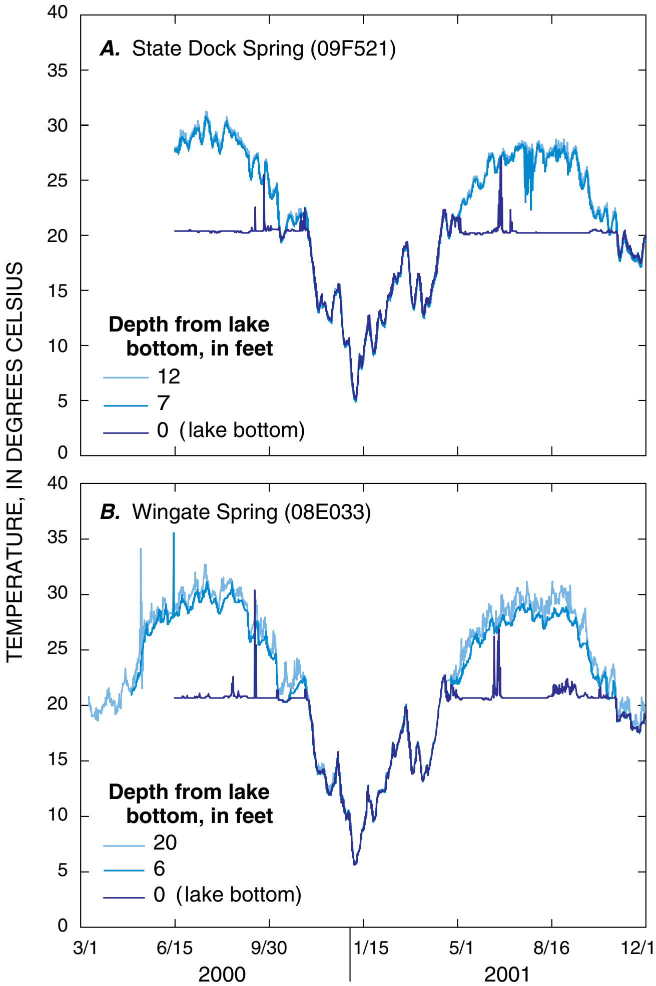


Figure 16. Lake-temperature variation with depth from March 2000 to December 2001 along Flint River impoundment arm to Lake Seminole at (*A*) State Dock Spring (09F521) and (*B*) Wingate Spring (08E033) (see figure 7 for spring locations).

Ground water from State Dock Spring and Wingate Spring flows in submerged channels, or spring runs, which, prior to impoundment, conveyed springflow overland to the Flint River. An array of temperature probes was installed at the springs, extending vertically downward from just below the lake surface to the lake bottom, into the spring runs, and water temperature was recorded every 24 minutes during the study period (fig. 16). Vertical water-temperature profiles also were made at these springs, and at other spring locations, from data collected during a reconnaissance of Lake Seminole during October 1999. Water temperature was measured during seasonal water-chemistry sampling during March, June, September, and December 2000 and during January 2001, and during streamflow and springflow measurements on Spring Creek during August and September 2000 (fig. 15; table 8). These data indicate that ground water enters Lake Seminole at several spring locations along the lake bottom and from spring runs located along the Spring Creek impoundment arm, and that springflow can be detected nearly year-round by using temperature measurements.

Ground water flowing in spring runs along the lake bottom, emanating from State Dock Spring and Wingate Spring, maintained a near-constant temperature of about 20°C from early May to early November 2001 (fig. 16). By comparison, water above the spring runs, extending upward toward the lake surface, exhibited seasonal- and diurnal-temperature variations and was warmer than water in the spring runs during these months (fig. 16). Although the lack of temperature data for May and June 2000 precludes an exact determination of when ground water began flowing in spring runs that year, the seasonal water-temperature variations with lake depth that were recorded at State Dock Spring and Wingate Spring during 2001 can be inferred to have occurred at about the same time during 2000. A water temperature of 20°C is consistent with water temperature measured during August and September 2000 in spring runs that are tributary to Spring Creek (fig. 15; table 8), with the ground-water temperature in wells sampled seasonally during 2000 (fig. 7), and with mean-annual air temperature (19.8°C) measured for Bainbridge, Ga. (Sever, 1965a).

The relatively cold lake water, less than 20°C, in the spring runs during November 2000 through April 2001 (fig. 16) is not a definitive indication that either State Dock Spring or Wingate Spring ceased flowing during this time. Temperature probes were not located at the spring openings, but at a distance of about 100 ft from the spring openings in the spring run. Therefore, it is possible that the springs were flowing year-round, but that low springflow and/or rapid mixing of relatively warm, less-dense ground water (springflow) with cool, dense lake water had dispersed the springflow into the lake-water column above the spring, preventing springflow from being contained in the spring run and from being detected by temperature probes. Such a dispersal, or mixing, is possible at State Dock Spring and Wingate Spring because the springs and their runs are adjacent to the preimpoundment channel of the Flint River. Because the Flint River impoundment arm conveys streamflow from the Flint River upstream of Bainbridge, Ga., to the dam and Apalachicola River, water currents in this part of the lake are strong enough to mix springflow with lake water within a short distance of the spring opening.

During early November 2000 and 2001, lake water may have "invaded" the spring runs as the lake cooled to a temperature below that of the water discharging from the springs. During water-chemistry sampling at State Dock Spring on December 11, 2000, the temperature of the water near the spring opening along the lake bottom was measured at 18.4°C (table 8). Above the spring, the surface temperature of the lake was 14.6°C, indicating that a relatively warm-water source, such as ground water, was entering the lake at the spring. At the spring run, however, temperature probes recorded a homogeneous vertical-temperature profile at about 5°C (fig. 16), indicating that any warm springflow would have completely dispersed into the surrounding cold lake water before reaching the probes. Similarly, during water-chemistry sampling at Wingate Spring, the water temperature near the spring opening was measured at 20.5°C on December 11, 2000 (table 8), indicating that the spring was flowing, although the temperature probe located in the spring run "downstream" of the spring opening recorded a water temperature of less than about 5°C (fig. 16).

Table 8. Water-temperature measurements at in-lake and off-channel springs to Lake Seminole, from October 1999 to January 2001.

[NAD 83, North American Datum of 1983; °C, degree Celsius; °, degree; ', minute; ", second; do., ditto; —, no data]

Spring	Latitude (North, NAD 83)	Longitude (West, NAD 83)	Site name (see fig. 7)	Measurement depth (feet)	Temperature (°C)	Date
In-Lake Springs						
Whiddon Spring	30°45'44"	84°46'58"	07E056	40	19.7	Oct. 5, 1999
Shackelford Spring	30°45'45"	84°48'33"	07E049	32	21.2	Oct. 5, 1999
do.	do.	do.	do.	—	18.5	Mar. 7, 2000
do.	do.	do.	do.	—	20.5	June 12, 2000
do.	do.	do.	do.	32	22.3	Sept. 12, 2000
do.	do.	do.	do.	30	13.3	Dec. 13, 2000
do.	do.	do.	do.	—	6.7	Jan. 11, 2001
State Dock Spring	30°53'37"	84°36'38"	09F521	32	19.3	Oct. 5, 1999
do.	do.	do.	do.	32	18.6	Mar. 6, 2000
do.	do.	do.	do.	32	20.3	June 12, 2000
do.	do.	do.	do.	34	20.3	Sept. 12, 2000
do.	do.	do.	do.	21.5	18.4	Dec. 11, 2000
Wingate Spring	30°46'49"	84°44'38"	08E033	26	18.8	Mar. 6, 2000
do.	do.	do.	do.	—	20.6	June 12, 2000
do.	do.	do.	do.	23	20.6	Sept. 12, 2000
do.	do.	do.	do.	—	20.5	Dec. 11, 2000
Sealy Spring	30°46'24"	84°50'49"	07E051	35	19.7	Oct. 7, 1999
do.	do.	do.	do.	40	16.5	Mar. 7, 2000
do.	do.	do.	do.	38	20.6	June 13, 2000
do.	do.	do.	do.	39.5	20.5	Sept. 12, 2000
do.	do.	do.	do.	41	13.1	Dec. 13, 2000
do.	do.	do.	do.	40	8.1	Jan. 11, 2001
Spring Creek — Off-Channel Springs						
Yates Spring	30°55'23"	84°44'40"	08F020	2.5*	21.7	Aug. 3, 2000
do.	do.	do.	do.	2.5*	20.7	Sept. 15, 2000
Sp2	30°56'29"	84°44'43"	08F507	5	20.6	Aug. 3, 2000
do.	do.	do.	do.	5	20.6	Sept. 15, 2000
Sp3	30°56'01"	84°44'39"	08F508	5	20.7	Aug. 3, 2000
do.	do.	do.	do.	5	20.7	Sept. 15, 2000
Sp5	30°56'07"	84°44'35"	08F506	5	20.7	Sept. 15, 2000

*Springflow temperature measured at spring run.

Other in-lake and off-channel springs exhibited seasonal water-temperature variations that indicate they provide a source of ground-water inflow to Lake Seminole nearly year-round (table 8). Vertical-temperature profiles at several spring locations were made during a reconnaissance of the lake during October 1999, and a few of these springs were sampled seasonally during 2000 and during January 2001 for water-chemistry analysis, as described previously. For example, Wingate Spring and State Dock Spring seem to flow year-round, as indicated by seasonal-temperature measurements during 2000, which yielded values that were near ground-water temperature, or about 20°C. Water temperatures at springs and spring runs tributary to the Spring Creek impoundment arm indicate that ground water having a temperature of about 20°C entered Lake Seminole at these locations during August and September 2000 (table 8).

When lake water becomes colder and denser than ground water, and ground-water levels adjacent to and beneath the lake are nearly equal to or less than lake stage, such as in late fall through early spring, it is possible for off-channel and in-lake springs to cease flowing and even reverse flow. By early January 2001, lake water cooled to nearly the temperature at which it attains maximum density, which is about 3.9°C (Drever, 1988) (fig. 16). This would establish a density potential between the cold lake water and relatively warm ground water in the Upper Floridan aquifer that could cause the spring to reverse flow, even if ground-water levels are higher than lake stage. A density potential could be larger than an opposing hydraulic gradient between the lake and aquifer, allowing lake water to leak into the Upper Floridan aquifer. Shackelford Spring and Sealy Spring contained water at temperatures that were less than ground-water temperatures during early March and December 2000 and January 2001 (table 8), but contained water at temperatures that were characteristic of ground water during October 1999 and during June and September 2000.These springs could have undergone flow reversal during the winter months, where lake water could have entered the Upper Floridan aquifer through spring openings by density-driven flow.

Other springs located in the bottom of Lake Seminole or along the Spring Creek impoundment arm, not described previously, also may contribute to water exchange between the lake and Upper Floridan aquifer. Maps prepared by Sever (1965a, pl. 1) and Atlantic Mapping, Inc. (©1998, used with permission) indicate locations of about 25 springs along the lake bottom and adjacent to the Spring Creek impoundment arm, including locations of springs mentioned previously. These springs could exhibit seasonal temperature variations that are similar to those measured during reconnaissance and water-chemistry sampling and measured with by temperature probes (figs. 16 and 17). If additional springs showed the same temperature variations as those measured, then numerous other locations are possible for ground-water inflow or lake leakage through the bottom of Lake Seminole.

Geologists' Accounts of Limestone-Dissolution Features Found during Site Exploration and Dam Construction

During the exploration of proposed sites for the lock and dam and during construction, Corps geologists and engineers compiled written descriptions of dissolution features in the limestone forming the foundation of Jim Woodruff Lock and Dam and in the present-day lake bottom (U.S. Army Corps of Engineers, 1948; James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., August 2002). Photographs taken by the Corps during 1950 (figs 18–23) further document the extent of dissolution features present near the dam (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., March 2003). These accounts provide evidence of the potential for lake leakage into the Upper Floridan aquifer and for ground-water inflow to the lake in areas of the lake bottom containing similar karst features as those described herein.

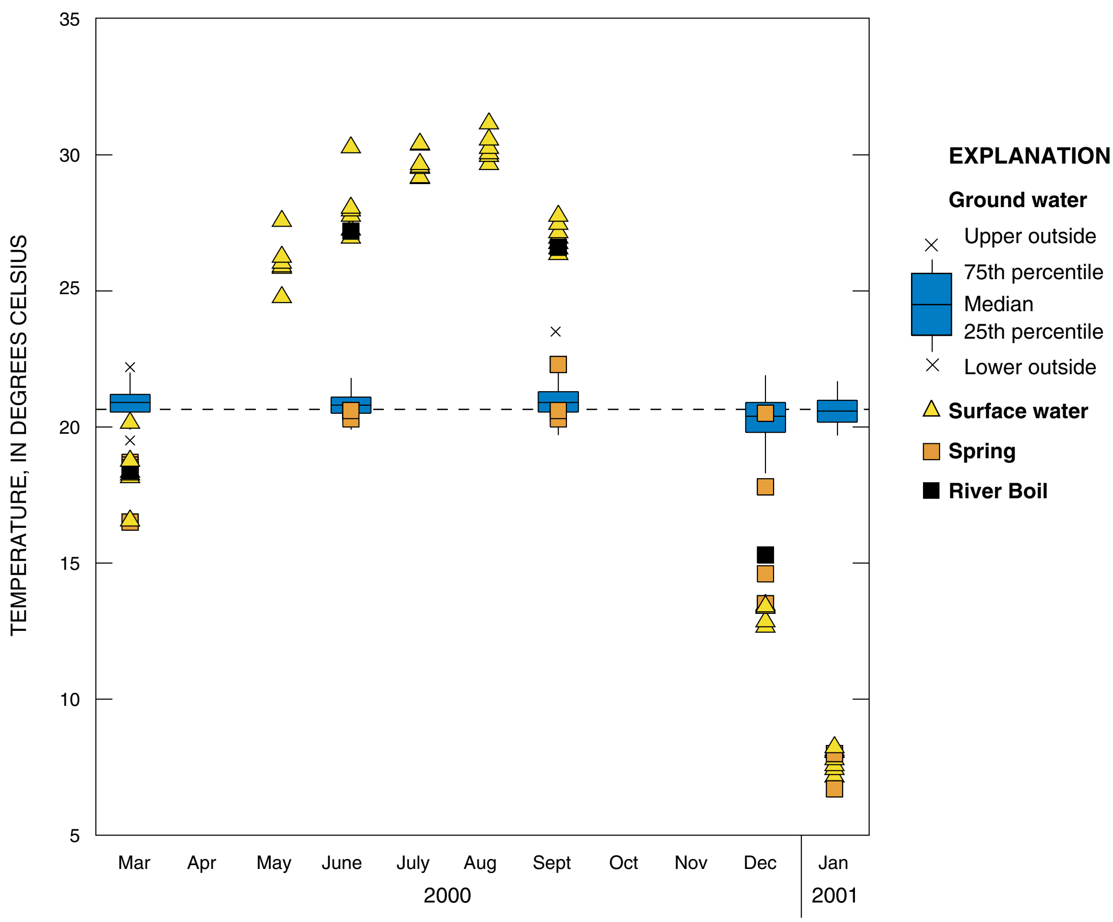


Figure 17. Temperature variation in ground water, surface water, and springflow in the Lake Seminole study area, from March 2000 to January 2001.

During the 8-year period prior to construction, beginning in 1938, the Corps investigated three sites before accepting the third site as the location for the lock and dam (U.S. Army Corps of Engineers, 1948). The first site positioned the axis of the dam normal to the Apalachicola River, about 900 ft downstream of its present location; the second site rotated the axis of the dam 25 degrees clockwise from the first axis by pivoting on the left downstream bank. The second site was "chosen principally on the basis of topography to accommodate a higher structure than that previously considered [along the first axis]" (U.S. Army Corps of Engineers, 1948, p. 2-3). The third site, and present-day location of the dam, was selected because it "afforded more favorable foundation conditions" than the previous two sites, and "by shifting to the upstream axis, which is essentially normal to the bed of the river … both the hydraulic and navigational features of the project are greatly improved" (U.S. Army Corps of Engineers, 1948, p. 2-2). Investigations at these sites consisted of drilling and logging more than 200 core holes, installing 24 observation wells for leakage studies west of the Chattahoochee and Apalachicola Rivers, and surface-geophysical testing by seismic and electrical-resistivity methods (U.S. Army Corps of Engineers, 1948).

> Exploration of [the first axis] … indicated a cavernous and deeply weathered bedrock. Axis number 2 … was likewise found to be both cavernous and covered with a heavy overburden mantle. … The selected axis, number 3, is regarded as the most favorable, from both engineering and geological aspects, of those explored and is further considered to be as suitable for the project as any other location in this … stretch of the river.
>
> *U.S. Army Corps of Engineers, 1948, p. 2-3*

Core-hole drilling and geologic logging indicated that the Tampa and Suwannee Limestones form the foundation rock of the lock and dam and compose most of the lake bed after impoundment. Along the axis of the dam, the Tampa Limestone "is characterized by a wide range of lithologic and textural differences … [that are] so irregularly distributed that correlations of the many weakened zones and stratigraphic horizons [would be] extremely difficult" (U.S. Army Corps of Engineers, 1948, p. 2-4). These weakened zones in the limestone would provide a strong hydraulic connection between the Upper Floridan aquifer and Lake Seminole.

> Weathering, leaching, oxidation, and solution are in evidence throughout the area investigated, and alternate hard and soft zones were penetrated by the borings. Due to the widely spaced drill holes and the poor core recovery, it is difficult to determine whether the soft zones occur in isolated pockets or are … [aligned] along beds or other structural features. However, due to the inability to correlate such beds between holes, and from observation in three 36-inch calyx holes, it is felt that the more common occurrence of the softer zones is in isolated pockets rather than along persistent structures. … [Calyx holes were 36-inch diameter boreholes that were used as shafts for mining and back filling of cavities.] The evidence of any fault movement is meager, and joints and fractures, although present, do not appear very persistent as single structures. The [relations] … between the structural weaknesses of the rock and the presence of cavities and channels are not definitely established, although the assumption is that they are, or were formerly, related. The majority of the solution cavities encountered are filled, although water-bearing open cavities were encountered in some of the borings.
>
> *U. S. Army Corps of Engineers, 1948, p. 2-4*

> This cavity filling is often a heavily leached calcareous clay which in most cases has either settled or partly washed away, leaving open portions usually at the top. … Other cavities are filled with alluvial material, silt, sand, mica flakes, the original material having been completely removed and replaced.
>
> *U.S. Army Corps of Engineers, 1948, p. 2-5*

Geologic information obtained from boreholes oriented along the axis of the dam indicates the presence of solution cavities and zones in the Tampa and Suwannee Limestones where water is lost from the borings to the aquifer (U.S. Army Corps of Engineers, 1948, appendix II, chart nos. 3.1, 4.1). Cavities and "water-lost" zones generally existed in the upper 25 ft of borehole into the limestone and also at the limestone-residuum contact. The water table measured in boreholes generally ranged from about 5 to 10 ft below land surface, which placed the water table from about 5 to 30 ft above the top of the residuum. A water table was not indicated on the geologic section, however, because 26 of 29 boreholes in the section contained "water-lost" zones in the limestone (U.S. Army Corps of Engineers, 1948, appendix II, chart nos. 3.1, 4.1). One set of cavities found in Calyx Hole Number 3, located along the axis of the dam between the Apalachicola River and east abutment, leaked water into the limestone at a rate of about 30 gal/min from two zones (U.S. Army Corps of Engineers, 1948, appendix II, chart no. 5).

Because the water-lost zones are located at or near the contact of the limestone with the overlying units, it can be inferred that these zones locally drained the water table by leakage into the underlying Upper Floridan aquifer. Although grouting along this geologic section remediated the apparent leakage condition that would have existed beneath the dam structure, it is possible for other locations within the impounded area behind and adjacent to the dam to contain similar water-lost zones. These zones could establish the potential for lake leakage into the Upper Floridan aquifer and promote the transport of lake water in the aquifer around the dam.

"[T]reatment of those cavities by grouting and dental methods … [was] considerable, but not prohibitive" to dam construction, and the Corps recommended cutoff curtain grouting using grout holes spaced every 5 ft, except in localized areas, "to render the foundation impermeable" (U.S. Army Corps of Engineers, 1948, p. 2-5). "Dental methods" refer to the process of cleaning out solution cavities by removing clay and other sediment, followed by replacement with cement. Besides cutoff curtain grouting, highly solutioned parts of the aquifer underwent "consolidation grouting" (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., March 2003), where a matrix of closely spaced wells drilled into the aquifer served as injection points for grouting (fig. 18).

Cavities were found in boreholes drilled along the axis of the dam in the fixed-crest overflow section (west of the lock), beneath the gated-spillway section (just east of the lock), and along the embankment section (east of the substation and powerhouse) (fig. 14). The largest cavity was located in the fixed-crest overflow section, measuring about 12 ft in its vertical dimension, and was removed during excavation (U.S. Army Corps of Engineers, 1948, p. 2-11). Along the upstream guide wall to the lock, a large cavity, perhaps partially filled with clay, was excavated prior to grouting (fig. 19).

> The hoses in the photograph are being used for dewatering; however, after such cavities in foundation areas were filled with dental concrete, grout was often pumped back through the dewatering hoses as consolidation grout.
>
> *James H. Sanders, Jr.,*
> *U.S. Army Corps of Engineers,*
> *Mobile District, written commun.,*
> *February 2005*

Figure 18. Washing of grout holes prior to consolidation grouting during construction of fixed-crest overflow section of Jim Woodruff Lock and Dam, circa 1950 (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., 2003).

At this location, the presence of “joint cavities” (fig. 20) indicated that solution along preexisting joints was the mechanism by which ground water removed limestone material from the aquifer, enlarging the joint openings. Near the lock, at the eastern end of the fixed-crest overflow section, other large cavities were discovered during excavation and were remediated by removing any clay that was present, followed by grouting (figs. 21*A*–*C*) (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., March 2003).

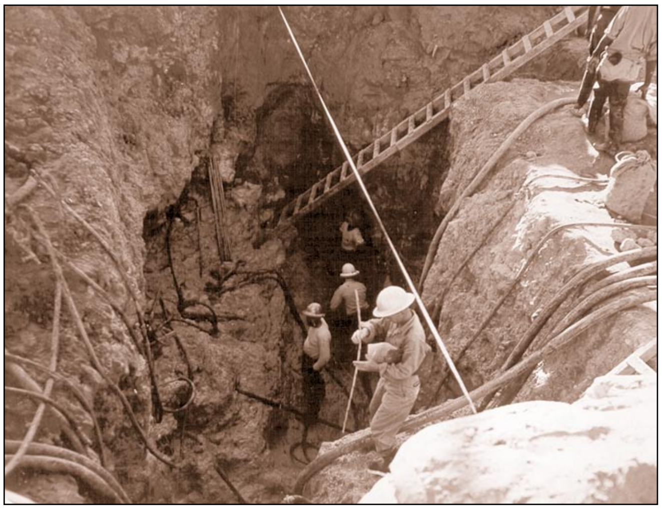


Figure 19. Upstream guide wall to the lock, looking westward, showing a limestone cavity found by the U.S. Army Corps of Engineers during dam construction, circa 1950 (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., 2003).

Figure 20. Joint cavity in upstream guide wall to the lock and dewatering methods used by the U.S. Army Corps of Engineers, circa 1950 (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., 2003).

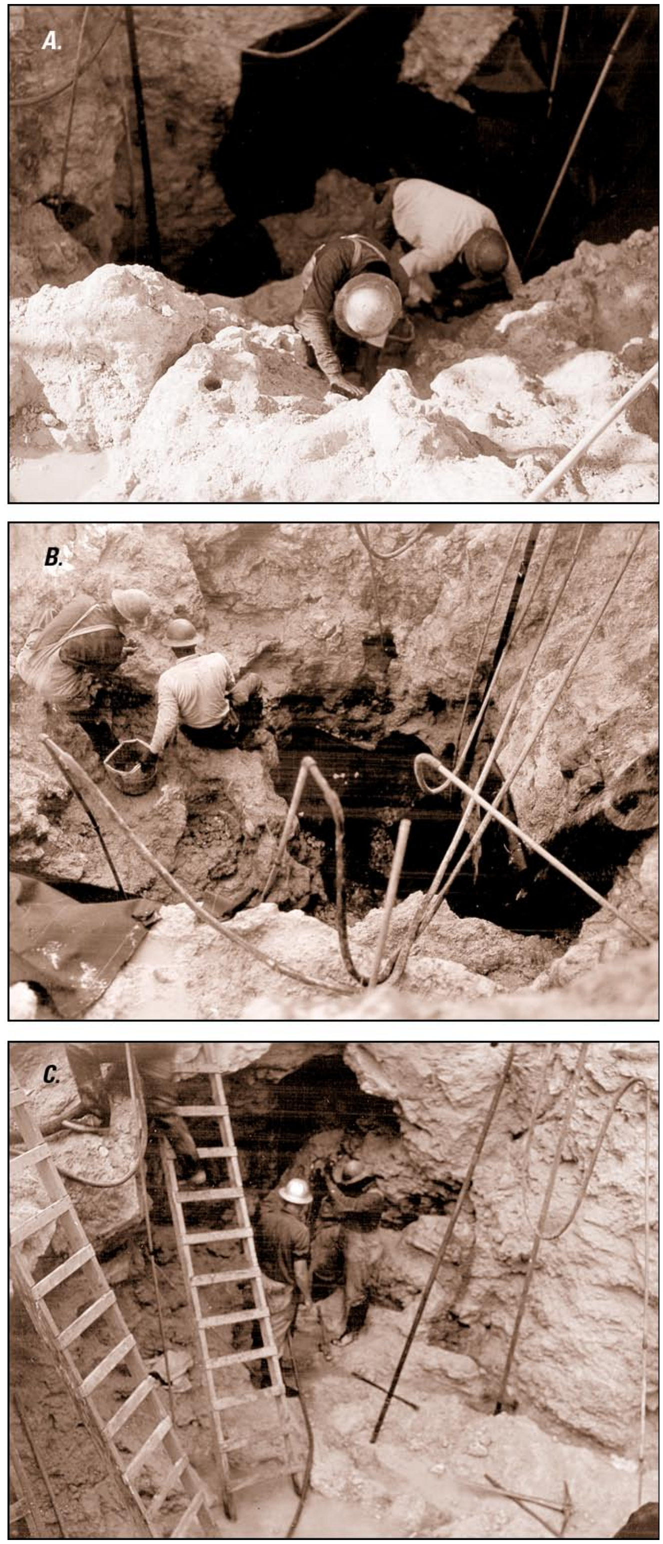


Figure 21. Solution cavity excavated at the northeastern end of the fixed-crest overflow section to the dam, near the lock, prior to grouting: (*A*) view looking northward; (*B*) view looking westward; and (*C*) solution cavity excavated at the southeastern end of fixed-crest overflow section, circa 1950 (James H. Sanders, Jr., U.S. Army Corps of Engineers, written commun., 2003).

