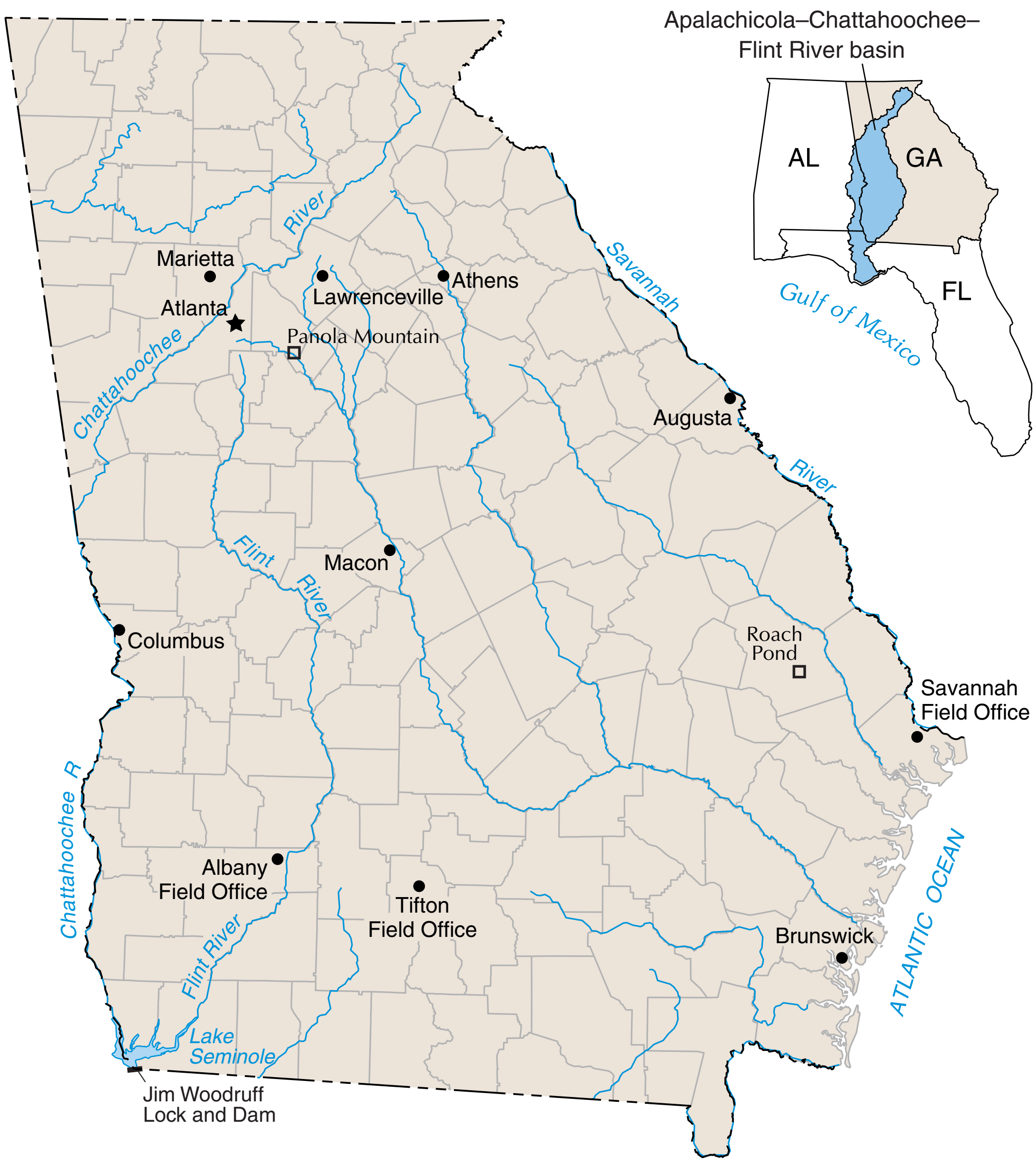
PAPERS, POSTERS, AND EXHIBIT
by U.S. Geological Survey personnel
at the Georgia Water Resources Conference 2001
The University of Georgia, Center for Continuing Education
Athens, Georgia
March 26–27, 2001



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

GEORGIA WATER RESOURCES CONFERENCE 2001

The University of Georgia, Center for Continuing Education

Athens, Georgia

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Keynote Speakers

- *Water-resources information for decision making* by Charles (Chip) G. Groat, Director, U.S. Geological Survey (Monday, March 26, 2001)
- *Water-related legislation in the 2000—-2001 Georgia General Assembly* by James E. Kundell, Institute of Government, The University of Georgia (Tuesday, March 27, 2001)

Papers, posters, and exhibits by the U.S. Geological Survey
(published in proceedings, Georgia Water Resources Conference, 2001)

U.S. Department of the Interior
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GROUND-WATER MONITORING AND EFFECTS OF THE 1998–2000 DROUGHT ON GROUND-WATER LEVELS IN GEORGIA

By Kristen B. McSwain and Nancy L. Barber

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia. p. 61.

Abstract. During the drought period of 1998–2000, ground-water levels throughout Georgia were affected by reduced recharge and increased ground-water pumpage. These combined effects caused record-low ground-water levels in some areas and near record lows in other areas. The drought has been notable not only for extreme low ground-water levels, but also because of the length of time these low ground-water levels have persisted.

Drought conditions began during summer 1998 in central Georgia and then extended into southwestern Georgia. During 1998, new period-of-record lows were recorded in 26 wells in 10 aquifers. During 1999, rainfall deficits exceeded 11 inches, and new period-of-record lows were recorded in 36 wells in 12 aquifers. By December 1999, the drought effects extended eastward to the Atlantic coast. When significant winter rains did not occur in early 2000, the drought effects extended northward, covering nearly all of Georgia. Ground-water levels declined rapidly during summer 1999, and with little or no recovery during the fall and winter, these declines continued into 2000.

In cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey, and city and county governments, the U.S. Geological Survey monitors ground-water levels throughout Georgia. A statewide water-level-measurement program began in 1938 and consisted of an observation-well network in the coastal area of Georgia that monitored variations in ground-water storage and quality. Since then, additional wells were added to the monitoring network (fig. 1) throughout Georgia to assist in water-resources management.

During 2000, continuous water-level measurements were obtained from 175 wells, of which 133 have a period of record that encompasses the drought period of 1998–2000. Twelve of the wells are equipped with electronic data recorders that transmit data via satellite. Data for these wells are displayed in near real-time on the World Wide Web and can be accessed at **http://water.usgs.gov/ga/nwis/current?type=gw**.

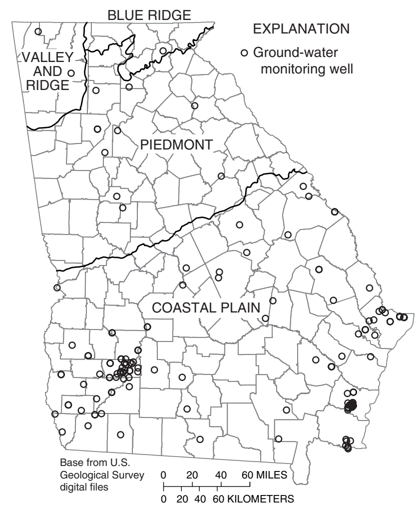

Figure 1. Continuous-recording observation well network.

In the Coastal Plain physiographic province, the rate of water-level decline was especially high near large agricultural areas that have extensive ground-water withdrawals for irrigation. In the Cretaceous aquifer systems, new record low water levels were recorded in 10 of 14 wells monitored during 2000. Increased pumpage for agricultural, industrial, and public supply in the Albany area and reduced recharge resulted in water-level declines in the Clayton and Claiborne aquifers. In 8 of 11 wells monitored in the Clayton aquifer and in 11 of 12 wells monitored in the Claiborne aquifer, new record low water levels were recorded during 2000.

New period-of-record lows were recorded during 2000 for 35 of 66 observation wells completed in the Floridan aquifer system. Although many wells in the Floridan aquifer system have shown downward trends in water levels for a number of years due to continuing increased pumpage, steeper declines in water levels occurred from 1998–2000 as a result of the drought.

Ground-water levels in the Piedmont Province of northern Georgia were below normal during the 1998–2000 drought. Water levels in crystalline-rock aquifers declined to record lows in 4 of 9 wells monitored during 2000—mostly located in the Metropolitan Atlanta area.

EFFECTS OF DROUGHT ON STREAM DISCHARGE AND GROUND-WATER LEVELS NEAR LAKE SEMINOLE, SOUTHWESTERN GEORGIA AND NORTHWESTERN FLORIDA, OCTOBER 1999 – AUGUST 2000

By Melinda S. Mosner

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 118-121.

Abstract. Stream discharge and ground-water levels were measured during Fall 1999, and Spring and Summer 2000, along selected stream reaches near Lake Seminole, southwestern Georgia–northwestern Florida. Baseflow was measured at 12 locations along Spring Creek, Fishpond Drain, and along the Flint, Chattahoochee, and Apalachicola Rivers and their tributaries. Ground-water levels were measured in 76 wells throughout the area surrounding Lake Seminole. Stream discharge and ground-water levels were highest in spring and lowest in summer; stream discharge in spring was almost four times greater than in summer. Although stream discharge and ground-water fluctuations during this period followed typical seasonal variations, continued drought conditions and ground-water pumping during the growing season limited the degree to which ground-water levels recovered during Winter and Spring 2000; as a result, less ground water contributed to the baseflow of streams than during normal conditions.

INTRODUCTION

Previous studies have shown a close hydraulic relation between ground-water and surface-water systems of the Dougherty Plain (Hicks and others, 1995; Torak and others, 1996). Under normal conditions, maximum amounts of ground water are discharged to streams during early spring when ground-water levels are highest. High evapotranspiration and heavy ground-water pumping during summer reduces rates of seepage into streams (Hicks and others, 1995). In June 1998, a severe drought exacerbated this relation, causing streamflows and ground-water levels at some locations to decline to record-low values. Average annual precipitation in the study area is 54 inches (The University of Georgia, 2000). From June 1998 through August 2000, a 27-month period, 95 inches of precipitation were recorded in southwest Georgia by the National Climatic Data Center, producing a precipitation deficit of nearly 27 inches. As a result, drought conditions reduced stream discharge in the study area to less than 12 percent of normal flow (U.S. Geological Survey, 2000).

Because ground water is the major water source for the region, and reduced surface-water flows may impact downstream users, a quantitative understanding of ground-water/surface-water relations is important for management of water resources in the Dougherty Plain area. In response to this need, the U.S Geological Survey, in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, is conducting investigations of ground-water and surface-water relations in the vicinity of Lake Seminole in the southern part of the Apalachicola-Chattahoochee-Flint (ACF) River basin (fig. 1). This paper discusses stream-discharge and ground-water-level data collected during October 1999, April 2000, and August 2000, and relates these data to drought conditions.

Description of Study Area

Lake Seminole is a 37,600-acre reservoir formed in the mid-1950's with construction of Jim Woodruff Lock and Dam. The lake is located in southwestern Georgia at the confluence of the Flint and Chattahoochee Rivers and forms the headwaters of the Apalachicola River (fig. 1). The reservoir lies within the Dougherty Plain, a region of karst topography developed in the underlying Ocala and Suwanee Limestones. These limestones are the major geologic units that constitute the Upper Floridan aquifer, which is the principal ground-water source in the region. The thickness of the Upper Floridan aquifer ranges from just a few feet in the northern extent of the Dougherty Plain to more than 500 feet near Lake Seminole; aquifer productivity increases with thickness (Torak and others, 1996). Rivers in the ACF River basin are hydraulically connected to the Upper Floridan aquifer and the undifferentiated overburden. Near Lake Seminole, the Upper Floridan is thinly confined; where the aquifer is in close proximity to major streams, it commonly is breached, allowing

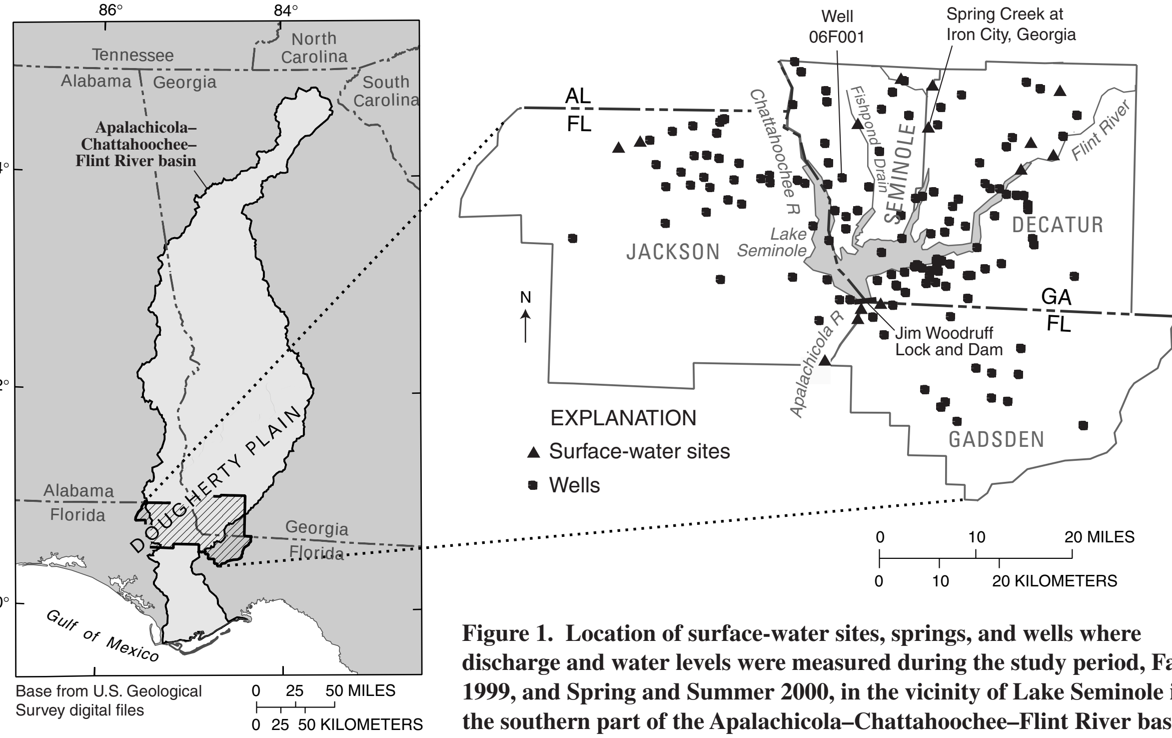

Figure 1. Location of surface-water sites, springs, and wells where discharge and water levels were measured during the study period, Fall 1999, and Spring and Summer 2000, in the vicinity of Lake Seminole in the southern part of the Apalachicola–Chattahoochee–Flint River basin.

flow between the stream and the ground-water system; thereby accelerating the dissolution of limestone and the development of springs (Torak and others, 1996).

Methods

Multiple discharge measurements were collected along selected stream reaches (fig. 1) during October 1999, April 2000, and August 2000 in the lower Apalachicola-Chattahoochee-Flint River basin using conventional methods, stream discharge and stage measurements, and acoustic Doppler current profiling. Ground-water discharge was measured at 17 springs upstream of Lake Seminole and south of Jim Woodruff Lock and Dam on the Apalachicola River. Water levels were measured in 76 wells in Georgia and Florida (fig. 1) using a steel tape. Net gains from or losses to the Upper Florida aquifer along selected stream reaches were calculated by subtracting upstream discharge measurements from downstream discharge measurements for each sampling period.

RESULTS

Three measurement periods were selected to characterize drought effects on seasonal low (October 1999) (fig. 2A), high (April 2000) (fig. 2B), and end of growing season (August 2000) (fig. 2C) ground-water and streamflow conditions. Annual ground-water highs typically occur during winter to late spring (February–April) and lows typically occur during summer and early fall (July–October), fluctuating by 20-30 feet yearly in response to precipitation and agricultural pumpage (fig. 3A). The hydrograph for well 06F001 (fig. 3A) shows typical annual water-level fluctuations during the years 1990-1997 preceding the drought, as the water level in the well recovers from ground-water pumping during the growing season. After the 1998 growing season, water levels recovered to only a fraction of previous years; water levels continue to decline as drought conditions affect water levels in the aquifer (fig. 3A).

Stream discharge generally is highest during winter and lowest during summer, following a pattern similar to the fluctuation of ground-water levels (fig. 3B). Typically, as water levels recover during fall and winter, ground water discharges to stream channels to become baseflow. The drought, however, suppressed the recovery of water levels in the aquifer, thereby reducing stream baseflow and resulting in a decrease of surface-water discharge. In October 1999, daily mean discharge at the gage at Spring Creek at Iron City, Ga., was comparable to the discharge measured in previous years (fig. 3B); however, flow generally increased to more than 2,000 cubic feet per second (ft^3/s) by spring. In April 2000, stream discharge at this gage was only 89 ft^3/s (fig. 2B), less than 10 percent of normal flow. By August 2000, the reach in the study area had gone dry—with less than 1 ft^3/s of discharge recorded at each gaging station in the study area (fig. 2C). Flows along the Flint River also are only a fraction of discharges

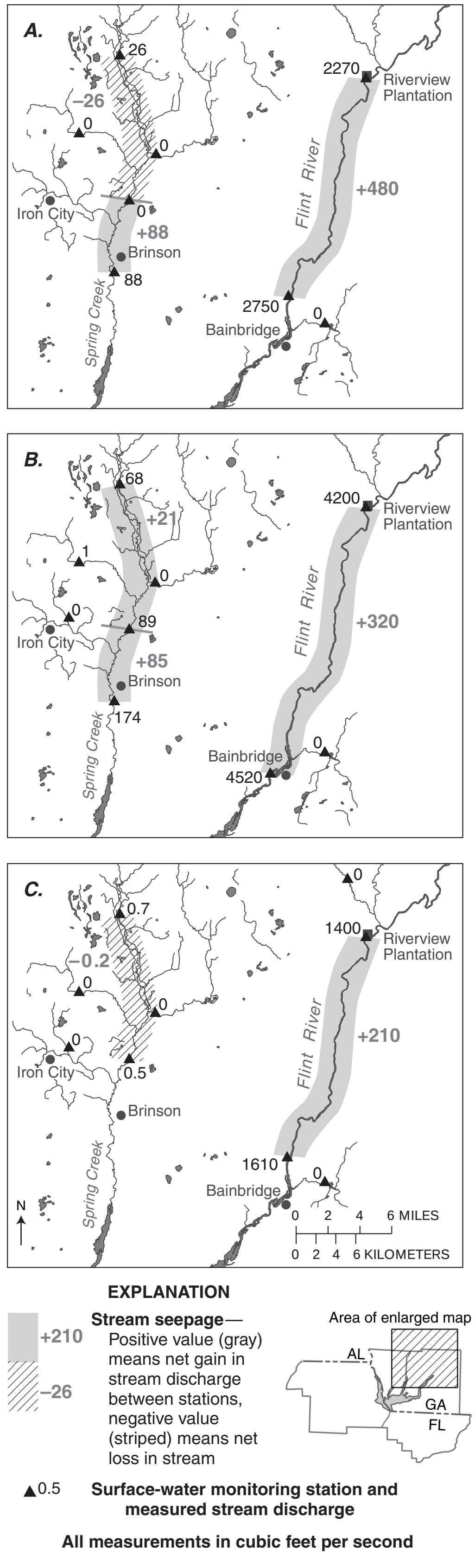

Figure 2. Stream seepage along the Flint River and Spring Creek reaches during *(A)* October 1999, *(B)* April 2000, and *(C)* August 2000.

recorded under normal conditions. In April 2000, discharge at the gage in Bainbridge was 4,520 ft^3/s (fig. 2B); from 1992-1997, discharge at this same gage generally was greater than 15,000 ft^3/s, three times the discharge during drought conditions.

The normal pool elevation for Lake Seminole is 77 feet above sea level; drought conditions caused lake levels to drop nearly 3 feet, to 74 feet above sea level. During previous years, ground-water levels fluctuated 20-30 feet; during the study period, however, water levels fluctuated only 10-15 feet, and often did not reach an elevation sufficient to contribute baseflow to streams near the lake. Potentiometric-surface maps of the Upper Floridan aquifer (fig. 4) show ground water flowed toward the impoundment arms of Lake Seminole during each sampling period, but also show little fluctuation in the magnitude or direction of flow between seasons. During all three sampling periods, ground-water elevations were essentially equal to lake level elevations north of the lake (fig. 4). Because ground-water levels are not recovering as they would under normal conditions, less ground water is discharging to streams, thus reducing flow to the impoundment arms. This is evident in Spring Creek where during October 1999 and August 2000, the northern portion of the reach was a losing reach (fig. 2A, 2C). Essentially, the stream channel lost water to the ground-water system; whereas under normal conditions or periods of typical seasonal flow (April 2000), the reach would have gained flow from ground-water discharge.