During excavation for the downstream guide wall to the lock, and in the area occupied by the lock itself, cavities and solution-enlarged joints were found that required removal of clay, followed by grouting (figs. 22*A–C*). The distinctively north-south trending set of cavities and joints that exist at this location are consistent in shape and pattern with other solution features that exist in the floodplain, described previously, which are now inundated by the impoundment. The existence of cavities and enlarged joints at depth, their orientation, and the degree to which they are filled with clayey sediment, provides insight into the origin of these solution features and their degree of hydraulic connection with the aquifer. Cavities similar to those found during preconstruction drilling and excavation, if located beneath the present-day lake bed, establish the potential for lake leakage into the Upper Floridan aquifer and for ground-water inflow to the lake.

A memorandum written on January 12, 1956, by Corps Project Geologist, Fremon L. Estep, to Corps Resident Engineer, W.R. Coryell, at Jim Woodruff Lock and Dam describes lake leakage into a cavern located in the lake bottom along the west bank, northwest of the sinkholes where dye was injected by the Corps during 2001 (fig. 14), as discussed previously (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., August 2002). Estep reported that while filling the reservoir during June 1954, a "definite flow of water through [a] cavern" located about 0.75 mi upstream of the dam on the west side of the lake was observed, with the level of the water above the cavern between "1 and 2 ft below the reservoir level," which had attained an altitude of about 62–65 ft at that time. It was reported further "that authorization [had] been made to grout or otherwise plug this cavern at the level of known flow" (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., August 2002). The daily log of construction, completed on September 12, 1956, for the Jim Woodruff Dam Project, indicated grouting a cavern on the right bank of the river; this general location is consistent with the location of the cavern discussed above. Most likely, concrete was placed in the mouth of the cavern, and then grouting was performed (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., August 2002).

Descriptions of the valley floor of the Apalachicola, Chattahoochee, and Flint Rivers characterize the karst topography and landscape near the dam and present-day lake bottom as containing numerous dissolution features that can establish a strong hydraulic connection between the lake and aquifer, allowing lake leakage to the aquifer and ground-water inflow to the lake. The lake bed beneath the lower reaches of Lake Seminole is underlain by the Suwannee Limestone, which is present at or near the surface (Sever, 1965a, pl. 2). "Extreme variations in lithology, degree of leaching, solution, and erosion" of the limestone has given rise to a lake-bed area that is relatively flat, except for the "shallow, saucer and canoe-shaped sinks or depressions … formed both by the underground 'erosion' of the overburden as well as the collapse of caverns in the soft, soluble formations. Subterranean drainage is considered extensive within this area" (U.S. Army Corps of Engineers, 1948, p. 2-5).

Figure 22. Cavities and solution-enlarged joints in excavations for (*A*) downstream guide wall of lock, view looking northward into cavity; (*B*) lower miter section of lock, view of partially clay-filled cavity along north-south trending joint; and (*C*) western part of lock, view of open-joint system, circa 1950 (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., 2003).

> A distinctive feature of the valley floor overburden is the abundance of sinks and depressions, ranging from deeply incised former river channels to rather shallow, canoe and cup-shaped sinks. The majority of the sinks or lakes may be considered as inactive or at least their outlets plugged, as little relation has been observed between fluctuations in their water levels with that of the river. Many of the smaller depressions drain very rapidly and thus are considered active. Owing to the alignment of the sinks in a general up and downstream direction, with a generally parallel orientation, it is not improbable that many of them are due to solution along joint, and even possibly fault, systems in the underlying limestone, wherein a gradual underground 'erosion' of the soil [overburden] has permitted its collapse. There is no evidence to date that any of the sinks have developed through the collapse of cavity roofs.
>
> *U.S. Army Corps of Engineers, 1948, p. 2-3*

The "smaller depressions [that] drain very rapidly" in the valley floor, described previously, might be present-day locations of direct recharge of lake water to the Upper Floridan aquifer. The "inactive sinks or lakes" that are filled with water but do not exhibit water-level fluctuations with the river can indicate a hydraulic connection with the Upper Floridan aquifer rather than with the river. If hydraulically connected with the underlying limestone, these features can represent locations for potential lake leakage to the Upper Floridan aquifer. An alternative explanation for the "inactive" water-level response of these sinks to changes in river stage is that the sinks are partially filled with low-permeability sediments—such as silt and clayey alluvium, as discussed previously—and, therefore, are hydraulically disconnected from the river and underlying aquifer. Ground-water-level observations by the Corps indicate that "near the river, the … [ground-water level] varies with river level, with an increasing lag in time … [as distance from the river increases]. It appears that wells [located] more than about 1½ miles from the river are influenced mostly by local rainfall and not appreciably by rises in the river" (U.S. Army Corps of Engineers, 1948, p. 2-13).

The occurrence of springs located along the western edge of the floodplain, just north of the western abutment to the dam (U.S. Army Corps of Engineers, 1948, appendix II, chart no. 1.1), indicates a hydraulic connection of the overburden and/or underlying aquifer with the floodplain prior to dam construction. These springs discharged into a slough, which represented a former river channel that "may have been able to erode and dissolve the underlying rocks" (U.S. Army Corps of Engineer, 1948, p. 2-5, 2-11). The slough was located where the former Polk Lake existed, about 2,000 ft to the west of, and roughly parallel to, the Apalachicola River; the slough was aligned normal to the axis of the dam. The former Polk Lake was bisected during construction of the fixed-crest overflow section of the dam (fig. 23), leaving a remnant of the lake located downstream of the dam, where it receives water from a boil named Polk Lake Spring (fig. 14).

> The remnant of Polk Lake downstream of the dam was backfilled with excavation spoil to [about] elevation 50, ... and the upstream remnant was backfilled to elevation 60, for a distance of 1,000 ft upstream of the dam. The closest source of lake leakage into the Tampa Limestone discovered during the recent hydrographic surveys (and documented by the dye test) was located 1,430 ft upstream of the dam. On the downstream side of the dam, Polk Lake spring has apparently broken through the spoil placed during construction.
>
> *James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., February 2005*

A few of the springs that formerly discharged to the slough in the former Polk Lake had become inundated by the impounded water, and now provide a source of hydraulic connection of the Upper Floridan aquifer with the present-day lake bed. Springflow once discharged at an altitude of 50–55 ft from the base of a hill that rises abruptly to an altitude of about 125 ft forming the western shore, or "west wall," of the lake (fig. 14). These springs are in close proximity to the structures that received dye injection by the Corps during 2001, except that these structures are located farther from the western shore than the injection points.

A few of the springs that once discharged to the slough connected to the former Polk Lake probably have undergone flow reversal due to impoundment.

> There was no indication on ... the hydrographic surveys that any of the springs, in the area backfilled with spoil, [have] undergone flow reversal. Flow reversal, however, has obviously developed upstream of where the spoil was placed.
>
> *James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., February 2005*

The normal-pool altitude of Lake Seminole, 77 ft, represents a 33-ft rise in water level from the stage of the Apalachicola River (U.S. Army Corps of Engineers, 1973) and provides a higher hydraulic potential than the head in the aquifer near the dam and along the west wall of the lake. During 1947 prior to impoundment, ground-water levels adjacent to the lake and along the west wall reached a maximum altitude of about 60 ft during April and a minimum altitude of about 50 ft during October (U.S. Army Corps of Engineers, 1948, appendix II, chart nos. 8 and 9). The impounded water at 77 ft provides the hydraulic potential to reverse springflow and initiate lake leakage into the Upper Floridan aquifer at the location of these springs and elsewhere along the lake bottom. The locations of dye injection, vortex flow, and caverns in the limestone that accept lake water, all located along the west wall of the lake, indicate lake leakage to the Upper Floridan aquifer; these features are located in the same general vicinity as the springs that formerly discharged to the former Polk Lake.

Figure 23. Drilling and grouting operations at the location of Polk Lake (mid-picture, near side of lake) and excavation for Jim Woodruff Lock and Dam (far side of lake), circa 1950 (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., 2003).

Hydrochemical Evidence of Lake Leakage and Ground-Water Inflow to Lake Seminole

Water-chemistry analyses of samples collected from the lake, streams, springs, and wells provide hydrochemical evidence of lake leakage into the Upper Floridan aquifer near Jim Woodruff Lock and Dam (tables A1–A15). As discussed previously, a higher lake stage than ground-water level near the dam creates a positive hydraulic potential for lake water to leak into karst limestone of the Upper Floridan aquifer, which forms the lake bottom. Once in contact with the aquifer, lake water mixes with ground water and is transmitted away from the lake along solution features, fractures, and joints in the limestone. Seasonal variations in the chemical composition of ground water, surface water, and springflow provide insight into the evolutionary pathways of these waters. Concentrations of naturally-occurring solute tracers and stable isotopes of oxygen and hydrogen (deuterium) in water samples collected from the lake, streams, springs, and wells have a diagnostic role in identifying representative end members and mixed fractions of water that leak from Lake Seminole into the Upper Floridan aquifer.

Water-Chemistry Sampling

Water samples were collected from 29 domestic and municipal wells completed in the Upper Floridan aquifer, 7 locations in Lake Seminole, and 5 in-lake springs during March, June, September, and December 2000 and during January 2001 (fig. 7; tables A1–A3) to characterize the chemical composition of ground water, surface water, and springflow as a means to identify lake water mixing with ground water. Two sites on the Apalachicola River just downstream of Jim Woodruff Lock and Dam also were sampled seasonally to determine the origin of water emanating from an in-channel spring, the River Boil (site 07D011, fig. 7).

Samples of ground water, surface water, and springflow were collected and prepared for analysis according to standard USGS procedures (Lane and Fay, 1997; Radtke, 1997; Wilde and Radtke, 1998; Wilde and others, 1998a,b,c; 1999a,b; and Myers and Wilde, 1999). Ground-water samples were collected after purging at least three casing volumes of water from the well and after field measurements of temperature, specific conductance, dissolved oxygen (DO), and pH had stabilized during well purging (Gibs and Wilde, 1999). Lake- and surface-water samples were collected at midchannel and middepth using a, nonisokinetic thief sampler (Van Dorn sampler; Webb and Radtke, 1998).

Springflow was sampled at or near spring orifices by lowering a Van Dorn sampler from a boat to the location along the lake bottom where field measurements of water temperature, specific conductance, DO, and pH indicated the presence of springflow. Springflow had higher specific conductance and pH, and lower DO, than surface water; springflow temperature was similar to the ground-water temperature (about 20°C) in wells located near the lake (tables A4–A6). Although the Van Dorn sampler is designed to collect a sample at a discrete point in the water column, uncertainty associated with locating in-lake springs and positioning the sampler exactly at the spring orifices probably resulted in collecting a mixed ground- and surface-water sample. Seasonal variation in springflow and mixing with surface water around the spring orifice also contributed to collecting a mixed-water sample instead of a single-source sample; the uncertainty of this occurrence could not be quantified and requires further study.

Physical and Chemical Properties

Water samples were analyzed for major ions, total organic carbon (TOC), alkalinity, naturally stable isotopes of oxygen and hydrogen, and radon-222 (tables A7–A15). Chemical analyses were performed at the USGS National Laboratories in Ocala, Fla., and Denver, Colo. (Fishman and others, 1994). Field measurements of water temperature, specific conductance, DO, and pH were taken at the time of sample collection; alkalinity values were determined in the field and in the laboratory by digital titration methods (Radtke and others, 1998) (tables A4–A6). Water samples analyzed for major ions and TOC were filtered through a 0.45-micrometer (µm) filter and were acidified in the field according to standard USGS procedures (Radtke, 1999; Radtke and others, 1999). Samples for radon-222 were collected using a syringe that extracted nonaerated water from the pump discharge or other sampling device and injected the sample below mineral oil contained in a small borosilicate glass vial (Wilde and Gibs, 1999).

Ground-Water Chemistry

Ground water from wells sampled near Lake Seminole (fig. 7) can be classified as a calcium-magnesium-bicarbonate type (fig. 24). An exception to this general classification is water from well 07D008, which is a calcium-magnesium-bicarbonate-sulfate type. This well is located in the Tallahassee Hills physiographic district (fig. 2), where ground water derived from wells tapping the Miocene Tampa Limestone contain higher sulfate concentrations than water from wells completed in the underlying Ocala Limestone (Sever, 1965a, table 4). Ground water from well 07D008 contained sulfate at concentrations (about 10 mg/L) that were about an order of magnitude greater than at other sites (1 mg/L), and contained radon-222 values ranging between 1,460 and 1,560 picocuries per liter (pCi/L) during seasonal sampling during 2000 and 2001 (table A10). The high sulfate can be attributed to dissolution of a localized gypsum deposit; high radon values can be caused by ground water in contact with phosphatic sands and clayey silts associated with the Hawthorn Group and with limestones composing the Upper Floridan aquifer (Wait, 1970).

Ground water from wells 08E034 and 06D002 contained higher concentrations of chloride, magnesium, potassium, and sodium than ground water sampled in the other parts of the study area (table A7). These chemical constituents in ground water are indicative of dissolution of dolomite, a magnesium carbonate, contained in the limestone of the Upper Floridan aquifer, and similar dissolution of glauconitic sediments, containing potassium, in the lower confining unit. The wide range in percent-magnesium composition in ground water (fig. 24) can be attributed to variations in the occurrence of magnesium-rich calcite in geologic formations comprising the upper semiconfining unit, Upper Floridan aquifer, and lower confining unit. The occurrence of sodium and chloride in ground water can be attributed to lake water mixing with ground water, which has been shown to occur near well 08E034, at least seasonally, as the hydraulic potential favored flow from the lake to the aquifer during April 2000 (fig. 8; table 8).

Iron concentrations in well 08E032 ranged from an unquantified presence to 400 mg/L, compared with 1–2 mg/L at other sites (table A7). This well is located between the Flint River impoundment arm of the lake and the Solution Escarpment, in a narrow zone that was reported by Sever (1965a) to contain high-iron concentrations. The dissolved-iron content of ground water in the Upper Floridan aquifer probably is derived from sediments containing pyrite (iron sulfide) or glauconite (potassium iron silicate). Ground water from wells in this area contain iron concentrations above the USEPA secondary drinking-water regulation of 0.3 mg/L (U.S. Environmental Protection Agency, 2000), low dissolved-oxygen concentrations (DO; table A4), and pH in the alkaline range (from 8 to 8.3, table A7). Water from well 08E032 also contains phosphorus, indicative of dissolution of phosphatic sediments contained in the Hawthorn Group and Oligocene limestone of the Upper Floridan aquifer (Wait, 1970).

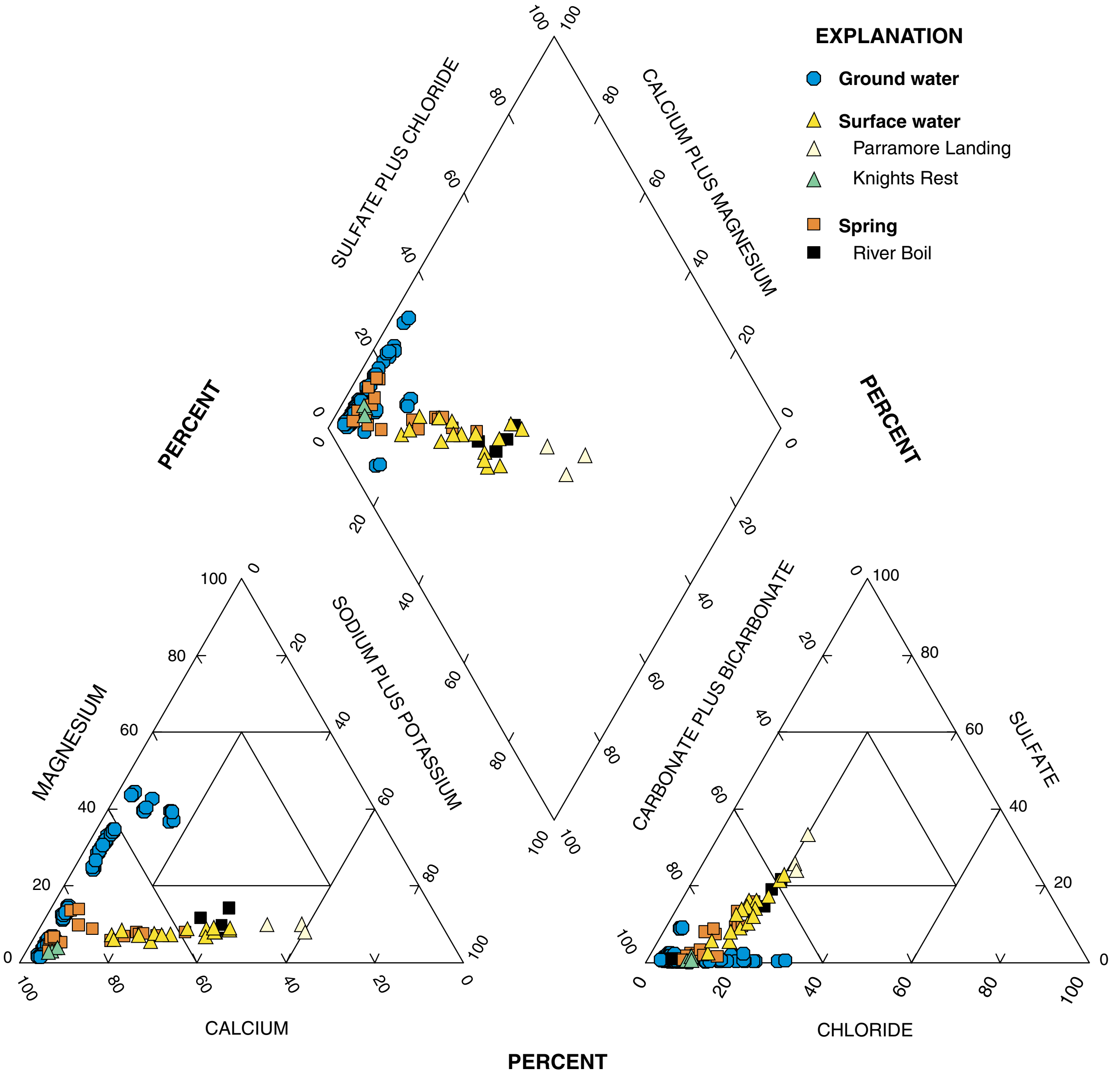


Figure 24. Hydrochemical-facies classification of ground water, surface water, and springflow in the Lake Seminole area, sampled during March, June, September, and December 2000 and during January 2001 (see figure 7 for location of Parramore Landing, Knights Rest, and River Boil).

Results of water-chemistry analyses indicate distinct groups of compositional similarity based on the relations in concentrations of calcium to magnesium and calcium to alkalinity (fig. 25). Two groups are defined from the relation between calcium and magnesium in ground-water samples (fig. 25*A*). Ground-water samples in Group 1 have higher magnesium and lower calcium concentrations than samples in Group 2. The Group 2 samples extend the trend of increased alkalinity with increased calcium concentration indicated by surface-water samples (fig. 25*B*); the Group 1 samples establish a similar, parallel trend of increased alkalinity with increased calcium concentration as Group 2, only at higher alkalinity concentrations.

Five ground-water samples seem to be anomalous in the relations of magnesium and alkalinity concentrations with calcium (fig. 25). These wells represent water from fairly shallow depths (from 40 to 100 ft); although, they are located in different areas surrounding the lake (see fig. 7 for location of wells 06D001, 06D002, 08E032, 08E034, and 08E035). Chemical constituents in ground water from these wells could be affected by local lithologic variations in the limestone of the Upper Floridan aquifer, and/or ground-water recharge from the residuum.

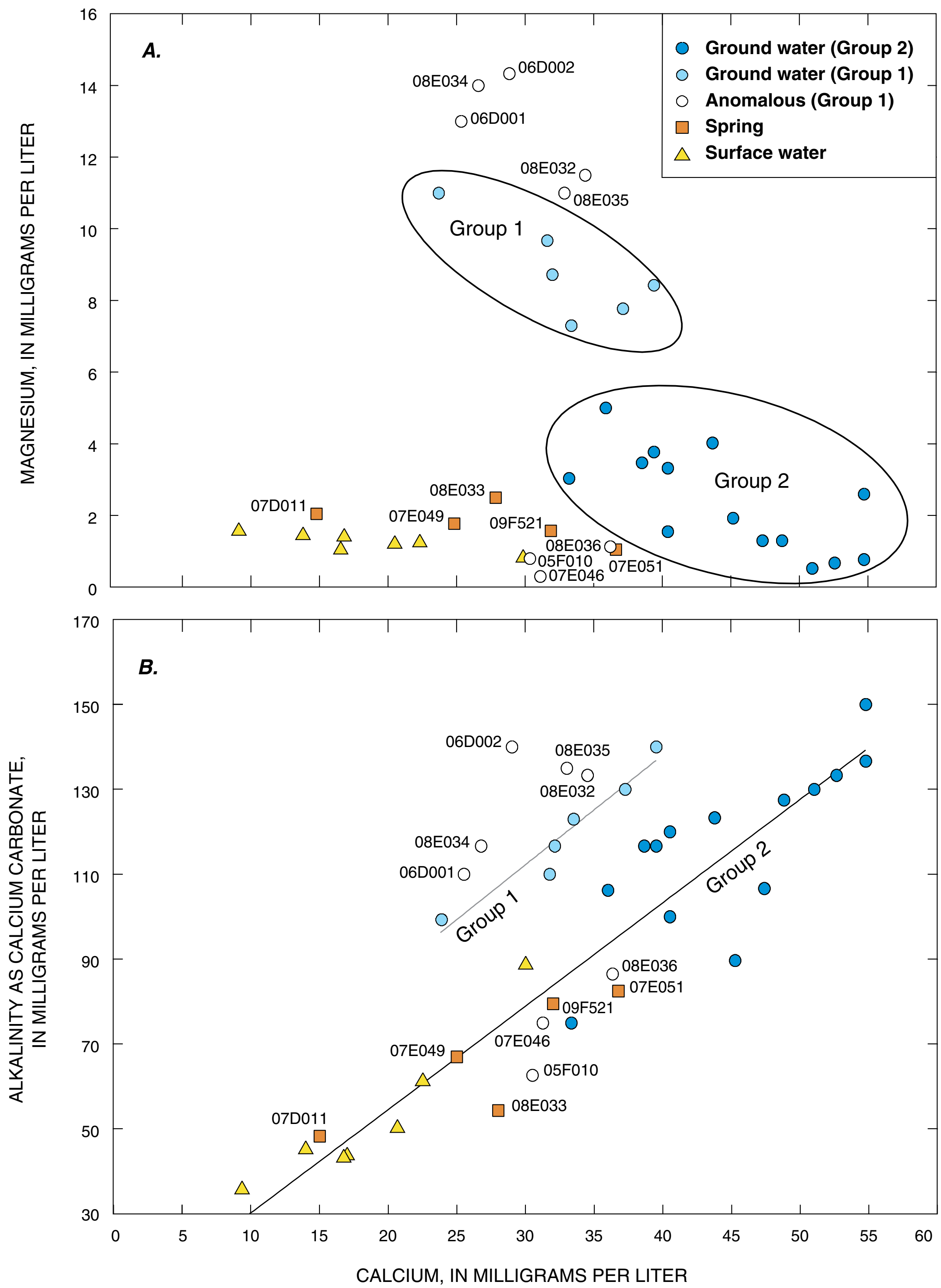


Figure 25. Average concentrations of (*A*) calcium and magnesium and (*B*) calcium and alkalinity in ground water, surface water, and springflow sampled in the Lake Seminole area during March, June, September, and December 2000 and during January 2001 (see figure 7 for location of labeled wells and River Boil).

The areal distribution of alkalinity, magnesium, and calcium indicates that higher concentrations of these chemical constituents occur in ground water from wells located close to Lake Seminole rather than from wells located farther away or that occur in surface water (figs. 26*A*–*C*). Dissolution of limestone and dolomite by ground water in the Upper Floridan aquifer, and ground-water flow toward Lake Seminole (figs. 8 and 10), can account for the occurrence of high concentrations of alkalinity, magnesium, and calcium in ground water near the lake. Compositional differences in the limestone, variable rates of vertical recharge from the residuum, and lake-water mixing with ground water, however, can cause variations in the concentrations of these chemical constituents in water samples.

Ground-water samples from wells located along the upper reaches of the impoundment arms and along the south side of the lake contained high alkalinity concentrations; ground water from both of these areas, however, differed greatly in concentrations of calcium and magnesium (fig. 26). Ground water from wells located along the upper reaches of the impoundment arms contained high concentrations of calcium and low magnesium (figs. 26*B* and *C*). Along the south side of the lake, ground-water samples contained calcium concentrations that were lower, and magnesium concentrations that were higher, than the concentrations in ground water along the upper reaches of the impoundment arms. Ground water along the south side of the lake probably derived the increased magnesium concentration from dissolution of dolomitic sediments in the Tampa and Suwannee Limestones (figs. 4 and 5).

Laboratory-derived water-chemistry analyses of ground-water samples (table A7) indicate ionic imbalances that are consistently greater than 5 percent, which might be considered outside most quality-assurance limits (Amy Swancar, U.S. Geological Survey, written commun., January 2005). A comparison of field properties measured during sampling (table A4) with the laboratory-derived values (table A7) did not indicate any anomalies in specific conductance, alkalinity, or pH, which might indicate precipitation of calcium or other ions and cause an ionic imbalance. Generally, laboratory-derived values for specific conductance, alkalinity, and pH were slightly higher than those measured as field properties during sampling and, therefore, were considered reliable estimates for ground water.