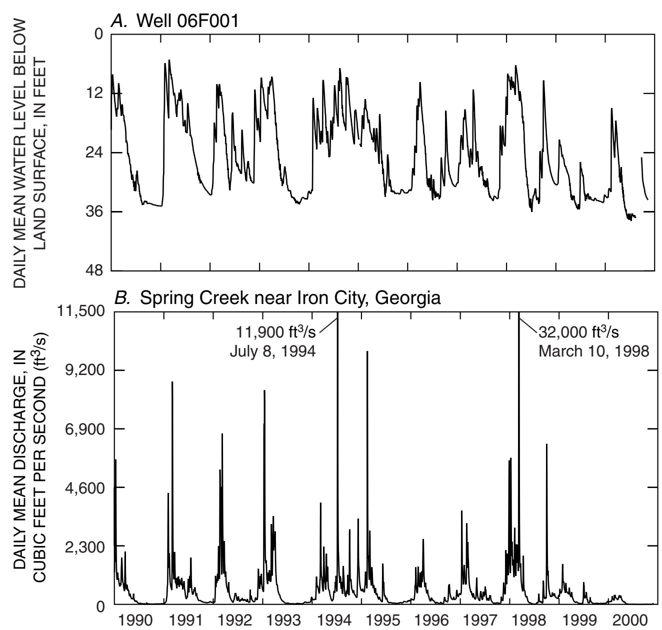

Figure 3. Hydrographs of daily mean *(A)* ground-water levels and *(B)* streamflow in the vicinity of Lake Seminole during Fall 1999, and Spring and Summer 2000.

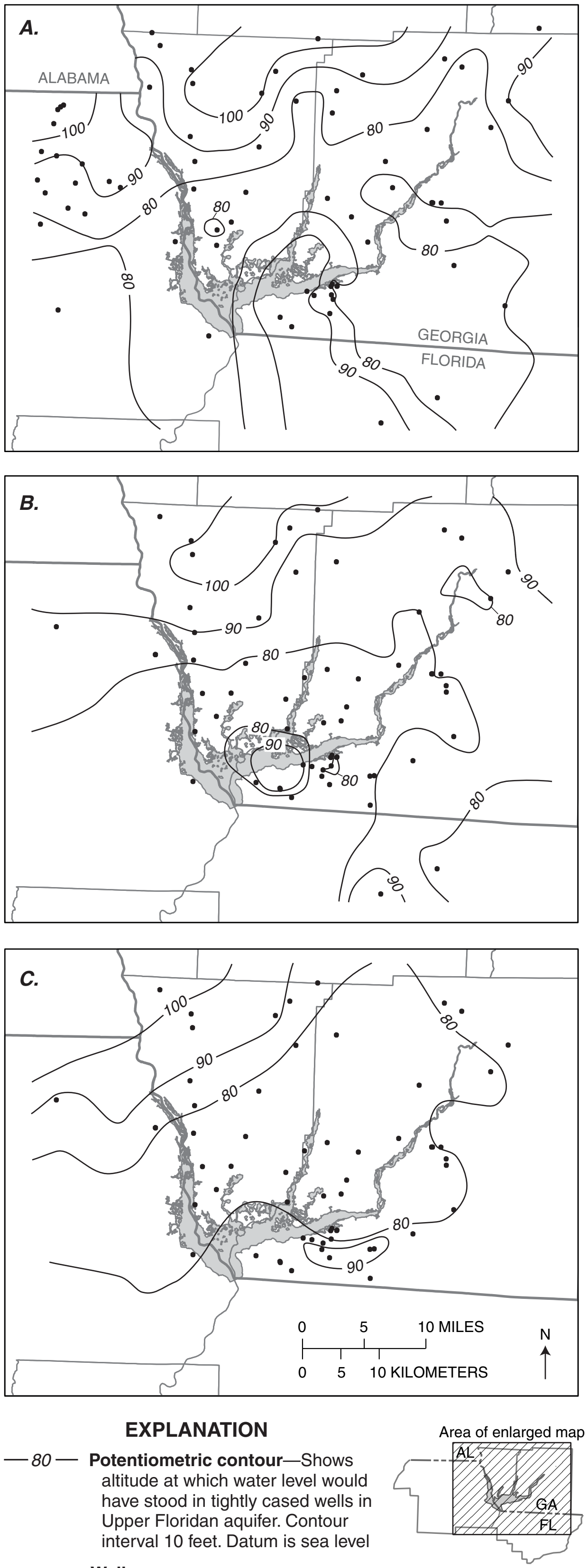

Figure 4. Potentiometric surfaces of the Upper Floridan aquifer during *(A)* October 1999, *(B)* April 2000, and *(C)* August 2000.

DISCUSSION

Although surface-water and ground-water conditions in the Lake Seminole area showed typical seasonal variations, with water levels declining in summer and early fall, and recovering in spring, drought conditions exacerbated the hydraulic relation between the ground-water and surface-water systems in the study area. Because the two systems are hydraulically connected, and therefore, interdependent, continuous monitoring of ground-water and surface-water conditions is necessary to delineate stream-aquifer relations, that can be used to effectively manage water resources in southwestern Georgia and adjacent states. Measurements collected during the three periods described in this paper provide a basis for developing this understanding and providing information needed to manage the area's water resources. Ongoing investigations of the water resources of the area are attempting to expand ground-water level and stream-discharge monitoring networks, to develop detailed hydrologic budgets, and to quantify stream–aquifer relations.

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U.S. Geological Survey, 2000 Georgia Drought Watch, 2000; *accessed* January 20, 2000, at **http://ga.water.usgs.gov/news/drought99/**.

PHYSICAL AND HYDROCHEMICAL EVIDENCE OF SURFACE-WATER/GROUND-WATER MIXING IN AND NEAR LAKE SEMINOLE, SOUTHWESTERN GEORGIA AND NORTHWESTERN FLORIDA

By Lynn J. Torak

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 122-128.

Abstract. Water resources of the Lake Seminole area in the lower Apalachicola–Chattahoochee–Flint River Basin emanate from an interconnected aquifer-stream-reservoir system that is centered around a constructed lake in a karst hydrogeologic setting. Ground water enters stream channels and the lake bottom by diffuse leakage and springflow; this water contains dissolved minerals from carbonate formations of the Upper Floridan aquifer. Water samples from wells adjacent to Lake Seminole contain higher concentrations of calcium and magnesium, and higher alkalinity and specific conductance than surface-water samples, which contain relatively high concentrations of total organic carbon and sulfate. Each of the four impoundment arms of Lake Seminole has a distinct water chemistry that can be attributed in part to the hydrodynamic connection of the lake bottom with the ground-water flow regime. Water chemistry and incremental discharge measurements in the Spring Creek impoundment arm indicate predominant ground-water discharge from the Upper Floridan aquifer into the lake. Chemical analyses and physical properties of water sampled from the dam pool and Apalachicola River indicate upwelling of lake water in the river downstream of Jim Woodruff Lock and Dam.

INTRODUCTION

Lake Seminole is a 37,600-acre reservoir that was created by the U.S. Army Corps of Engineers in the mid-1950's by constructing the Jim Woodruff Lock and Dam. The lake impounds the Flint and Chattahoochee Rivers near their confluence at the Georgia–Florida State line (fig. 1) and forms the headwaters of the Apalachicola River. The principal rivers of the lower Apalachicola–Chattahoochee–Flint (ACF) River basin are hydraulically connected to karstic and dolomitic limestone formations of the Upper Floridan aquifer and to carbonate residuum and alluvial deposits of the undifferentiated overburden, deriving baseflow from ground-water discharge from these units. The Upper Floridan aquifer underlies about 6,800 square miles of the lower ACF River basin and is one of the most transmissive and productive carbonate aquifers in the United States. Ground water is utilized extensively in the study area for agricultural, industrial, and domestic uses; such uses have been shown to reduce ground-water flow to streams (Torak and others, 1996; Torak and McDowell, 1996).

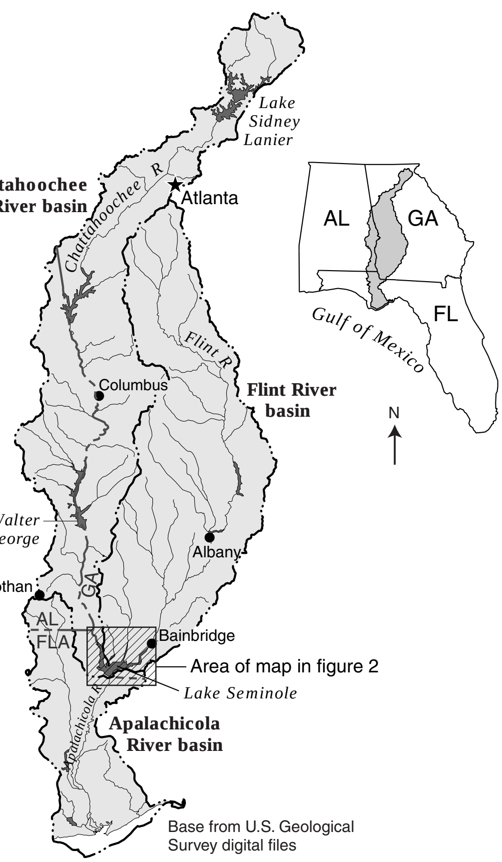

Figure 1. Location of Lake Seminole and the Apalachicola–Chattahoochee–Flint River basin, southwestern Georgia and northwestern Florida.

Recently, the lower ACF River basin has become the object of water-allocation negotiations between the states of Alabama, Florida, and Georgia (U.S. Army Corps of Engineers, 1999). Most of the ground water in the Upper Floridan aquifer originates as rainfall that enters the limestone directly through sinkholes or indirectly by infiltration through undifferentiated overburden. Sever (1965) estimated that 670 million gallons per day (Mgal/d), or 22 inches per year, of the region's annual 52-inch average rainfall recharges the Upper Floridan aquifer in the study area; of this amount, about 590 Mgal/d is not transmitted outside the study area under existing hydraulic gradients, but is discharged through springs into Lake Seminole.

In July 1999, the U.S. Geological Survey (USGS), in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, began a study to develop a water budget for Lake Seminole that incorporates surface-water and ground-water inflows and outflows, and atmospheric processes. This paper describes physical and hydrochemical evidence of surface water mixing with ground water in and around Lake Seminole. This information will help explain the origin and distribution of chemical constituents in the water resources of the Lake Seminole area and provide insight to the relative magnitude of water-budget components in the aquifer–stream–reservoir system.

Methods

During late-February and early-March 2000, 44 water samples were collected from wells, springs, streams, and Lake Seminole using standard sampling techniques of the U.S. Geological Survey (Wilde and others, 1999). Water samples were analyzed at USGS National Laboratories in Arvada, Colo., and Ocala, Fla., for major inorganic ions and total organic carbon (TOC) (fig. 2). At some stream sites, calcium (Ca) and magnesium (Mg) concentrations measured in water sampled in June 2000 were substituted for the late-February, early-March results, because samples were not collected during the earlier sampling period.

Water levels were measured in wells and stream stage and discharge measurements were made along springs and streams in October 1999, and in April, August, and September 2000. In September 2000, discharge measurements were made along the Spring Creek impoundment arm of Lake Seminole using conventional discharge-measuring techniques and acoustic Doppler current profiling.

RESULTS

Analyses of water samples from wells, springs, streams, and Lake Seminole indicate that ground water has higher values of specific conductance and alkalinity, and higher concentrations of Ca and Mg than surface water, which contains higher concentrations of TOC and sulfate (fig. 2). These results are particularly evident for Sealy's Spring (fig. 2), which, although located in the bottom of Lake Seminole, contains chemical constituents that indicate a ground-water origin. Higher concentrations of chemical constituents in ground water than in surface water are consistent with carbonate dissolution of limestone (Ca and Mg carbonate) units that form the Upper Floridan aquifer; an increase in TOC is consistent with organic enrichment of surface water (Appelo and Postma, 1994).

Stream-discharge measurements and flow from numerous springs along Spring Creek indicate that most flow into Lake Seminole from the Spring Creek impoundment arm originates as ground water (fig. 3). Additional physical evidence of ground-water flow into Spring Creek and Lake Seminole is indicated by the water level in wells surrounding the Spring Creek impoundment arm (fig. 4); these were higher than lake level during all periods of measurement in 1999 and 2000. Water chemistry corroborates physical evidence of ground water mixing with surface water, because water from wells adjacent to Spring Creek contain chemical constituents in concentrations that are similar to water sampled from the creek (fig. 2).

Physical and hydrochemical evidence of ground water mixing with surface water exists in the Apalachicola River directly downstream of Jim Woodruff Lock and Dam. Here, water containing concentrations of chemical constituents similar to lake water "boils" up from the Upper Floridan aquifer at a discharge point in the bottom of the river (fig. 2). Apparently, water from behind the dam enters the Upper Floridan aquifer by leakage through the lake bottom, then flows in the aquifer beneath the dam, subsequently discharging through the channel bottom of the Apalachicola River. Flow measurements made using acoustic Doppler current profiling in October 1999 and April 2000 indicate that the "River Boil" discharges about 140 and 210 cubic feet per second, respectively, into the Apalachicola River.

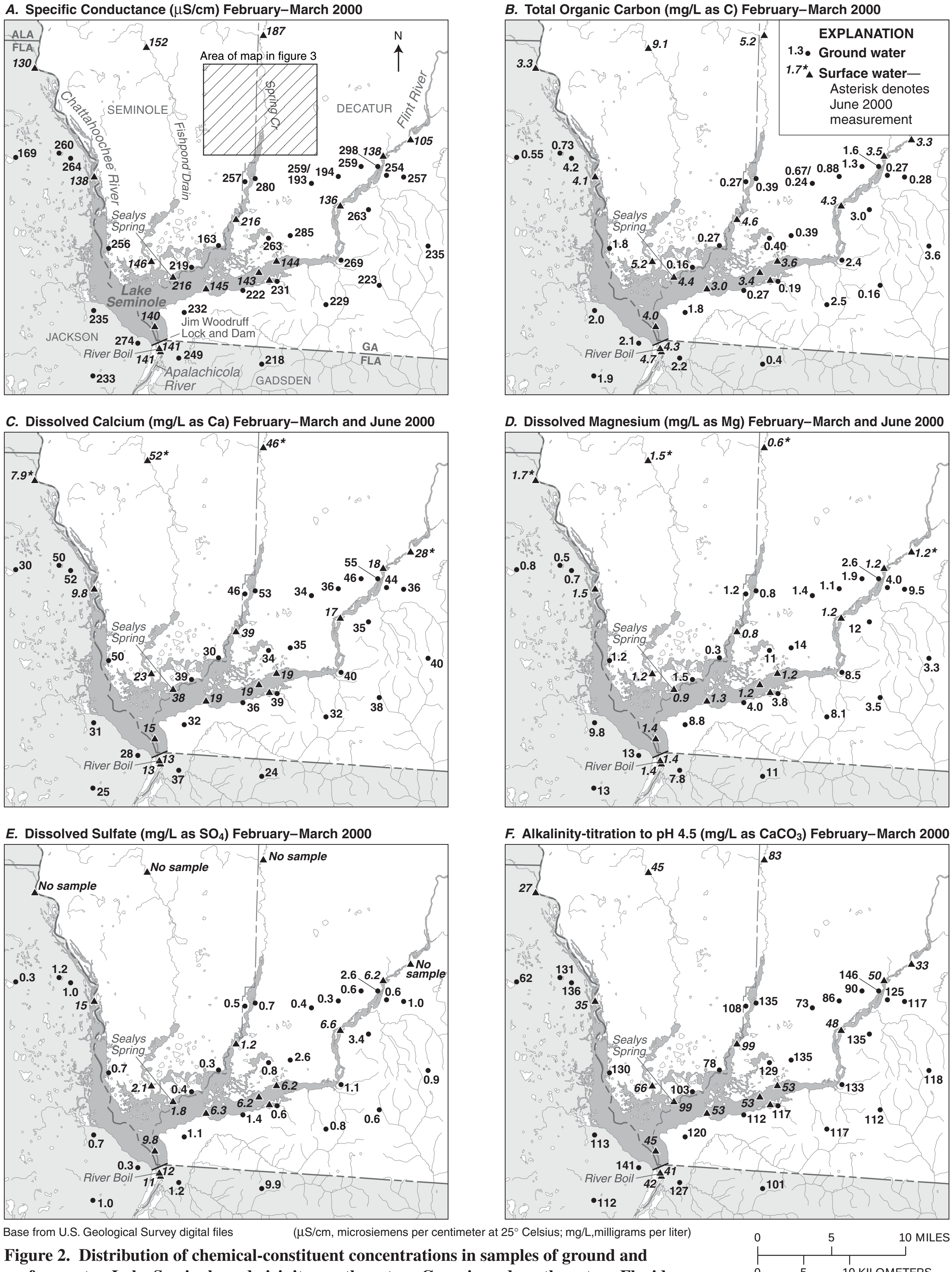

Figure 2. Distribution of chemical-constituent concentrations in samples of ground and surface water, Lake Seminole and vicinity, southwestern Georgia and northwestern Florida.

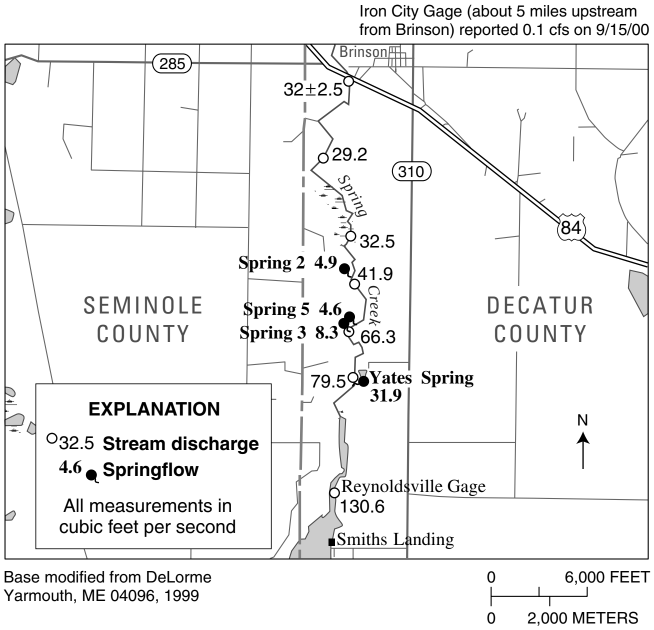

Figure 3. Spring Creek impoundment arm to Lake Seminole showing locations of stream-discharge and springflow measurements made on September 15, 2000.

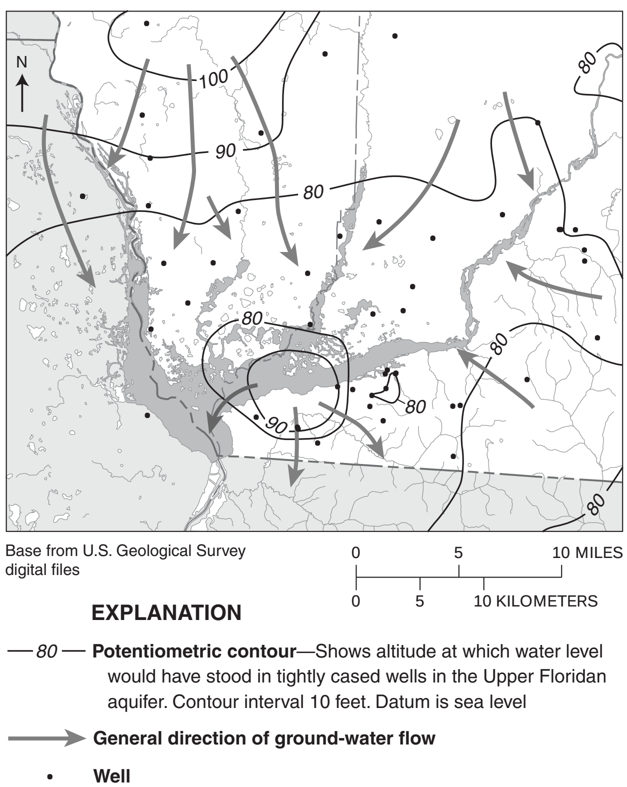

Figure 4. Potentiometric surface of water level in wells completed in the Upper Floridan aquifer, April 2000.

DISCUSSION AND CONCLUSIONS

Water from streams, Lake Seminole, and the Upper Floridan aquifer in the lower ACF River basin has a distinct chemical signature that can be used to investigate flow and mixing processes in and around the lake. Ground-water discharge by diffuse leakage along the four impoundment arms of Lake Seminole and by springflow located in the lake bottom and adjacent to Spring Creek create a complex mixing environment evidenced by hydrochemical data and physical hydrologic characteristics. Although these water-chemistry analyses share similarities with previous water-chemistry studies in the karst environment of the Upper Floridan aquifer in the Suwannee River Basin (Katz and others, 1997; Crandall and others, 1999), the karst features of the Lake Seminole area and the irregular impoundment-arm geometry result in a unique mixing environment for ground-water discharges to the lake. Ground water enters Lake Seminole by diffuse vertical leakage and point inflow from springs. These two main mechanisms for ground-water inflow to the lake are distributed widely along the lake's impoundment arms and preclude detection of downstream water-quality trends in the impoundment arms. Ground water contains higher concentrations of Ca, Mg, and alkalinity, and lower concentrations of TOC and sulfate, which is indicative of carbonate dissolution in the Upper Floridan aquifer. Chemical analyses and physical properties of water sampled from the dam pool and Apalachicola River indicate upwelling of lake water in the river channel downstream of Jim Woodruff Lock and Dam.