Surface-Water Chemistry

Surface water is predominantly a calcium-sodium-bicarbonate type, with in-lake springs plotting between ground- and surface-water concentrations (fig. 24). Surface-water composition varies only slightly with season, but greatly with location, ranging from a calcium-magnesium-bicarbonate type in the Spring Creek impoundment arm (Knights Rest sample site), to a sodium-potassium-bicarbonate type in the Chattahoochee River impoundment arm (Parramore Landing sample site; fig 24; table A8). As described previously, ground-water inflow to the Spring Creek impoundment arm increases the calcium and magnesium concentration of surface water. Similar ground-water inflow to Fishpond Drain and the Chattahoochee River impoundment arms can be inferred from the potentiometric surfaces of the Upper Floridan aquifer (figs. 8 and 10). The relatively high streamflow entering the Chattahoochee River impoundment arm, however, dilutes the calcium and magnesium contained in ground water entering the reach. Other surface-water samples contain varying amounts of ground water that has entered Lake Seminole through in-lake springs and diffuse inflow across the lake bed. The water chemistry of these samples plots between the extreme values for Spring Creek (Knights Rest) and the Chattahoochee River (Parramore Landing) (fig. 24).

Concentrations of alkalinity, magnesium, and calcium for surface-water samples differ among the impoundment arms and indicate differences in ground-water inflow and lake water mixing that occurs in each part of the lake (fig 26; table A8). In general, alkalinity, magnesium, and calcium concentrations in surface water are less than concentrations in ground water from wells located adjacent to the lake and from in-lake springflow. The relatively high ground-water component of streamflow along the Spring Creek impoundment arm relative to surface-water inflow, as discussed previously, elevates the concentrations of calcium and alkalinity in surface water contained in this impoundment arm, compared with concentrations of these chemical constituents in the other three impoundment arms (figs. 26*A* and *C*). The relatively high volume of streamflow to ground-water inflow along the Chattahoochee and Flint River impoundment arms dilutes the concentrations of alkalinity and calcium present in these parts of the lake (fig. 26*C*). Ground-water and surface-water inflow to the Fishpond Drain impoundment arm is small; concentrations of alkalinity, magnesium, and calcium, however, resemble concentrations of these chemical constituents in the Chattahoochee and Flint River impoundment arms and in the lake area near the dam.

The percent milliequivalents per liter of dissolved calcium relative to the percentages of dissolved concentrations of the remaining cations (sodium, potassium, and magnesium) in surface-water samples from the four impoundment arms constitutes a percent-calcium ranking (table 9) that is useful in identifying the source of water to Lake Seminole. The percent-calcium ranking is derived from the cation plot on the trilinear diagram (fig. 24), and gives the relative abundance of calcium present in a water sample with regard to the other cations, with the percent milliequivalents per liter of all cations present in a sample totaling 100 percent. High percent-calcium rankings for surface water in the Spring Creek, Fishpond Drain, and Flint River impoundment arms indicate a carbonaceous-rock influence on the surface-water chemistry that can occur by ground-water inflow to the lake from the Upper Floridan aquifer. The relatively low percent-calcium ranking for water in the Chattahoochee River impoundment arm indicates less of an influence of carbonaceous rock on water contained in this part of the lake than in the other three impoundment arms. This can be caused by less ground-water inflow to the Chattahoochee River impoundment arm than to the other impoundment arms or a less-carbonaceous source of ground water that flows into the Chattahoochee River than flows into the other impoundment arms.

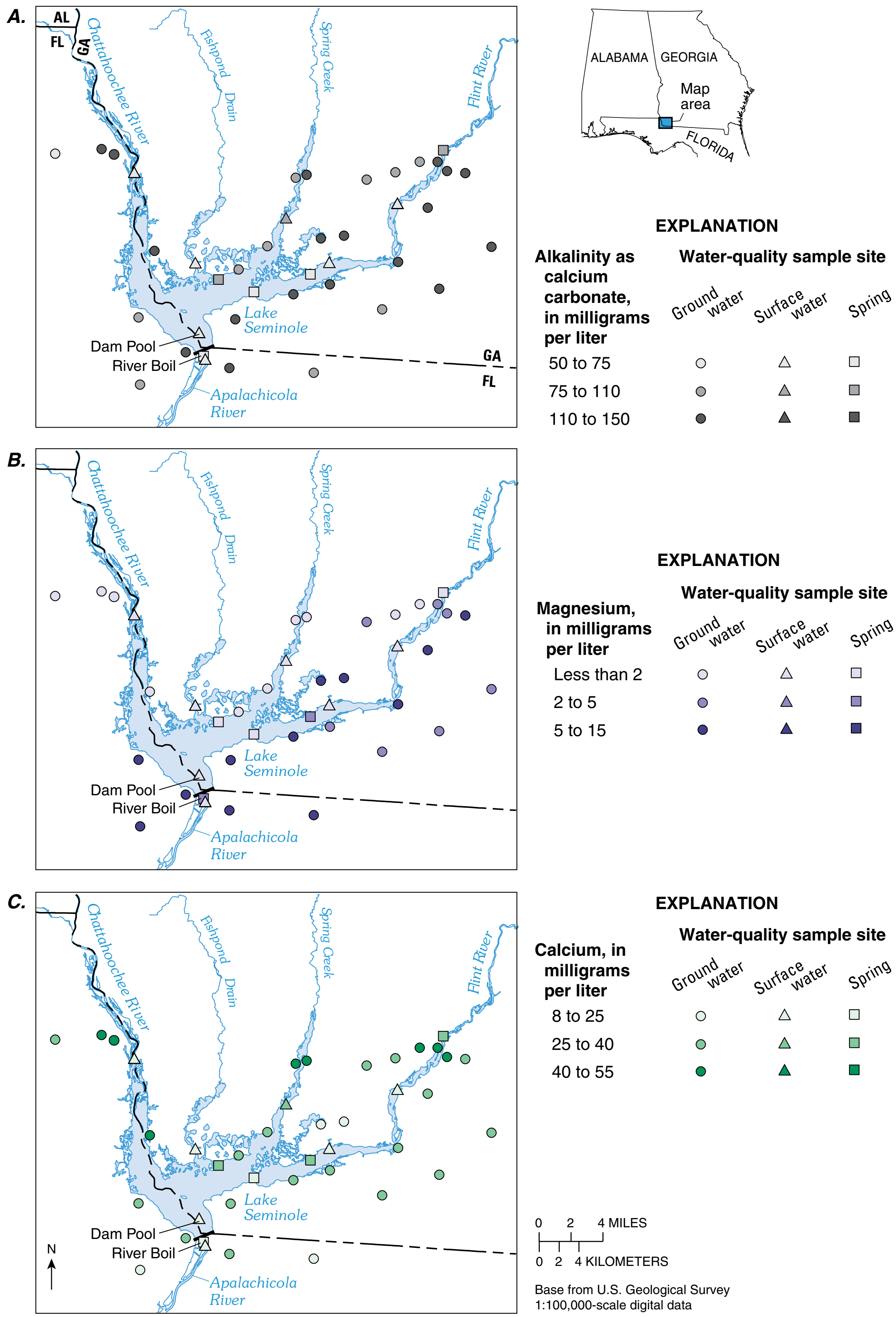


Figure 26. Areal distribution of average concentrations of (*A*) alkalinity, (*B*) magnesium, and (*C*) calcium in ground water, surface water, and springflow sampled in the Lake Seminole area during March, June, September, and December 2000 and during January 2001.

Table 9. Percent-calcium ranking for surface-water sites in the study area.

Surface-water site (see figs. 26 and 27)	Calcium ranking (percent)
Spring Creek	95
Fishpond Drain	75
Flint River	68–72
Dam Pool	60
Apalachicola River	55
Chattahoochee River	35

The percent-calcium rankings of surface water in the Apalachicola River and Dam Pool (table 9) indicate a dilution of calcium in the Apalachicola River by ground water. In a "closed system" (no water exchange between the Upper Floridan aquifer and Lake Seminole), the percent-calcium rankings for the Dam Pool and Apalachicola River would be the same. Ground-water inflow to the lake and Apalachicola River from the Tampa and Suwannee Limestones contained in the Upper Floridan aquifer, located south and east of Lake Seminole, can dilute lake water of calcium because ground water from these units contains lower calcium concentration (and ranking) than the Dam Pool (fig. 26C).

Springflow Chemistry

The chemical composition of springflow entering Lake Seminole through the lake bottom seems to vary seasonally between chemical compositions that are similar to ground water and those of surface water (fig. 24) (tables A7–A9). Of the five springs sampled, the chemical compositions of water from Shackelford Spring (07E049), Wingate Spring (08E033), and State Dock Spring (09F521) (fig. 7) are characteristically similar to ground water during June and September and similar to surface water during March and December 2000. Water from Sealy Spring (07E051) (fig. 7) is characteristic of ground water during all the sample times; although the December 2000 sample contained higher sulfate and less carbonate than samples taken during March, June, and September 2000, indicating some mixing with surface water and possibly reverse flow of lake water into the spring. In addition, the temperature of the water in the spring opening during March 2000 (16.5°C, table 8) indicated invasion of the spring by cold, dense surface water, as the lake cooled during the winter months.

Seasonal variations in water chemistry of in-lake springs perhaps is more the result of sampling a mixture of surface water and springflow than of seasonal changes to the chemical composition of springflow (table A9). As discussed previously, sampling involved lowering a Van Dorn sampler (Webb and Radtke, 1998, p. 29, 30) into the lake to a position at or near the lake bottom where monitoring of the physical properties of water temperature, specific conductance, pH, and dissolved-oxygen content indicated the presence of ground water. Low springflow during March and December 2000 made locating and sampling in-lake springs difficult. The relatively warm ground water issuing from the spring openings dispersed into the cold lake-water column during March and December 2000. As a result, sampling at the precise location of the spring opening was problematic, and samples collected from some springs might have contained a lake-water fraction mixed with the springflow.

The concentration of chemical constituents in water sampled at the River Boil (07D011) (fig. 7; table A9) is characteristic of surface water year-round (fig. 24), although June and September concentrations had attained characteristics similar to ground water. The concentration of magnesium in water sampled from the River Boil was higher than the concentration in water samples from Lake Seminole, near the dam, and from the Apalachicola River, but consistent with the magnesium concentration of in-lake springs, indicating that the River Boil contains a ground-water fraction mixed with surface water (figs. 25*A* and 26*B*).

Solute-Tracer Analysis

Conservative-solute tracers typically are nonreactive chemical constituents of water, which were used to (1) delineate ground-water flowpaths in the Upper Floridan aquifer adjacent to and beneath Jim Woodruff Lock and Dam; (2) identify sources and sinks of water entering and exiting Lake Seminole, respectively; (3) quantify recharge rates to the aquifer; and (4) determine the chemical evolution of ground water as a means to identify lake leakage. Tracer analysis involves interpreting changes in end-member concentrations of chemical constituents that are present in ground water, surface water, and springflow.

Major ions, calcium, silica, radon-222, dissolved organic carbon, chloride, sodium and bicarbonate, and naturally-occurring stable isotopes—deuterium (^{2}H) and oxygen-18 (^{18}O)—exhibit relatively large differences in end-member concentrations and are suitable as solute tracer to identify ground water, surface water, springflow, and mixed fractions of each in water samples collected from the lake, springs, wells, and streams. Although potassium, sulfate, sodium, calcium, and magnesium exhibited large differences in concentration between end members of ground water and surface water (tables A7–A9), these are affected by geochemical and biological processes, making them nonconservative ions and therefore unsuitable for solute-tracer analysis.

Chloride was the principal major ion used in the solute-tracer analysis due to its conservative chemical characteristics and relatively large difference in concentration of end-member water samples. Chloride concentrations in most ground-water samples ranged from 2 to 4.5 mg/L and showed no seasonal variation. The exceptions were samples from wells 07E047, 08E031, 08E034, 08F499, and 06D002 (fig. 7), which had higher chloride values than other wells (table A7). The relatively high chloride concentrations indicate a connection with surface water, which generally contains higher chloride concentrations than ground water. Ground water sampled from well 08E034 consistently had chloride concentrations that were from about 7.5 to 8.5 mg/L higher than other ground-water samples. Well 08E034 is located between the Spring Creek and Flint River impoundment arms, in an area where ground-water levels were lower than lake stage (fig. 8), establishing the potential for lake leakage to the aquifer. Ground water from well 06D002 contained higher chloride values during March, September, and December than during June 2000, when the chloride concentration was similar to that of the other wells. Well 06D002 is located just west of Jim Woodruff Lock and Dam (fig. 7), in an area west of where dye-tracing studies by the Corps during 2001 indicated lake leakage (Roger A. Burke, Plan Formulation Branch, U.S. Army Corps of Engineers, written commun., April 2003).

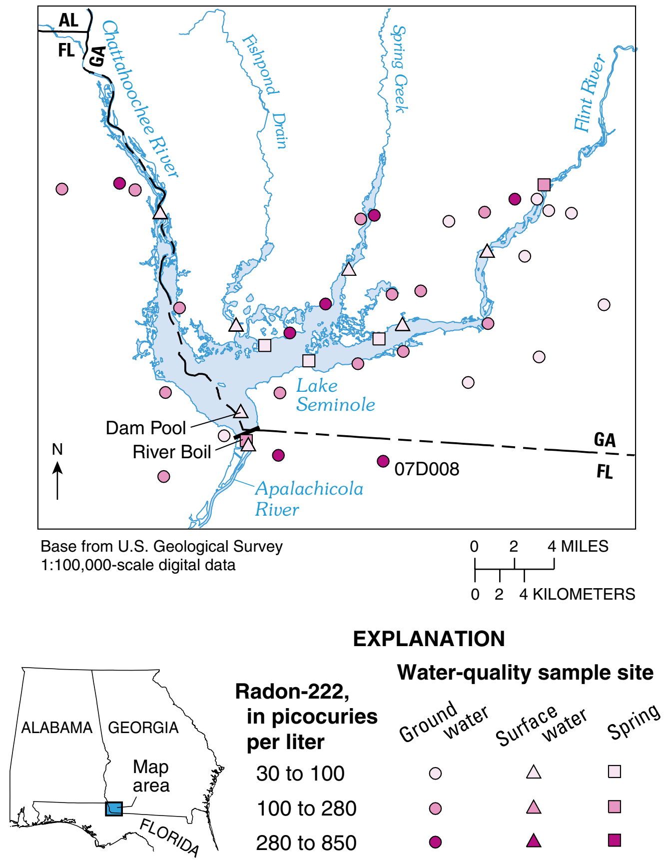


Figure 27. Areal distribution of average radon-222 concentrations for ground water, surface water, and springflow sampled in the Lake Seminole area during March, June, September, and December 2000 and during January 2001.

Radon-222

Radon-222, or simply radon, is a naturally-occurring, chemically inert radioactive gas present in virtually all soil and rock. Radon concentrations can vary widely (Nazaroff and others, 1988). Radon is emitted as a decay product of radium-226, the fifth daughter in the decay of uranium-238. As radon forms, some atoms leave the soil or rock and enter the surrounding air or water (Samet and Nero, 1989). Highly phosphatic sediments in the Hawthorn Group and phosphatic sandy Oligocene limestone and dolomite from the coastal area of Georgia are proportionately more radioactive than other local geologic units, indicating a source of radon to ground water; the high-radioactive zones are represented as peaks, kicks, or points on natural-gamma, geophysical logs (Wait, 1970). The volatility and the short half-life of 3.83 days make radon an effective solute tracer of ground water, because radon will separate from water readily through aeration or in a reasonable length of time when exposed to atmospheric conditions (Chandler, 1989). Thus, the concentration of radon is higher in ground water and lower in surface water.

The distribution of average concentrations of radon in water samples indicates that surface water and springflow contain lower concentrations of radon than ground water (fig. 27; tables A10–A12), owing to the opportunity for degassing to the atmosphere. Radon concentrations in some ground-water samples located southeast of Lake Seminole, on the Tifton Upland (fig. 2), were low (30–100 pCi/L), perhaps indicating a recent meteoric origin for ground water or the presence of rock and sediment having a relatively low uranium content. An exceptionally high concentration of radon in this area occurred, however, in well 07D008 (fig. 27), as noted previously. Conversely, some ground-water samples from wells located close to the lake exhibited radon concentrations that indicate little opportunity for degassing (280–850 pCi/L), as compared with surface-water samples, which contained low radon concentrations (fig. 27).

Deuterium and Oxygen-18 Stable Isotopes

Isotopes of oxygen and hydrogen are natural tracers that can be used to discern between surface water and ground water and to identify mixing of ground water with surface water. Isotopic analyses of ground water and springflow from the Upper Floridan aquifer indicate that ambient ground water has a distinct isotopic composition, or signature, compared with surface water (James B. McConnell, U.S. Geological Survey, oral commun., January 1997). Thus, ambient ground water and surface water would contain isotopic signatures of end-member components of a two-component mixing model. Differences in isotopic signatures for ground water, surface water, and springflow were used to identify the source of water to Lake Seminole, wells, and springs.

Oxygen has three stable isotopes, the heaviest and least abundant is oxygen-18; the stable heavy isotope of hydrogen is deuterium (Faure, 1977). Physical processes operating on the water molecule before percolation through the unsaturated zone—such as evaporation, condensation, freezing, melting, and chemical reactions—result in fractionation of hydrogen and oxygen isotopes; that is, the lighter isotopes, oxygen-16 and hydrogen, enter the vapor phase while the heavier isotopes, oxygen-18 and deuterium, are enriched in the liquid phase (Faure, 1977). Ground water that has been recharged by precipitation, which has not undergone additional fractionation (enrichment), will contain the isotopic signature of precipitation and can be distinguished from surface water, provided climatic conditions during the time of recharge are similar to those of the present. Conversely, surface water that originated as precipitation will undergo isotopic fractionation (enrichment) of the heavy isotopes, deuterium and oxygen-18, as surface water is subjected to the physical processes mentioned above. Ground water that has been recharged by surface water containing heavy-isotopic fractionation also will attain an enriched heavy-isotopic composition.

Ground water and springflow were sampled and analyzed for deuterium and oxygen-18 during March, June, September, and December 2000 and during January 2001; surface-water samples were collected and analyzed monthly during 2000, except during January, February, and May (tables A13–A15). The USGS Reston Stable Isotope Laboratory (RSIL) in Reston, Virginia, conducted deuterium and oxygen-18 isotopic analyses. Isotopic results were normalized, reported in per mil relative to Vienna standard mean ocean water (VSMOW) and calculated using the following equations (Coplen, 1994),

$$R_O = \left[\frac{^{18}O}{^{16}O}\right], \quad (1)$$

and

$$R_H = \left[\frac{^{2}H}{^{1}H}\right], \quad (2)$$

where R_x is the ratio of the isotope to its element ($x = O$ or H) and,

$$\delta_x = \left[\frac{R_x}{R_{std}} - 1\right] \times 1{,}000, \quad (3)$$

where δ_x is the isotopic ratio in per mil, and R_{std} is the isotopic ratio of the standard sample, VSMOW (Coplen, 1994).

Isotopic values of deuterium and oxygen-18 in groundwater samples collected during March, June, September, and December 2000 and during January 2001, plotted in a scattered pattern about the global meteoric water line (GMWL) (fig. 28) (Coplen, 1994), indicating that the isotopic composition of the precipitation that recharged the aquifer is similar to that of the present day (Boyd, 1998). The GMWL is defined in Coplen (1994) by the equation,

$$\delta\,^{2}H = 8\delta\,^{18}O + 10, \quad (4)$$

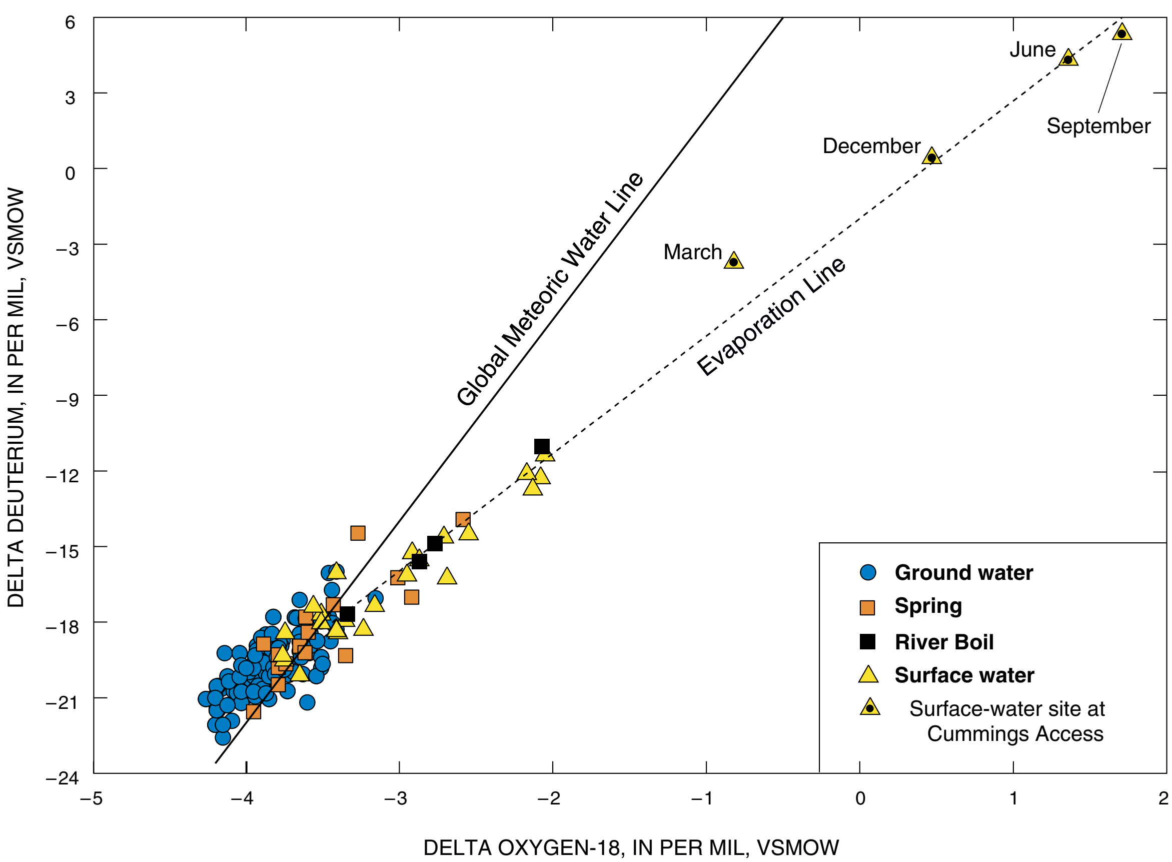


Figure 28. Average deuterium and oxygen-18 values for ground water and springflow sampled during March, June, September, and December 2000, and for surface water sampled monthly from March through December 2000, except during May 2000 (see figure 7 for location of Cummings Access; VSMOW, Vienna standard mean ocean water [Coplen, 1994]).

where all terms have been defined previously. In addition, the isotopic concentrations for ground-water samples indicate that the meteoric water that infiltrated the unsaturated zone and recharged the Upper Floridan aquifer did not undergo additional isotopic fractionation.

The isotopic composition of surface-water samples collected from Lake Seminole and the Apalachicola River is consistent with the global-average isotopic composition of surface water, plotting on a line that indicates enrichment of deuterium and oxygen-18 owing to evaporation (fig. 28). Enrichment of deuterium and oxygen-18 in surface water by evaporation causes isotopic results to plot on a hypothetical "evaporation line" that plots below the GMWL and has a slope of 5 (Faure, 1977). Surface-water samples plot below the GMWL, and slightly below the evaporation line, on a line having a slope of about 4.7, indicating isotope enrichment as a result of evaporation. Surface-water samples from Cummings Access, Ga. (fig. 7), are more enriched than samples from other surface-water sites (fig. 28), most likely because low flow from Fishpond Drain and the confining shape of the impoundment arm (fig. 7) inhibit circulation with water from other parts of the lake.

Analyses of monthly surface-water samples indicate distinct isotopic compositions for the Chattahoochee River and Flint River impoundment arms and the Apalachicola River (fig. 29; table A14). Isotopic compositions of water in the Chattahoochee River impoundment arm and Apalachicola River exhibit similar seasonal variation, characterized by increased fractionation from spring through late summer, most likely the result of higher evaporation during that time of year compared with late fall and winter. Isotopic enrichment of water from the Flint River impoundment arm is not as pronounced as in the Chattahoochee River impoundment arm or in the Apalachicola River, probably due to increased ground-water inflow along the Flint River impoundment arm compared with the Chattahoochee River impoundment arm.

Lack of seasonal variation in isotopic composition in ground-water samples (table A13) lends itself to several hydrologic interpretations concerning water exchange between Lake Seminole and the Upper Floridan aquifer. A year-round steady rate of lake leakage into the aquifer would establish isotopic equilibrium in the mixed fraction of water sampled from wells; this explanation is implausible, however, because the isotopic composition of ground-water samples plots on the GMWL, indicating no isotopic enrichment from mixing of ground water with surface water. Surface-water samples plot on the evaporation line (fig. 28) because, as described previously, fractionation of hydrogen and oxygen isotopes by physical processes acting on the surface water causes enrichment of the heavy isotopes oxygen-18 and deuterium. Alternatively, ground water that flows toward the lake after having achieved isotopic equilibrium with infiltrated precipitation would account for the seasonal stability in isotopic composition of ground-water samples near the lake. This latter explanation also implies no lake leakage occurs near the wells; physical and other hydrochemical evidence, however, indicates that lake leakage and ground-water inflow to the lake are active processes occurring beneath and around Lake Seminole. Therefore, a no-lake-leakage scenario is highly implausible.

Isotope Mixing-Model Results

Results of isotopic analysis were used to identify the mixing proportion of surface water and ground water in the River Boil, a springlike feature emanating from the channel bottom of the Apalachicola River just downstream of Jim Woodruff Lock and Dam (fig. 14). Distinct isotopic compositions of ground water from a nearby well (06D002), representing meteoric water, and isotopically enriched surface water from the Dam Pool in Lake Seminole (fig. 14), represent two end-member components of a simple mixing model used to analyze ground- and lake-water fractions present in discharge from the River Boil.