The complex interconnection of ground water and surface water in the lower Apalachicola-Chattahoochee-Flint River basin poses several interesting implications relative to the water-allocation negotiations. Thoroughly understanding the mixing dynamics of ground- and surface-water components of the stream-reservoir–aquifer system is essential for developing effective water-management strategies that not only account for these components, but contain provisions to quantify the contribution of each component to the entire flow regime. Mixing model relations based on the distinct chemical signatures of ground water and surface water could be developed in areas where lake leakage is suspected to occur. Such relations would be particularly useful from a water-management and allocation perspective, especially for evaluating ground-water flow near the dam and across the Georgia-Florida State line, where changes in leakage might indicate changes in ground-water flow across the State line and/or increased leakage from the lake. Physical and hydrochemical evidence of ground water mixing with surface water indicates that ground water and surface water form a single hydrologic entity, although each reacts differently with the surface and subsurface environment. Effective management of the basin's water resources will be based on utilizing this scientific knowledge and understanding of the interconnection of ground-water and surface-water flow to develop water-allocation practices that incorporate all components of the stream-reservoir-aquifer system.

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COMPARISON OF PRE- AND POST-IMPOUNDMENT GROUND-WATER LEVELS NEAR THE JIM WOODRUFF LOCK AND DAM SITE JACKSON COUNTY, FLORIDA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 127-128.

Abstract. In 1999, the U.S. Geological Survey (USGS) and the Georgia Department of Natural Resources, Environmental Protection Division, began a cooperative study to investigate the hydrology and hydrogeology of the Lake Seminole area, southwestern Georgia, and northwestern Florida. Lake Seminole is a 37,500-acre impoundment that was created in 1954 by the construction of the Jim Woodruff Lock and Dam just south of the confluence of the Chattahoochee and Flint Rivers (fig. 1). Recent negotiations between the States of Alabama, Florida, and Georgia over water-allocation rights have brought attention to the need for a better understanding of both the hydrologic and hydrogeologic systems associated with Lake Seminole.

Vernon and others (1958) studied the geology in the Lake Seminole area just before the reservoir was filled. They indicated that underlying the study area immediately to the west of the Jim Woodruff Lock and Dam is a sequence of units composed of alternating layers of sand and clay grading into carbonate rock units.

Current and pre-Lake Seminole ground-water levels and flow paths were compared as part of this study. Pre-impoundment ground-water levels measured in the 1940's by the U.S. Army Corps of Engineers in the vicinity of the then-proposed dam (U.S. Army Corps of Engineers, 1948) were examined and compared with a potentiometric-surface map based on ground-water levels that were measured in July 2000 by the USGS as part of this investigation.

Comparing pre-impoundment and post-impoundment ground-water levels indicate that the creation of Lake Seminole has altered local ground-water flow directions on the southwest side of the impoundment. Pre-impoundment water levels indicate that ground-water flowed in an easterly direction to the Chattahoochee and Apalachicola Rivers. A recent (July 2000) potentiometric-surface map of the area indicates flow directions have shifted to a southerly direction just west of the Jim Woodruff Lock and Dam.

The effect of filling the reservoir on ground-water levels also is indicated by long-term water-level data from a well near Lake Seminole in Florida. Sporadic, long-term water-level measurements began at this well in 1950 and have continued during filling of the reservoir (1954-1957) until 1982. These data indicate that the water level in this well has risen more than 10 feet since the filling of the reservoir. Prior to filling, the hydraulic gradient at this location sloped east and northeast to the Chattahoochee River. Now it slopes in a southerly direction near the western end of Jim Woodruff Lock and Dam and to the Apalachicola River.

In conclusion, pre- and post-impoundment ground-water levels indicate that the creation of Lake Seminole has altered ground-water-flow directions in the area immediately to the west of the Jim Woodruff Lock and Dam. Lack of pre-impoundment data precludes comparing pre- and post-water levels in other areas around the lake.

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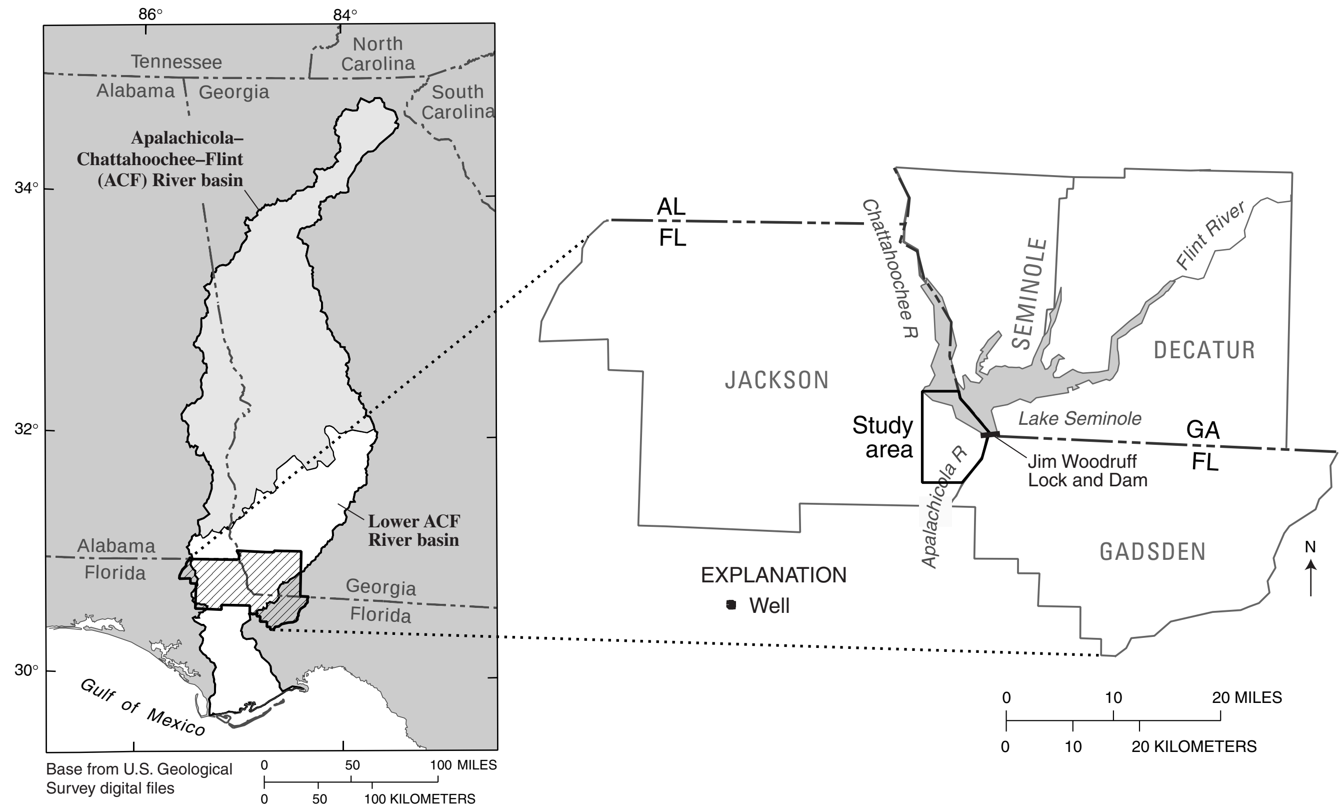

Figure 1. Location of study area.

SIMULATED EFFECTS OF PUMPAGE AND CLIMATIC CONDITONS ON STREAM-AQUIFER FLOW IN STREAMS HARBORING FEDERALLY PROTECTED MUSSEL SPECIES, NORTHWESTERN FLORIDA AND SOUTHWESTERN GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 129-130.

Abstract. In 1999, the U.S. Geological Survey (USGS) and the U.S. Fish and Wildlife Service began a cooperative investigation in the lower Apalachicola-Chattahoochee-Flint (ACF) River basin (fig. 1) to determine effects of pumpage and extreme climatic conditions on stream reaches that are habitat to federally protected mussel species. This study links the results of a previous USGS ground-water flow modeling study (Torak and McDowell, 1996) with results of recent mussel surveys presented by Brim Box and Williams (2000) and by Paula Johnson (Joseph W. Jones Ecological Research Center, Newton, Georgia, written commun., 1999). Results of this study will aid the U.S. Fish and Wildlife Service in the management of federally protected mussel species and in assessing water-allocation alternatives developed by the States of Alabama, Florida, and Georgia.

The lower ACF River basin encompasses about 6,800 square miles of the Coastal Plain physiographic province in parts of southeastern Alabama, northwestern Florida, and southwestern Georgia. Principal rivers drain sandy and carbonate beds of the Upper Floridan aquifer and Intermediate system (Torak and others, 1996), as well as undifferentiated surficial deposits.

Ground-water and surface-water in the study area are interconnected and interdependent. During spring and summer, agricultural demands for ground-water, coupled with the seasonal decline of aquifer water levels, reduce streamflow from conditions that occurred earlier in the year. Drought conditions during summer can accentuate already low ground-water-levels and surface-water-flow conditions and pose a threat to federally protected mussel species that make their habitat in streambeds of the lower ACF River basin. The high degree of interconnection between the aquifer and streams in this region suggests that increased ground-water pumpage caused by drought or agricultural practices can reduce stream flow, lower water levels, and thus have a detrimental effect on mussel habitat.

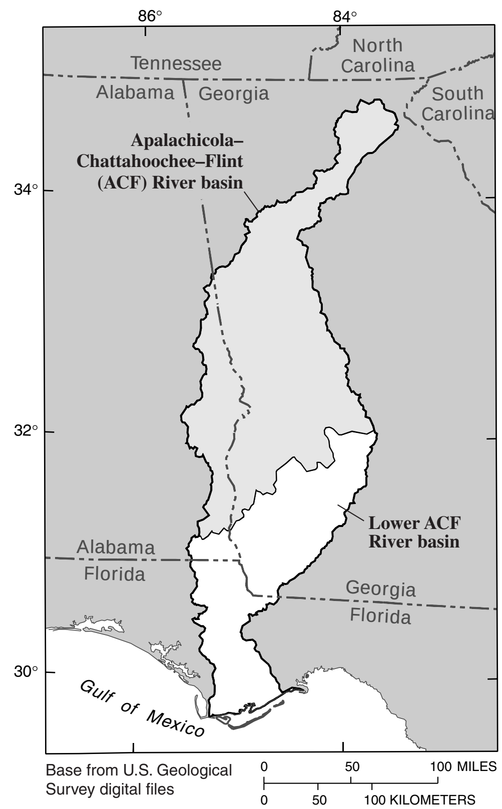

Figure 1. Location of the lower Apalachicola–Chattahoochee–Flint River basin.

Thirty seven stream reaches in the lower ACF River basin were ranked according to the simulated effects of pumpage and climatic conditions on ground-water inflow to or surface-water outflow from reaches that were reported in a modeling study by Torak and McDowell (1996). The simulated ground-water inflow to and surface-water outflow from the reach occurs across the wetted perimeter of the streambed and was termed stream-aquifer flow (Torak and McDowell, 1996). Stream reaches were ranked either high, medium, or low, depending upon the relative change in simulated stream-aquifer flow to the reach due to changes in pumpage. The ranking procedure was affected by the type of stream, either minor or major, and in some cases, was affected by inflow to the reach from upstream.

The rank of each reach was assigned by determining the magnitude of pumpage that was required to simulate zero stream-aquifer flow; plots of stream-aquifer flow by pumping rate were constructed for this purpose using model results listed in Torak and McDowell (1996). A "high" sensitivity ranking was given to a reach if stream-aquifer flow for the reach was zero at pumping rates that were less than five times the estimated October, 1986 pumping rate. This means that minor (low order) streams ranked high would dry up at a pumping rate less than 5 times the October 1986 basin pumping rate and that major stream reaches (high order streams) ranked high would be neither gaining or losing stream reaches. If stream–aquifer flow was zero for pumpage that was between five and ten times the estimated October 1986 pumping rate, then the reach was assigned a rank of "medium." To reaches containing zero stream-aquifer flow for pumpage greater than ten times the October 1986 pumping rate, a "low" rank was assigned. For major streams, simulated zero stream-aquifer flow did not produce dry-stream conditions; thus the reach is neither gaining nor losing.

Results indicate that 13 of the 37 simulated reaches ranked high in response to pumpage. Of these 13 reaches, 11 contain federally protected mussel species. Of the 37 reaches, the most sensitive reach to pumpage during drought conditions occurs along Spring Creek. This is verified by streamflow records at a continuous-recording gaging station at this location during the year 2000. Zero discharge occurred twice during the fall.

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USING THE DIGITAL ENVIRONMENTAL ATLAS OF GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 160-161.

Abstract. The U.S. Geological Survey (USGS) and Georgia Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey, recently released (2000, updated and re-released in 2001) a two-volume Compact Disc (CD) set entitled "Digital Environmental Atlas of Georgia" (Atlas) containing computer readable data sets for geographic information systems (GIS). The Atlas not only provides a wide range of traditional maps, but also enables users to experiment with their own individually created maps through personal-computer-based GIS software included on the CDs. The information on the CD set will help Georgia's students learn more about their State and will be useful to businesses and various local, State and Federal agencies.

The CDs contain 38-digital map data sets covering the State of Georgia that are useful to the general public, private industry, schools, and government agencies. The data sets include:

- towns and cities;
- public lands;
- State parks;
- trails and greenways;
- county boundaries;
- geographic names;
- hydrologic units;
- shorelines;
- soils;
- major roads;
- public airports;
- river reach–major streams;
- roads;
- USGS Ground-Water Site Inventory;
- hydrography;
- 7.5-minute topographic quadrangle index;
- USGS surface-water monitoring stations;
- elevation contours;
- 1:250,000-scale digital elevation model;
- 1:100,000-scale digital raster graphic;
- 1:250,000-scale digital raster graphic;
- 1:500,000-scale digital raster graphic;
- land cover;
- Level I land use, Level II land use;
- pipelines;
- transmission lines and miscellaneous transportation;
- railroads;
- river corridors with mean-annual streamflow greater than 400 cubic feet per second;
- 1:250,000-scale slope;
- National forests;
- physiographic provinces;
- surficial geology;
- geologic dikes;
- geologic faults;
- ground-water pollution susceptibility;
- most significant ground-water recharge areas; and the
- Georgia Department of Transportation state highway map.

ArcExplorer[1/],Version 1.1 software, by Environmental Systems Research Institute, Inc., is included on the CDs. ArcExplorer allows the user to display combinations of data sets and attributes using selected colors and patterns. Spatial and logical queries also can be performed to locate selected sets of attributes. ArcExplorer gives the user the ability to perform the following spatial functions using the data sets on the CDs:

- overlay multiple data sets;
- identify data-set features;
- find and locate features using data-set attributes;
- query the data sets using Boolean logic;
- create tables of selected data-set features;
- create custom maps for use in reports; and
- measure areas and distances within data sets.

Three examples of these capabilities are illustrated below. The included ArcExplorer GIS interface depicting user-selected spatial data is shown in figure 1. Results from a query of residential land use by county (DeKalb) is shown in figure 2. Both tabular and graphical results are displayed. A schist mica/gneiss/amphibolite geologic formation in the vicinity of Stone Mountain, over a 1:100,000-Scale topographic map of the area is shown in figure 3. Additional examples depicting a variety of uses for the data covering the functionalities listed above are included on the CD.

Additional GIS information for Georgia may be accessed through the USGS, Georgia District World Wide Web home page at **http://ga.water.usgs.gov** or on the Georgia Department of Natural Resources website at **http://www.dnr.state.ga.us**. Similar information products are being made available by the Georgia GIS Clearinghouse (with active participation from a number of Federal and State and local agencies), website at **http://www.gis.state.ga.us**.

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[1/]Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

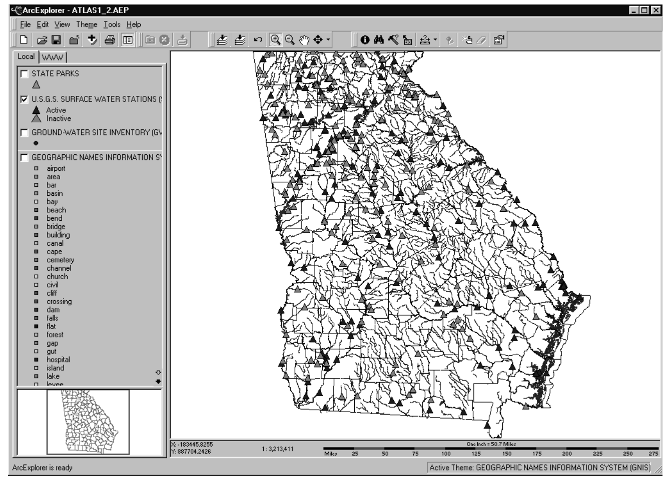

Figure 1. ArcExplorer GIS interface to the Digital Environmental Atlas of Georgia.

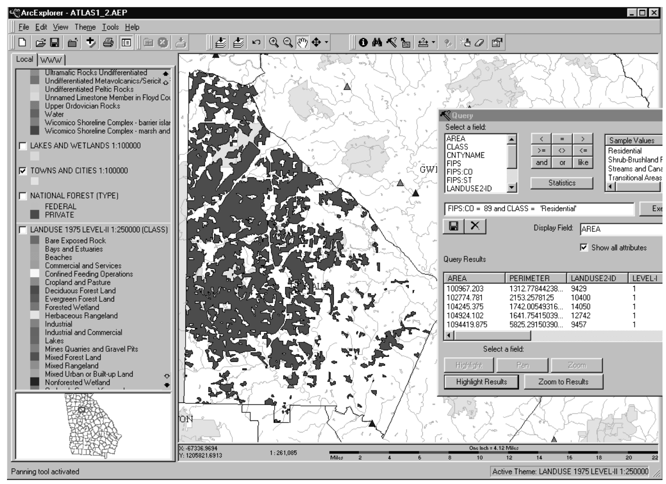

Figure 2. Selection and display of residential land use by selected county (DeKalb County, for example).

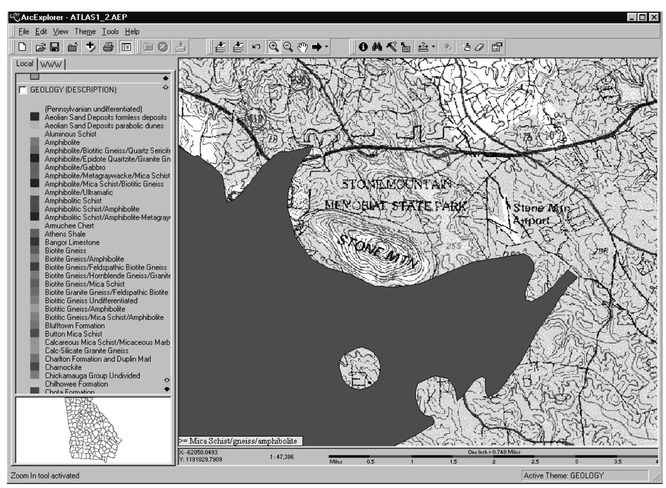

Figure 3. Mica schist/gneiss/amphibolite geologic formation in the vicinity of Stone Mountain, Georgia.

USING THE DIGITAL SURFACE-WATER ANNUAL DATA REPORT FOR GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 162-164.

Abstract. The U.S. Geological Survey (USGS), Georgia District, in cooperation with Federal, State, and local agencies, has revised the Georgia Surface-Water Annual Data Report—previously published as a paper report—to a new, more informative and functional format on CD-ROM. The new format is based on a geographic information system (GIS) user interface that allows the user to view map locations of the hydrologic monitoring stations and networks within their respective basins.

Several methods are provided for users to easily search for and retrieve data on stations. Graphical summaries of the current water year—October to September—and selected historical data illustrate seasonal and annual stream characteristics. Users can view or print out site information and data tables in the traditional paper report format, or download data for their use with other applications.

This digital data report includes the annual surface water data that has historically been published as a paper report. The CD-ROM, Georgia Surface-Water Annual Data Report, adds more functionality for the user, including graphical views of the data, digital files of data sets from each gaging station, a site location map, and photography at selected station locations. These options for a streamflow (discharge) station are shown in figure 1. The CD-ROM also contains user-friendly help and examples.

The first page of the station summary (fig. 2) gives the user a graphical summary of the selected streamflow station. An annual hydrograph, a graph of historic monthly statistics (maximum, minimum and mean), a graph of annual mean streamflow, a graph of annual peakflows, a site location map, and a photograph are included for most sites. The summary file is comprised of a station manuscript, which contains descriptive information, period of record, location, historical extremes, record accuracy and comments, as well as annual data tables of daily records, monthly statistics, and period-of-record statistics.

The data sets contained on this CD-ROM include the stage and streamflow from all continuous and non-continuous gaging stations for the 1999 water year. All continuous water-quality monitoring data sets also are included in this release. Discrete water-quality sampling sites and continuous ground-water-level monitoring wells are shown as network data layers; however no measurement data are included on this CD-ROM. Work is proceeding on similar CD-ROM reports for each of these networks.

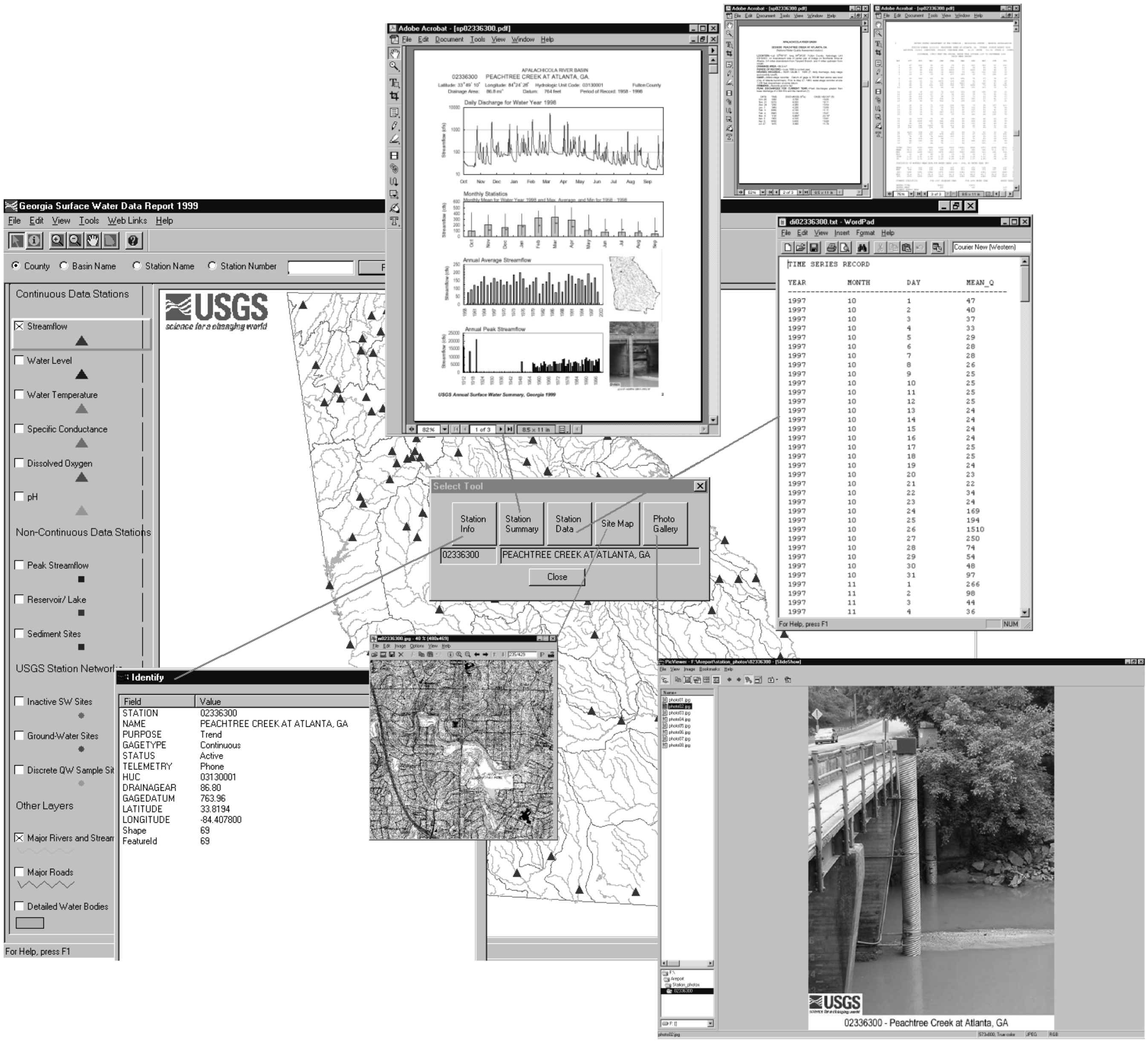


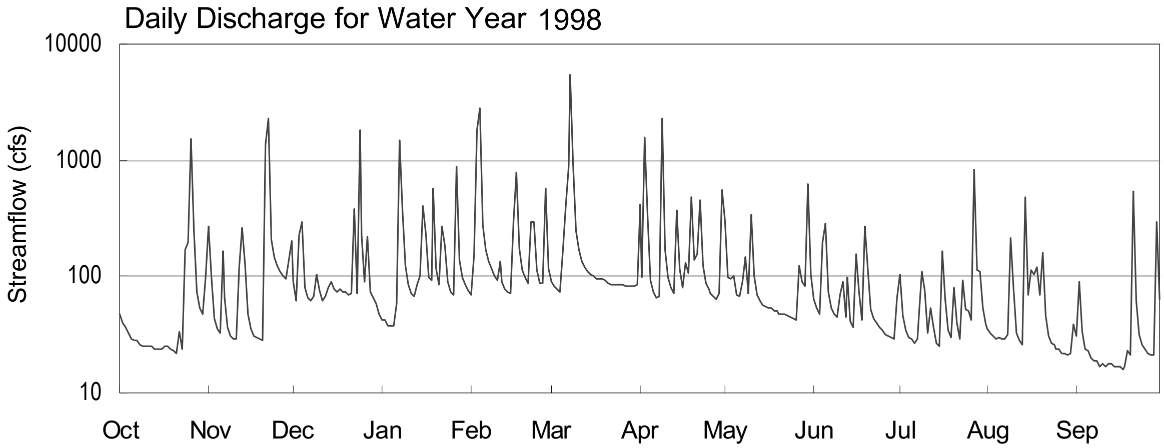
Figure 1. Options for a selected streamflow (discharge) station.

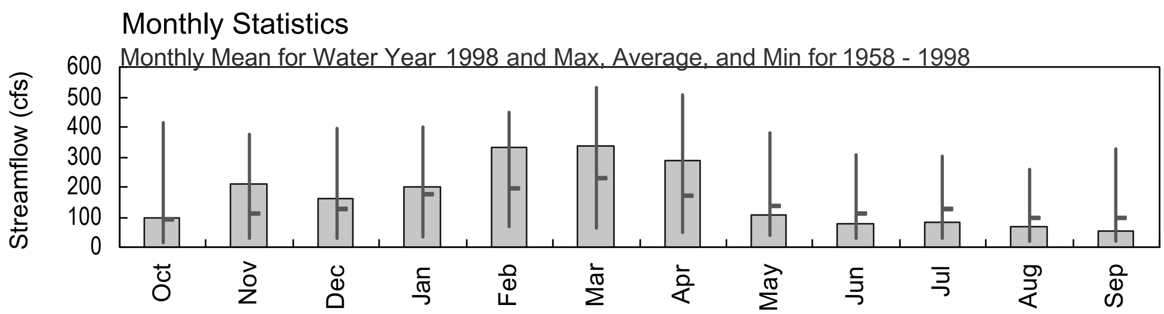
APALACHICOLA RIVER BASIN

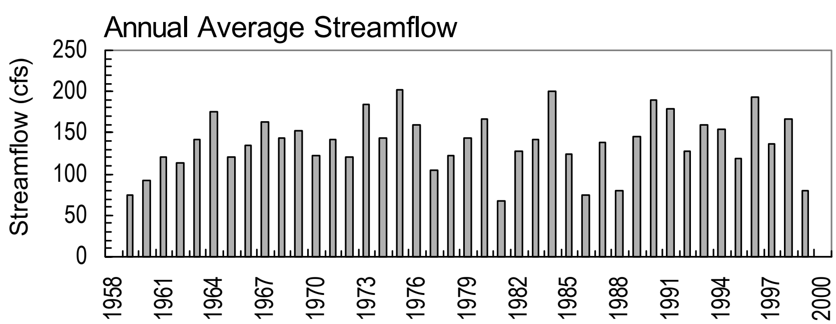
02336300 PEACHTREE CREEK AT ATLANTA, GA.

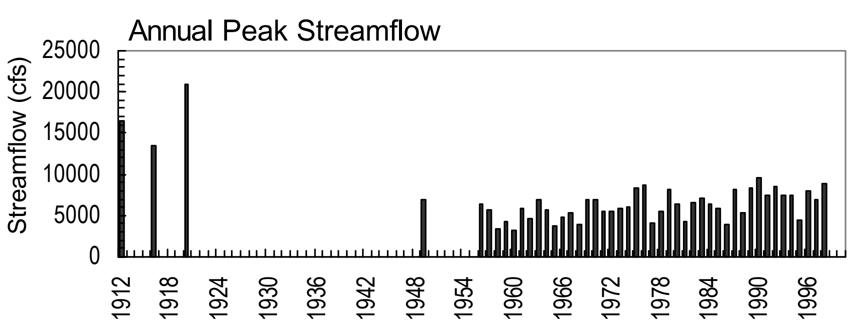
Latitude: 33°49'10" Longitude: 84°24'28" Hydrologic Unit Code: 03130001 Fulton County

Drainage Area: 86.8 mi² Datum: 764 feet Period of Record: 1958 - 1998









USGS Annual Surface Water Summary, Georgia 1999 2

Figure 2. Graphical summary page for Peachtree Creek at Atlanta.

GEORGIA HYDROWATCH—A NEW CONCEPT IN HYDROLOGIC MONITORING FOR GEORGIA

By Brian E. McCallum[1/] and John K. Joiner[2/]

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at the University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 165-168.

Abstract. The U.S. Geological Survey (USGS), Atlanta, Ga., is currently in the process of establishing a statewide real-time hydrologic monitoring network called *Georgia HydroWatch*. In cooperation with numerous Federal, State, and local agencies, the USGS is upgrading many of the existing 143 stream-gaging, coastal, and water-quality stations to include satellite telemetry that relay hydrologic data from the monitoring stations to the USGS office in Atlanta. Combined in this upgrade is the installation of rain gages at as many sites as possible—for better drought monitoring and flood forecasting. To ensure reliable data reception, the USGS has installed a satellite-data receiver station so data are received directly from the satellite at the office; and then automatically entered into the USGS data base and the Georgia District World Wide Web page within minutes of transmission from a gage.

INTRODUCTION

The U.S. Geological Survey (USGS), Atlanta, Ga., is forming the foundation for a statewide real-time hydrologic monitoring network of automated gaging stations—called the *Georgia HydroWatch*. The network will provide continuous real-time river stage, streamflow (discharge), precipitation, meteorological, and water-quality data to interested parties. These data currently are displayed on the USGS World Wide Web page (**http://wwwdgadrv.er.usgs.gov/usgs/**); however, new means of disseminating the data will be implemented once the upgrade of the network of stations is completed. The *Georgia HydroWatch* concept was formulated in January 2000, and has quickly received support throughout the State because of its relevance to water-resources issues facing Georgia. This paper includes a general overview of the statewide network, a description of the instrumentation used at the gaging stations, an overview of the satellite transmission process, how the data are disseminated to users, and a discussion of how these real-time data are valuable to many different users.

OVERVIEW OF STATEWIDE NETWORK

As of December 2000, the network of 143 gaging stations operated by the USGS has three levels of telemetry available to relay hydrologic data to the USGS office in Atlanta. *Satellite telemetry* refers to delivery of data via satellite, in four-hour intervals. *Phone telemetry* refers to delivery of data using landline modems that interrogate each station twice daily. *No telemetry* stations require USGS personnel to visit a site on a routine basis and manually retrieve recorded data. The sites displayed as *proposed upgrades* will be upgraded with satellite telemetry and a rain gage during fiscal year 2001. Of these 143 stations, only one currently transmits water-quality data, and only two transmit meteorological data—such as wind speed and wind direction. Precipitation data from rain gages are transmitted from 12 stations statewide. During fiscal year 2001, plans are to instrument at least 22 additional stations to transmit water-quality data, more than 90 additional rain gages statewide, and add a third meteorological station.

Figure 1. Typical U.S. Geological Survey gaging station.

Prior to January 2000, landline telephone telemetry was the preferred method to relay hydrologic data collected by the USGS, Georgia. When that system was installed in the late 1970's, landline telephone telemetry was state-of-the-art. Compared to today's technology; however, it is obsolete and unreliable. In January 2000, the USGS proposed to convert to satellite telemetry and to install rain gages at every gaging station, with the goal of being 100 percent real-time satellite telemetry within three years. This ambitious goal requires the funding support of numerous cooperating agencies, and a significant investment of time and training. Advantages and benefits of conversion to satellite telemetry include more reliable and timely data collection; reduction of ongoing telephone line service costs; and elimination of outdated instrumentation.

INSTRUMENTATION

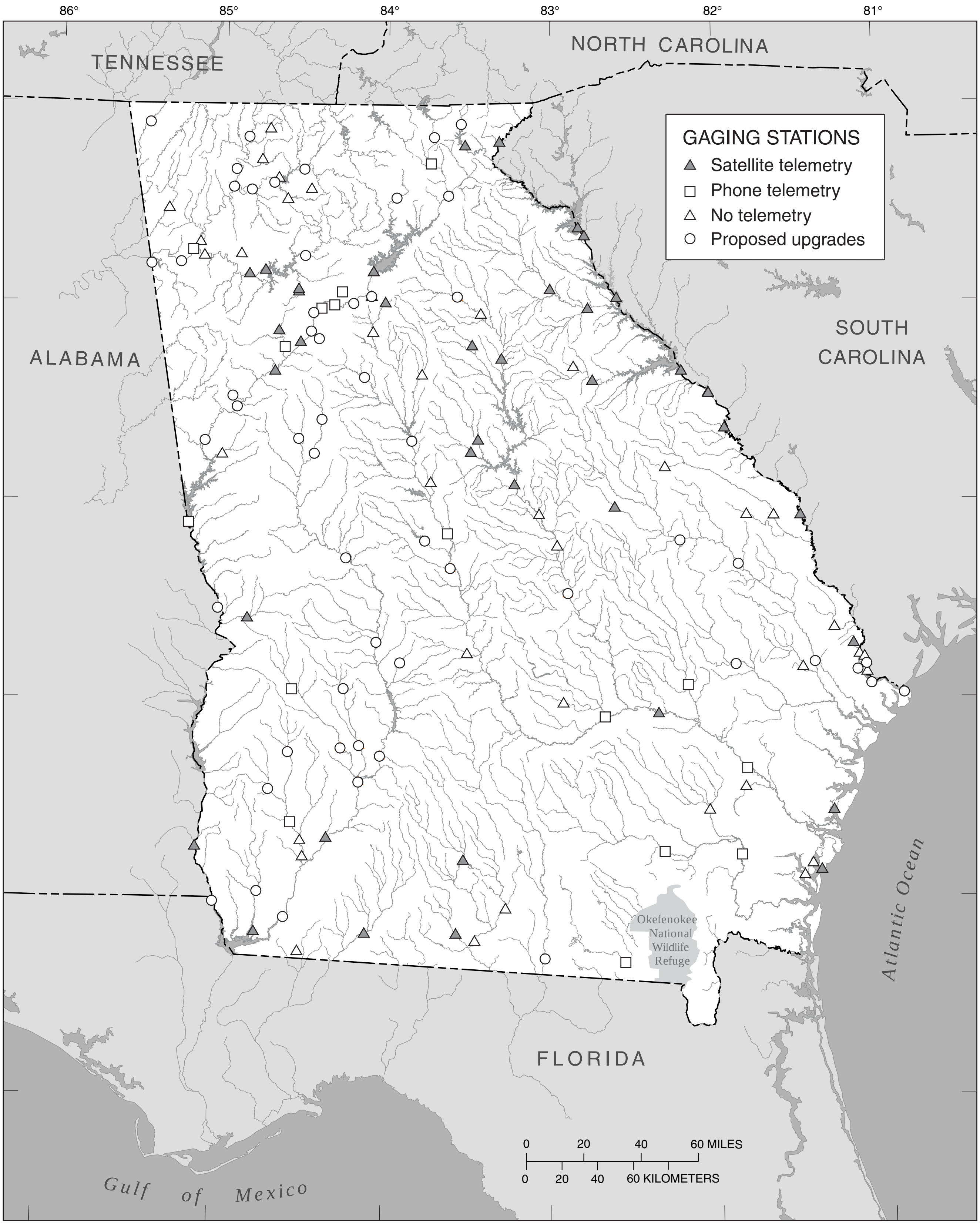
The USGS has developed a standard instrumentation package for the network of gaging stations to better facilitate achievement of the three-year goal. Each gaging station upgrade consists of a commercially available Data Collection Platform (DCP), a water-level sensor, a tipping-bucket rain gage, and an independent power system. The DCP houses a Geostationary Orbiting Earth Satellite (GOES) satellite radio transmitter equipped with a backup data logger. The DCP can accept input from various digital and analog hydrologic sensors, and uses on-board memory to store, manipulate, and transmit data. Typical water-level sensors include a float and pulley system using a digital incremental shaft encoder, submersible electronic pressure transducers, or non-submersible "bubbler" pressure transducers. The tipping-bucket rain gage has a self-calibrating feature that measures the intensity of a rainfall event and compensates for loss of water during the tip of the bucket. The independent power system uses a 20-watt solar panel and rechargeable battery. All instrumentation is housed in a steel or aluminum gage shelter that usually is mounted on the downstream side of a bridge. A typical example of one of these gaging stations is shown in figure 2.

SATELLITE TRANSMISSION PROCESS

Currently, the GOES satellite transmitters use 100-baud rate radios to transmit digital data in a one-minute transmit window once every four hours. Depending upon the quantity of data to be transmitted, a message can be either in ASCII text or in pseudo-binary format. A typical gaging station can easily transmit eight hours of 15-minute stage, rainfall, and battery-voltage data, as well as DCP diagnostic information, within the one-minute window using the ASCII text format. By transmitting eight hours of data, there is a four-hour overlap of *redundant* data in case of an interference problem with the previous transmission. A new system using 300-baud rate radios is proposed to be implemented by 2010 and would allow hourly data-transmission intervals.

In addition to four-hour standard transmission intervals, a DCP can be programmed to use satellite emergency channels to transmit in an instantaneous mode. Pre-set thresholds are programmed into the DCP to trigger this instantaneous mode (for example, stream stage, where the threshold is set to the gaging station's flood stage). The stage sensor is interrogated every 15 minutes, and if that threshold is exceeded, an instantaneous transmission is sent; this process will continue until that threshold is no longer exceeded. The USGS is currently using a combination of four types of instantaneous thresholds: (1) rainfall rate-of-change, (2) stage rate-of-change, (3) water level, and (4) wind speed. The values of these thresholds and the combinations of their use are usually site specific.

A standard transmission is sent from the DCP to the GOES satellite and relayed through a ground receiver station in Wallops, Va.; then re-transmitted to a commercial satellite. From this commercial satellite, the USGS can directly receive the signal. Automated processing software decodes the signal, places the data directly into the USGS data base, and then posts the data to the USGS, Georgia District World Wide Web page within five minutes of arrival of the transmission. The most recent hydrologic data can be transferred "from the stream to your screen" in less than 15 minutes.



Base from U.S.Geological Survey
Digital files

Figure 2. The Georgia HydroWatch network, December 2000.

Currently, the Internet World Wide Web page is the only automatic means of disseminating USGS real-time hydrologic data. Real-time data are considered provisional and subject to change upon final review. The USGS, Georgia District, web page is located at:

http://ga.water.usgs.gov.

For a National scope of interest, hydrologic information can be found at USGS web page:

http://water.usgs.gov

The USGS is exploring other means of automated data dissemination, including faxes, emails, and voice messages once the gaging-station network upgrade is completed. Other non-automated means of disseminating hydrologic data include the USGS annual data report and data requests to the USGS, Atlanta, Ga.

WHY ESTABLISH THE GEORGIA HYDROWATCH?

The question arises: “Why should the USGS and its cooperators establish the *Georgia HydroWatch* real-time hydrologic monitoring network?” The answer is that with the current public attention of water resources in Georgia, the need for accurate and timely hydrologic information is imperative. The State of Georgia is facing water-resources concerns from both a quantity-of-water and quality-of-water standpoint. The citizens of Georgia also are potentially at risk from natural hazards—such as floods, hurricanes, and drought. Real-time data can be used for various purposes, including flood warning, drought mitigation and response, water-quality emergencies, reservoir operations, saltwater contamination of coastal ground-water supplies, and fisheries habitat monitoring. Water-resource managers need these data to be able to make informed decisions regarding the protection of human and aquatic life, property, and the environment. The USGS Georgia HydroWatch network will be a useful tool for the water-resource managers to help make such decisions.

URBANIZATION EFFECTS ON STREAMFLOW IN THE ATLANTA, GEORGIA AREA

By Norman E. Peters[1/] and Seth Rose[2/]

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26.-27, 2001, at the University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 246-249.