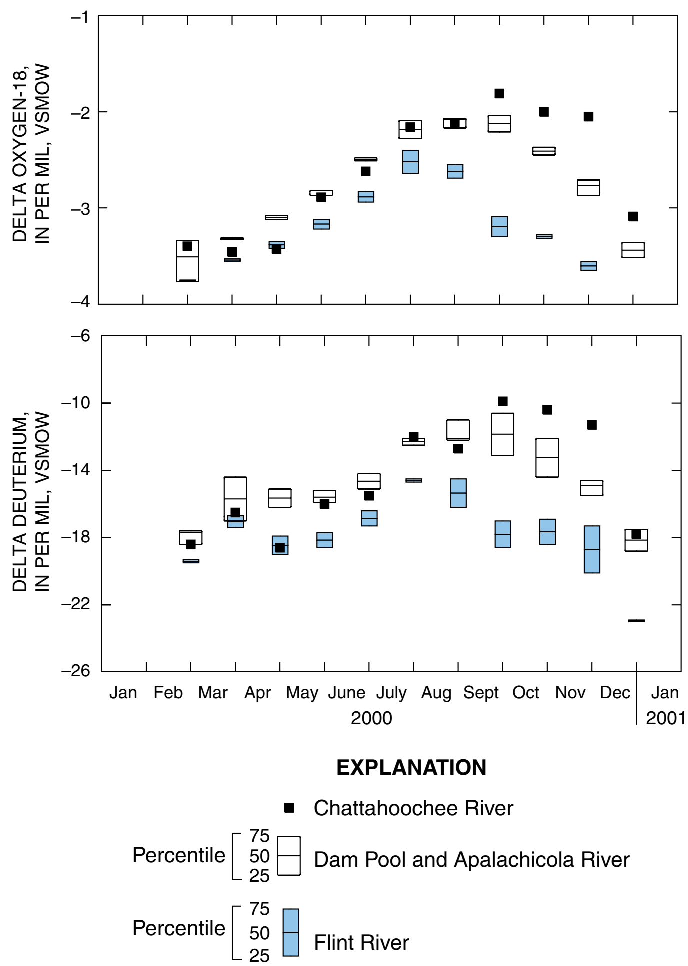


Figure 29. Box plot of deuterium and oxygen-18 values for surface water sampled during 2000 and 2001 (VSMOW, Vienna standard mean ocean water [Coplen, 1994]).

Hydrogeologic conditions along the lake bottom and in the Upper Floridan aquifer favored the use of the Dam Pool sample site (station 02357490) and well 06D002 (fig. 14), respectively, as end-member components to the mixing model. Dye-tracing experiments performed during 2001 by the Corps identified lake water leaking into sinkhole structures in the immediate area behind the dam; this water subsequently discharges to the River Boil. Another dye-tracing experiment also identified a source of surface water and ground water for the River Boil on the right downstream bank of the Apalachicola River, where water from Polk Lake Spring enters a sinkhole. The positive hydraulic potential in the Upper Floridan aquifer allows the mixture of ground water and surface water to flow toward the River Boil. The relatively short travel time for water to reach the River Boil from sinkhole structures near the dam (from about 5 to 7 hours), and from the sinkhole on the right downstream bank of the Apalachicola River (about 1½ hours), reduces the likelihood of changes in isotopic composition of the lake water along its flowpath. Thus, oxygen-18 and deuterium can be regarded as conservative tracers in the mixing model.

The fraction of ground water, f_{gw}, in a sample of the mixture of ground water and lake water discharging from the River Boil is calculated from the isotopic compositions of the end-member components by the following binary mixing equation (Crandall and others, 1999),

$$f_{gw} = (C_{sw} - C_m) / C_{gw} - C_{sw}), \qquad (5)$$

where C_{sw}, C_m, and C_{gw} are the isotopic concentrations in surface water (from the Dam Pool), the mixture (River Boil), and in ground water (well 06D002), respectively.

The Isotope Mixing Line between ground water in well 06D002 and surface water from the Dam Pool of Lake Seminole gives an indication of the relative proportion of lake water to ground water that is present in discharge from the River Boil (fig. 30). This relative proportion is given by the location along the mixing line where the isotopic composition of water from the River Boil plots. For December 2000, water from the River Boil plots nearly at the location along the mixing line where the isotopic composition for the Dam Pool plots (fig. 30), indicating that the River Boil contains mostly lake

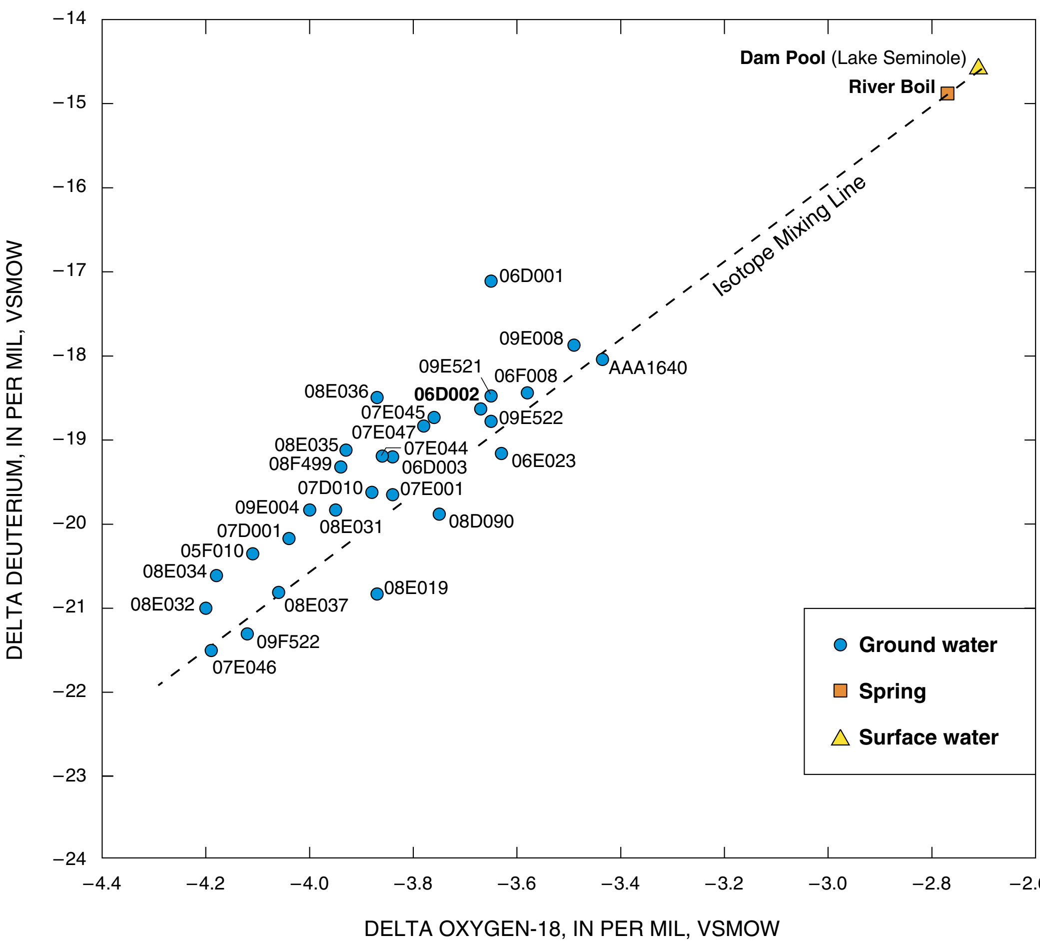


Figure 30. Isotope mixing line for the River Boil (07D011) (bold) and end-member components of lake water from the Dam Pool (bold) (station 02357490) and of ground water from well 06D002 (bold) near Jim Woodruff Lock and Dam, December 2000 (see figure 7 for locations; VSMOW, Vienna standard mean ocean water [Coplen, 1994]).

water that has leaked from behind the dam and has been transported through the Upper Floridan aquifer. Using well 06D002 as the most likely ground-water end-member component of the wells sampled, the isotope mass balance indicates that discharge from the River Boil contains about 92 percent lake water, or about a 13-to-1 ratio of lake water to ground water.

The sensitivity of the method for predicting the fractional composition of the mixed-water component discharging from the River Boil depends on the precision of the isotope analyses and the difference in composition between the two end-member components; sensitivity is expressed by the equation (Payne, 1983),

$$S = \frac{\pm X}{Y}\,, \qquad (6)$$

where $\pm X$ is the 95-percentile uncertainty in the isotopic analysis, and Y is the isotopic difference between the two end members, both expressed in per mil. The 95-percentile uncertainties associated with the oxygen-18 and deuterium isotopic analyses are 0.2 and 2.0 per mil, respectively (Haiping Qi, U.S. Geological Survey Reston Stable Isotope Laboratory, written commun., July 2000). The distinct differences in isotopic composition of end-member components, about 1 per mil for oxygen-18 and about 4.5 per mil for deuterium (fig. 30), allowed the mixing proportion of water discharging from the River Boil to be determined with good precision.

Water-quality data also support the high proportion of lake water in the River Boil, in addition to results of the mixing-ratio analysis for oxygen and hydrogen isotopes (tables A7–A9). Major-ion concentrations in water samples taken seasonally at the River Boil (07D011) compare favorably with concentrations of major ions in corresponding seasonal samples taken at the end-member site of the Dam Pool of Lake Seminole (station 02357490), but are dissimilar to major-ion concentrations of water samples collected from nearby well 06D002 (fig. 14). The seasonal water chemistry of the River Boil also compares favorably with the water chemistry of samples taken from the Apalachicola River downstream of the River Boil (station 02357998).

Seasonal variation in isotopic composition of the end-member components and the River Boil (tables A13–A15) will affect the determination of the fractional composition of the mixed-water component discharging from the River Boil. Likewise for springflow, inadvertent mixing of unknown proportions of river water with discharge from the River Boil during sampling will affect the mixing-ratio determination. During the August 2001 dye-tracing experiment, river water mixing with River Boil discharge at the time of sampling was alleviated by the sampling method. The Corps installed a tube in the opening of the River Boil that was attached to a sampler on shore, thus obtaining a sample of "pure" River Boil discharge for isotopic analysis (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., February 2005). Seasonal variation in the isotopic composition of end-member samples, however, precluded a more exact determination of the ratio of lake water to ground water to be made from the August 2001 samples than the mixing ratio determined from the December 2000 samples.

End-member selection will affect the determination of the fractional composition of the mixed-water component discharging from the River Boil. Use of the isotopic composition of ground water from most other wells besides 06D002 would result in a lower proportion of ground water, and thus a higher proportion of lake water, discharging from the River Boil than the proportion obtained by using well 06D002. This is evidenced by the position of wells along the isotope mixing line; wells that plot downslope from well 06D002 indicate a decreased ground-water component in the River Boil compared with wells that plot upslope of well 06D002.

Assessment of Limestone Dissolution and Potential for Lake Leakage into Karst Features Underlying Lake Seminole

The assessment of karst features underlying Lake Seminole focused on evaluating hydrochemical properties associated with calcite dissolution, the main hydrochemical mechanism promoting hydraulic connection of the Upper Floridan aquifer with Lake Seminole, and on identifying karst-solution features in the lake bottom using remote-sensing information. The remote-sensing techniques used in this assessment were digital-orthorectified aerial photographs of preimpoundment conditions, a map showing navigational and bathymetric features (Atlantic Mapping, Inc., ©1998, used with permission), and results of hydrographic surveys performed by the Corps. Both elements of the assessment contribute toward evaluating the potential for lake leakage into the aquifer and for enhanced sinkhole formation and collapse, which would increase the likelihood of sudden partial or complete draining of the lake.

Calcite-Saturation Indices

Calcite-saturation indices of ground water, surface water, and springflow were used to evaluate the saturated or undersaturated condition of water in contact with limestone in the Upper Floridan aquifer underlying Lake Seminole. Water that is undersaturated with regard to calcite and that flows through limestone beneath the lake would have the potential to dissolve calcite and enlarge solution openings, thus increasing the potential for lake leakage, sinkhole formation and collapse, and sudden lake drainage. Calcite-saturation indices for ground water, surface water, and springflow were calculated using the USGS geochemical modeling program NETPATH (Plummer and others, 1994). NETPATH finds net geochemical mass-balance reactions for evolutionary water compositions that are consistent with the observed chemical and stable-isotope data. The reactions are assumed to take place in a closed environment; that is, no gas exchange is expected between the Upper Floridan aquifer and the atmosphere, and all geochemical reactions occur within the water-rock-organic-matter system (Plummer and others, 1998a). Model calculations assume dissolved-ion species are at equilibrium. Mass-balance calculations determine the dominant processes controlling water chemistry.

Equations for calculating the dissolution of calcite and solubility product ($K_{sp(calcite)}$) of the reaction in a dilute solution are given as,

$$CaCO_{3(calcite)} = Ca^{2+} + CO_3^{2-}, \quad (7)$$

Stumm and Morgan (1981), and

$$K_{sp(calcite)} = (a_{Ca^{2+}} + a_{CO_3^{2-}}) \,/\, (a_{CaCO_3}) = 10^{-8.48}, \quad (8)$$

Drever (1988), where $a_{Ca^{2+}} + a_{CO_3^{2-}}$, and $a_{CO_3^{2-}}$, are activities (or concentrations) of calcium and carbonate ions, and of calcite, respectively (Drever, 1988), and $K_{sp(calcite)}$ is the solubility product at 25°C. The mineral saturation index, *SI*, is given as,

$$SI = \log(IAP/K_{sp}), \quad (9)$$

where *IAP* is the ion activity product. Calculations were made using field measurements of temperature, pH, dissolved oxygen, and alkalinity, in addition to laboratory values of major ions. Given the error range for pH (0.1 unit), alkalinity (10 percent), and the potential for degassing, a calculated SI range of −0.2 to 0.2 is considered saturated with respect to calcite (Sprinkle, 1989).

NETPATH model results indicate seasonal variability of calcite saturation in ground water, surface water, and springflow, with ground water exhibiting saturated to oversaturated conditions year-round, and springflow and surface water fluctuating between saturated and undersaturated conditions (fig. 31). A slight undersaturation of ground water during June 2000, characterized by negative SI values, indicates a potential for karstic dissolution of limestone by ground water during the summer. Calcite-saturation indices for surface water sampled during 2000 indicate that most locations in Lake Seminole and the Apalachicola River were undersaturated year-round, except for December, when all sampling locations exhibited undersaturated conditions. The pronounced undersaturation of calcite in lake water during December 2000 can be attributed to low ground-water inflow to Lake Seminole and tributary streams during the winter, a result of drought conditions that prevailed during that time. Agricultural withdrawal of ground-water from the Upper Floridan aquifer and lack of precipitation had reduced ground-water levels to record lows by fall 2000. Drought conditions continued into winter and further lowered ground-water levels, reducing inflow to Lake Seminole and tributaries.

Springflow exhibited undersaturated conditions with regard to calcite during March and December 2000 (fig. 31), partly the result of the drought and partly because of the inability to accurately locate and collect a representative sample from in-lake springs, as discussed previously. The undersaturated conditions exhibited by springflow during March and December 2000 also can be attributed to low ground-water flow to in-lake springs.

Ground water can become less saturated with regard to calcite in specific areas around Lake Seminole because of local recharge to the Upper Floridan aquifer from precipitation, lake leakage, and open gas exchange of carbon dioxide with the atmosphere. During April 2000, the hydraulic potential existed between the Flint River and Spring Creek impoundment arms for surface water undersaturated with respect to calcite to leak from Lake Seminole into the Upper Floridan aquifer (fig. 8). This area contains ground water having the lowest calculated values for calcite-saturation indices (fig. 32), which possibly indicates a lake-water source or recent meteoric origin, although calcite-SI values still were relatively high, indicating oversaturation. Another ground-water sample taken just west of the Spring Creek impoundment arm along the northern shore of the main body of the lake also exhibited a low calcite-saturation index, perhaps indicating lake leakage into the Upper Floridan aquifer, although ground water in this area is still oversaturated with regard to calcite. The low value for the calcite-saturation index in a ground-water sample collected southeast of Lake Seminole might indicate local recharge to the Upper Floridan aquifer, because it is near one of the highest values of calcite-saturation index calculated for ground water.

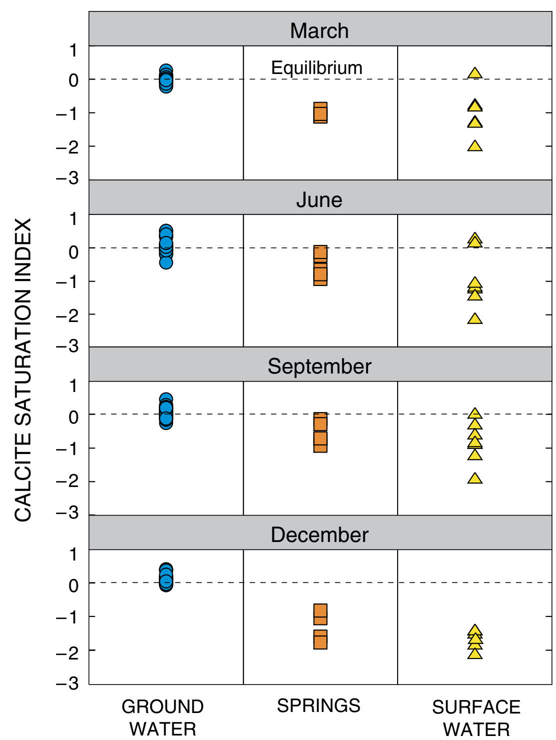


Figure 31. Mineral-saturation index of calcite for ground water, surface water, and springflow in the Lake Seminole area sampled during March, June, September, and December 2000.

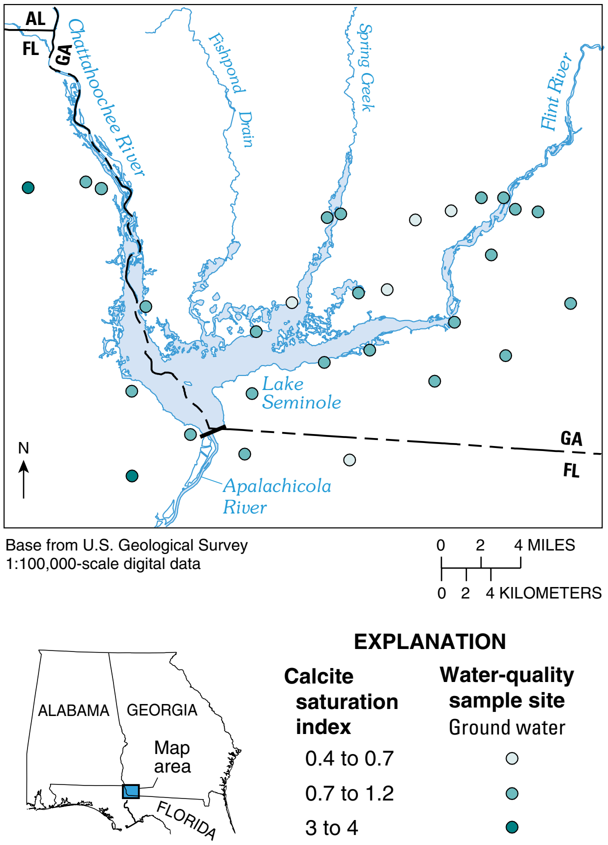


Figure 32. Areal distribution of average mineral-saturation index of calcite for ground-water samples in the Lake Seminole area during 2000.

Water in the Upper Floridan aquifer evolves geochemically under open carbon-dioxide conditions (Katz, 1992), where the influence of atmospheric carbon dioxide decreases the pH of infiltrating precipitation and increases the potential for calcite dissolution. An increased calcite-dissolution potential is identified in undersaturated ground water as negative SI values. Dissolution of limestone results in increased concentrations of calcium and alkalinity in ground water (Stumm and Morgan, 1981), which is evidenced to varying degrees in wells located around the lake (figs. 26*A* and *C*). Limestone dissolution increases the potential for lake leakage by enlarging flow pathways where lake water enters the Upper Floridan aquifer. Lake water mixing with ground water, and local recharge of precipitation to the Upper Floridan aquifer, creates undersaturated conditions in ground water with regard to calcite and increases the potential for limestone dissolution, further increasing the potential for lake leakage. In addition, during cold months, lake water would have greater undersaturation than during warm months because of the increased carbon-dioxide retention of cold water, resulting in lower pH. As described previously, cold, dense lake water could leak into the Upper Floridan aquifer in the vicinity of in-lake springs when ground-water levels are less than or slightly above lake level, thereby increasing the potential for limestone dissolution.

Despite the relatively high potential for limestone dissolution to occur from lake water mixing with ground water in the Upper Floridan aquifer, a relatively low potential exists for limestone dissolution to cause sudden sinkhole collapse followed by catastrophic lake drainage. Ground-water levels and lake stage are nearly the same proximate to the lake. These hydraulic conditions form low vertical and lateral hydraulic gradients in the Upper Floridan aquifer and correspondingly low flow rates between the lake and aquifer. An exception to these hydraulic conditions is near Jim Woodruff Lock and Dam, where the 30-ft difference in water level between the Apalachicola River and Lake Seminole establishes the potential to form relatively high hydraulic gradients and correspondingly high rates of lake leakage into the Upper Floridan aquifer.

Remote-Sensing Techniques and Interactive Map

Documentation of karst features by the Corps during construction of Jim Woodruff Lock and Dam provided key physical evidence about the hydraulic connection of the Upper Floridan aquifer with the lake in the area of the construction sites. In the remaining impoundment area, which is now lake bottom, the absence of first-hand accounts and detailed mapping of karst features required that remote-sensing techniques be used to indirectly obtain hydrogeologic information to identify additional karst features and to infer hydraulic connection of the aquifer with the lake. Aerial photographs of preimpoundment conditions and recent hydrographic surveys conducted by the Corps (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., August, 2001), and a map showing navigation features and general bathymetry (Atlantic Mapping, Inc., ©1998, used with permission), contain hydrologic information that identify karst features in the bottom of Lake Seminole where lake leakage to the Upper Floridan aquifer might occur, or where ground-water inflow to the lake is possible. The interactive map contained in this report uses these remote-sensing techniques to provide a visualization of karst features in the lake bottom and surrounding area.

Instructions to Download, Install, and Use Interactive Map

The interactive map of Lake Seminole requires Internet access to download a compressed file containing map information and the ESRI ArcReader™ program. Instructions to download and install the map are provided below.

- Download the lakeseminole.zip file: *http://ga.water.usgs.gov/lakeseminole/lakeseminole.zip* and save it to a hard-disk drive.
- Extract the files into a directory named “LakeSeminole.”
- Install the ERSI ArcReader™ program from ERSI Web site at *http://www.esri.com/software/arcgis/arcreader/index.html*

In the zip file, the directory “Data” contains data used to create the layers shown in the ArcReader™ map document. The directory “PMF” (published map file) contains the published map file “photomosaic.pmf” along with subdirectories for seven PMFs and four figures, which are hyperlinked to the photomosaic.pmf by the “clickable” symbols on the interactive map. File extension “.pmf” is the naming convention for a map document; however, depending on the setup of a computer, the extension may not be visible. The directory “Metadata” contains text files describing layers used in the project. The “User guide” file includes detailed instructions on ArcReader™ functionality.

To open the interactive map double-click on the ArcReader™ map document “photomosaic.pmf” in the PMF directory. A Table of Contents and a Data, or Layout, window should open (fig. 33); it contains two data frames: an “Index Map,” and a “Photomosaic.” The Table of Contents window lists all layers in the map and shows features that each layer represents. Layers in the Table of Contents are organized into data frames, which are groups of layers displayed together in the Data or Layout window. The Index Map is a map of the Southeastern States with the area of Lake Seminole highlighted. The Photomosaic contains detailed features referenced in the report such as roads, sinkholes, hydrographic surveys, orthorectified-aerial photographs, USGS digital raster graphic (DRG) of the area around Lake Seminole, the lake boundary, and areas of interest around the dam.

The initial map view (Photomosaic and Table of Contents windows) remains open in a separate window from the report text. Interactive features are accessed by clicking on the symbol on the initial map view that corresponds with the description in the text; all references to interactive features in this report are noted with the expression “(interactive map)” added to the text following the description. Interactive features can be viewed as conventional illustrations throughout the report, however, if interactive processes are not desired.

Comparison of Preimpoundment Aerial Photographs with Mapped Navigational Features

Aerial photographs of the preimpoundment lake area and surrounding region were taken by the Corps during 1952 and early 1954; filling of the lake began during May 1954 and concluded during February 1957. Fifty-three photographic negatives were scanned at a resolution of 150 lines per inch and were assembled in an orthorectified-photomosaic showing the preimpoundment lake area (interactive map). Photographic negatives were orthorectified to DRG images of 1:24,000-scale topographic maps (fig. 34*A*; interactive map) by using a geographic information system (Walls and Hamrick, 2003).

Orthorectification allowed karst features that were identified in the aerial photographs to be map-verified by using the corresponding DRG images (fig. 35; interactive map). Map verification of photo-identified karst features was limited to the land area adjacent to Lake Seminole, because the DRG images did not show topographic contours or hydrography in the preimpoundment area. Earliest topographic maps in the region show the presence of the lake, even though the maps predate impoundment. As a result, karst features identified in aerial photographs as being located on the present-day lake bottom were verified on a map showing navigational features, bathymetry, and symbols marking springs, submerged ponds, and depressions in the lake bottom (fig. 34*B*). This verification allowed photographic identification of in-lake springs and other karst features of the floodplain landscape, which are now inundated, and might indicate hydraulic connection of the lake with the Upper Floridan aquifer (fig. 34*B*).

Visual inspection of the aerial photomosaic of preimpoundment conditions in the Lake Seminole area identified more than 250 karst features located in the now-inundated floodplains of the Flint and Chattahoochee Rivers and on the land area between Spring Creek and Fishpond Drain (interactive map). The identified karst features range in area from about 240 square feet (ft^2) to 2.3 million ft^2, and most of them exhibit shapes that are consistent with sinkholes, sinkhole ponds, springs, and spring runs.

A large assemblage of karst features was identified from the aerial photographs as located along the western lakeshore and floodplain of the Chattahoochee River impoundment arm (interactive map). Aerial photographs indicate that sinkholes are scattered throughout this area, which extends about 13 mi upstream from the dam. Circular and elongated sinks, elongated ponds, and spring runs to the Chattahoochee River and the former Polk Lake can be seen in the aerial photographs in this area (interactive map) (fig. 36*A*), indicating hydraulic connection with either a water table within the floodplain alluvium or the Upper Floridan aquifer.

Comparison of the aerial photomosaic with the map showing navigational and bathymetric features (figs. 36*A* and *B*) indicates that a forested, elongated, and meandering depression exists near the western lakeshore and trends roughly parallel to the Chattahoochee River, which is located less than 1 mi east of this feature. This elongated depression is larger in scale but consistent in shape with similar features that were identified as springs and spring runs in the aerial photographs and on the map showing navigational features to the Flint River (fig. 34*A* and *B*). The meandering course of the spring run near the western lakeshore trends southeastward in the floodplain to an area within 0.5 mi upstream of the dam that was mapped by the Corps (U.S. Army Corps of Engineers, 1948, appendix II, chart no. 2.1) as containing springs, which discharged to the former Polk Lake. The location of these springs is consistent with those used as injection points in dye-tracing experiments by the Corps during 2001, implying not only hydraulic connection of the lake bottom with the Upper Floridan aquifer, but a flow reversal in the springs, caused by impoundment.

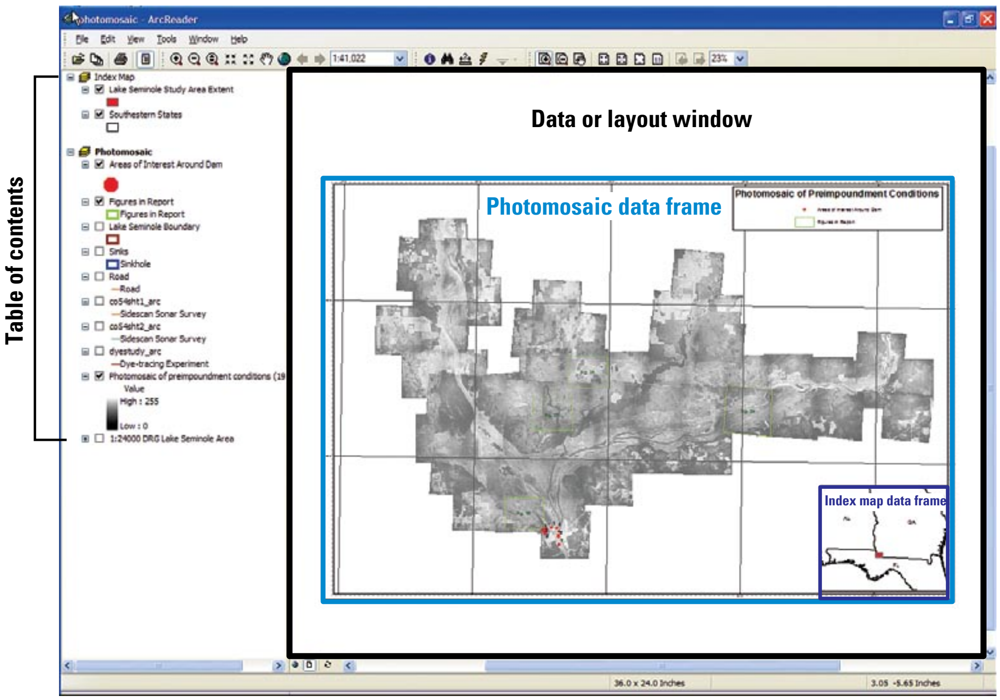
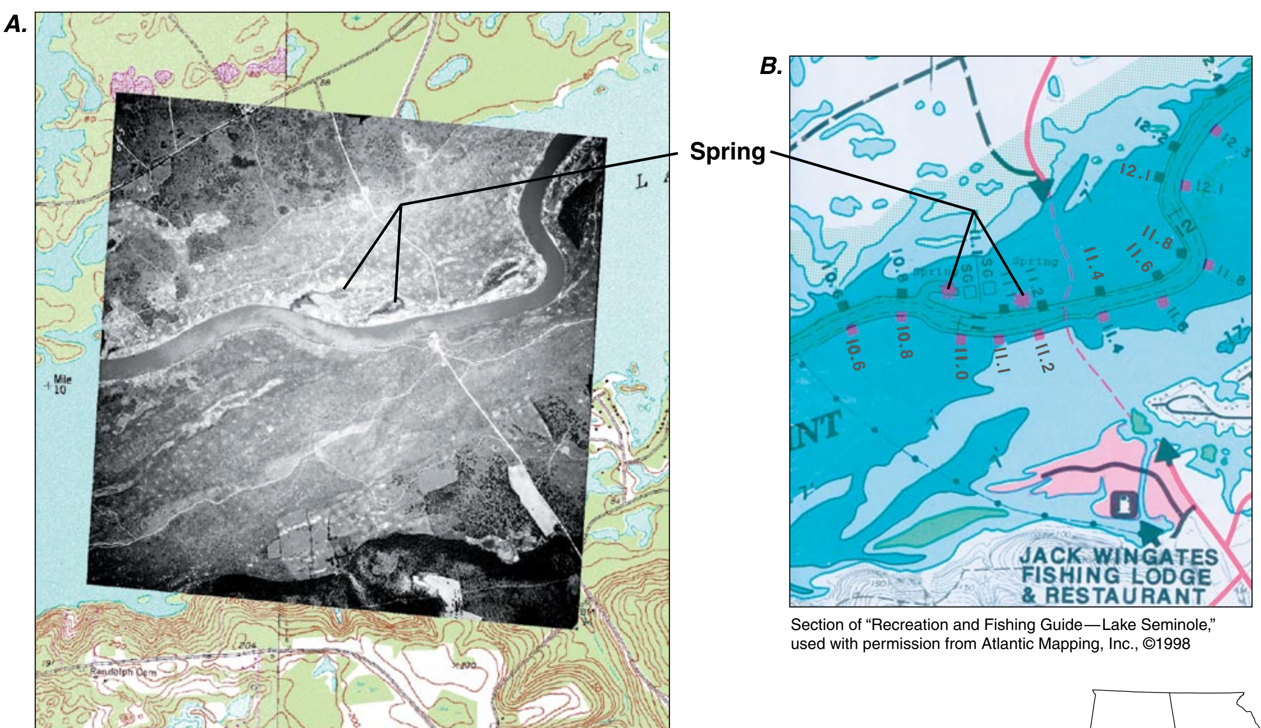


Figure 33. Initial view of interactive map document.



Base from U.S. Geological Survey digital raster graphics 1:24,000 scale
Faceville, 1974; Reynoldsville, 1955
1954 aerial photo from U.S. Army Corps of Engineers archives

Section of "Recreation and Fishing Guide—Lake Seminole," used with permission from Atlantic Mapping, Inc., ©1998

Figure 34. (*A*) Preimpoundment aerial photograph of part of Lake Seminole area, orthorectified to digital raster graphic image of 1:24,000-scale topographic map, showing springs and spring runs leading to reach of Flint River downstream of Bainbridge, Georgia; and (*B*) map of bathymetric features of approximate area shown in the preimpoundment aerial photograph, identifying two springs in the present-day lake bottom (modified from Torak, 2003) (see interactive map).

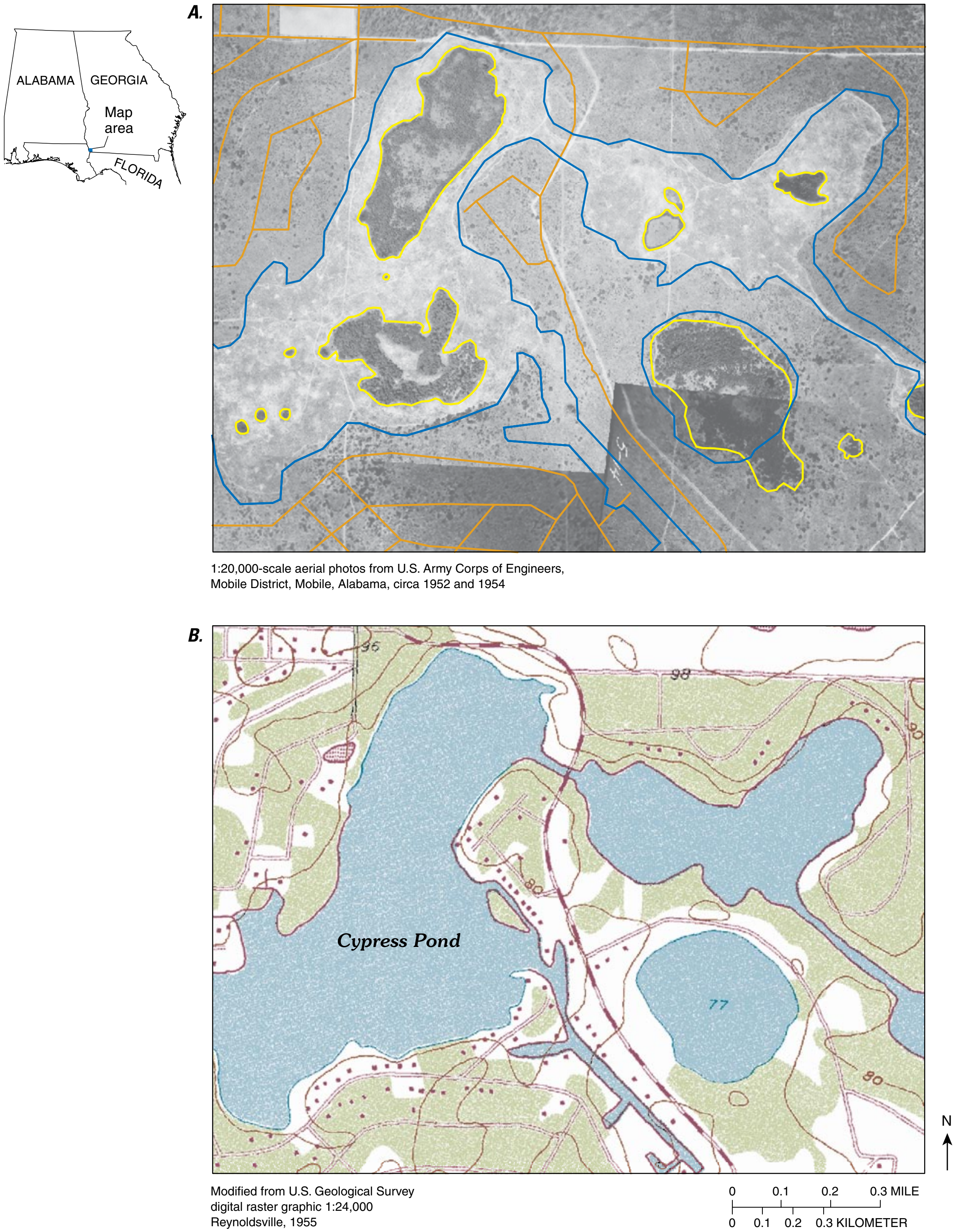
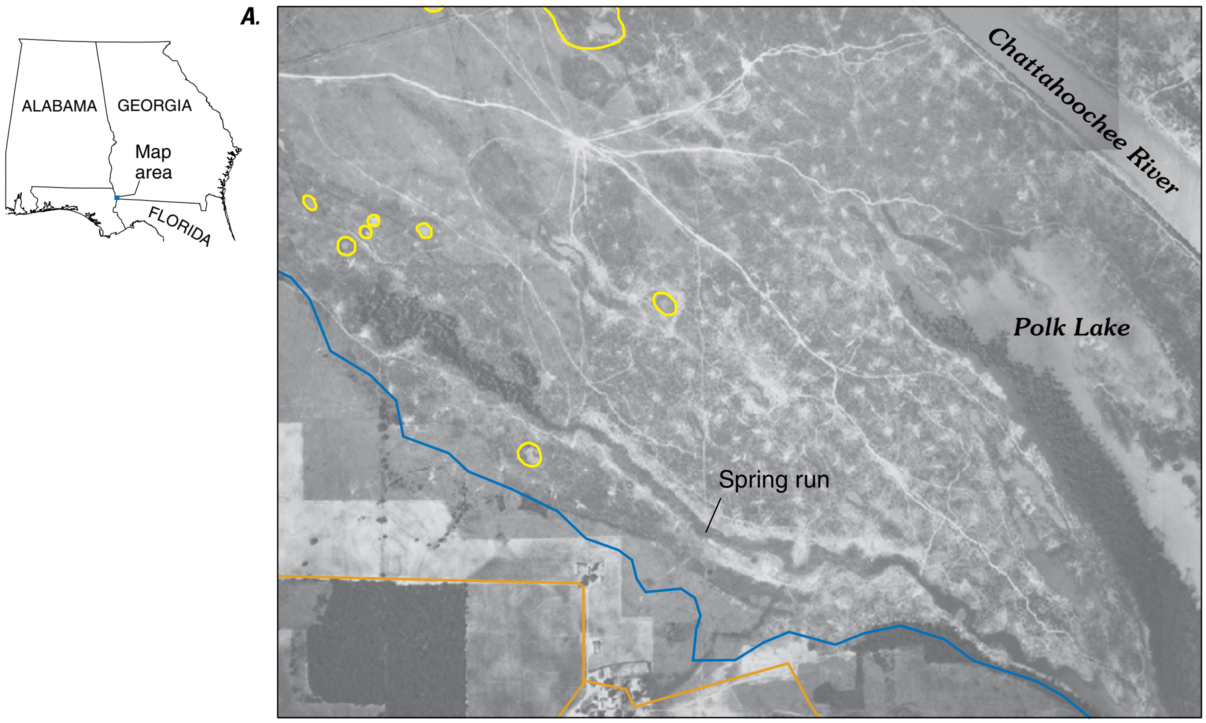


Figure 35. (*A*) Preimpoundment aerial photograph of Lake Seminole area, Cypress Pond, karst features (outlined in yellow), current lake boundary (outlined in blue), and road (orange) (modified from Walls and Hamrick, 2003), Reynoldsville, Georgia; and (*B*) digital raster graphic image of part of 1:24,000-scale topographic map showing approximate area of the preimpoundment aerial photograph (see interactive map).

A.



1:20,000-scale aerial photos from U.S. Army Corps of Engineers,
Mobile District, Mobile, Alabama, circa 1952 and 1954

B.

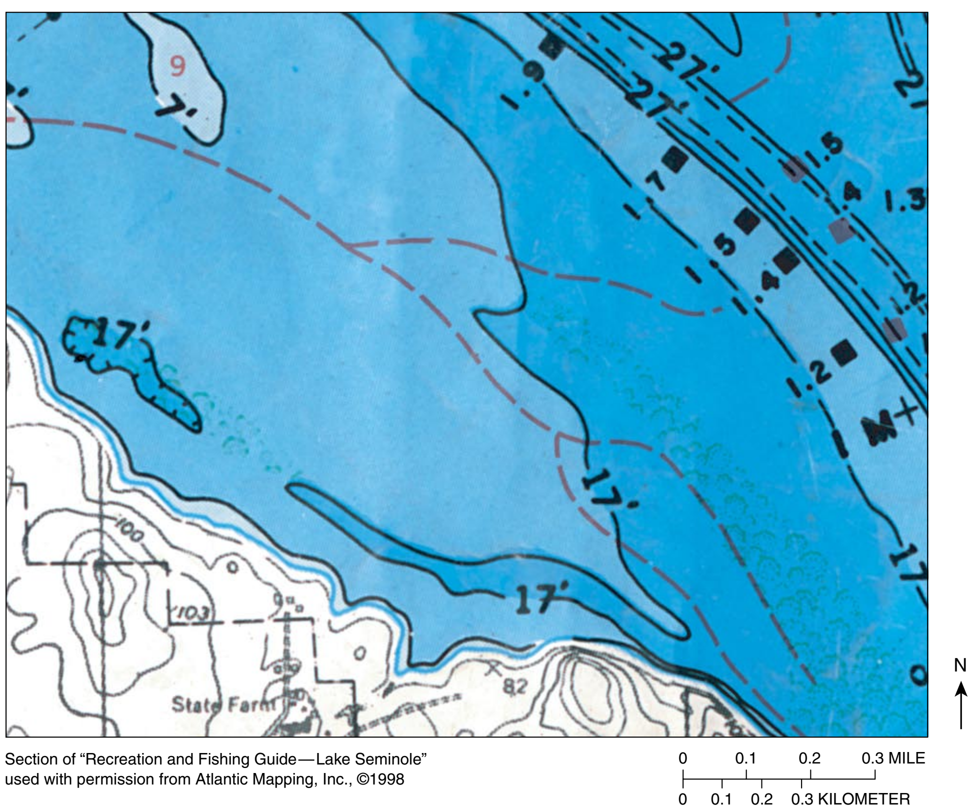


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Figure 36. (*A*) Preimpoundment aerial photograph of part of Lake Seminole area, ponds, and spring runs leading to the Chattahoochee River and former Polk Lake (upstream of the present-day location of Jim Woodruff Lock and Dam), karst features (outlined in yellow), current lake boundary (outlined in blue), and roads (orange) (modified from Walls and Hamrick, 2003); and (*B*) map of bathymetric features showing approximate area of the preimpoundment aerial photograph (see interactive map).

Other springs or spring runs were not as easily identified from the aerial photomosaic of preimpoundment conditions as those located along the western lakeshore. These obscure karst features were first located on the map showing navigational features and in-lake springs, and then verified by using the aerial photographs (figs. 37*A* and *B*). The aerial photomosaic indicated that these springs were located on the preimpoundment land area between the Chattahoochee River and Fishpond Drain. The westernmost of these two springs has a circular shape with several roads leading to it; a spring run, however, is not visible in the aerial photograph. The easternmost of these two springs is located along the tree-lined course of Fishpond Drain and is nearly imperceptible on the aerial photograph. The map of navigational and bathymetric features, however, showed two in-lake springs that were located between the Chattahoochee River and Fishpond Drain, near the lower reach of Fishpond Drain where it joins the main body of the lake.

Comparison of Preimpoundment Aerial Photographs with Hydrographic Surveys

Hydrographic surveys of the lake bottom—near the lock and dam, along the west wall of the lake, and in the tail race downstream of the gated spillway of the dam—were used to identify karst features that could act as leakage mechanisms for lake water to enter the Upper Floridan aquifer. A Corps contractor performed surveys on September 13 and 14, 2000, and on May 29, 2001, which consisted of collecting bathymetric data using a multibeam echosounder (sonar) and sidescan sonar (James H. Sanders, Jr., U.S. Army Corps of Engineers, Mobile District, written commun., August, 2001). The field data were processed into map form, which were then registered to topographic maps and orthorectified preimpoundment aerial photographs (interactive map; fig. 38).

Comparison of hydrographic surveys with orthorectified-aerial photographs indicates that numerous circular and elongated depressions, consistent in shape with sinkholes on land, are located in the lake bottom throughout the area surveyed (fig. 38*A*; identified bathymetric feature 1 [IBF1], interactive map). Along the western lakeshore, these depressions trend southeastward from the area where springs and a spring run most likely conveyed ground water from the Upper Floridan aquifer to the former Polk Lake (fig. 36). Some of these circular and elongated depressions are located near a vortex in the lake bottom and near reverse springs and sinkholes that were used by the Corps in dye-tracing experiments (fig. 38*A* and *C*; IBF2, interactive map). The bathymetry shows a northeast-trending channel located about 0.5 mi upstream of the dam (fig. 38*A;* IBF3, interactive map) that apparently drained the area located along the western lakeshore to the Chattahoochee River. This area also drained to a spring run to the southeast.

Directly upstream of the powerhouse and gated-spillway section of the dam, and adjacent to the upper guide wall of the lock, the bathymetric map indicates the presence of circular depressions and trenches in the lake bottom (fig. 38*A*; IBF4, interactive map). These features depict extensive sinkhole formation in limestone of the Upper Floridan aquifer; subsequent construction excavation was required to remove alluvium, residuum, and weathered and solutioned limestone from karst features in order to lay the foundation of the dam on solid rock. Photographs taken during construction (figs. 18–23), and written accounts by Corps geologists, indicate that sinkholes “occur in some profusion upstream from the dam site, and some are probably connected with or related to the cavities encountered in the foundation rock” (U.S. Army Corps of Engineers, 1948, p. 2-14). The old channels to the Chattahoochee and Flint Rivers, upstream of the dam, are shown on the map of navigational and bathymetric features (fig. 38*D*); however, details of trenches and sinkholes, which are provided by the hydro-graphic survey in this area (fig. 38*A* and *B*; IBF5, interactive map), are not shown.

The bathymetric map indicates that circular and elongated depressions consistent in shape with sinkholes and other karst features are located in the tail race to the gated spillway of the dam and downstream of the lock (fig. 38*A* and *B*, IBF6, interactive map). This area was considered by the Corps during preconstruction exploration as a potential location for the axis of the dam, but was determined to be less favorable than the present location because of the occurrence of “cavernous and deeply weathered bedrock” (U.S. Army Corps of Engineers, 1948, p. 2-3). Although the lock was “founded on one of the better zones of the Tampa Limestone, … [local] dental treatment, including washing and mining of filled cavities and badly leached zones” was required (U.S. Army Corps of Engineers, 1948, p. 2-3). Downstream of the lock, the bathymetric map shows an irregular channel bottom to the Apalachicola River, characteristic of karst topography (fig. 38*A* and *B*; IBF7, interactive map). During preimpoundment conditions, this area was located on the eastern edge of the right downstream floodplain, about 20 ft above and just west of the natural course of the Apalachicola River. Foundation exploration maps indicate that excavation of as much as 50 ft of “questionable foundation material” was required to meet design specifications in this area (U.S. Army Corps of Engineers, 1948, p. 2-6; appendix II, chart no. 1.1). The resulting bathymetry probably represents the top of the Tampa Limestone, thus the Upper Floridan aquifer, with cavities, sinkholes, and caverns remediated by grouting to eliminate leakage. The River Boil (fig. 14) is located in this area in an elongated trench in the limestone.

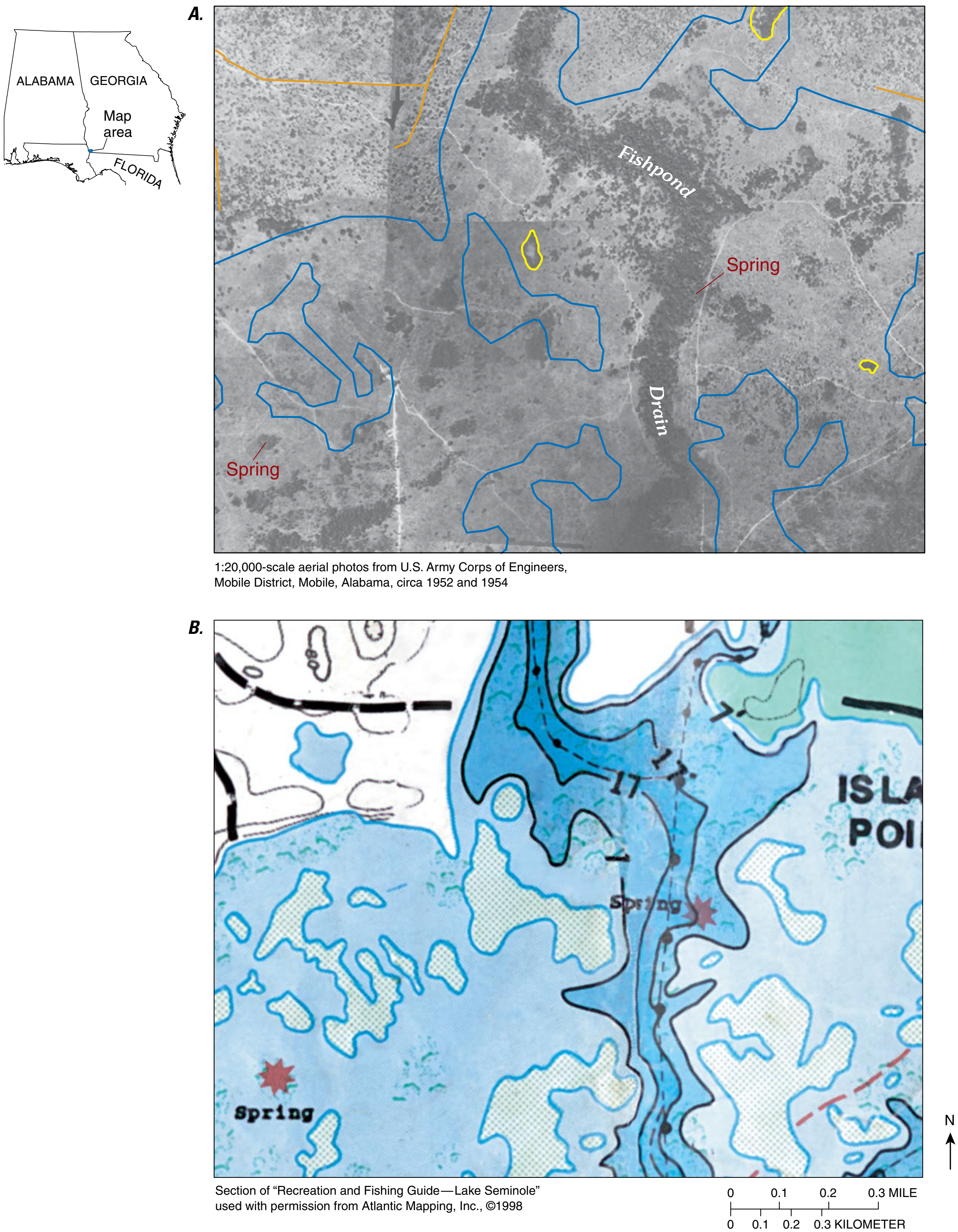

Figure 37. (*A*) Preimpoundment aerial photograph of part of Lake Seminole area along Fishpond Drain, two springs located on the lake bottom, karst features (outlined in yellow), current lake boundary (outlined in blue), and roads (orange) (modified from Walls and Hamrick, 2003); and (*B*) map of bathymetric features of approximate area of the preimpoundment aerial photograph (see interactive map).