Abstract. For the period from 1958 to 1996, streamflow and rainfall characteristics of a highly urbanized watershed were compared with less-urbanized and nonurbanized watersheds in the vicinity of Atlanta, Georgia. Water levels in several wells completed in surficial and crystalline-rock aquifers also were evaluated. Annual runoff coefficients (runoff as a fractional percentage of precipitation) ranged from 0.31 to 0.34 and were not significantly different for the urban stream (Peachtree Creek). Peak flows for the largest 25 stormflows at Peachtree Creek were 30 to 80 percent greater than peak flows for the other streams. A 2-day storm recession constant for Peachtree Creek was much larger, that is streamflow decreased more rapidly, than for the other streams. Average low flow of Peachtree Creek was 25 to 35 percent less than the other streams, possibly the result of decreased infiltration caused by the more efficient routing of stormwater and the paving of ground-water recharge areas. The timing of ground-water level variations was similar annually in each well, reflecting the seasonal recharge. Although water-level monitoring only began in the 1980s for the two urban wells, water levels displayed a notable decline compared to non-urban wells since then—this is attributed to decreased ground-water recharge in the urban watersheds due to increased imperviousness and related rapid storm runoff. Likewise, the increased urbanization from the 1960s to the 1990s of the Peachtree Creek watershed produced more runoff than urbanization in the less urbanized Big Creek and Sweetwater Creek watersheds.

INTRODUCTION

Urbanization has a significant effect on many of the processes that control streamflow (McCuen, 1998). Hydrologic effects of urbanization include (1) a higher proportion of precipitation appears as surface runoff; (2) catchment response to precipitation is accelerated and the lag time between precipitation and runoff is decreased; (3) peakflow magnitudes are increased for all but the largest storm events; (4) low flow is decreased due to reduced contributions from ground-water storage; and (5) water quality is degraded by effluent discharges and non-point sources (Shaw, 1994). This paper compares and contrasts streamflow responses of urbanized streams with less-urbanized streams in the Atlanta area and discusses the effects of urbanization on stormflow response. This paper is a summary of a more extensive analysis of streamflow in the region by Rose and Peters (*in press*).

Methods

Four unregulated Georgia streams in the Piedmont Province were selected based on the availability of long-term (35 to 38 years) streamflow and precipitation data (table 1). The drainage basins vary from urbanized (Peachtree Creek watershed) to less urbanized (Sweetwater Creek and Big Creek watersheds) to rural (Middle Oconee River watershed).

Daily mean streamflow was extracted from the U.S. Geological Survey (USGS) database; daily precipitation was obtained from National Climatic Data Center records (EarthInfo Inc., 1996). Watershed characteristics were compared among sites including drainage area, mean slope, and topographic index, $ln(a/tan\beta)$ (Kirkby, 1975). For the topographic index, a is the area draining through a point from upslope and $\tan\beta$ is the local slope angle. The mean slope and topographic index were derived from 1 degree (1:250,000 scale) digital elevation model (DEM) data (USGS1-degree DEM, 2000). Land-use change was semi-quantitatively assessed through an analysis of census data for 1970, 1985 and 2000 (Atlanta Regional Commission, 2000a); and 1998 multi-resolution land characteristics and national land-cover data (U.S. Environmental Protection Agency MRLC NLCD, 2000) using ArcView 3.2[1/].

[1/]The use of brand names in this report is for information purposes only and does not imply endorsement by the U.S. Government.

Table 1. Characteristics of select streams and watersheds in the Atlanta area
[AA = Atlanta WSO Airport; AB = Atlanta Bolton; AWS = Athens WSO Airport; Da = Dallas; Dg = Douglasville; Dl = Dahlonega 2 NW; G = Gainesville; My = Maysville; N = Norcross; W = Winder

Station name	USGS station number	Drainage area (square kilometer)	Period of record	Gage elevation (meter)	Mean *ln(a.tan/β)*	Mean slope (percent)	Rain gages	1998 Land use (percent)					
								Open water	Wetland	Urban	Forest	Agriculture	Other
Middle Oconee River near Athens	02217500	1,015	1958-95	169	5.4	3.4	AWS, G, My, W	0.3	1.0	4.0	64.0	30.3	0.5
Big Creek near Alpharetta	02335700	186	1961-95	293	5.9	2.6	Dl, N	0.5	1.3	13.0	65.5	18.7	0.9
Peachtree Creek in Atlanta	02336300	225	1958-95	233	5.8	2.6	AA, AB, N	0.4	0.0	54.7	42.0	2.6	0.2
Sweetwater Creek near Austell	02337000	396	1958-95	261	5.8	2.4	Da, Dg	0.9	3.0	13.8	65.8	15.6	0.9

Four parameters were used to assess stream hydrographs—

- annual runoff coefficient (RC: annual runoff divided by annual precipitation);
- peak daily discharge for the largest 25 stormflow events;
- 2-day recession constant (k_2) for events that produced a daily stormflow maximum of 15 millimeters (mm)/day (after Domenico and Schwartz, 1998);

$$Q_2 = Q_p e^{-kt} \quad (1)$$

$$k_2 = (1/t) \ln Q_p/Q_2 \quad (2)$$

  where Q_p = peak discharge, Q_2 = discharge 2 days after peak, t = 2 days, and k_2 = 2-day recession constant (hr^{-1}); and
- lowest daily runoff during the summer (May through September).

For each parameter, one-tailed t-tests were used to determine statistically significant differences between runoff characteristics of Peachtree Creek and the three other streams. Daily mean ground-water levels also were extracted from the USGS database for three long-term monitoring wells in the area. The ground-water level variations were compared for a relatively non-urban well screened in the surficial aquifer (Spalding County), that is in residuum, and two urban wells in the crystalline-rock aquifer (Dekalb County and Fulton County).

RESULTS AND DISCUSSION

During the 35 to 38 years of record, annual precipitation averaged 1340 mm (±190 mm) and was similar among streams. Annual runoff averaged 440 mm (± 115 mm) resulting in annual runoff coefficients (RCs) of 31 to 34 percent.

Annual runoff coefficient: Regression of annual runoff on precipitation for each stream strongly suggests that the primary factors controlling runoff are evapotranspiration and total annual precipitation. The intercept is negative for all streams, indicating that a minimum amount of annual precipitation is required to generate runoff. Although the average annual RCs and the slopes of the regressions are similar, the regression for Peachtree Creek differs subtly from the other streams. The intercept is the smallest indicating that less precipitation is required to generate runoff than for the other streams. This result is consistent with the rapid runoff response of highly urbanized watersheds, that is due to increased imperviousness and construction (typically concrete) of drainage systems (Schueler, 1994; Arnold and Gibbons, 1996).

Peak runoff: Rapid channeling of street runoff through large diameter storm drains is probably the most distinguishing characteristic of urban runoff. To characterize peak runoff, the 25 largest magnitude daily runoff events were selected for each stream. The daily runoff for the 25 highest magnitude daily stormflows for Peachtree Creek (35-71 mm) is significantly higher than the other streams ($\alpha<0.01$). Median runoff for 25 daily stormflows at Peachtree Creek (43 mm) was the largest of all streams. Furthermore, median runoff for Peachtree Creek was 30 percent greater than Big Creek, and more than 80 percent greater than either Sweetwater Creek or the Middle Oconee River.

2-day recession constants: For Peachtree Creek, 148 storm events generated runoff exceeding 15 mm/day magnitude, which were from 2 to 3 times more than the other watersheds. Also, storm recession constants for Peachtree Creek were significantly higher (t-tests, $\alpha<$ 0.0001) than the recession constants of the other watersheds. For example, the average 2-day recession constant for Peachtree Creek (1.19 per day) was significantly higher than the other streams, and in particular, than less urbanized Big Creek (0.80 per day) and Sweetwater Creek (0.44 per day). These results indicate that storm recessions in the highly urbanized watersheds are not sustained, and the hydrograph is ìspikyî compared with less-urbanized watersheds.

Low flow: Low-flow values of Peachtree Creek (average = 0.19 mm/day) were significantly lower ($\alpha \leq 0.05$) than the other streams. The average low flow value for Peachtree Creek was from 25 to 35 percent less than low-flow values for the less-urbanized Big Creek and Sweetwater Creek watersheds. This result indicates that storm runoff is much more efficiently conveyed to streams during storm events and results in a very brief recession period.

Ground-water level variations: Ground-water levels in the Atlanta area vary seasonally, with the highest water table and associated highest baseflow occurring during the dormant winter ground-water recharge period, and lowest during the growing season in summer. Monthly mean ground-water levels in the urban wells are highly correlated ($\alpha<0.01$) with the non-urban well for a given year, that is the water level in each well varies seasonally. However, water levels in the urban wells have decreased compared to those in non-urban areas, as shown by the decadal change in the relation between the urban and non-urban wells (fig. 1). This result suggests that urbanization, and in particular the increased imperviousness, increases runoff and decreases ground-water recharge.

Effects of land-use changes: Population and associated land use changed in the watersheds—these changes were not uniform among the watersheds (table 2). The percentage population increase from the years 1970 to 1985 for the two less-urbanized streams—Big Creek and Sweetwater Creek—is higher (79 and 90 percent, respectively) than for the urban stream—Peachtree Creek (20 percent). However, population density of Peachtree Creek increased by more than three times that of either Big Creek or Sweetwater Creek. To assess this effect, temporal variations in annual runoff coefficients of Peachtree Creek were compared with those of the two adjacent, rapidly urbanizing watersheds. For each year, the difference between the RC of Peachtree Creek and that of Big Creek and Sweetwater Creek were computed and evaluated for each decade from the 1960s to the 1990s (fig. 2). The RC difference is a measure of the relative effects of urbanization on annual water yield for Peachtree Creek compared to the other streams. The urbanization of Peachtree Creek results in a progressive, statistically significant ($\alpha<0.01$)), decadal increase in annual water yield relative to the other streams. These results indicate that the relatively higher population density increase in the Peachtree Creek watershed results in an increase in annual runoff (greater imperviousness, and less recharge or evapo-transpiration) than in the less urbanized Big Creek and Sweetwater Creek watersheds.

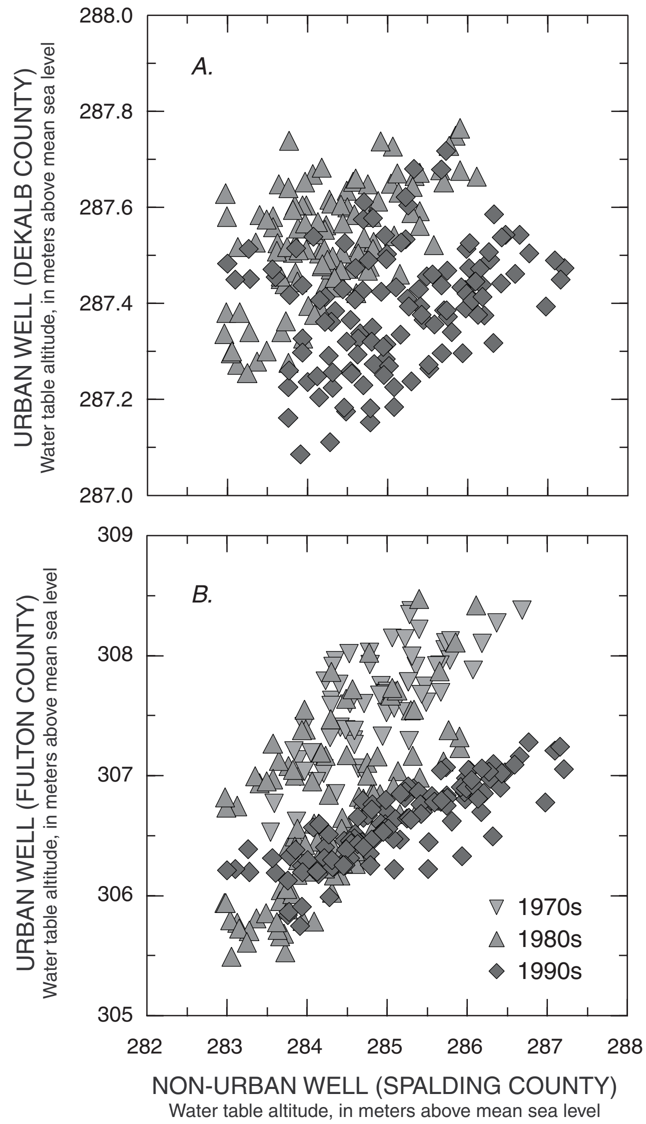

Figure 1. Relations between monthly mean ground-water levels in two urban wells with a non-urban index well. Each relation shows the decadal variations.

Table 2. Population density of watersheds for the streams in the Atlanta area (Atlanta Regional Commission, 2000b)

Stream	Population Density (people per square kilometer) 1970	1985	Change (percent of 1970)
Middle Oconee River near Athens	187	260	40
Big Creek near Alpharetta	53	95	79
Peachtree Creek in Atlanta	1,220	1,470	20
Sweetwater Creek near Austell	75	140	90

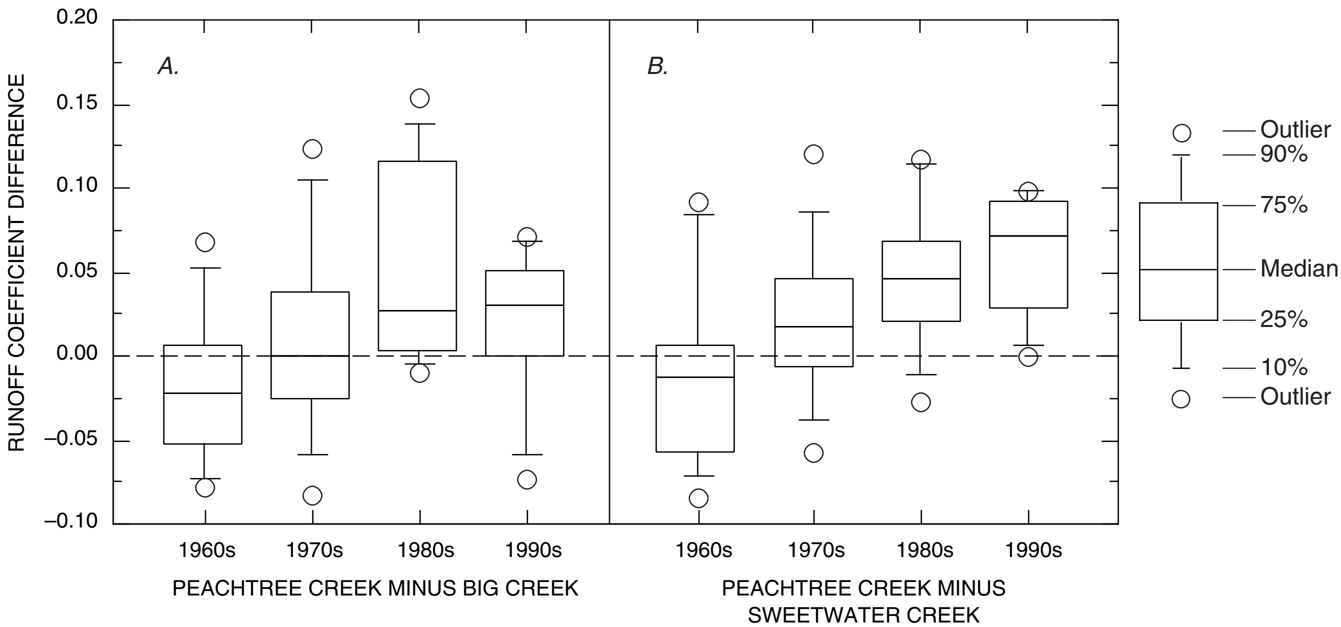

Figure 2. Decadal differences in the annual runoff coefficients between Peachtree Creek and *(A)* Big Creek and *(B)* Sweetwater Creek.

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PRESENCE OF PHARMACEUTICALS IN WASTEWATER EFFLUENT AND DRINKING WATER, METROPOLITAN ATLANTA, GEORGIA, JULY–SEPTEMBER 1999

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 282.

Abstract. Human and veterinary pharmaceutical compounds are a source of increasing environmental concern because they are used in large quantities and their physical and chemical properties make them likely to be transported into hydrologic systems, where their effects on human health and aquatic ecosystems generally are unknown. The U.S. Geological Survey (USGS) and Centers for Disease Control and Prevention (CDC) began a study to determine the occurrence of selected pharmaceuticals in treated effluent discharged upstream of drinking-water intakes, in raw drinking water, and in finished drinking water in the upper Chattahoochee River watershed in Metropolitan Atlanta. Water samples were collected at 11 sampling sites once per month during low-flow conditions from July–September 1999. Two research analytical methods, recently developed or modified by the USGS Toxics Program, were used to quantify prescription and nonprescription pharmaceuticals, including antibiotics, at parts per billion (ppb) and sub-ppb concentrations in filtered water samples.

The number of pharmaceuticals detected by site type decreased from 16 in treated wastewater-effluent samples, to 10 in raw-water samples from drinking-water intakes, to three in finished-drinking-water samples. Four prescription pharmaceuticals detected were dilitiazem, dehydronifedipine, metformin, and gemfibrozil. Five nonprescription pharmaceuticals detected were caffeine, 1,7-dimethyl xanthine, cotinine, cimetidine, and acetominophen. Eight antibiotics detected were trimethoprim, sulfamethazine, sulfamethoxazole, sulfadimethoxine, erythromycin-H_2O, roxithromycin, lincomycin, and enrofloxacin. Seven prescription and nonprescription pharmaceuticals and fourteen antibiotics were analyzed for, but were not detected. The only three pharmaceuticals detected in finished-drinking-water samples—caffeine, cotinine, and acetominophen—are widely used nonprescription pharmaceuticals. The detection of antibiotics in raw drinking water is of particular concern because the presence of these chemicals in the environment may lead to the development of resistant bacterial strains, thus diminishing the therapeutic effectiveness of antibiotics. The combination of the detection of numerous prescription and nonprescription pharmaceutical compounds in treated effluent, raw drinking water, and finished drinking water; and the absence of pharmaceutical manufacturing facilities, suggests that human usage of pharmaceuticals is one source of these compounds in water resources within the upper Chattahoochee River watershed.

COMPOSITION AND CHANGES IN ATMOSPHERIC DEPOSITION NEAR ATLANTA, GEORGIA, 1986-99

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REFERENCE: *Proceedings of the 2001 Georgia Water Resources Conference*, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 483-487.

Abstract. Trends in dry and wet deposition were investigated using data from a weekly sampling network at the Panola Mountain Research Watershed (PMRW), a forested research site 25 km, southeast of Atlanta, Georgia. Wet and dry atmospheric deposition has been monitored using various methods at PMRW since 1985, as a site of National Oceanic and Atmospheric Administration (NOAA) Atmospheric Integrated Monitoring Network (AIRMoN-dry) and following protocols of the National Trends Network (NTN). These data were compared for overlapping collection periods and analyzed for temporal trends. From 1986-99, the annual wet deposition of sulfur (S) and nitrogen (N) averaged 400 and 300 eq ha^{-1} (6.4 and 4.2 kg ha^{-1}), respectively. Inferential model estimates of annual dry S and N deposition from 1986-97 averaged 230 and 160 eq ha^{-1} (3.7 and 2.2 kg ha^{-1}), respectively. From 1993-99, net S deposition (dry deposition plus canopy interactions) for coniferous and deciduous throughfall (throughfall minus precipitation) averaged 400 and 150 eq ha^{-1} (6.8 and 2.3 kg ha^{-1}), respectively. The pH of precipitation is acidic, the volume weighted mean (VWM) pH (from H concentration) is 4.44 for 1986-99. Coniferous throughfall also is acidic having an annual volume-weighted mean VWM pH of 4.42 from 1993-99. The inferential model estimates are within this range and the variation in net S deposition of throughfall is attributed to variations in the leaf area index above the collectors and the representativeness of the collectors of throughfall for each canopy type. Temporal variations in precipitation SO_4 concentrations are similar to the atmospheric SO_4 concentrations, and are highest in summer and lowest in winter. In contrast, atmospheric SO_2 concentrations are negatively correlated with the atmospheric SO_4 concentrations. Atmospheric deposition trends were not detected for the entire sampling period, but were detected for shorter periods (four to five year). Annual S and N deposition increased from 1986 to 1990, decreased from 1991 to 1994, and increased from 1995 to 1999. The recent S and N deposition increase does not reflect the expected emission reductions associated with the January 1, 1995, implementation of Phase I of Title IV of the 1990 Clean Air Act Amendments.

INTRODUCTION

Atmospheric deposition is a major source of chemical constituents to many ecosystems. The transfer occurs by three major pathways: (1) precipitation scavenging, in which particles are incorporated in hydrometeors and deposited in the resulting rain, snow, sleet or hail; (2) interception by fog and mist; and (3) dry deposition, in which large particles, aerosols and gases are removed by surfaces in the ecosystem. In the Atlanta, Georgia area, pathways (1) and (3) dominate, and the temporal and spatial variations in atmospheric deposition reflect variations in the constituent sources, transport from the source to the receptor, and deposition. Wet deposition can be monitored using a wet-only precipitation collector. Dry S and N deposition can be modeled using air quality and micrometeorology (Hicks and others, 1991). Also, total S deposition to a forest can be monitored by collecting throughfall, *i.e.*, water that travels through the forest canopy; dry S deposition at Panola Mountain Research Watershed (PMRW) can be determined by subtracting the wet deposition from the total S deposition (Cappellato and others, 1998). Expectations were that with the January 1, 1995, implementation of Phase I of Title IV of the 1990 Clean Air Act Amendments, atmospheric sulfur (S) deposition would decrease in response to SO_2 emission reductions. This paper discusses atmospheric deposition at the PMRW (fig. 1), a forested watershed near Atlanta, to determine the relative contribution of wet and dry deposition to total atmospheric deposition and to evaluate temporal trends in the atmospheric deposition.