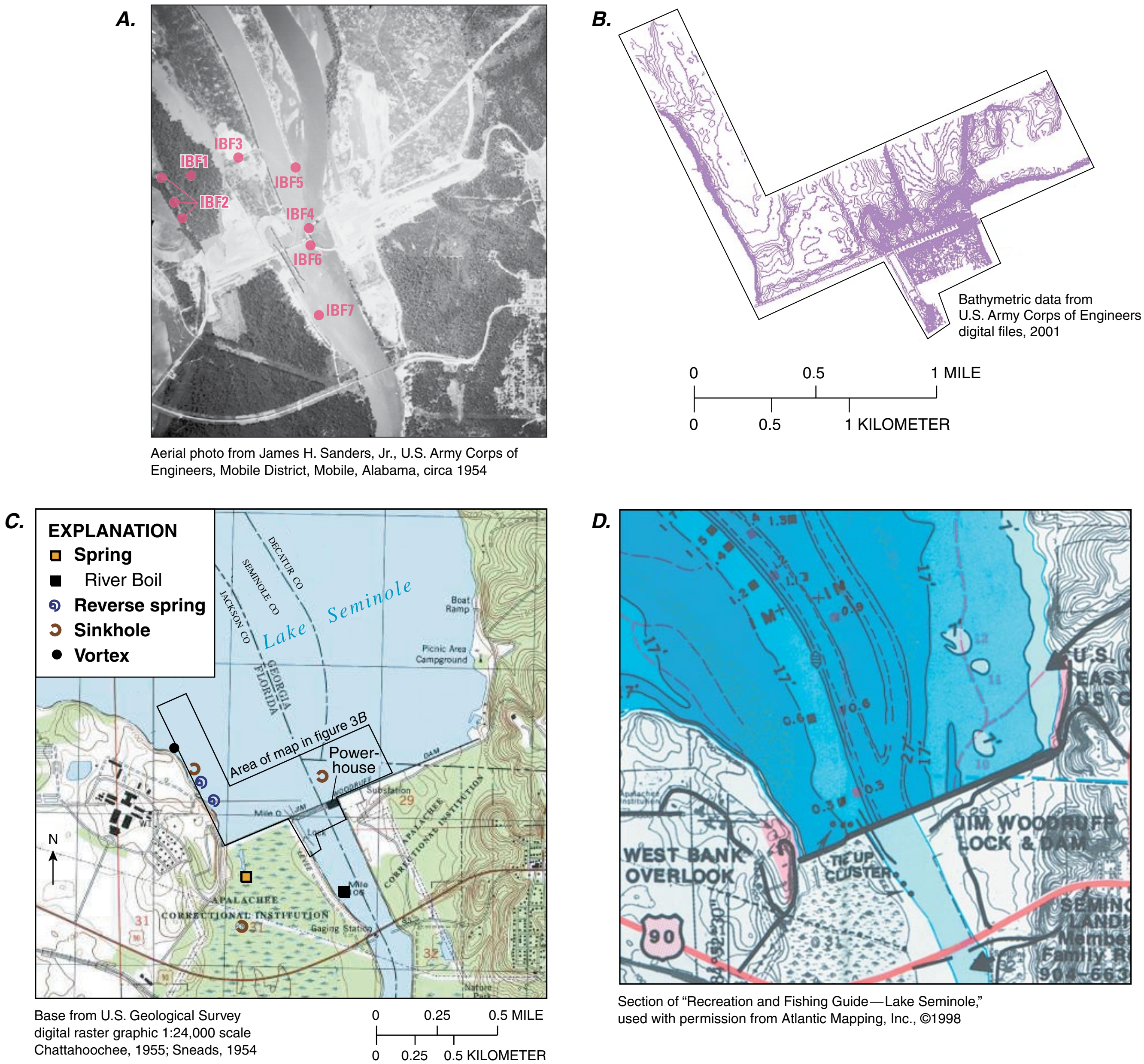

Figure 38. (*A*) Aerial photograph of construction site for Jim Woodruff Lock and Dam, 1954 (IBF, identified bathymetric feature); (*B*) bathymetric map of impounded area directly behind dam and along western shore of Lake Seminole; (*C*) digital raster graphic of Lake Seminole and vicinity showing area of bathymetric map and locations of vortex, sinkholes, and reverse springs adjacent to dam; and (*D*) map showing navigation and bathymetric features of Lake Seminole near Jim Woodruff Lock and Dam (from Torak, 2003) (see interactive map).

Physical and Hydrochemical Factors Affecting Leakage Potential and Sinkhole Collapse

In addition to limestone dissolution by lake-water leakage into the Upper Floridan aquifer, physical hydrologic processes can work in conjunction with limestone dissolution to increase the potential for lake-water leakage into karst features underlying Lake Seminole, and over time can increase the potential for sinkhole formation, expansion, and collapse. Lake water that leaks into the Upper Floridan aquifer along the western lakeshore and discharges into Polk Lake Spring and the River Boil has the potential to enlarge flow pathways in the aquifer by eroding solution features, fractures, and joints, as relatively fast-moving "lake water," which is undersaturated with regard to calcite, flows continuously through the Upper Floridan aquifer and contacts the limestone.

Results of dye-tracing experiments indicate that lake water leaking into the aquifer can travel at velocities of about 500 ft per hour, assuming that the lake leakage travels along the most direct and unimpeded (straight-line) pathways from sinkholes along the western shore to the Polk Lake Spring and the River Boil. Although exact flow pathways of lake leakage around the dam are unknown, preconstruction photographs and geologists' accounts confirm that caverns, fractures, and joints in the limestone create tortuous flow pathways in the limestone, and that sediment often is transported along with ground water. Conduit dimensions in the limestone can narrow (or expand) along flow pathways, changing average flow velocities and pathway lengths in the aquifer from an assumed straight line. Rough and irregularly shaped boundaries within solution features increase the tortuosity of flow pathways, further increasing ground-water velocities and erosion processes. Lake water that is undersaturated with regard to calcite and flowing at relatively high velocities in complex flow pathways near the dam can create a high potential for increased lake leakage into the Upper Floridan aquifer and for sinkhole formation, expansion, and collapse.

The combination of seasonal changes in lake-water temperature, ground-water level, and potential for calcite dissolution increases the potential for lake leakage and sinkhole formation, expansion, and collapse in some areas of Lake Seminole containing in-lake springs. As described previously, lake-temperature data indicate that some in-lake springs either stop flowing or reverse flow and become areas of lake leakage from late fall through early spring when ground-water levels near the lake are equal to or below lake stage, and lake water cools and becomes denser than ground water. For these conditions, density-driven flow and a reversed hydraulic gradient between Lake Seminole and the Upper Floridan aquifer can cause lake leakage into in-lake springs, thereby increasing the potential for limestone dissolution and sinkhole formation and collapse near the lake. The cold lake water contains more carbon dioxide than warm lake water, further increasing the potential for limestone dissolution and sinkhole formation by lake water that is in contact with the aquifer during this time of year.

Although there is a high thermodynamic, kinetic, and physical potential for calcite removal in the aquifer (dissolution and erosion), which may result in sinkhole formation, expansion, or collapse, the rate of calcite removal is unknown; thus, the time of impending or future sinkhole activity cannot be known. It should be noted, however, that no new sinkhole activity has been reported in the Lake Seminole area since the lake was filled to normal pool altitude in 1957. This probably is because limestone dissolution is a relatively slow process, and the lake is a relatively new hydrologic feature.

Monitoring Changes in Physical and Hydrochemical Components of the Flow System to Evaluate Lake Leakage

Physical and hydrochemical evidence of leakage from Lake Seminole into the Upper Floridan aquifer and of ground-water inflow from the aquifer to the lake, discussed herein, allows an effective monitoring plan to be developed that would improve understanding of the interaction of stream-lake-aquifer components and would document changes to the current level of ground-water and surface-water interaction. Key elements of this monitoring network can be used to assess changes in the potential for sinkhole collapse in the lake bottom and provide a warning for sudden, complete, or partial lake drainage as a result of increased limestone dissolution. It should be noted that recent sinkhole activity has not been reported in the bottom of Lake Seminole or in the immediate area, possibly because water levels in the Upper Floridan aquifer near and beneath the lake are nearly equal to lake stage. This hydrologic condition virtually eliminates the hydraulic potential for water exchange between the lake and aquifer. There are exceptions, however, to this generalized hydrologic condition, as indicated below.

Existing ground-water- and surface-water-level data indicate that the highest potential for lake leakage occurs in the area surrounding Jim Woodruff Lock and Dam owing to the 30-ft water-level difference between the lake and the Apalachicola River. In areas away from the dam, a relatively low potential for lake leakage exists because ground-water levels and lake stage are nearly the same; a high potential exists for ground water to discharge into Lake Seminole in areas adjacent to the upper reaches of the impoundment arms where ground-water levels are higher than lake stage (figs. 8 and 10; tables 4 and 5). Therefore, ground-water level monitoring that is focused on the immediate area around Jim Woodruff Lock and Dam would assist in identifying changes in hydraulic gradients in the Upper Floridan aquifer that can indicate increased lake leakage to the aquifer. Similar monitoring adjacent to the upper reaches of the impoundment arms would help identify changes in ground-water discharge to the lake from current conditions.

Hydrographic surveys, dye tracing, and physical and hydrochemical evidence have identified locations in the lake and surrounding area that are susceptible to either lake leakage or ground-water discharge and that leak water to the River Boil in the Apalachicola River. Locations of sinkholes in the lake bottom along the western shoreline of Lake Seminole, along the western bank of the river adjacent to the River Boil, Blue Spring, and in the lake adjacent to Jim Woodruff Lock and Dam have been identified as areas where lake water can leak into the Upper Floridan aquifer. An effective plan to identify changes to current leakage conditions would consist of continuous ground-water-level monitoring along the western shore of the lake and western bank of the Apalachicola River downstream to Blue Spring, seasonal water-chemistry sampling and analysis from nearby wells and surface-water sites, and discharge measurements at the River Boil and at channels leading to the sinkhole along the western bank of the Apalachicola River (fig. 14). Current daily monitoring of lake stage by the Corps (*http://water.sam.usace.army.mil/acfframe.htm*) is adequate to define lake level for leakage evaluation. Further detailed analyses of the hydrographic surveys might identify additional structures in the lake bottom that allow lake water to leak into the Upper Floridan aquifer and discharge to the River Boil. Once identified, these locations of possible lake leakage could be verified with dye tracing.

Calcite-saturation indices for springflow, surface water, and ground water indicate seasonal variability in the potential for karstic dissolution of limestone, although most locations in Lake Seminole and the Apalachicola River are undersaturated year-round (figs. 31 and 32). Undersaturated lake water—combined with the relatively high (13-to-1) ratio of lake water to ground water that was calculated for the River Boil using isotopic analyses, and the high hydraulic gradient between the lake and Apalachicola River—creates a relatively high potential for lake leakage to enlarge flowpaths in the aquifer. Lake leakage can increase with limestone dissolution, thereby increasing the potential for collapse of solution features, such as sinkholes and caverns, which might constitute flowpaths for conveying lake water to the River Boil. A monitoring network incorporating seasonal evaluation of calcite-saturation indices and isotopic concentrations of oxygen-18 and deuterium contained in end-member components and in the mixture of surface water and ground water emanating from Polk Lake Spring, Blue Spring, and the River Boil would provide information about temporal changes in the chemical composition of lake leakage caused by changes in the mixing ratio of lake water to ground water and by limestone dissolution.

Conclusions

Solutioning and chemical weathering of limestone comprising bottom material of Lake Seminole and foundation rock to Jim Woodruff Lock and Dam hydraulically connect the lake with the Upper Floridan aquifer, promoting lake leakage and ground-water inflow through the lake bottom. Near the dam, impoundment of Lake Seminole increased preimpoundment surface-water levels by as much as 30 feet (ft), inundating previously dry land and establishing a positive hydraulic potential for leakage to occur from the lake to the Upper Floridan aquifer. Positive hydraulic gradients of ground water moving toward Lake Seminole along upstream reaches of the impoundment arms promote ground-water inflow to the lake from the Upper Floridan aquifer. Seasonal water-level fluctuations in the Upper Floridan aquifer adjacent to the lake and between the impoundment arms establish complex patterns of ground-water inflow to the lake and lake leakage to the aquifer. Short-term cycles of ground-water withdrawal, such as occur during irrigation pumping, cause rapid, sometimes diurnal reversals that could affect flow into and out of the lake and Upper Floridan aquifer.

Written accounts by U.S. Army Corps of Engineers (Corps) geologists during dam construction during the late 1940s and early 1950s, accompanied by construction-era photographs, were used to identify locations beneath and near present-day dam structures and in the now-inundated floodplains of the principal rivers where limestone is subject to dissolution and possible cavity and sinkhole formation from flowing ground water. Maps produced by the Corps during foundation exploration document the existence of springs, sinkholes, and large karst-solution features in the limestone near the location of the present-day dam and in the lake bottom, thus confirming the hydraulic connection of the lake with the Upper Floridan aquifer. More than 250 karst features having the potential to hydraulically connect the lake and aquifer have been identified from preimpoundment aerial photographs taken during dam construction. Some features identified in the photographs coincide with locations of mapped springs, spring runs, and other depressions that are characteristic of sinkholes and sinkhole ponds in karst terrane. Seasonal water-temperature variations at or near in-lake springs indicate that some springs discharge ground water through the lake bottom nearly year-round; other springs either cease flowing during winter months or preclude detection of rapid mixing because of springflow with lake water.

Along the western lakeshore and directly upstream of the dam, a positive hydraulic potential exists between the lake and Upper Floridan aquifer, which, coupled with karst-solution features present in the lake bottom, provides the hydrologic mechanism for lake leakage to occur. Hydrographic surveys utilizing multibeam and sidescan sonar verified the existence of sinkholes, spring runs, former stream channels, and deep trenches cutting into limestone of the Upper Floridan aquifer that is now on the lake bottom. In this area, the impounded water reversed preimpoundment hydraulic gradients and directions of ground-water flow, allowing lake water to leak into the Upper Floridan aquifer through karst solution features. Lake leakage was manifested as vortex flow, visible from the lake surface, and reverse-flowing springs located at sinkholes in the lake bottom.

Results of dye-tracing studies indicate that lake water leaks into the Upper Floridan aquifer along the western side of the lake from multiple sinkholes located less than 0.5 mi from the dam. This lake leakage travels through the Upper Floridan aquifer around the western abutment of the dam, rather than beneath it, at velocities of about 500 ft per hour, to at least one discharge point on land, located about 800 ft downstream of the dam in the western floodplain of the Apalachicola River. Here, a mixture of lake water and ground water "boils up" in a swampy area at Polk Lake Spring at a rate of about 10 cubic feet per second (ft^3/s) and flows southward, where it converges with northward flowing water (about 30 ft^3/s) that originates from a nearby spring (Blue Spring) and zone of diffuse ground-water discharge. The combined ground-water and lake leakage from Polk Lake Spring disappears into a sinkhole located on the western bank of the Apalachicola River, where it once more becomes subterranean flow in the Upper Floridan aquifer. Water entering the sinkhole discharges through a ledge, fracture, or elongated solution opening in limestone (the River Boil) comprising the channel bottom of the Apalachicola River, about 900 ft downstream of the dam and upstream of the streamgaging station at Chattahoochee, Fla. (station 02358000). Flow of lake water leaking around the western abutment of the dam is small (about 10 ft^3/s), compared with discharge emanating from the River Boil (140–220 ft^3/s); therefore, the River Boil receives lake leakage from sources yet to be determined. Water from the River Boil represents from about 1 to 3 percent of total streamflow measured at the streamgaging station at Chattahoochee, Fla.

Physical, chemical, and isotopic constituents contained in water samples confirm mixing of ground water with lake water in limestone that comprises the Upper Floridan aquifer, lake bottom, and foundation rock to the dam. Distinct chemical and isotopic signatures of ground water and lake water allow identification of lake water mixing with ground water and determination of the proportion (fraction) of each that is present in lake leakage. Binary mixing-model analysis using naturally-occurring isotopes of oxygen and hydrogen (oxygen-18 and deuterium, respectively) indicate a 13-to-1 ratio of lake water to ground water discharging from the Upper Floridan aquifer into the channel bottom of the Apalachicola River at the River Boil, just downstream of Jim Woodruff Lock and Dam. Calcite-saturation indices of water samples indicate undersaturation of lake water, which can promote limestone dissolution of the aquifer-rock matrix when lake water contacts limestone in the Upper Floridan aquifer, such as occurs during lake leakage. The relatively short residence time (5–7 hours) and rapid flow velocity (nearly 500 ft per hour) of lake water leaking into the Upper Floridan aquifer and exiting downstream of the dam implies that a sufficient supply of calcite-undersaturated water is in continuous contact with the limestone, thus maintaining a high potential for limestone dissolution. Seasonal fluctuations in calcite-saturation indices for lake water create a higher potential for limestone dissolution during late fall through early spring than during summer.

Despite the relatively high potential for limestone dissolution to occur from lake-water mixing with ground water in the Upper Floridan aquifer, a relatively low potential exists for limestone dissolution to cause sudden sinkhole collapse followed by catastrophic lake drainage. Ground-water levels and lake stage are nearly the same proximate to the lake. These hydraulic conditions form low vertical and lateral hydraulic gradients in the Upper Floridan aquifer and correspondingly low flow rates between the lake and aquifer. An exception to these hydraulic conditions occurs near Jim Woodruff Lock and Dam, where the 30-ft difference in water level between the Apalachicola River and Lake Seminole establishes the potential to form relatively high hydraulic gradients and correspondingly high rates of lake leakage into the Upper Floridan aquifer.

An effective plan to monitor the physical and hydrochemical components of the stream-lake-aquifer flow system that are assumed to govern lake leakage into the Upper Floridan aquifer would include periodic ground-water level and stream-discharge measurements, water-chemistry sampling with corresponding analyses, and discharge measurements at the River Boil. The monitoring would focus on the immediate area around Jim Woodruff Lock and Dam and include the western shoreline of Lake Seminole, River Boil on the Apalachicola River, and land area along the western bank of the river that contributes flow to the sinkhole on land adjacent to the River Boil. The hydraulic potential for lake leakage is greater in the area surrounding Jim Woodruff Lock and Dam than in surrounding areas of the lake due to the 30-ft water-level difference that exists between the lake and the river. Seasonal or semiannual evaluation of calcite-saturation indices and isotopic concentrations of oxygen-18 and deuterium contained in end-member components and in the mixture of surface water and ground water emanating from Polk Lake Spring and the River Boil would provide information about temporal changes in the chemical composition of lake leakage and ground water.

Ground-water levels near the dam and discharge measurements at the River Boil, at the Apalachicola River, and in spring runs to Polk Lake Spring and the sinkhole on land adjacent to the River Boil could be used to document changes in hydraulic potential and leakage conditions caused by limestone dissolution. A network to monitor ground-water-level, streamflow, and water chemistry would improve understanding of the interaction of these components and provide a measure of warning with regard to increased lake leakage and the potential for catastrophic sinkhole collapse followed by sudden, complete, or partial lake drainage.

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Appendix
Hydrogeologic and Water-Chemistry Data

Table A1. Well-construction data for selected wells in the Lake Seminole, Georgia, study area, 2000.

[do., ditto; group 1, depth to water 9–74 feet and 138–221 feet; group 2, depth to water 90–130 feet; —, no data]

Site name (see fig. 7)	Site identification number	Physiographic location (see fig. 2)	Well depth (feet)	Casing depth (feet)	Average depth of water below land surface during 2000 (feet)	Group
05F010	305313085013601	Marianna Lowlands	113	104	18	1
06D001	304033084560901	Tallahassee Hills	122	86	35	1
06D002	304230084530701	do.	210	117	47	1
06D003	304421084560001	Marianna Lowlands	120	120	102	2
06E023	304758084551301	Dougherty Plain	220	130	74	1
06F008	305330084584001	Marianna Lowlands	105	65	19	1
07D001	304420084500001	Solution Escarpment	—	—	120	2
07D008	304123084444101	Tallahassee Hills	—	—	130	2
07D010	304140084502001	do.	214	82	90	2
07E001	304539084460301	Dougherty Plain	154	—	102	2
07E044	305210084451901	do.	83	82	28	1
07E045	304656084493501	do.	100	95	20	1
07E046	304815084472601	do.	44	42	19	1
07E047	305159084460201	do.	123	120	38	1
08D090	304454084402401	Tifton Upland	340	274	221	1
08E019	304613084434301	Solution Escarpment	147	143	9	1
08E031	304753084385101	Dougherty Plain	240	—	110	2
08E032	305227084373501	do.	119	111	24	1
08E034	304858084424701	do.	—	—	32	1
08E035	304836084442201	do.	15	95	16	1
08E036	305223084394001	do.	09	105	47	1
08E037	305157084412901	do.	97	86	51	1
08F499	305258084380501	do.	120	114	22	1
09E004	305223084351301	do.	75	68	37	1
09E008	304823084333001	Tifton Upland	320	250	138	1
09E521	304603084364701	do.	294	224	185	1
09E522	305228084362101	Dougherty Plain	105	90	33	1
09F522	305258084370501	do.	86	84	13	1
AAA1640	305313084575201	Marianna Lowlands	220	170	31	1

Table A2. Selected surface-water sites in the Lake Seminole, Georgia, study area, 2000.

[—, no data]

Station number	Site name (see fig. 7)	Location	Depth of river channel at sample location (feet)			
			March	June	September	December
02357998	Apalachicola River	Apalachicola River below Jim Woodruff Lock and Dam	16	13	9	8
02357490	Dam Pool	Lake Seminole above Jim Woodruff Lock and Dam (river mile 1)	16	13	11	—
02357395	Cummings Access	Fishpond Drain	13	16	15	—
02356025	Ten Mile Still	Flint River (river mile 12.6)	27	—	26	26
02357160	Knights Rest	Spring Creek	11	—	16	12
02356020	Hales Landing	Flint River (river mile 20.7)	18	18	21	19
02344064	Parramore Landing	Chattahoochee River (river mile 14.2)	12	17	13	—

Table A3. Selected spring sites in the Lake Seminole, Georgia, study area, 2000.

[—, no data]

Site name (see fig. 7)	Spring name	Site identification number	Other identifier	Depth to spring in river channel (feet)			
				March	June	September	December
07D011	River Boil	304213084514201	Apalachicola River	—	10	21	20
07E049	Shakelford Spring	304545084483301	Flint River (river mile 6.8)	—	—	32	30
07E051	Sealy Spring	304624084504901	Spring Creek	40	38	40	41
08E033	Wingate Spring	304645084445901	Flint River (river mile 10.9)	26	—	23	30
09F521	State Dock Spring	305337084363801	Flint River (river mile 26.4)	32	32	34	22

Table A4. Field properties for ground water from selected wells in the Lake Seminole, Georgia, study area, 2000.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; °C, degree Celsius; $CaCO_3$, calcium carbonate; —, no data]

Site name (see fig. 7)	Sampling date	Oxygen, dissolved (mg/L)	pH (standard units)	Specific conductance (µS/cm)	Temperature, water (°C)	Alkalinity (mg/L as $CaCO_3$)
05F010	Mar. 2	7.6	8.1	165	21.6	—
	June 13	9.1	8.1	162	21.1	61
	Sept. 13	8.4	8	168	21.2	62
	Dec. 14	8	8.1	155	21.4	65
06D001	Mar. 7	5	7.9	227	20.9	—
	June 13	5.3	6	220	20.6	110
	Sept. 13	4.8	7.9	233	21	110
	Dec. 12	4.2	7.9	227	20.9	110
06D002	Mar. 2	0.1	7.8	273	21.3	—
	Sept. 13	0.1	7.8	282	21.4	140
	Dec. 13	1	8	284	20.9	140
06D003	Mar. 2	5.6	7.9	230	21.1	—
	June 13	6.2	7.9	221	20.8	110
	Sept. 13	6.1	7.8	236	23.5	110
	Dec. 13	6	8.2	220	21	110
06E023	Feb. 29	1.9	7.6	250	20.5	120
	Mar. 6	0.5	7.4	251	20.5	—
	June 13	2.2	7.5	251	20.8	130
	Sept. 13	—	—	—	—	150
	Dec. 12	—	7.7	251	19.8	110
06F008	Mar. 8	1.7	7.5	254	20.4	—
	June 12	1.7	8.8	253	19.9	130
	Sept. 14	1.9	7.5	261	20.6	130
	Dec. 14	1.3	7.6	245	20.4	130
07D001	Mar. 7	3	7.8	226	20.8	—
	June 14	4	4.9	224	20.4	120
	Sept. 12	3.2	7.8	233	20.7	120
	Dec. 12	2.6	7.9	233	20.6	110
07D008	Mar. 2	0.1	8.1	217	22	—
	June 12	0.3	9	210	21.7	100
	Sept. 12	0.6	8	224	22	99
	Dec. 13	0.5	8.4	204	21.9	99
07D010	Mar. 2	5.7	7.8	249	21.5	—
	June 12	6.4	8.3	238	20.9	130
	Sept. 12	6.2	7.8	250	21.5	130
	Dec. 13	4.3	8.1	234	20.9	130
07E001	Feb. 29	3.2	—	—	20.7	120
	June 14	3.5	5.3	223	20	120
	Sept. 12	3.3	7.9	229	20.1	120
	Dec. 12	2.6	7.7	230	20.3	130
07E044	Mar. 6	0.6	7.3	272	21.4	—
	June 14	0.5	7.3	273	21.1	140
	Sept. 11	0.1	7.6	292	21.4	140
	Dec. 12	—	7.5	290	20.6	130
07E045	Mar. 1	2.9	7.8	209	21	—
	June 13	5.3	7.7	212	20.8	100
	Sept. 11	0.3	7.9	218	21.2	103
	Dec. 12	—	7.9	221	19.8	97
07E046	Mar. 1	2.3	8	144	21.3	—
	June 13	5.5	7.8	159	21.7	73
	Sept. 11	0.3	8	156	21.8	72
	Dec. 12	—	8	164	20.3	80
07E047	Mar. 1	1.7	7.7	249	20.7	—
	June 13	2.5	7.5	252	20.7	110
	Sept. 11	0.2	7.9	262	20.9	110
	Dec. 12	—	7.7	262	19.9	100

Table A4. Field properties for ground water from selected wells in the Lake Seminole, Georgia, study area, 2000.—Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; °C, degree Celsius; $CaCO_3$, calcium carbonate; —, no data]

Site name (see fig. 7)	Sampling date	Oxygen, dissolved (mg/L)	pH (standard units)	Specific conductance (µS/cm)	Temperature, water (°C)	Alkalinity (mg/L as $CaCO_3$)
08D090	Feb. 29	3.2	7.8	212	21.1	95
	June 14	3.6	—	214	20.6	110
	Sept. 11	3.1	7.8	207	20.7	110
	Dec. 11	3.2	7.8	216	20.8	110
08E019	Mar. 6	0.7	7.7	226	20.7	—
	June 12	2.1	8.1	223	20.4	110
	Sept. 11	1.9	7.8	235	20.5	120
	Dec. 11	1.6	7.7	232	20.4	120
08E031	Mar. 3 [1]	2.9	6.8	256	19.5	140
	Sept. 12	4.7	7.8	273	19.7	130
	Dec. 13	—	7.8	272	19.4	150
08E032	Mar. 6	0.4	7.8	260	19.9	—
	June 12	1.4	7.8	259	19.9	130
	Sept. 12	1.1	7.9	270	20.1	130
	Dec. 13	—	7.9	278	18.3	140
08E034	Mar. 6	0.8	7.8	267	22.2	—
	June 13	7	7.9	281	21	120
	Sept. 12	—	—	—	—	110
	Dec. 12	—	7.9	289	20.5	120
08E035	Mar, 1	1.5	7.8	254	21	—
	June 13	5.8	7.8	244	21	150
	Dec. 12	—	7.9	259	20.3	120
08E036	Mar. 3	1.3	7.9	185	20.8	—
	Sept. 13	7.2	7.7	209	20.9	87
	Dec. 12	—	7.9	200	20.1	86
08E037	Mar. 3	1.3	8.1	185	20.9	—
	June 14	8.2	7.9	185	21.3	70
	Sept. 12	0.2	8.2	192	21.3	74
	Dec. 12	—	8.2	192	21.3	81
08F499	Mar. 3	1.3	7.8	251	20.9	—
	June 14	7.4	7.8	252	21	83
	Sept. 12	—	—	—	—	89
	Dec. 13	—	7.9	266	18.9	97
09E004	Mar. 3	0.8	7.8	249	20.4	—
	June 12	3.4	7.8	246	20.5	120
	Sept. 13	4.5	7.7	312	20.5	120
	Dec. 13	—	8	284	19.4	110
09E008	Feb. 29	1.7	7.7	225	21	120
	June 14	1.9	7.5	223	20.6	120
	Sept. 11	7.8	7.8	234	20.8	120
	Dec. 11	1.8	7.7	231	20.8	120
09E521	Mar. 7	5.1	7.6	216	20.9	—
	June 14	5.7	7.3	212	20.6	110
	Sept. 12	5.2	8	230	21	110
	Dec. 12	4.7	7.8	222	20.3	130
09E522	Mar. 3	0.8	7.7	246	20.6	—
	June 12	3.2	7.6	254	20.6	120
	Sept. 13	3	7.6	272	20.6	120
	Dec. 13	—	7.8	258	19.2	130
09F522	Mar. 3	0.7	7.5	272	20.1	—
	June 14	2.3	7.5	287	20	160
	Dec. 13	—	7.6	300	18.5	140
AAA1640	Mar. 8	3.1	7.5	259	20.7	—
	June 12	1.4	7.7	261	20.1	130
	Sept. 14	1.3	7.5	268	21.1	140
	Dec. 14	1	7.6	250	20.5	130

[1]Average value from duplicate samples.

Table A5. Field properties for surface water from selected sites in the Lake Seminole, Georgia, study area, 2000 and 2001.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; °C, degree Celsius; $CaCO_3$, calcium carbonate; —, no data]

Downstream-order number	Site name (see fig. 7)	Sampling date	Oxygen, dissolved (mg/L)	pH (standard units)	Specific conductance (µS/cm)	Temperature, water (°C)	Alkalinity (mg/L as $CaCO_3$)
02357998	Apalachicola River	Mar. 8, 2000	9.0	7.5	136	18.4	—
		June 13, 2000	7.9	7.4	145	27.8	—
		Sept. 11, 2000	6.8	7.6	138	26.6	51
		Dec. 12, 2000	11.1	7.2	146	13.4	37
02357490	Dam Pool	Mar. 7, 2000	6.8	7.8	137	18.3	—
		June 13, 2000	5.8	7.3	139	28.1	—
		Sept. 11, 2000	5.9	7.7	156	27.2	55
		Dec. 12, 2000	8.8	7.1	148	13.5	36
02357395	Cummings Access	Mar. 7, 2000	5.5	7.5	154	18.8	—
		June 13, 2000	9.1	7.8	80	30.3	—
		Sept. 12, 2000	0.7	7.2	116	26.8	49
		Dec. 12, 2000	9.2	7.5	121	12.9	38
02356025	Ten Mile Still	Mar. 6, 2000	7	7.7	140	18.4	—
		June 12, 2000	7.4	8.2	186	28	—
		Sept. 11, 2000	5.5	7.7	172	26.4	75
		Dec. 11, 2000	8.6	7.3	144	12.7	48
02357160	Knights Rest	Mar. 7, 2000	8.3	8.1	210	20.2	—
		June 13, 2000	1.4	7.2	180	27	—
		Sept. 12, 2000	5.8	7.9	207	27.5	89
		Jan. 11, 2001	7	8.1	208	8.1	—
02356020	Hales Landing	Mar. 6, 2000	6.8	7.6	132	18.2	—
		June 12, 2000	8.2	8.1	186	27.3	—
		Sept. 12, 2000	5.9	7.6	149	27	51
		Dec. 11, 2000	8.6	7.3	148	13.4	50
02344064	Parramore Landing	Mar. 7, 2000	7.1	7.2	132	16.6	—
		June 13, 2000	5.3	6.9	129	28.1	—
		Sept. 11, 2000	4.7	7	146	27.8	36
		Dec. 12, 2000	8.1	6.9	183	13.5	36
		Jan. 10, 2001	8.2	7.6	173	7.2	—

Table A6. Field properties for selected springs sampled in the Lake Seminole, Georgia, study area, 2000 and 2001.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; °C, degree Celsius; $CaCO_3$, calcium carbonate; —, no data]

Site name (see fig. 7)	Sampling date	Oxygen, dissolved (mg/L)	pH (standard units)	Specific conductance (µS/cm)	Temperature, water (°C)	Alkalinity (mg/L as $CaCO_3$)
07D011	Mar. 8, 2000	8.4	7.7	138	18.4	—
	June 13, 2000[1]	7.3	7.4	158	27.2	—
	Sept. 11, 2000	6.8	7.6	139	26.6	57
	Dec. 12, 2000	10	7.2	188	15.3	40
07E049	Mar. 7, 2000[1]	6.3	7.6	139	18.5	—
	June 12, 2000	0.1	7.4	221	20.5	—
	Sept. 12, 2000[1]	0.4	7.2	209	22.3	93
	Dec. 13, 2000	7.1	7.2	151	14.6	41
	Jan. 11, 2001	7.4	7.7	99	6.7	—
07E051	Mar. 7, 2000[1]	0.8	7.2	211	16.5	—
	June 13, 2000[1]	2.8	7.5	234	20.6	—
	Sept. 12, 2000	3.3	7.6	227	20.5	100
	Dec. 13, 2000[1]	8.1	7.4	167	13.1	65
	Jan. 11, 2001[1]	7	8	172	8	—
08E033	Mar. 6, 2000[1]	6.3	7.7	139	18.7	—
	June 12, 2000[1]	0.1	7.7	238	20.6	—
	Sept. 12, 2000	2	7.5	231	20.6	120
	Dec. 11, 2000[1]	2.7	7.5	226	20.5	48
09F521	Mar. 6, 2000[1]	6.1	7.7	136	18.6	—
	June 12, 2000[1]	3.9	7.6	253	20.3	—
	Sept. 12, 2000	4.2	7.5	237	20.3	95
	Dec. 11, 2000	6.3	7.3	204	17.8	64

[1]Average value from duplicate samples.

Table A7. Ion concentrations in ground water from selected wells in the Lake Seminole, Georgia, study area, 2000.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; ANC, alkalinity noncarbonation; $CaCO_3$, calcium carbonate; <, less than; —, no data; M, presence verified but not quantified]

Site name (see fig. 7)	Sampling date	Ionic balance (percent)	Solids, sum of constituents, dissolved (mg/L)	pH, laboratory (standard units)	Specific conductance, laboratory (µS/cm)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	ANC, unfiltered, laboratory[1] (mg/L as $CaCO_3$)	Bromide, dissolved (mg/L as Br)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (mg/L as As)	Boron, dissolved (mg/L as B)	Iron, dissolved (mg/L as Fe)	Manganese, dissolved (mg/L as Mn)
05F010	Mar. 2	6	99	8.1	169	78	30	0.8	0.5	1.4	62	<0.05	4.3	<0.1	5.9	0.3	<2	7	<1	<0.2
	June 13 [2]	6	101	8.1	172	81	31	0.8	0.5	1.5	63	—	4.7	<0.1	5.6	0.4	—	—	<1	<0.2
	Sept. 13	6	99	8.1	172	78	30	0.8	0.5	1.6	63	—	4.6	<0.1	5.9	0.3	—	—	<2	<1
	Dec. 14	7	103	8.1	171	81	31	0.8	0.4	1.6	62	—	4.5	<0.1	5.8	0.3	—	—	<2	<1
06D001	Mar. 7	7	130	8.1	233	116	25	13	0.3	1.9	112	<0.05	3.8	0.1	9.5	1	<2	9	<1	<0.2
	June 13	7	131	8.1	234	118	26	13	0.3	1.7	114	—	3.9	0.1	9.3	1.1	—	—	M	<0.2
	Sept. 13	7	—	8.2	236	116	25	13	0.3	1.8	113	—	3.8	0.1	9.6	<0.2	—	—	<2	<1
	Dec. 12	8	130	8.2	233	118	26	13	0.3	1.8	114	—	3.8	0.1	9.5	1.1	—	—	<2	<1
06D002	Mar. 2 [2]	9	154	8	274	123	28	13	1.2	9.6	141	0.05	5.2	0.2	12	0.3	8	24	<1	<0.2
	Sept. 13	7	154	8	280	121	27	13	1.3	9.9	142	—	5.8	0.2	12	0.4	—	—	<2	<1
	Dec. 13	11	161	8.4	301	150	32	17	0.9	5.9	145	—	6.6	0.2	11	1.7	—	—	<2	<1
06D003	Mar. 2	8	131	8.1	235	118	31	9.8	0.2	1.7	113	<0.05	3.3	0.1	10	0.7	<2	8	<1	<0.2
	June 13	8	132	8	234	119	32	9.6	0.3	1.8	115	—	3.6	0.1	9.6	0.8	—	—	<1	<0.2
	Sept. 13	7	130	8.1	235	116	31	9.4	0.3	1.8	114	—	3.6	0.1	9.8	0.7	—	—	<2	<1
	Dec. 13	9	137	8.2	237	123	33	9.9	0.3	1.8	114	—	4	0.1	10	0.8	—	—	M	<1
06E023	Feb. 29 [2]	7	139	7.9	265	130	50	1.2	0.6	1.7	135	<0.05	2.9	<0.1	7.7	0.7	<2	8	<1	<0.2
	Mar. 6	8	143	7.9	256	127	49	1.2	0.6	1.8	130	<0.05	2.9	<0.1	7.6	0.7	<2	8	<1	<0.2
	June 13	9	144	8	253	130	50	1.3	0.5	1.8	129	—	3.2	<0.1	7.5	0.9	—	—	<1	<0.2
	Sept. 13	8	160	8	257	126	48	1.4	0.6	2	127	—	3.4	<0.1	7.8	1	—	—	<2	<1
	Dec. 12	8	134	7.9	248	123	47	1.4	0.5	2.1	123	—	3.8	<0.1	7.7	1.1	—	—	M	<1
06F008	Mar. 8	7	144	8	260	127	50	0.5	0.5	1.7	131	<0.05	3	<0.1	6.9	1.2	<2	6	M	1.3
	June 12	6	144	7.9	260	127	50	0.5	0.5	1.7	132	—	3.2	<0.1	6.9	1.3	—	—	M	0.4
	Sept. 14	7	146	8.3	258	129	51	0.5	0.5	1.8	132	—	3.2	<0.1	7.1	1.2	—	—	<2	<1
	Dec. 14	9	145	8.3	260	135	53	0.6	0.5	1.8	132	—	3.3	<0.1	7.2	1.4	—	—	10	<1
07D001	Mar. 7 [2]	7	129	8.1	232	116	32	8.8	0.3	1.7	120	<0.05	2.6	0.1	10.0	1.1	<2	8	M	0.5
	June 14 [2]	7	127	8.3	227	113	32	8.1	0.3	1.6	118	—	2.6	0.1	9.9	1.1	—	—	M	0.3
	Sept. 12 [2]	8	131	8.1	234	117	33	8.8	0.3	1.7	120	—	2.8	0.1	10	1.1	—	—	M	<1
	Dec. 12	8	122	8.1	232	118	32	9.3	0.3	1.7	120	—	3	0.1	10	1.3	—	—	M	<1

Table A7. Ion concentrations in ground water from selected wells in the Lake Seminole, Georgia, study area, 2000.—Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; ANC, alkalinity noncarbonation; $CaCO_3$, calcium carbonate; <, less than; —, no data; M, presence verified but not quantified]

Site name (see fig. 7)	Sampling date	Ionic balance (percent)	Solids, sum of constituents, dissolved (mg/L)	pH, laboratory (standard units)	Specific conductance, laboratory (µS/cm)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	ANC, unfiltered, laboratory[1] (mg/L as $CaCO_3$)	Bromide, dissolved (mg/L as Br)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (mg/L as As)	Boron, dissolved (mg/L as B)	Iron, dissolved (mg/L as Fe)	Manganese, dissolved (mg/L as Mn)
07D008	Mar. 2	8	133	8.2	218	105.0	24	11.0	1.7	3.2	101	<0.05	2	0.3	20.0	9.9	5	10	M	0.3
	June 12 [2]	6	132	8.2	220	104	24	11	1.8	3.2	104	—	2.2	0.3	19	10	—	—	M	0.3
	Sept. 12	7	132	8.1	222	105	24	11	1.7	3.4	105	—	2.2	0.3	20	9.7	—	—	M	<1
	Dec. 13	8	133	8.3	218	105	24	11	1.7	3.4	102	—	2.4	0.3	21	10	—	—	M	<1
07D010	Mar. 2	8	142	8.1	249	125	37	7.8	0.4	2.3	127	<0.05	2.7	0.1	13	1.2	<2	9	<1	<0.2
	June 12	6	143	8.1	249	121	36	7.6	0.5	2.3	128	—	3.1	0.1	13	1.6	—	—	<1	<0.2
	Sept. 12	8	144	8.1	245	124	37	7.6	0.4	2.4	126	—	3.1	0.1	13	1.4	—	—	<2	<1
	Dec. 13	10	146	8.3	247	131	39	8.1	0.4	2.5	126	—	3.4	0.1	14	1.5	—	—	<2	<1
07E001	Feb. 29	6	128	8	222	106	36	4	0.3	1.6	112	<0.05	2.4	<0.1	8.2	1.4	<2	8	M	0.4
	June 14	5	132	8.2	229	111	31	8.1	0.3	1.6	119	—	3	0.2	12	0.8	—	—	<1	<0.2
	Sept. 12	9	131	8.2	228	117	33	8.5	0.3	1.7	116	—	3.1	0.2	13	0.8	—	—	<2	<1
	Dec. 12	9	142	8.1	231	121	34	8.7	0.3	1.8	118	—	3.3	0.2	13	1	—	—	<10	<1.5
07E044	Mar. 6	8	153	7.7	280	136	53	0.8	0.4	2.3	135	<0.05	4.1	<0.1	5.9	0.7	<2	7	M	0.2
	June 14 [2]	7	156	8.1	277	135	53	0.7	0.4	2.2	137	—	4.2	<0.1	5.8	0.7	—	—	<1	0.4
	Sept. 11	8	160	7.8	292	146	57	0.8	0.4	2.5	143	—	4.5	<0.1	6.1	0.9	—	—	<2	<1
	Dec. 12	9	156	8	280	143	56	0.8	0.3	2.3	139	—	4.4	<0.1	5.9	1	—	—	<2	<1
07E045	Mar. 1	6	120	8	219	104	39	1.5	0.1	1.6	103	0.3	2.6	<0.1	5.6	0.4	<2	7	M	<0.2
	June 13	9	124	8	217	111	42	1.6	0.2	1.6	104	—	3.1	<0.1	5.5	0.6	—	—	<1	<0.2
	Sept. 11	7	122	8.1	218	106	40	1.5	0.1	1.8	104	—	3	<0.1	5.6	0.6	—	—	<2	<1
	Dec. 12	8	120	8.1	216	109	41	1.6	0.1	1.7	102	—	3.3	<0.1	5.7	0.6	—	—	<2	<1
07E046	Mar. 1	6	—	8.1	163	76.2	30	0.3	<0.1	1.2	78	<0.05	2.6	<0.1	5.6	0.3	<2	6	M	<0.2
	June 13	8	89	8.1	163	81.2	32	0.3	0.1	1.3	79	—	2.9	<0.1	5.4	0.3	—	—	M	0.2
	Sept. 11	8	—	8.1	163	78.7	31	0.3	<0.1	1.4	78	—	2.7	<0.1	5.6	0.2	—	—	M	<1
	Dec. 12	9	—	8.1	163	81.2	32	0.3	<0.1	1.3	77	—	2.8	<0.1	5.7	0.3	—	—	M	<1
07E047	Mar. 1 [2]	6	143	7.9	257	120	46	1.2	0.6	1.7	109	<0.05	4.9	<0.1	5.3	0.5	<2	8	M	<0.2
	June 13	6	147	8	254	123	47	1.3	0.6	1.7	110	—	5.1	<0.1	5.1	0.6	—	—	<1	<0.2
	Sept. 11 [2]	6	151	8	265	126	48	1.4	0.6	1.9	108	—	5.9	<0.1	5.4	0.6	—	—	<2	<1
	Dec. 12 [2]	7	146	8	259	127	49	1.3	0.6	1.8	109	—	5.5	<0.1	5.3	0.6	—	—	<2	<1

Table A7. Ion concentrations in ground water from selected wells in the Lake Seminole, Georgia, study area, 2000.—Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; ANC, alkalinity noncarbonation; $CaCO_3$, calcium carbonate; <, less than; —, no data; M, presence verified but not quantified]

Site name (see fig. 7)	Sampling date	Ionic balance (percent)	Solids, sum of constituents, dissolved (mg/L)	pH, laboratory (standard units)	Specific conductance, laboratory (µS/cm)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	ANC, unfiltered, laboratory[1] (mg/L as $CaCO_3$)	Bromide, dissolved (mg/L as Br)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (mg/L as As)	Boron, dissolved (mg/L as B)	Iron, dissolved (mg/L as Fe)	Manganese, dissolved (mg/L as Mn)
08D090	Feb. 29	7	115	8	229	113	32	8.1	0.3	1.6	117	<0.05	2.9	0.2	12	0.8	<2	8	M	<0.2
	June 14	7	121	8.3	218	108	37	3.9	0.3	1.7	113	—	2.4	<0.1	8	1.3	—	—	<1	<0.2
	Sept. 11	7	121	8	221	108	37	3.9	0.3	1.8	112	—	2.4	<0.1	8.2	1.4	—	—	<2	< 1
	Dec. 11	9	120	8	221	112	38	4.1	0.3	1.7	112	—	2.6	<0.1	8.4	1.6	—	—	<2	<1
08E019	Mar. 6	7	128	8	231	113	39	3.8	0.3	1.9	117	<0.05	3.1	<0.1	8	0.6	<2	8	<1	0.3
	June 12	7	126	8	230	113	39	3.7	0.4	1.8	117	—	3.2	<0.1	8	0.7	—	—	M	1.1
	Sept. 11	7	128	8	233	115	40	3.7	0.2	2	118	—	3.3	<0.1	8	0.7	—	—	M	3.1
	Dec. 11	8	131	8.1	233	116	40	3.9	0.3	1.9	117	—	3.5	<0.1	8.1	0.7	—	—	<2	1.2
08E031	Mar. 3	8	157	8	269	135	40	8.5	0.5	2.2	133	<0.05	4.9	0.2	13	1.1	<2	10	M	<0.2
	June 13	6	151	8.1	266	129	38	8.2	0.5	2.3	133	—	5	0.1	13	1.3	—	—	M	<0.2
	Sept. 12	7	151	8.1	268	132	39	8.3	0.5	2.4	133	—	5.3	0.2	13	1.2	—	—	M	<1
	Dec. 13	9	166	8	269	138	41	8.7	0.5	2.4	133	—	5.4	0.2	13	1.4	—	—	M	<1
08E032	Mar. 6[2]	9	145	8.1	263	137	35	12	0.6	2.1	135	<0.05	3.4	<0.1	6.4	3.4	3	10	400	9.5
	June 12[2]	8	139	8.1	259	128	33	11	0.6	1.9	127	—	3.6	<0.1	6.1	3.1	—	—	M	1.2
	Sept. 12	6	140	8.1	266	130	34	11	0.6	2	135	—	3.6	<0.1	6.4	3.3	—	—	10	1.8
	Dec. 13	–3	185	8.2	268	139	36	12	0.6	2.1	138	—	3.9	0.1	6.4	4.1	—	—	50	3.5
08E034	Mar. 6	6	155	8.1	285	123.0	26	14.0	1.1	9.1	118	<0.05	13.0	<0.1	6.9	2.6	<2	10	M	<0.2
	June 13	6	155	8.2	284	125	27	14	1.1	8.9	120	—	12	<0.1	6.8	2.5	—	—	M	0.4
	Sept. 12	6	154	8.2	286	125	27	14	1.1	9.1	119	—	13	<0.1	7.2	2.4	—	—	M	<1
	Dec. 12	7	155	8.1	284	125	27	14	1.1	9.3	117	—	12	<0.1	7.1	2.7	—	—	M	<1
08E035	Mar. 1	8	142	8	263	130	34	11	0.3	2.2	129	<0.05	3.8	<0.1	7.3	0.8	<2	9	M	<0.2
	June 13	8	153	8	249	128	33	11	0.3	2.2	123	—	4	<0.1	7.2	1	—	—	<1	<0.2
	Dec. 12	7	134	8.1	254	125	32	11	0.2	2.3	125	—	4.1	<0.1	7.5	1	—	—	<2	<1
08E036	Mar. 3	7	—	8.1	194	94.4	36	1.1	<0.1	1.4	86	<0.05	3	<0.1	6.5	0.3	<2	6	M	<0.2
	Sept. 13	7	—	8.1	198	94.4	36	1.1	<0.1	1.7	88	—	3.4	<0.1	6.5	0.4	—	—	<2	<1
	Dec. 12	8	—	8.1	198	97.3	37	1.2	<0.1	1.7	87	—	3.4	<0.1	6.5	0.5	—	—	<2	<1
08E037	Mar. 3[2]	7	113	8.1	193	91	34	1.5	0.2	1.5	74	<0.05	4.1	<0.1	6.2	0.4	<2	6	M	<0.2
	June 14	4	108	8	192	85.7	32	1.4	0.2	1.6	73	—	4.2	<0.1	5.8	0.4	—	—	M	<0.2
	Sept. 12[2]	7	111	8.1	237	116	33	7.8	0.4	2.1	109	—	4.2	<0.1	6.9	0.7	—	—	<2	<1
	Dec. 12	7	118	8	189	91.1	34	1.5	0.2	1.8	73	—	4.6	<0.1	6	0.5	—	—	<2	<1

Table A7. Ion concentrations in ground water from selected wells in the Lake Seminole, Georgia, study area, 2000.—Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; ANC, alkalinity noncarbonation; $CaCO_3$, calcium carbonate; <, less than; —, no data; M, presence verified but not quantified]

Site name (see fig. 7)	Sampling date	Ionic balance (percent)	Solids, sum of constituents, dissolved (mg/L)	pH, laboratory (standard units)	Specific conductance, laboratory (µS/cm)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	ANC, unfiltered, laboratory[1] (mg/L as $CaCO_3$)	Bromide, dissolved (mg/L as Br)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (mg/L as As)	Boron, dissolved (mg/L as B)	Iron, dissolved (mg/L as Fe)	Manganese, dissolved (mg/L as Mn)
08F499	Mar. 3	6	154	8	259	123	46	1.9	0.2	1.8	90	0.07	5.8	<0.1	6.9	0.6	<2	7	M	<0.2
	June 14	4	148	7.9	259	118	44	1.9	0.2	2	90	—	5.8	<0.1	6.6	0.7	—	—	M	<0.2
	Sept. 12	4	156	8.1	261	120	45	1.9	0.2	2.1	91	—	5.8	<0.1	6.9	1	—	—	M	<1
	Dec. 13	20	125	8.2	261	123	46	2	0.2	2.1	90	—	6	<0.1	6.7	0.9	—	—	<2	<1
09E004	Mar. 3	8	144	8.1	257	129	36	9.5	0.3	1.9	117	<0.05	4.2	<0.1	7.2	1	<2	9	<1	<0.2
	June 12	4	137	8.1	245	114	33	7.7	0.3	1.9	116	—	3.9	<0.1	6.6	1.1	—	—	M	<0.2
	Sept. 13	5	167	8	298	143	39	11	0.4	2.1	120	—	6.3	<0.1	7.4	1	—	—	M	<1
	Dec. 13	9	149	8.3	280	138	37	11	0.4	2.2	117	—	6	<0.1	7.2	1.1	—	—	<2	<1
09E008	Feb. 29	7	130	7.9	235	113	40	3.3	0.4	1.9	118	<0.05	2.8	< 0.1	8.2	0.9	<2	9	M	<0.2
	June 14	7	129	8	232	113	40	3.3	0.4	2	118	—	3	<0.1	8.1	1	—	—	<1	<0.2
	Sept. 11	7	133	8	235	116	41	3.3	0.3	2.1	119	—	3	<0.1	8.3	1	—	—	<2	<1
	Dec. 11	8	130	8.1	234	116	41	3.4	0.4	2	118	—	3.3	<0.1	8.4	0.9	—	—	<2	<1
09E521	Mar. 7	7	124	8	223	109	38	3.5	0.2	1.7	112	<0.05	2.5	<0.1	8.7	0.6	<2	7	<1	<0.2
	June 14	7	123	8	221	109	38	3.4	0.2	1.8	113	—	2.5	<0.1	8.7	0.7	—	—	M	0.2
	Sept. 12	8	125	8	225	112	39	3.5	0.6	1.8	113	—	2.9	<0.1	8.9	0.7	—	—	<2	<1
	Dec. 12[2]	9	136	8.1	223	113	40	3.5	0.2	1.8	112	—	2.9	<0.1	8.9	0.8	—	—	<2	<1
09E522	Mar. 3	8	141	8	254	126	44	4	0.3	1.8	125	<0.05	3.2	<0.1	7.6	0.6	<2	8	M	<0.2
	June 12	5	137	8	252	121	42	3.9	0.3	1.9	126	—	3.5	<0.1	7.2	0.8	—	—	<1	0.2
	Sept. 13	8	140	8.1	254	126	44	4	0.4	2.1	126	—	3.6	<0.1	7.6	0.7	—	—	<2	<1
	Dec. 13	9	144	8.1	256	130	45	4.2	0.3	2.1	125	—	3.8	<0.1	7.6	0.8	—	—	<2	<1
09F522	Mar. 3	9	168	7.8	298	148	55	2.6	0.5	2.3	146	<0.05	3.5	<0.1	11	2.6	<2	8	M	<0.2
	June 14	6	171	8	293	143	53	2.5	0.6	2.5	147	—	3.8	< 0.1	9.9	2.8	—	—	<1	<0.2
	Sept. 12	8	167	7.8	296	146	54	2.6	0.6	2.6	146	—	4	<0.1	10	3	—	—	<2	<1
	Dec. 13[2]	10	169	8	293	153	57	3	0.5	2.7	146	—	4.25	<0.1	11	3.4	—	—	<2	<1
AAA1640	Mar. 8	8	149	7.9	264	133	52	0.7	0.4	1.8	136	<0.05	2.6	< 0.1	7.9	1	<2	7	M	<0.2
	June 12	7	148	7.9	266	132	52	0.6	0.4	1.7	138	—	2.7	<0.1	7.8	1.1	—	—	<1	<0.2
	Sept. 14[2]	7	150	7.9	269	132	52	0.7	0.5	2	138	—	2.7	<0.1	7.9	1	—	—	<2	<1
	Dec. 14[2]	10	150	8.4	264	140	55	0.7	0.4	1.8	137	—	2.9	<0.1	8	1.1	—	—	<2	<1

[1]Derived from titration to 4.5 pH.