Figure 1. Panola Mountain State Conservation Park, near Atlanta, Georgia.

Methods

The 41-ha PMRW is about 25 km southeast of Atlanta, Georgia, in the Panola Mountain State Conservation Park and is one of five small watersheds of the USGS Water, Energy, and Biogeochemical Budgets Program (Baedecker and Friedman (2000); Peters and others, 2000). Deciduous and coniferous throughfall (1993-99) and wet deposition using National Atmospheric Deposition Program/National Trends Network (NADP/NTN) protocols (1985-99) were monitored weekly (Dossett and Bowersox, 1999). From August 1985 through November 1997, dry S and N deposition was monitored weekly by combining air concentrations from a filterpack with micrometeorological data in a resistance model (Hicks and others, 1991; Meyers and others, 1991). The site at PMRW is part of the National Oceanic and Atmospheric Administration (NOAA) AIRMoN-dry network (NOAA, 2000); dry deposition estimates will herein be called NOAA dry deposition.

Precipitation and throughfall were collected weekly from wet/dry precipitation collectors and analyzed for major ion concentrations. Amounts of precipitation and throughfall were determined by the volume collected and the collector area. Major solutes (Na, K, Ca, Mg, NH_4, Cl, NO_3, and SO_4) were determined by ion chromatography prior to 1991. Since 1991, the cations—Na, K, Ca, and Mg—are determined by direct current plasma on a filtered (0.45 μm) acidified aliquot, and NH_4 is determined colorimetrically using salicylate hypochlorite.

Individual solute deposition in precipitation was computed by multiplying the solute concentration by the rainfall or throughfall amount. The Kendall test (Gilbert, 1987), a nonparametric test, was used to determine if changes in annual deposition were increasing or decreasing.

RESULTS AND DISCUSSION

Precipitation and wet deposition

For calendar years 1986-99, annual precipitation at PMRW averaged 1,225 mm and ranged from 860 mm in 1987 to 1,580 mm in 1994. Monthly precipitation ranged from 5 mm in June 1990, to 455 mm in July 1994, a result of tropical storm Alberto. The cation composition (Na, K, Ca, Mg, NH_4, and H) of precipitation is dominated by H (~50 percent) and NH_4 (~20 percent), and the anion composition (Cl, NO_3, and SO_4) is dominated by SO_4 (>50 percent) and NO_3 (~25 percent). Precipitation is acidic with the annual pH (from H concentration) averaging 4.44 and ranging from 4.21 to 4.66; the pH of weekly samples, however, was more variable ranging from 3.29 to 6.37 with the lowest pH values generally found in the lowest-volume samples. Deposition, and cation and anion composition varied seasonally—the seasons were divided into sequential 3-month periods with March–May for spring; June–August for summer; September–November for fall; and December–February for winter (fig. 2). The highest H (lowest pH) and SO_4 deposition typically were during the summer and spring. Summer SO_4 deposition was more than three times the winter deposition, which was the season for the lowest deposition of any solute. Na and Cl deposition varied the least among seasons, but even for these solutes, summer deposition was 2.0 and 1.3 times the winter deposition, respectively. The pH of precipitation is controlled primarily by the concentrations of SO_4 and NO_3; the r^2 of a linear regression of H concentration on SO_4 was higher than on NO_3 (0.91 and 0.73, respectively). The stronger association with SO_4 compared to NO_3 concentrations reflects the concentrations in precipitation, that is SO_4 dominates NO_3 by a factor of two and the annual averages were 36 and 16 μeq l^{-1}, respectively. Individual solute concentrations were highest in the lowest-volume samples, reflecting the concentrating effect of washout from the atmosphere. However, relations between solute concentration and rainfall are not statistically significant ($p<0.05$) and display considerable heteroscedasticity, having the largest concentration variance during weeks with the lowest rainfall.

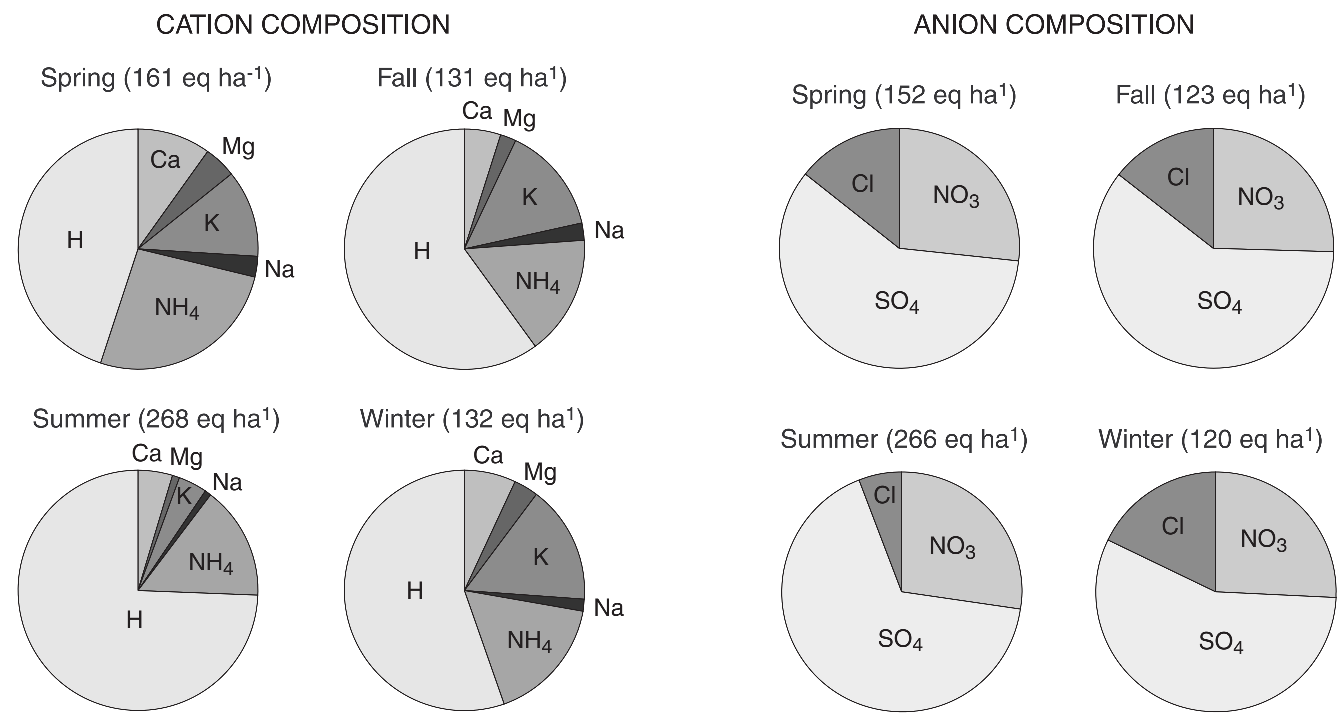

Figure 2. Seasonal cation and anion composition of wet atmospheric deposition at the Panola Mountain Research Watershed near Atlanta, Georgia, 1986–99. The average seasonal cation and anion deposition is given in parentheses.

Air quality and NOAA dry S and N deposition

Air concentrations of S and N species, measured with the filterpack, were positively skewed, *i.e.*, with most of the weekly values less than the mean. Consequently, median concentrations are reported to represent the populations. SO_2 concentrations varied seasonally, with high concentrations in winter and low concentrations in summer; the highest median SO_2 concentration (8.2 μg m^{-3}) was in February and the lowest (3.2 μg m^{-3}) was in August. In contrast, SO_4 concentrations were low in winter and high in summer—the lowest median weekly SO_4 concentration (2.8 μg m^{-3}) was in December and the highest (8.8 μg m^{-3}) was in July. The variation reflects the more rapid conversion of SO_2 to SO_4 under warmer conditions in summer; during the study period, median-monthly air temperatures at PMRW ranged from 5.9 ° C in January to 25.6 ° C in July. The SO_4 concentration of precipitation varied seasonally and was similar to and probably related to atmospheric SO_4 concentrations through aerosol washout during rainstorms. In contrast to SO_4, aerosol NO_3 concentrations were low, and varied seasonally with high median-monthly concentrations in spring (0.24 μg m^{-3}) and low concentrations in summer (0.08 μg m^{-3}). The HNO_3 concentrations were higher than aerosol NO_3 and were less variable seasonally than the other N and S species; the highest median concentration was 1.6 μg m^{-3} in March and the lowest was 1.2 μg m^{-3} in November.

The annual dry S (SO_4 plus SO_2) and N (HNO_3 plus NO_3) deposition averaged 230 and 160 eq ha^{-1} (3.7 and 2.2 kg ha^{-1}), respectively. The annual N deposition was highly correlated with the S deposition (r = 0.95). Weekly NOAA dry SO_4 deposition varied seasonally (fig. 3) having the same pattern as the air concentrations. The SO_2 deposition was more variable throughout the year compared to SO_4 (fig. 3). The NOAA SO_2 deposition is sensitive to surface wetness and temperature; surface wetness varies markedly throughout the year, which may explain the high variability in SO_2 deposition. Seasonal variations in N species deposition were not as pronounced as those for the S species (fig. 3). The highest deposition for both HNO_3 and NO_3 occurred in late winter and spring and the lowest in summer, which is comparable to the variations in SO_2 concentrations and deposition.

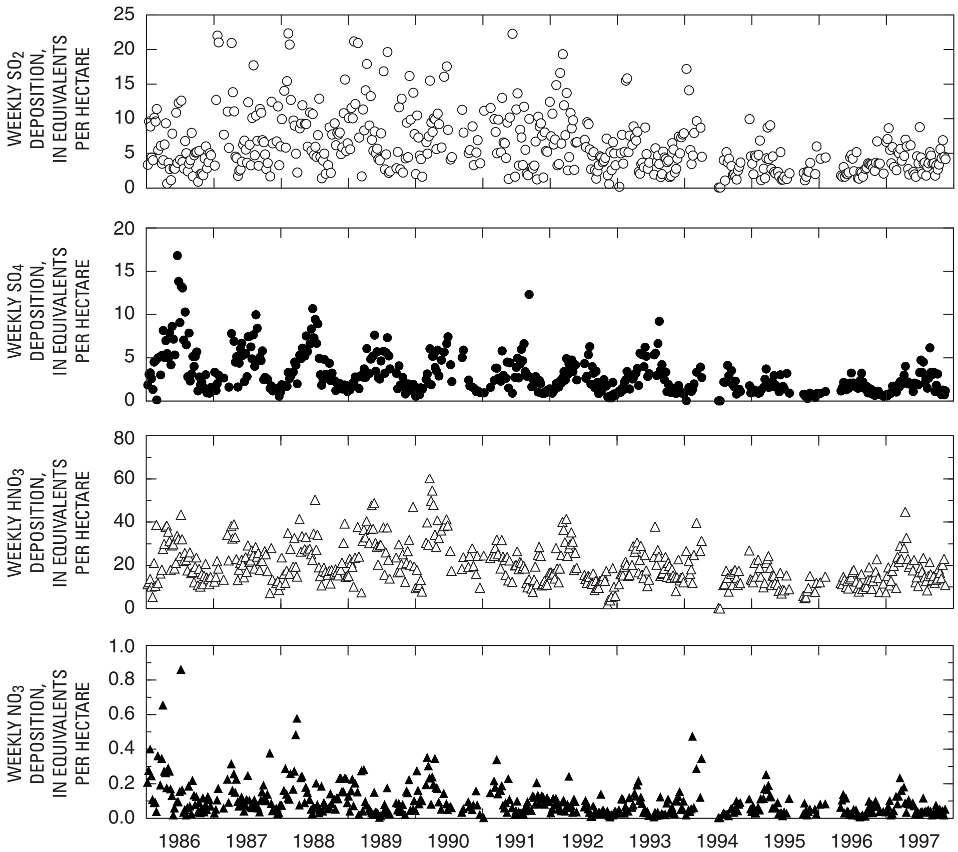

Figure 3. Weekly dry S and N deposition for 1986–97, estimated by combining weekly air concentrations from a filterpack and hourly micrometeorology in a resistance model.

Throughfall estimates of dry S deposition

From 1993-99, net S deposition (dry deposition plus canopy interactions) for coniferous and deciduous throughfall (throughfall minus wet deposition) averaged 400 and 150 eq ha^{-1} (6.8 and 2.3 kg ha^{-1}), respectively. The differences are attributed to variations in the leaf area index (LAI, leaf surface area per unit land surface area) above the collectors and the representativeness of the throughfall collectors for each canopy type. LAI was not measured and representativeness was not evaluated. During the same collection period as that of the throughfall, the wet S deposition averaged 350 eq ha^{-1} (6.0 kg ha^{-1}). The dry S deposition estimated from the throughfall S mass balance, therefore, ranges from 30 to 53 percent. In a mass-balance study of dry S deposition for a 500-mi^2 lichen and moss covered bedrock outcrop at PMRW, Peters (1989) reported that 30 percent of the total atmospheric S deposition to the outcrop was dry deposition, which is similar to the results presented herein. The lower estimate for the outcrop (Peters, 1989) and for the deciduous throughfall, probably reflects a lower LAI; and hence, a low filtering of atmospheric constituents of the respective canopies. From a rainstorm-based S cycling study at PMRW conducted from October 1987 to November 1989, Cappellato and others (1998) estimated the dry S deposition to be about 42 percent of the total atmospheric S deposition to the deciduous and coniferous forests.

Temporal trends in annual deposition

Trends in the annual wet deposition of H, SO_4, and NO_3 from 1986 to 1999 were not statistically significant (fig. 4). Deposition trends for these solutes, however, are statistically significant for shorter periods; SO_4, and NO_3 increased from 1985 to 1990 ($p < 0.01$), H, SO_4, and NO_3 decreased from 1991 to 1994 (p<p0.05), and H, SO_4, and NO_3 increased from 1995 to 1999 ($p<0.01$ for SO_4, and NO_3 and $p<0.05$ for H). Concentrations and deposition of H, SO_4, and NO_3 were lowest in 1994. The increasing trends in solute deposition since 1995 are of interest because atmospheric S deposition was expected to decrease due to SO_2 emission reductions associated with the January 1, 1995, implementation of Phase I of Title IV of the 1990 Clean Air Act Amendments. No trends were detected in rainfall amount. The SO_4 concentration and deposition are highly correlated with NO_3 (>0.99), and H is highly correlated with SO_4 plus NO_3 (>0.96).

The annual total deposition, as measured by weekly throughfall, increased significantly after 1994 to the coniferous forest for SO_4 and H ($p<0.05$), and to the deciduous canopy for H ($p <0.01$). A trend in annual dry deposition (throughfall minus wet deposition) was not detected for any solute; this may be due to the imprecision of this method for estimating dry deposition.

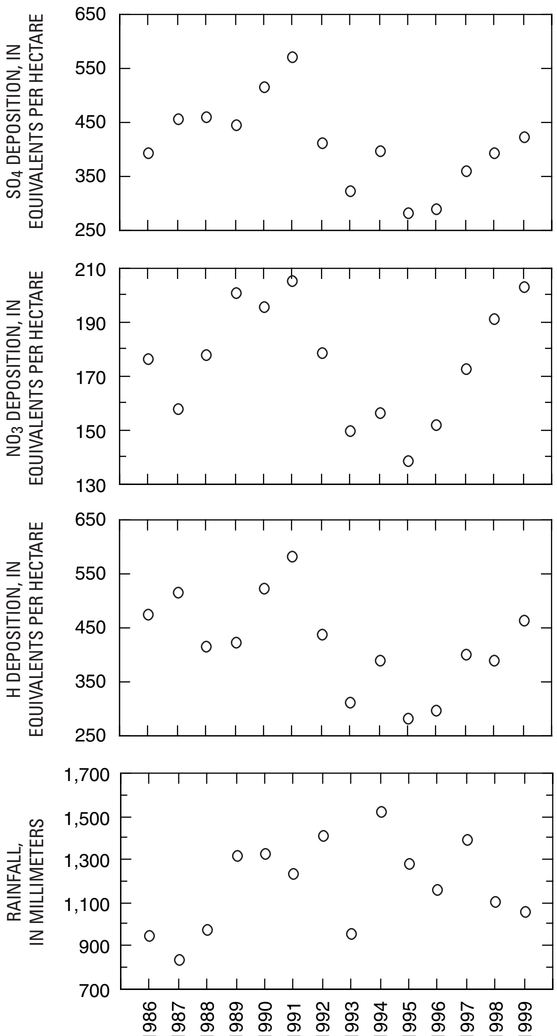

Figure 4. Temporal trends in annual SO_4, NO_3, and H wet deposition and rainfall at the Panola Mountain Research Watershed, near Atlanta, Georgia, 1986–99.

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A CONCEPTUAL PROGRAM FOR WATER-QUALITY MONITORING IN THE UPPER CHATTAHOOCHEE RIVER BASIN IN GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 497-500.

Abstract. The Chattahoochee River is a major resource for drinking water, aquatic life, recreation, and wastewater assimilation in the States of Georgia, Alabama and Florida. The rapid growth of the Atlanta metropolitan area has put a substantial strain on the basin's water resources. The U.S. Geological Survey (USGS) has developed a conceptual program to evaluate the current status of, and to monitor changes in, the water quality of the upper Chattahoochee River basin (from the headwaters to Columbus, Georgia). The concept is both multifaceted and multidisciplinary, and would be phased in over four years. Components of the program are intended to: (1) better detect health risks from bacteria and various chemical constituents; (2) implement an intensive basinwide sampling effort to provide an assessment of current water-quality conditions and identify local areas of concern; (3) establish current baseline conditions; (4) provide a framework for assessing changes in water quality; and (5) develop a state-of-the-art real-time water-quality monitoring network throughout the basin.

INTRODUCTION

The Chattahoochee River basin is a major resource for drinking water, aquatic life, recreation, and wastewater assimilation in the State of Georgia as well as in the neighboring states of Alabama and Florida. The rapid growth of the Atlanta metropolitan area has placed a substantial strain on the basin's water resources. Between 1970 and 1995, the population of the 10-county Atlanta metropolitan area nearly doubled from 1.5 to 2.9 million (Gregory and Frick, 2000). Numerous Federal, State, and local projects have been undertaken, or are underway, to monitor selected water-quality and quantity parameters in the watershed. However, there is no comprehensive basinwide-monitoring program to provide a framework for these individual efforts.

The Chattahoochee Riverway Project (CRP) Task Force is a multi-organizational (the Trust for Public Land, the Georgia Conservancy, the Upper Chattahoochee Riverkeeper, the Turner Foundation, the Georgia Department of Natural Resources, the National Park Service Chattahoochee River National Recreation Area, the U.S. Geological Survey, and several other Federal agencies), multidisciplinary group established by the Governor of Georgia as part of the Greenway Initiative and combines aspects of former Vice-President Gore's Partnership for Regional Livability. The Governor tasked this group with developing a strategy for maintaining the Chattahoochee watershed as a viable resource. The CRP has established a monitoring subcommittee to develop a comprehensive basinwide plan to address water-quality issues in the Chattahoochee River basin. In conjunction with the CRP Task Force, the subcommittee set three main goals for the monitoring program: (1) develop a means of establishing, as near real-time as practicable, a knowledge of bacteria levels in the river to advise recreational users of potential health risks; (2), provide a basinwide water-quality 'snapshot' of the upper Chattahoochee River basin to set reference points for current and future monitoring programs; and (3) design a state-of-the-art real-time water-quality monitoring network to facilitate timely, informed decisions relative to water-quality issues in the Chattahoochee River basin. As an active participant in the CRP and monitoring subcommittee, and at their request, the USGS developed a conceptual program to meet these three goals. The program is designed to determine the current status, and to monitor ongoing changes in the water quality of the upper Chattahoochee River basin including important tributaries (from the headwaters to Columbus, Georgia). The program was designed by augmenting the existing streamgaging and sampling network currently operated by the USGS (fig. 1). Details of the conceptual program are described herein.