[2]Average value from duplicate samples.

Table A8. Ion concentrations in surface water from selected sites in the Lake Seminole, Georgia, study area, 2000.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; ANC, alkalinity noncarbonation; —, no data; <, less than; M, presence verified but not quantified]

Downstream-order number and site name (see fig. 7)	Sampling date	Ionic balance (percent)	Solids, sum of constituents, dissolved (mg/L)	pH, laboratory (standard units)	Specific conductance, laboratory (µS/cm)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	ANC, unfiltered, laboratory[1] (mg/L as $CaCO_3$)	Bromide, dissolved (mg/L as Br)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (mg/L as As)	Boron, dissolved (mg/L as B)	Iron, dissolved (mg/L as Fe)	Manganese, dissolved (mg/L as Mn)
02357998 Apalachicola River	Mar. 8[1]	4	78	7.6	141	38	13.0	1.4	2.2	10.5	42	<0.05	7.5	<0.10	5.2	11.0	2.4	28	20	9.2
	June 13[1]	4	71	7.7	147	44	15	1.5	1.9	11	28	—	6.6	0.1	6.1	11	—	—	<1	7.3
	Sept. 11[1]	5	87	7.8	155	42	14	1.6	2.2	13	51	—	8.2	0.1	5.2	12	—	—	10	10
	Dec. 12	6	82	7.6	150	43	15	1.4	2	12	46	—	7.6	0.1	6.6	13	—	—	40	17
02357490 Dam Pool	Mar. 7[1]	5	78	7.8	140	43	15	1.4	1.9	8.8	45	<0.05	6.8	<0.1	5.6	9	<0.2	22	30	.6
	June 13	4	81	7.5	143	34	11	1.5	2.3	13	41	—	7.3	0.1	6.2	14	—	—	20	1.1
	Sept. 11	7	91	7.8	158	46	16	1.5	2.1	13	53	—	8	0.1	5.4	11	—	—	M	2
	Dec. 12	6	83	7.5	150	41	14	1.5	2.1	13	45	—	7.8	0.1	6.5	14	—	—	80	30
02357395 Cummings Access	Mar. 7	5	78	8	146	62	23	1.2	0.7	3.8	66	<0.05	5.1	0.4	1.9	2.1	2.2	10	20	.5
	June 13	1	71	9.3	83	29	10	0.9	0.2	4	33	—	4.8	<0.1	5	2.2	—	—	40	2.1
	Sept. 12	5	63	7.6	120	47	17	1.0	0.5	4.1	51	—	5	<0.1	4.7	1.4	—	—	20	<1
	Dec. 12	7	58	7.8	120	47	17	1.2	0.2	4.9	49	—	5.4	<0.1	3.5	2.6	—	—	30	<1
02356025 Ten Mile Still	Mar. 6	5	83	7.7	144	52	19	1.2	1.3	6.5	53	<0.05	6.3	<0.1	7	6.2	<2	11	50	22
	June 12	5	104	8	185	73	27	1.3	1.1	6.8	78	—	6	<0.1	6	5.2	—	—	M	1
	Sept. 11	7	113	7.8	194	70	26	1.3	1.3	11	75	—	8.1	<0.1	8.2	7.6	—	—	M	12
	Dec. 11	8	83	7.7	150	50	18	1.3	1.6	9.1	51	—	6.8	<0.1	8.3	8.9	—	—	30	21
02357160 Knights Rest	Mar. 7	7	116	8.1	216	101	39	0.8	0.5	2.5	99	<0.05	4.7	<0.1	2.8	1.2	<2	8	30	4
	June 13	5	92	7.5	184	68	26	0.7	0.3	2	87	—	4.4	<0.1	3.3	0.6	—	—	60	87
	Sept. 12	7	111	8	206	98	38	0.7	0.7	2	97	—	4.4	<0.01	6.1	0.7	—	—	30	2.9
02356020 Hales Landing	Mar. 6	5	79	7.7	136	47	17	1.2	1.3	7.1	48	<0.05	6.4	<0.1	7.4	6.6	<2	12	70	27
	June 12	5	103	8	185	72	27	1.2	1.2	6.8	77	—	5.8	<0.1	5.4	5.3	—	—	M	2
	Sept. 12	7	89	7.7	150	45	16	1.2	1.6	12	51	—	7.8	<0.1	8.6	8.5	—	—	10	13
	Dec. 11	8	84	7.8	154	53	19	1.3	1.6	8.7	54	—	6.7	<0.1	8.5	8.3	—	—	50	18
02344064 Parramore Landing	Mar. 7	3	80	7.4	138	31	9.8	1.5	2.6	13	35	<0.05	8.3	0.1	5.7	15	<2	37	30	66
	June 13	4	76	7.2	132	26	7.8	1.5	2.7	14	33	—	7.7	0.1	4.8	16	—	—	20	56
	Sept. 11	5	83	7.4	150	29	8.8	1.7	3	17	38	—	9.2	0.1	3	17	—	—	10	98
	Dec. 12	6	102	7.5	184	35	11	1.7	3.4	22	44	—	10	0.2	5.8	25	—	—	20	77

Table A9. Ion concentrations for selected springs in the Lake Seminole, Georgia, study area, 2000.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; ANC, alkalinity noncarbonation; $CaCO_3$, calcium carbonate; <, less than; —, no data; M, presence verified but not quantified]

Site name (see fig. 7)	Sampling date	Ionic balance (percent)	Solids, sum of constituents, dissolved (mg/L)	pH, laboratory (standard units)	Specific conductance, laboratory (µS/cm)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	ANC, unfiltered, laboratory [1] (mg/L as $CaCO_3$)	Bromide, dissolved (mg/L as Br)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (mg/L as As)	Boron, dissolved (mg/L as B)	Iron, dissolved (mg/L as Fe)	Manganese, dissolved (mg/L as Mn)
07D011	Mar. 8	5	79	7.6	141	38	13	1.4	2.2	11.0	41	<0.05	7.5	0.1	5.2	12.0	<2	28	20	8.6
	June 13	5	90	7.7	160	49	16	2.1	1.9	11	53	—	8.1	0.1	6.2	11	—	—	M	8
	Sept. 11	9	406	7.7	166	52	16	3	2.1	15	54	—	11	0.1	5.7	12	—	—	M	15
	Dec. 12	8	86	7.7	151	45	15	1.7	2.1	13	45	—	8.4	0.1	6.5	14	—	—	20	20
07E049	Mar. 7	6	82	8	145	53	19	1.3	1.3	6.3	53	0.1	5.9	<0.1	6.9	6.3	<2	11	40	5.9
	June 12	4	114	7.8	208	89	32	2.3	0.6	3.5	99	—	3.4	<0.1	6.9	.9	—	—	M	140
	Sept. 12	5	116	7.5	214	92	33	2.2	0.7	5.4	101	—	4.5	<0.1	7.6	2.4	—	—	<2	260
	Dec. 13	8	77	7.9	140	—	16	1.3	1.5	9.6	47	—	6.6	<0.1	7.4	9.1	—	—	40	51
07E051	Mar. 7	7	116	7.5	216	99	38	0.9	0.9	2.7	99	<0.05	5.3	<0.1	4.7	1.8	<2	9	M	220
	June 13	17	88	7.8	145	82	31	1.1	0.3	2.6	65	—	3.9	<0.1	5.6	1.3	—	—	40	5.6
	Sept. 12	9	124	7.9	221	112	43	1.2	0.2	2.4	107	—	3.6	<0.1	6.2	.7	—	—	M	1.6
	Dec. 13 [2]	8	97	8.1	202	92	35	1	0.8	4.6	85	—	5.6	<0.1	4.1	5.9	—	—	25	2.4
08E033	Mar. 6	5	83	7.8	143	52	19	1.2	1.3	6.6	53	<0.05	6.1	<0.1	7	6.2	<2	11	40	19
	June 12	12	117	7.9	210	108	37	3.7	0.4	2.3	100	—	3.1	<0.1	8.1	.9	—	—	M	71
	Sept. 12	20	133	7.7	196	106	36	3.8	0.4	3.2	79	—	4.1	<0.1	8.5	2.2	—	—	<2	110
	Dec. 11	11	84	7.7	152	55	20	1.3	1.5	8.8	53	—	6.5	<0.1	8.2	8.5	—	—	70	26
09F521	Mar. 6	5	80	7.8	138	50	18	1.2	1.2	6.6	50	<0.05	6.1	<0.1	7.3	6.2	<2	11	70	37
	June 12 [2]	7	135	8	236	115	43	1.8	0.3	2	106	—	4.3	<0.1	7.2	2.2	—	—	M	5.3
	Sept. 12	6	131	8	239	113	42	1.9	0.3	2.3	105	—	4.2	<0.1	7.1	1.6	—	—	<2	4.4
	Dec. 11	10	95	7.7	174	68	25	1.4	1.2	7.3	66	—	6.2	<0.1	8.5	6.7	—	—	30	17

[1]Derived from titration 4.5 pH.

[2]Average value from duplicate samples.

Table A10. Radon-222 concentrations in ground water from selected wells in the Lake Seminole, Georgia, study area, 2000 and 2001.

[pCi/L, picocuries per liter; Σ, Sigma]

Site name (see fig. 7)	Sampling date	Radon-222	
		Concentration (pCi/L)	Σ precision estimate (pCi/L)
05F010	Mar. 2, 2000	143	18
	June 13, 2000[1]	125	18
	Sept. 13, 2000	136	19
	Dec. 14, 2000	121	16
06D001	Mar. 7, 2000	274	19
	Sept. 13, 2000	269	22
	Dec. 12, 2000	240	21
06D002	Mar. 2, 2000[1]	100	17
	Sept. 13, 2000	107	18
	Jan. 24, 2001	26	17
06D003	Mar. 2, 2000	215	20
	June 13, 2000	207	21
	Sept. 13, 2000	214	20
	Jan. 24, 2001[1]	235	20
06E023	Feb. 29, 2000[1]	134	17
	Mar. 6, 2000	112	20
	June 13, 2000	124	18
	Sept. 13, 2000	116	20
	Dec. 12, 2000	117	17
06F008	Mar. 8, 2000	410	22
	June 12, 2000	421	24
	Sept. 14, 2000	454	25
	Dec. 14, 2000	375	21
07D001	Mar. 7, 2000	197	17
	June 14, 2000[1]	156	19
	Sept. 12, 2000[1]	175	21
	Dec. 12, 2000	167	19
07D008	Mar. 2, 2000	1,550	37
	June 12, 2000[1]	1,560	41
	Sept. 12, 2000	1,470	38
	Jan. 24, 2001	1,460	36
07D010	Mar. 2, 2000	811	29
	June 12, 2000	790	31
	Sept. 12, 2000	820	32
	Jan. 24, 2001	867	29
07E001	Feb. 29, 2000	222	18
	June 14, 2000	226	20
	Sept. 12, 2000	258	21
	Dec. 12, 2000	235	20
07E044	Mar. 6, 2000	414	23
	June 14, 2000[1]	807	31
	Sept. 11, 2000	844	29
	Dec. 12, 2000	967	32
07E045	Mar. 1, 2000	280	20
	June 13, 2000	281	21
	Sept. 11, 2000	277	20
	Dec. 12, 2000	322	21
07E046	Mar. 1, 2000	617	25
	June 13, 2000	835	30
	Sept. 11, 2000	764	28
	Dec. 12, 2000	818	30
07E047	Mar. 1, 2000[1]	719	17
	June 13, 2000	135	19
	Sept. 11, 2000[1]	136	18
	Dec. 12, 2000[1]	127	18
08D090	Feb. 29, 2000	70	14
	June 14, 2000	50	16
	Sept. 11, 2000	55	17
	Dec. 11, 2000	49	15
08E019	Mar. 6, 2000	169	17
	June 12, 2000	190	20
	Sept. 11, 2000	173	18
	Dec. 11, 2000	208	18
08E031	Mar. 2, 2000	157	21
	June 13, 2000	152	18
	Sept. 12, 2000	154	20
	Jan. 24, 2001	175	18
08E032	Mar. 6, 2000[1]	42	18
	June 12, 2000[1]	63	18
	Sept. 12, 2000	56	16
08E034	Mar. 6, 2000	90	16
	June 13, 2000	90	18
	Sept. 12, 2000	90	18
	Dec. 12, 2000	126	19
08E035	Mar. 1, 2000	102	15
	June 13, 2000	140	18
	Dec. 12, 2000	141	19
08E036	Mar. 2, 2000	120	20
	Sept. 13, 2000	121	20
	Dec. 12, 2000	115	18
08E037	Mar. 2, 2000[1]	58	20
	June 14, 2000	36	15
	Sept. 11, 2000	46	17
	Sept. 12, 2000[1]	95	19
	Dec. 12, 2000	61	17
08F499	Mar. 2, 2000	266	23
	June 14, 2000	277	20
	Sept. 12, 2000	269	23
	Jan. 23, 2001	328	19
09E004	Mar. 2, 2000	69	18
	June 12, 2000	73	19
	Sept. 13, 2000	78	18
	Jan. 24, 2001	86	16
09E008	Feb. 29, 2000	73	14
	June 14, 2000	70	15
	Sept. 11, 2000	74	16
	Dec. 11, 2000	80	16
09E521	Mar. 7, 2000	90	15
	June 14, 2000	52	15
	Sept. 12, 2000	71	17
	Dec. 12, 2000[1]	47	15
09E522	Mar. 2, 2000	55	19
	June 12, 2000	77	18
	Sept. 13, 2000	88	18
	Jan. 24, 2001	94	16
09F522	Mar. 2, 2000	51	18
	June 14, 2000	54	16
	Sept. 12, 2000	83	19
	Jan. 23, 2001	87	15
AAA1640	Mar. 8, 2000	181	18
	June 12, 2000	189	19
	Sept. 14, 2000[1]	180	20
	Dec. 14, 2000[1]	180	18

[1]Average value from duplicate samples.

Table A11. Radon-222 concentrations in surface water from selected sites in the Lake Seminole, Georgia, study area, 2000 and 2001.

[pCi/L; picocuries per liter; Σ, Sigma; <, less than]

Downstream-order number and site name (see fig. 7)	Sampling date	Radon-222	
		Concentration (pCi/L)	Σ precision estimate total (pCi/L)
02357998 Apalachicola River	Mar. 8, 2000[1]	40	14
	June 13, 2000[1]	28	16
	Sept. 11, 2000[1]	36	17
	Dec. 12, 2000	27	15
02357490 Dam Pool	Mar. 7, 2000[1]	34	16
	June 13, 2000	33	17
	Sept. 11, 2000	<26	14
	Dec. 12, 2000	28	15
02357395 Cummings Access	Mar. 7, 2000	<26	17
	June 13, 2000	39	15
	Sept. 12, 2000	28	14
	Dec. 12, 2000	34	16
02356025 Ten Mile Still	Mar. 6, 2000	54	15
	June 12, 2000	27	17
	Sept. 11, 2000	36	16
	Dec. 11, 2000	27	15
02357160 Knights Rest	Mar. 7, 2000	26	16
	June 13, 2000	53	15
	Sept. 12, 2000	33	16
	Jan. 11, 2001	42	15
02356020 Hales Landing	Mar. 6, 2000	32	17
	June 12, 2000	46	18
	Sept. 12, 2000	31	14
	Dec. 11, 2000	57	16
02344064 Parramore Landing	Mar. 7, 2000	<26	17
	June 13, 2000	46	15
	Sept. 11, 2000	45	17
	Dec. 12, 2000	30	16

[1]Average value from duplicate samples.

Table A12. Radon-222 concentrations in springs sampled in the Lake Seminole, Georgia, study area, 2000 and 2001.

[pCi/L, picocuries per liter; Σ, Sigma]

Site name (see fig. 7)	Sampling date	Radon-222	
		Concentration (pCi/L)	Σ precision estimate (pCi/L)
07D011	Mar. 8, 2000	40	15
	June 13, 2000[1]	72	16
	Sept. 11, 2000	130	20
	Dec. 12, 2000	36	16
07E049	Mar. 7, 2000	58	14
	June 12, 2000	99	16
	Sept. 12, 2000[1]	112	17
	Jan. 11, 2001	42	15
07E051	Mar. 7, 2000	26	17
	June 13, 2000	89	16
	Sept. 12, 2000	158	18
	Jan. 11, 2001[1]	58	16
08E033	Mar. 6, 2000	43	14
	June 12, 2000	150	18
	Sept. 12, 2000	32	14
	Dec. 11, 2000[1]	38	15
09F521	Mar. 6, 2000	70	15
	Mar. 6, 2000	39	18
	June 12, 2000[1]	169	21
	Sept. 12, 2000	168	18
	Dec. 11, 2000	75	17

[1]Average value from duplicate samples.

Table A13. Isotopic data for ground-water from selected wells in the Lake Seminole, Georgia, study area, 2000.

[δ, delta; ^{2}H, deuterium; ^{18}O, oxygen-18; –, negative; —, no data]

Site name (see fig. 7)	Isotopic ratio[1], per mil							
	March		June		September		December	
	δ^{2}H	δ^{18}O	δ^{2}H	δ^{18}O	δ^{2}H	δ^{18}O	δ^{2}H	δ^{18}O
05F010	–20.7	–4.1	–22.6	[2]–4.2	–22.1	–4.1	–20.4	–4.1
06D001	–17.8	–3.7	–20	–3.7	–19.2	–3.7	–17.1	–3.7
06D002	[2]–18.8	[2]–3.5	–21.2	–3.6	–20.1	–3.5	–18.6	–3.7
06D003	–19	–3.8	–19.2	–3.9	–20.1	–3.8	–19.2	–3.8
06E023	[2]–17.5	[2]–3.2	–16.7	–3.4	–17.8	–3.5	–19.2	–3.6
06F008	–18.2	–3.6	–18.9	–3.6	–19.4	–3.5	–18.4	–3.6
07D001	[2]–20.7	[2]–4.1	[2]–20.9	[2]–4	–20.8	[2]–4.1	–20.2	–4
07D008	–18.6	–3.9	[2]–20.2	[2]–4	–20.6	–4	—	–4
07D010	–20.1	–3.9	–20.3	–4	–20.6	–4	–19.6	–3.9
07E001	–19.3	–3.9	–20.7	–3.9	–19.5	–4	–19.7	–3.8
07E044	–18.7	–3.8	[2]–20.2	[2]–3.9	[2]–21.1	–3.9	–19.2	–3.9
07E045	–18.7	–3.6	–17.8	–3.8	–20	–3.6	–18.7	–3.8
07E046	–19.2	–4.1	–21.9	–4.1	–21	–3.9	–21.5	–4.2
07E047	[2]–18.4	[2]–3.8	–19.8	–3.8	[2]–20.7	[2]–3.7	[2]–18.8	[2]–3.8
08D090	–17.8	–3.7	–19.4	–3.8	–20.1	–3.7	–19.9	–3.8
08E019	–17.9	–3.5	–19.2	–3.6	–18	–3.5	–20.8	–3.9
08E031	–20.1	–4	–19.7	–4	–20.5	–3.9	–19.8	–4
08E032	[2]–21.2	[2]–4.2	[2]–21.1	[2]–4.3	–22.1	–4.2	–21	–4.2
08E034	–20.6	–4.2	–21.5	–4.2	–20.7	–4.2	–20.6	–4.2
08E035	–18.9	–3.9	–19.9	–3.9	[2]–20.1	[2]–3.9	–19.1	–3.9
08E036	–20.2	–3.9	–20.4	–3.9	–20.1	–3.8	–18.5	–3.9
08E037	[2]–20.7	[2]–4	–20.8	–4	–21.2	–4	–20.8	–4.1
08F499	–20.7	–3.9	–19.5	–3.9	–20.8	–4	–19.3	–3.9
09E004	–20	–4	–20.5	–4	–20.9	–4	–19.8	–4
09E008	–19.7	–3.5	–17.9	–3.6	–19.8	–3.5	–17.9	–3.5
09E521	–18.5	–3.8	–19.7	–3.7	–20	–3.8	[2]–18.5	[2]–3.7
09E522	–18.6	–3.6	–19.1	–3.6	–19.4	–3.6	–18.9	–3.7
09F522	–20.2	–4.1	–19.2	–4	–20.6	–4.1	[2]–21.3	[2]–4.1
AAA1640	–16.1	–3.5	–18.8	–3.5	[2]–18.1	[2]– 3.4	[2]–18	[2]–3.4

[1]δ_x is the isotopic ratio expressed as $\delta_x = \left[\frac{R_x}{R_{std}} - 1\right] \times 1{,}000$, and R_x is the ratio of the isotope to its element ($x = H$ or O); R_{std} is the isotopic ratio of the standard sample; VSMOW, Vienna standard mean ocean water (Coplen, 1994).

[2]Average value from duplicate samples.

Table A14 Isotopic data for surface water from selected sites in the Lake Seminole, Georgia, study area, 2000 and 2001.

[δ, delta; ^{2}H, deuterium; ^{18}O, oxygen-18; —, no data]

Site identification number	Sample location	Isotopic ratio[1], per mil																					
		2000																		2001			
		March		April		June		July		August		September		October		November		December		January		August	
		$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$
[2]02357998	Apalachicola River downstream of River Boil[3]	[4]–18.4	–3.8	–17.0	–3.0	[4]–15.2	[4]–2.9	–14.2	–2.5	–12.5	–2.3	–12.2	–2.1	–10.6	–2.0	–12.1	–2.4	–15.5	–2.9	–17.5	–3.4	—	—
[2]02357700	Apalachicola River upstream of River Boil[3]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	–18.9	–3.5
[2,5]07D017	Sinkhole downstream of dam on right bank[3]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	–19.2	–3.5
[2]02357495	Sinkhole in lake upstream of powerhouse[3]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	–18.5	–3.3
02344080	Lake upstream of lock[3]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	–19.4	–3.5
02357490	Dam Pool[2]	–17.6	–3.5	–14.4	–3.3	[4]–16.1	[4]–3	–15.1	–2.5	–12.1	–2.1	–12.1	–2.1	–13.1	–2.2	–14.4	–2.5	–14.6	–2.7	–18.8	–3.5	—	—
02357395	Cummings Access[2]	–3.7	–.8	–2.8	–.6	[4]3.3	[4]1	–1.4	.1	4.1	1.2	4.7	1.5	2.9	1.1	1.4	.7	.5	.5	–5.8	–1.2	—	—
02356025	Ten Mile Still[2]	–19.3	–3.8	–16.7	–3.5	[4]–18.2	[4]–3.2	–17.3	–2.8	–14.5	–2.4	–16.2	–2.7	–17	–3.1	–16.9	–3.3	–17.3	–3.6	–22.9	–4.3	—	—
02357160	Knights Rest[2]	–16	–3.4	–17.5	–3.4	[4]–18.3	[4]–3.4	–16.6	–3.1	–17.1	–3.2	–17.7	–3.3	–18.2	–3.4	–16.4	–3.5	–18	–3.5	–22.1	–4.1	—	—
02356020	Hales Landing[2]	–19.5	–3.8	–17.4	–3.6	[4]–17.9	[4]–3.4	–16.4	–2.9	–14.7	–2.6	–14.5	–2.6	–18.6	–3.3	–18.4	–3.3	–20.1	–3.7	–23	–4.3	—	—
02344064	Parramore Landing[2]	–18.4	–3.4	–16.5	–3.5	[4]–17.3	[4]–3.2	–15.5	–2.6	–12	–2.2	–12.7	–2.1	–9.9	–1.8	–10.4	–2	–11.3	–2.1	–17.8	–3.1	—	—

[1]δ_x is the isotopic ratio expressed as $\delta_x = \left[\frac{R_x}{R_{std}} - 1\right] \times 1{,}000$, and R_x is the ratio of the isotope to its element (x = H or O); R_{std} is the isotopic ratio of the standard sample; VSMOW, Vienna standard mean ocean water (Coplen, 1994).

[2]See figure 7 for location.

[3]See figure 14 for location.

[4]Average value from duplicate samples.

[5]Classified as ground-water site.

Table A15. Isotopic data for selected springs in the Lake Seminole, Georgia, study area, 2000 and 2001.

[δ, delta; ^{2}H, deuterium; ^{18}O, oxygen-18; —, no data; –, negative]

Site name (see fig. 7)	Spring name	Isotopic ratio, per mil[1]									
		March 2000		June 2000		September 2000		December 2000		August 2001	
		δ^{2}H	δ^{18}O	δ^{2}H	δ^{18}O	δ^{2}H	δ^{18}O	δ^{2}H	δ^{18}O	δ^{2}H	δ^{18}O
07D007	Polk Lake Spring	—	—	—	—	—	—	—	—	–19.2	–3.4
07D011	River Boil	–17.7	–3.3	–15.6	–2.9	–11	–2.1	–14.9	–2.8	[2]–19.1	[2]– 3.4
07E049	Shakelford Spring	–19.8	–3.8	–20.5	–3.8	[2]–19.2	[2]–3.6	–19.3	–3.4	—	—
07E051	Sealy Spring	–14.5	–3.3	–16.2	–3	–17.3	–3.4	[2]–13.9	[2]– 2.6	—	—
08E033	Wingate Spring	–20.6	–3.8	–19	–3.7	–17	–2.9	[2]–18.4	[2]–3.6	—	—
09F521	State Dock Spring	[2]–19.3	[2]–3.8	[2]–18.9	[2]–3.9	–21.6	–4	–19.7	–3.7	—	—

[1] δ_x is the isotopic ratio expressed as $\delta_x = \left[\frac{R_x}{R_{std}} - 1\right] \times 1{,}000,$ and R_x is the ratio of the isotope to its element ($x = H$ or O); R_{std} is the isotopic ratio of the standard sample; VSMOW, Vienna standard mean ocean water (Coplen, 1994).

[2] Average value from duplicate samples.

Manuscript approved for publication, April 26, 2005
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