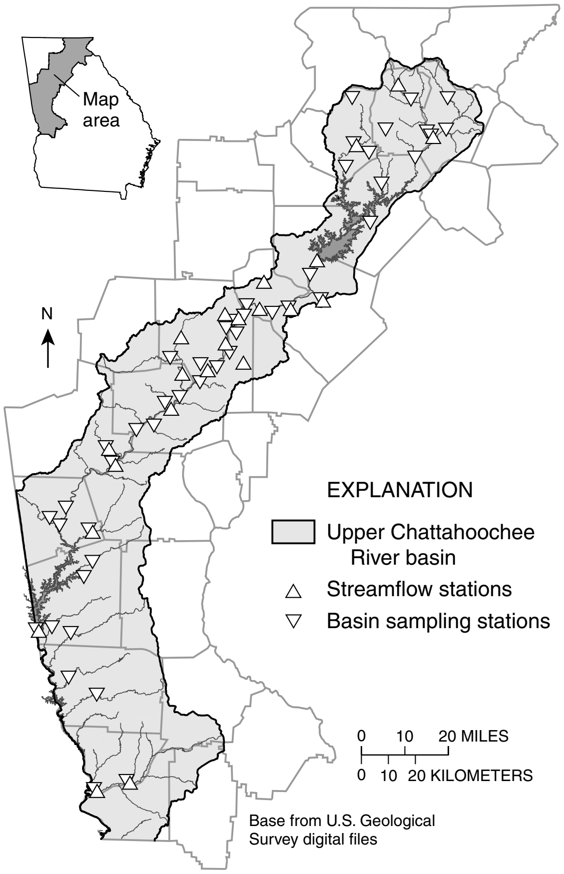

Figure 1. Current (2001) USGS monitoring network in the upper Chattahoochee River basin.

THE CONCEPTUAL MONITORING PROGRAM

The conceptual program developed by the USGS for the CRP monitoring subcommittee employs a four-phase hierarchical approach, with each phase requiring approximately one year for initial implementation. The first three phases are intensive, and are designed to: (1) establish long-term real-time core monitoring stations; (2) collect substantial numbers of water-quality samples for physical, chemical, and biological analysis; and (3) analyze the resulting data to develop a broad view of the water-quality status of the upper Chattahoochee River basin. The fourth phase entails the continuation and maintenance of the monitoring network to document any changes in water quality. It should be noted that this conceptual program was designed as a starting point from which more ongoing, site-specific, monitoring efforts might emerge. Further, should the initial effort prove successful, the conceptual approach ultimately might be applied statewide.

Phase One: Core Monitoring Sites

Phase One of the water-quality monitoring program has four components: (1) establish seven 'core' continuous water-quality monitoring stations along the main-stem of the Chattahoochee River; (2) complete a real-time streamflow and rainfall monitoring network throughout the basin and surrounding areas; (3) establish monthly water-quality sampling and analysis programs at the seven sites described in component 1; and (4) enhance and continue the ongoing Chattahoochee BacteriALERT program (discussed later in this paper). Because streamflow is a requisite for estimating constituent loads, the seven core stations would be located at existing USGS streamgaging sites. These sites include: (1) Chattahoochee River at Helen; (2) Chattahoochee River at Buford Dam, near Buford; (3) Chattahoochee River near Norcross; (4) Chattahoochee River at Atlanta; (5) Chattahoochee River at Fairburn; (6) Chattahoochee River at Franklin; and (7) Chattahoochee River at Columbus. To some extent, pragmatic issues affected site selection; for example, the Fairburn site already was instrumented as a continuous water-quality monitoring station, and as a result, a substantial amount of historical data already exist for this location. Further, plans already existed and were being implemented to instrument both the Franklin and Columbus sites. The Helen location was selected as a control site because it is relatively free of human impacts. The Buford location was selected to document water-quality changes resulting from the retention of water in Lake Lanier prior to release. The Norcross and Atlanta sites are part of the ongoing BacteriALERT program. Lastly, the Columbus site was selected as the downstream limit for the conceptual monitoring program. As such, water-quality data would be required as a boundary condition for any subsequent modeling.

Stream stage, discharge, rainfall, water temperature, specific conductance, dissolved oxygen (DO), pH, and turbidity would be measured at each core site. Four sites also would be instrumented to record wind speed, wind direction, air temperature, and barometric pressure for general background information. Although these data are not critical for establishing the water-quality status of the river, these data may be useful in establishing relations between meteorological data and constituent concentrations associated with nonpoint-source runoff.

Component 1 was designed with the eventual goal of real-time modeling; hence, all water-quality sensors at the seven sites would be equipped with satellite telemetry to relay data to a central location. Following completion of Component 1, the monitoring network would consist of five streamgaging stations without satellite telemetry or rain gages (fig. 2). As part of Component 2, fifteen stations, located outside the basin, would be upgraded to record real-time precipitation data to permit an accurate estimate of areal rainfall distribution during storms. These external sites would provide a more accurate representation of the effect of precipitation on discharge, within the upper Chattahoochee River basin. Ten of these sites would be located at existing USGS stations; whereas five either would be entirely new, or would be selected from currently inactive sites. Six of the fifteen stations also would include other meteorological sensors.

As part of Component 3, discrete water-quality samples would be collected at each of the seven core sites listed in Component 1. Sample collection would be timed so that at least 85% of normal annual flow conditions would be covered. The samples would be analyzed for various chemical constituents including trace elements, nutrients, organic and agricultural chemicals, as well as other selected constituents. Sample collection and subsequent analysis would be used for calibrating monitoring sensors in an attempt to establish relations between the discrete samples and the continuous water-quality monitoring data, with the expectation that eventually, discrete sampling could be scaled back and replaced by real-time water-quality monitoring surrogates.

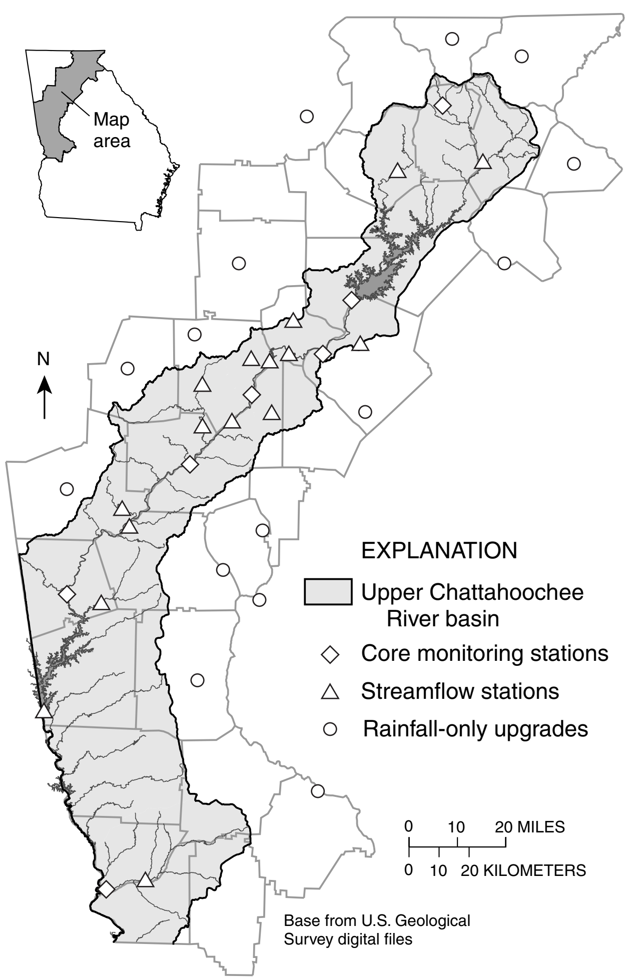

Figure 2. Automated USGS monitoring network for Phase One.

Component 4 of Phase One is the Chattahoochee BacteriALERT program, which is designed to determine the most recent bacterial concentrations practicable, at the Norcross and Atlanta core sites. A pilot program currently is underway with volunteers from the National Park Service (NPS) and the Upper Chattahoochee Riverkeeper (UCR). The volunteers collect water samples Monday through Thursday each week, and deliver the samples to the USGS Georgia District Office in Atlanta. The samples are analyzed and bacterial levels are displayed on the Chattahoochee Riverway Project web page (**http://ga.water.usgs.gov/bacteria**). Bacteria levels are provided in conjunction with information on both State and Federal regulatory limits, so that recreational users may assess the potential human health risks from water contact. Also, the NPS posts prominent visual indicators of subjective health risks (high, medium, or low) at heavily used recreational sites along the river.

Phase Two: Basin Status

Phase Two of the conceptual monitoring program is designed to determine the water-quality status of the upper Chattahoochee River basin through the collection and analysis of water samples. This program element would begin in the second year, and has three data components: (1) a high-flow synoptic study; (2) a low-flow synoptic study; and (3) storm/event sampling.

Components 1 and 2 are labor-intensive synoptic sampling efforts that would occur during separate two-week intervals when different flow regimes exist in the watershed. Component 1 is a high-flow study designed to evaluate the effects of nonpoint-source runoff on the river; whereas Component 2 is a low-flow equivalent designed to evaluate the effects of point-source inputs on the river. About 150 sampling sites would be occupied during each synoptic—one site upstream of a tributary to the Chattahoochee River; one site downstream of the tributary inflow; and one site located near the centroid of the tributary drainage area. Complete sediment and water sample analyses would be performed as part of each synoptic. These studies are intended to identify relatively localized areas in the basin where potential water-quality problems may exist. Such areas may require subsequent evaluative monitoring. In addition, the synoptics should provide a consistent basinwide framework for utilizing and understanding additional data collected during local monitoring efforts.

Substantial inputs from nonpoint sources occur during storms. Component 3 of Phase Two is intended to evaluate the impact of storms on water quality. To that end, attempts would be made to sample one storm annually at five of the seven core stations. Sites directly below reservoirs were not considered due to flow regulation by dams. Samples would be collected throughout a storm, with emphasis on collecting at least two samples during the rising limb, one near the peak, and two on the falling limb of the hydrograph. The samples would be analyzed for water and suspended sediment-associated constituents (*e.g.*, trace elements, nutrients, organic, and agricultural chemicals) so that concentrations could be compared to pre-storm/baseline conditions. This program element would provide information on the significance of storms relative to the annual fluxes of various chemical parameters, as well as bacteria, in the basin.

Phase Three: Data Analysis and Network Expansion

Phase Three of the conceptual monitoring program includes data reporting and interpretation based on the information collected during the previous two years. Further, this phase may require an expansion of the real-time water-quality monitoring network. In this instance, expansion would focus on selected tributaries in the upper Chattahoochee River basin. Two analysis and two data components comprise this phase: (1) publication of a basic data report; (2) in-depth interpretive studies with accompanying published reports; (3) potential expansion of the continuous monitoring network; and (4) continued storm sampling.

Components 1 and 2 of Phase Three would lead to a data report (CD-ROM-based) which could be used as a reference for ongoing local monitoring efforts. Further, where there is sufficient justification, appropriate interpretive reports on selected water-quality issues would be published. At a minimum, a basinwide status report, based on the high- and low-flow synoptics described under Phase Two would be published. Another potential report could describe the relations between discrete sample constituent concentrations and continuously monitored water-quality parameters. Wherever feasible, appropriate surrogates would be identified for purposes of limiting subsequent water sample collection and analysis.

Component 3 might require the installation of as many as twenty new continuous water-quality monitoring stations located throughout the basin. As noted in the description of Phase Two, the synoptic and storm sampling programs would be used, in part, to identify relatively localized areas where potential water-quality problems may require additional evaluation. For example, these stations could be used to highlight such issues as point- and nonpoint-inputs, pre-development conditions, and land-use changes caused by urban growth and changing demographics. These stations would be identical to the core stations described in Phase One; however, such installations should not be viewed as long-term. Studies would be highly focused on a specific issue(s), and the sites would be maintained only long enough to determine the significance of local inputs, to specific basin water-quality concerns, and for potential modeling purposes.

Component 4 represents a continuation of the storm sampling effort initiated in Phase Two. Because only one storm per site per year would be scheduled for sampling, it would be necessary to continue the effort for a number of years to develop a complete data set. Continuation of this effort also might provide a means of tracking land-use changes throughout the basin.

Phase Four: Long-Term Monitoring

Phase Four of the conceptual monitoring program was designed with the assumption that by the end of the third year, data collection would have become routine. Phase Four and beyond should permit long-term water-quality trend analysis in the upper Chattahoochee River Basin and provide important information on evolving water-quality conditions and issues. Actual sampling would be limited, and only intended to maintain instrument and model calibration. Final structure of the long-term monitoring network would provide sufficient data for informed management of the upper Chattahoochee River basin.

BEYOND PHASE FOUR

During the ensuing years, at approximately five- to ten-year intervals, intense synoptic studies similar to those outlined in Phase Two would be performed to update the water-quality framework ('snapshot') of the basin. In addition, at regular intervals, the existing monitoring network would be re-evaluated in light of such factors as changing land-use practices, the location of new point sources (*e.g.*, new water treatment plants), and changes in population density and demographics. These re-evaluations might necessitate changes in the existing monitoring network.

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ESTIMATING CHATTAHOOCHEE RIVER TRIBUTARY STREAM TEMPERATURES IN THE VICINITY OF ATLANTA, GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 501.

Abstract. Recent development of the Georgia Department of Natural Resources, Environmental Protection Division (GaEPD) Chattahoochee River Water Quality Model (GaEPD-RIV1) required hourly estimates of 47 tributary stream temperatures in the Atlanta, Ga., vicinity for a sustained period of about six months. An interagency team consisting of the U.S. Geological Survey, GaEPD, and Law Environmental, Inc., engineers devised an "index station" method of estimating hourly stream temperatures at unmeasured sites by using data from nearby sites having stream temperature recorders.

Methods of estimating "Stream Temperature Characteristics in Georgia (Dyar and Alhadeff, 1997)" were expanded to include calculations of daily (hourly) variations from selected index stations located nearby and transferring those variations as estimates to unmeasured sites. To assess the index station method of estimating stream temperatures at unmeasured sites, 16 of the 47 sites were equipped with stream-temperature recorders, including the Suwannee Creek site shown in figure 1 below. The figure shows a comparison of modeled hourly versus actual recorded stream temperatures. The method assumes similar climate and unnatural effects occurring at both the index and unmeasured sites.

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Dyar, T.R., and Alhadeff, S.J., 1997, Stream-temperature characteristics in Georgia: U.S. Geological Survey Water-Resources Investigations Report 96-4203, 150 p.

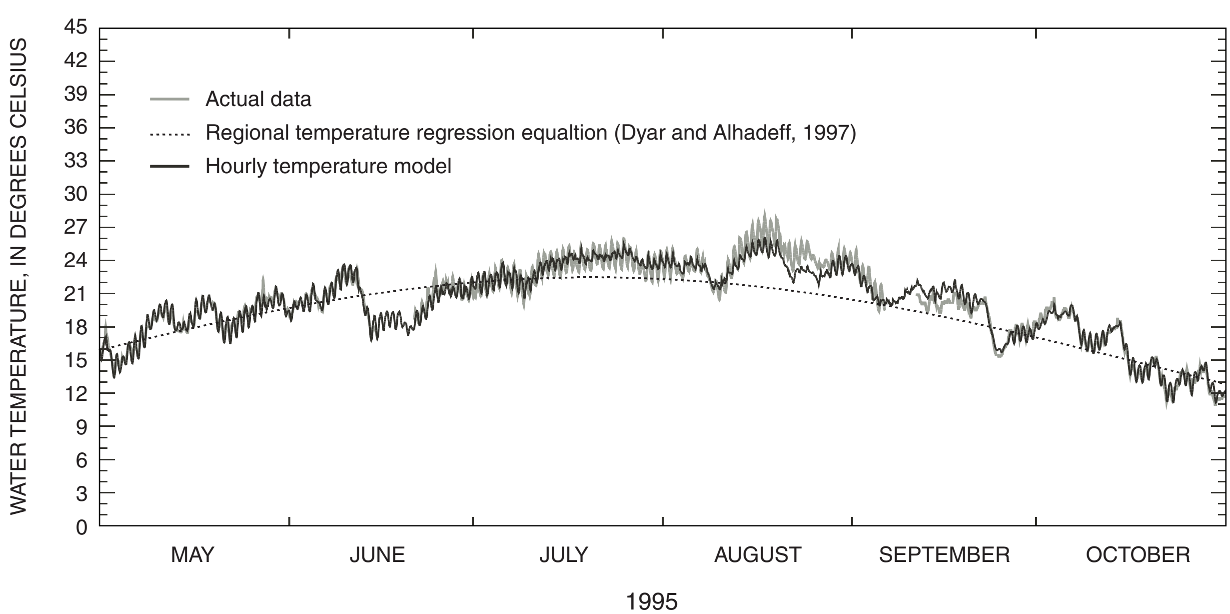

Figure 1. Modeled and actual temperature data at Suwannee Creek, May through October 1995.

INDICATOR-BACTERIA CONCENTRATIONS IN STREAMS OF THE CHATTAHOOCHEE RIVER NATIONAL RECREATION AREA, MARCH 1999–APRIL 2000

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 510-513.

INTRODUCTION

In 1999, the U.S. Geological Survey (USGS) in cooperation with the National Park Service, began a two-year study designed to evaluate microbial contamination in streams in and near the Chattahoochee River National Recreation Area (CRNRA). The CRNRA is comprised of 14 park units and the 48-mile reach of the Chattahoochee River downstream from Buford Dam to Peachtree Creek (fig. 1). The Chattahoochee River is one of Georgia's most utilized water resources—supplying drinking water to a large percentage of people in Metropolitan Atlanta and serving as a receiving waterbody for treated wastewater as well as untreated urban runoff. The CRNRA is a significant recreational resource in Metropolitan Atlanta, accounting for about 75 percent of all public green space in a 10-county area (Kunkle and Vana-Miller, 2000). The CRNRA attracted about 2.9 million visitors in 1999, 30 percent of whom participated in water-based activities (William J. Carroll, National Park Service, oral commun., 2000). Microbial contamination is an issue in the CRNRA due to the high numbers of people using the Chattahoochee River as a recreational resource and the potential sources of contamination such as nonpoint runoff and treated and untreated wastewater effluent.

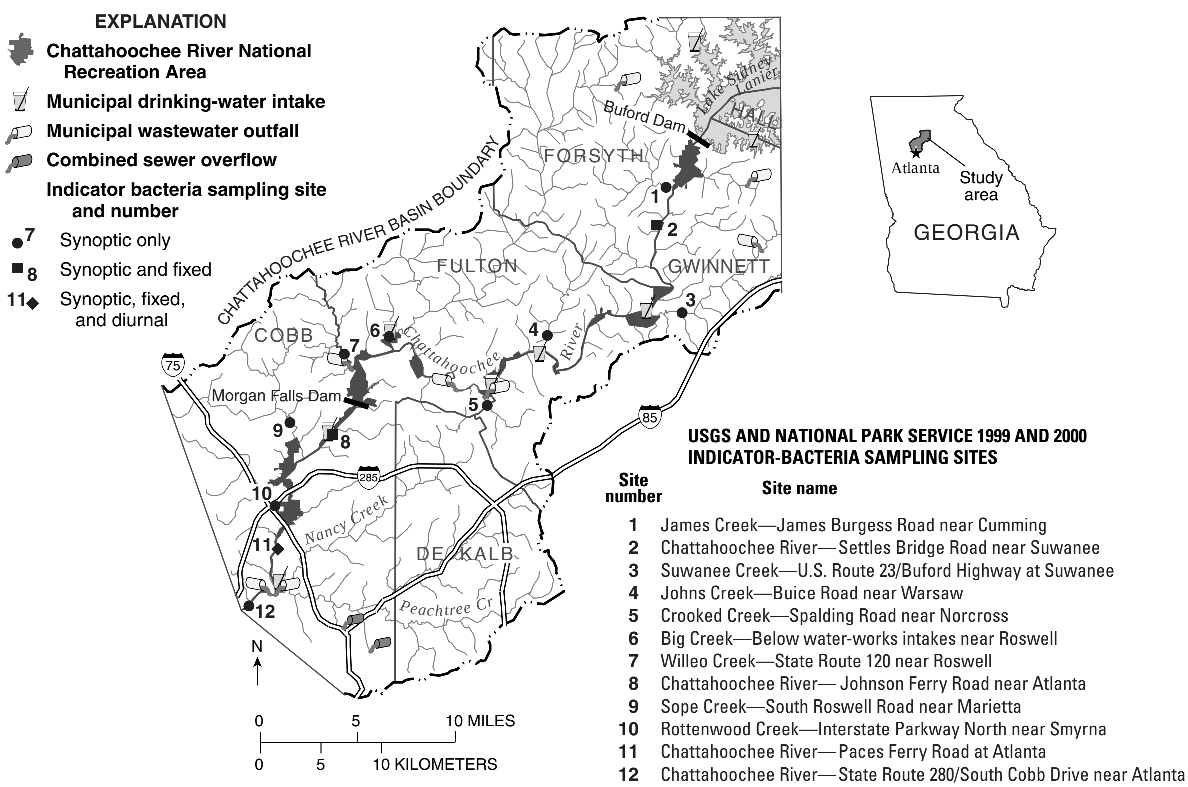

Figure 1. Location of study area, Chattahoochee River National Recreation Area, and indicator-bacteria sampling sites in the study area.

The presence of indicator bacteria does not necessarily prove that pathogens are in the environment; however, the presence of indicator bacteria does show that contamination by fecal material has occurred. Measuring concentrations of indicator bacteria is more cost effective than testing for specific pathogens and provides information relevant to health risks associated with water-contact activities. Fecal-coliform bacteria have been widely used by State and Federal agencies as the preferred indicator bacteria. Georgia Environmental Protection Division's (GaEPD) microbial water-quality standards are based on the geometric-mean concentration of fecal-coliform bacteria calculated from at least 4 samples collected within a 30-day period (Georgia Environmental Protection Division, 2000; table 1). GaEPD geometric mean standard from May to October is 200 colonies per 100 milliliters (col/100 mL). In 1986, the U.S. Environmental Protection Agency (USEPA) recommended that states adopt *Escherichia coli* (*E. coli*) and *enterococci* standards for use in recreational waters (U.S. Environmental Protection Agency, 1986a) based on research showing direct relations between these bacteria and swimming-associated gastroenteritis (U.S. Environmental Protection Agency, 1986b).

The broad objectives of this study were to investigate the existence, severity, and extent of microbial contamination in the Chattahoochee River and eight major tributaries within the CRNRA (fig. 1). This was accomplished by (1) summarizing existing recent fecal-coliform data (Gregory and Frick, 2000) (2) conducting routine monitoring of three indicator-bacteria at three sites on the Chattahoochee River from March 1999 to April 2000 (3) conducting synoptic surveys at four mainstem and eight tributary sites during low-flow and storm-flow conditions and (4) conducting diurnal sampling at one mainstem site. This paper briefly summarizes fecal-coliform bacteria, *E. coli*, and *enterococci* concentrations measured as part of this study on the Chattahoochee River and tributary streams from March 1999 to April 2000.

Study design and methods

Three Chattahoochee River sites were sampled every 5 days from March–October 1999 and every eight days from October 1999–April 2000. Synoptic sampling of four Chattahoochee River sites and eight tributary stream sites was conducted on four dates during low-flow and storm-flow conditions. Diurnal samples were collected every 2 hours for 26-hours during a period of dry-weather and stable-flow conditions at the Chattahoochee River at Paces Ferry Road on August 4–5, 1999. Indicator-bacteria samples were collected according to USGS protocols for the equal-width-increment technique and using isokinetic samplers (Wilde and others, 1999). Except for two grab samples, all water samples were composites of multiple vertical samples at each site. Samples were chilled immediately after collection and hold times were typically less than 4 hours. Indicator-bacteria concentrations were deter-

Table 1.Georgia fecal-coliform standards and U.S. Environmental Protection Agency recommended criterion and standards for indicator bacteria

[—, no standard or criterion has been set]

Indicator bacteria	Time period that standards and criterion apply	Georgia fecal-coliform bacteria standards[1/]		U.S. Environmental Protection Agency		
				Criterion[2/]	Standards[3/]	
		30-day geometric mean[4/]	Single-sample maximum[5/]	Single sample[5/]	30-day geometric mean[d]	Single-sample maximum
Fecal-coliform bacteria	May–October[6/]	200	—	400	—	—
	November–April	1,000	4,000	—	—	—
E. coli	year round	—	—	—	126	235
Enterococci	year round	—	—	—	33	61

[1/]Georgia Environmental Protection Division (2000)

[2/]U.S. Environmental Protection Agency (1997)

[3/]U.S. Environmental Protection Agency (1986a and b)

[4/]Based on at least four samples collected from a given sampling site over a 30-day period at intervals not less than 24 hours. The geometric mean of a series of N terms is the N^{th} root of their product. For example, the geometric mean of 2 and 18 is 6—the square root of 36.

[5/]Georgia waters are deemed **not supporting** designated uses (impaired) when 25 percent or more samples have fecal-coliform bacteria concentrations greater than the applicable review criterion or standard (400 or 4,000 col/100 mL) and **partially supporting** when 11 to 25 percent of samples exceed the review criterion or standard.

[6/]In Georgia regulations for water-quality control, May–October is defined as the period when water contact recreation activities are expected to occur. The State of Georgia does not encourage swimming in surface waters since a number of factors which are beyond the control of any State regulatory agency contribute to elevated levels of fecal-coliform bacteria.

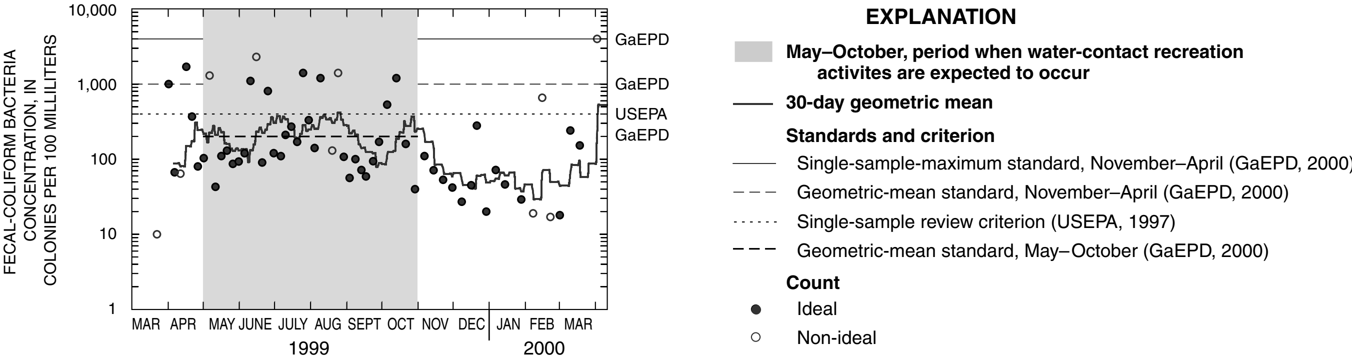

Figure 2. Temporal variations of fecal-coliform bacteria concentrations in the Chattahoochee River at Atlanta (Paces Ferry Road), March 1999–April 2000.

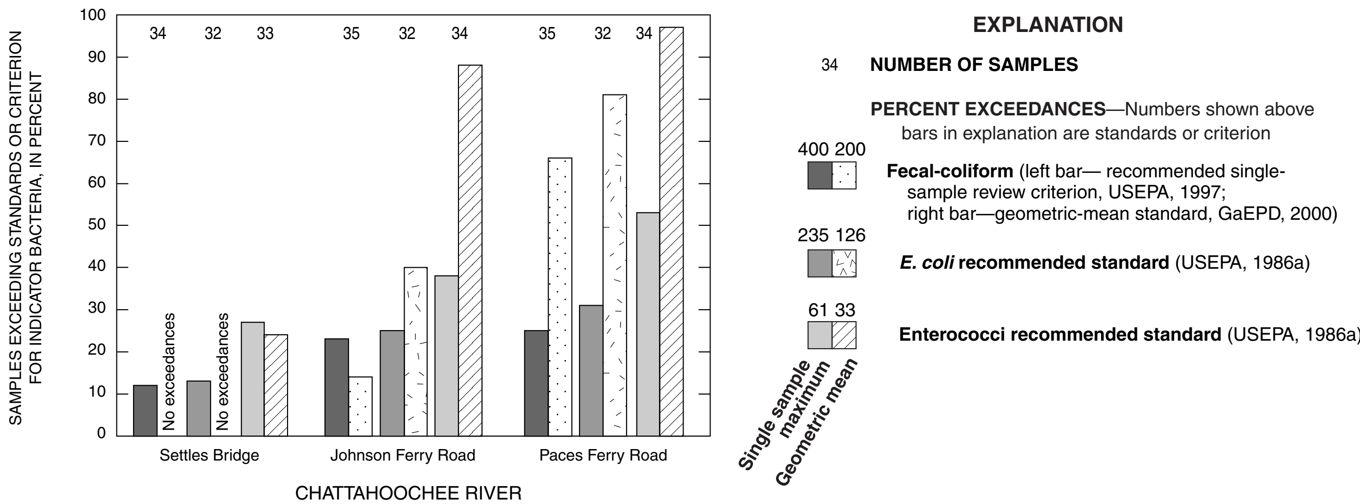

Figure 3. Percentage of samples exceeding standards or criterion for indicator bacteria at three Chattahoochee River sites, May–October 1999.

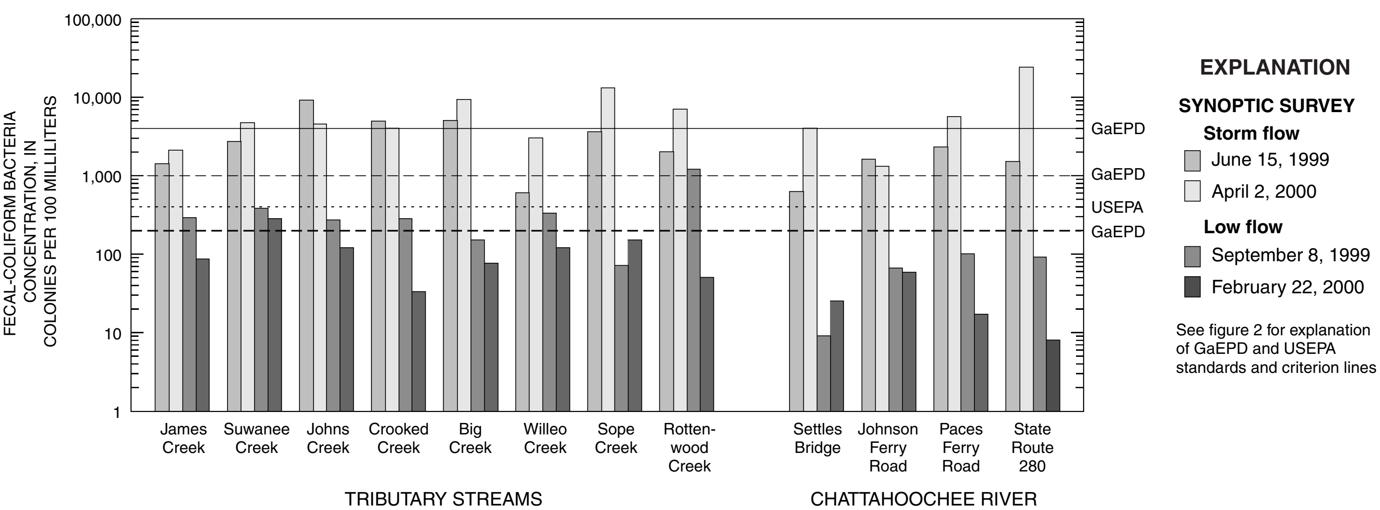

Figure 4. Fecal-coliform bacteria concentrations in water samples collected during four synoptic surveys of selected sites in the study area, 1999–2000.

-mined using the membrane filtration procedure using m-FC media for fecal-coliform bacteria, m-TEC media for *E. coli,* and EIA media for enterococci (Myers and Wilde, 1999).

Results

The geometric-mean of fecal-coliform bacteria concentrations commonly exceeded GaEPD standards in samples collected from the Chattahoochee River at Paces Ferry Road (fig. 2), especially during May to October 1999 when water-contact recreation activities are expected to occur. In the reach of the Chattahoochee River which flows through Metropolitan Atlanta, indicator-bacteria concentrations in water samples and the percentage of samples exceeding bacteria standards increased from the upstream monitoring site at Settles Bridge to the downstream monitoring site at Paces Ferry Road. From May to October 1999, the percentage of samples exceeding the geometric-mean standards (table 1) at the three routine monitoring sites ranged from 0 to 66 percent for fecal-coliform bacteria, from 0 to 81 percent for *E. coli*, and from 24 to 97 percent for enterococci (fig. 3).

Synoptic surveys indicated lowest fecal-coliform bacteria concentrations occurred in the Chattahoochee River and tributaries during low-flow conditions; whereas, the highest fecal-coliform bacteria concentrations occurred during storm-flow conditions (fig. 4). During low-flow conditions, fecal-coliform bacteria concentrations in tributary streams were generally higher than concentrations in the Chattahoochee River; during storm-flow conditions—the same relation is true. In all storm-flow synoptic samples, the USEPA recommended single-sample review criterion of 400 col/100 mL for fecal-coliform bacteria was exceeded. During low-flow conditions, indicator-bacteria concentrations generally were 1 to 2 orders of magnitude less than concentrations measured during the two storm-flow synoptic surveys. One low-flow synoptic sample collected at Rottenwood Creek exceeded the USEPA recommended review criterion.

During diurnal sampling, indicator-bacteria concentrations were lowest during the late afternoon, following the period of most intense sunlight, and highest during the night (fig. 5). Concentrations of fecal-coliform bacteria, *E. coli*, and enterococci were approximately 4, 6, and 8 times higher, respectively, during the night than when sunlight intensity was highest. Daily fluctuations in sunlight intensity may be a source of variability in indicator-bacteria concentrations during low-flow conditions and in shallow water.

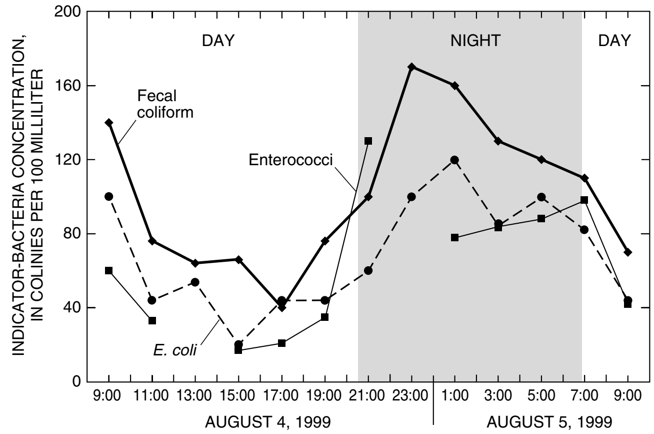

Figure 5. Diurnal variation in indicator-bacteria concentrations in the Chattahoochee River at Atlanta (Paces Ferry Road), August 4 and 5, 1999.

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FIELD MONITORING OF BRIDGE SCOUR IN GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia., p. 518-520

Abstract. Scour or erosion of the streambed near the foundations of a bridge is often referred to as "bridge scour." Bridge scour is caused by the interaction between turbulent flows induced by bridge structures and the streambed. These turbulent flows erode the streambed and cause scour holes. The Georgia Institute of Technology and the U.S. Geological Survey (USGS), in cooperation with the Georgia Department of Transportation and the Federal Highway Administration (FHWA), are conducting an investigation to improve bridge scour predictions by combining field monitoring, physical modeling in the laboratory, and three-dimensional numerical modeling of bridge scour. By integrating three-dimensional numerical modeling with laboratory and field measurements, it is proposed that some of the uncertainties associated with bridge scour predictions would be significantly reduced.

INTRODUCTION

Scour of the streambed at bridge piers and abutments is the leading cause of bridge failures in recent history. Bridge scour is the measure of the decrease in the channel bed elevation due to the interaction of turbulent flows induced by a bridge structure and the streambed. The turbulent flows erode the streambed and cause scour holes. Bridge scour is a function of flow energy, sediment-transport capacity, and bridge characteristics. Complexities associated with bridge scour have hampered satisfactory analyses and prediction procedures.

A bridge scour research project that integrates three-dimensional numerical modeling with laboratory and field measurements is being conducted by the Georgia Institute of Technology and the USGS, in cooperation with the Georgia Department of Transportation and the FHWA. The integration of the three components is intended to improve bridge scour predictions using one-dimensional methods. Greater accuracy of bridge scour predictions may lead to increased confidence in bridge design; thus, increasing public safety of the citizens who use the bridges. Improved bridge scour predictions may also decrease unnecessary expenses for scour countermeasures, making the bridge design process more efficient.

This paper discusses the field monitoring and sampling component of the project. This component of the research project will provide detailed field measurements of bridge scour that can be used to calibrate and refine the scale effects of laboratory and numerical models, so that bridge scour prediction techniques may be improved.

FIXED-FIELD INSTRUMENTATION

Channel geometry is the most fundamental component of a bridge scour data set and requires concurrent measurements of streambed elevation and horizontal position. Echo sounders measure the distance between a transducer and the streambed by emitting an acoustic pulse and measuring the time required for the pulse to reflect off the streambed and return to the transducer. Digital recording echo sounders process the signal and provide a single digital value through a computer port. Downward looking fathometers will be deployed on the upstream and downstream side of bridge piers and abutments (if abutments project into the streamflow). Fathometers are typically installed about three feet above the maximum bed elevation. Installation of transducers close to the streambed reduces any problems with the fathometer beam intersecting the edge of a bridge pier or abutments and reduces the possibility of debris hitting and damaging the transducers. Cables will run from each fathometer transducer to the fathometer array-control box in the instrument shelter. Satellite telemetry will provide water-level data so that approaching floods may be monitored in order to determine when to deploy a mobile field measuring crew. Channel bed elevations at monitoring points will be recorded by a minimum of once every hour.

Field instrumentation will be installed at four bridge sites, which will be chosen to represent various sediment types in Georgia. Detailed fixed instrumentation will be installed at two sites. One site will be located in the Coastal Plain Province, and the second site will be located in the Piedmont Province. Less-detailed fixed instrumentation will be installed at the remaining two USGS gaging stations. The detailed sites will have the following equipment:

- stage sensor;
- cross-channel two-dimensional velocity sensor;
- fathometer array to record streambed elevation;
- raingage;
- data logger and controller for each device;
- solar panel and instrumentation shelter; and
- satellite telemetry.

The less-detailed sites will have the same equipment except for the velocity sensor.

Stream stage affects scour directly (limiting dimensions of vortices and flow fields) and indirectly (as a measure of velocity and sediment transport capacity). The stage sensor will be a submerged pressure transducer or an acoustic device. The stage sensor will be a high-accuracy (0.02 foot, 6 millimeter minimum accuracy), standard USGS application device. Stage will be recorded at 15-minute intervals.

Water velocity is a critical bridge scour parameter that is used to quantify the available scour energy. The cross-channel velocity sensor provides two-dimensional velocity for a series of points across the channel in the bridge-approach section. The sensor will be mounted at a fixed location and aimed across the channel. These devices are being used to develop index velocity-discharge relations at many sites where stage is not an adequate indicator of discharge. The velocity meter uses acoustic-Doppler technology and has its own system controller on site. Velocities will be recorded at 15-minute intervals.

MOBILE FIELD INSTRUMENTATION

A mobile scour data-collection system has four components: instruments to measure velocity and channel-geometry data; instruments to deploy equipment in the water; an instrument to measure the horizontal position of the data collected; and a data storage device. For this investigation, an acoustic Doppler current profiler (ADCP) will be deployed from a manned or remote control boat and used to measure three-dimensional velocity profiles. A recording digital fathometer will be used to measure channel depths. Horizontal position will be measured using a kinematic differential Global Positioning System (GPS). Some of the parameters collected with the mobile instrumentation include:

- detailed channel geometry at and near the bridge;
- approach-flow velocities over the study reach;
- water-surface slope during flood events;
- visual analysis and notes on the surface velocity direction, channel and overbank;
- roughness, and vegetation cover;
- approximate measurements of the extent and composition of debris;
- photographs of channel and bridge at flood and low-flow conditions;
- water temperature;
- bridge and pier geometry; and
- bed-sediment samples and soil boring logs from the bridge crossing.

All data will be recorded and used to interpret and extend the data collected by the fixed instrumentation, and for the mathematical modeling component of this investigation.

STREAMBED SEDIMENT SAMPLING

Bed-material characteristics are important determinants of streambed erodibility and bed-material transport conditions. Techniques for bed-material sampling in sand-bed streams are described in Edwards and Glysson (1988), and Ashmore and others (1988). The objective for any of the collection techniques is to ensure that a representative sample is collected. The BMH-53 or BMH-80 hand samplers are used to collect the samples in sand-bed streams that are wadable. A BM-54 is used to collect samples in sand-bed streams that are too deep to be waded. Procedures are not well defined for sampling cohesive bed-materials; but a BMH-53 or similar cylinder sampler may be used on wadable streams. The type of sampler used will always be noted with the bed-material data.

Sampling locations will be selected to ensure samples are representative of the bed material controlling the sediment-transport processes in the study reach. In streams with cohesive beds, Sediment in the zone of scour will be sampled. In sand channels with uniform bed-material characteristics, the sampling location is not difficult to determine; but in coarse-bed streams with riffles and pools, bed-material characteristics vary significantly and a representative sample is much more difficult to obtain. Noncohesive bed-material in a scour hole is often coarser than and atypical of bed material controlling the sediment-transport processes of the stream. Thus, samples collected directly from a scour hole should be avoided when determining representative bed-material characteristics for the channel reach.

Bed material samples will be collected from several locations both in the bridge approach and the bridge sections, including in local scour holes. Bed-material samples will be analyzed by the Georgia Institute of Technology laboratories for grain-size distribution and other properties related to bridge scour.

SUMMARY

The data-collection process for the field monitoring component of the bridge scour research project will be conducted using fixed and mobile instrumentation to measure velocity and scour depth and by sampling streambed sediment within the study reach. Field instrumentation will be installed at four bridge sites, which will be chosen to represent various sediment types in Georgia. Detailed fixed-scour instrumentation will be installed at two of the sites, whereas only limited instruments in combination with existing streamflow gaging stations and historical scour measurements will be employed at the other two sites. Mobile instrumentation will be deployed during scour events at the two detailed study sites and will include detailed measurement of hydraulic and bathymetric data through the study reach. Bed-material samples will be collected at all sites. All data will be used for the physical and mathematical components of the project.

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WATER-QUALITY MONITORING IN GWINNETT COUNTY

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 521-524.

INTRODUCTION

In 85 percent of streams and 99 percent of lakes in Georgia that do not meet designated uses, nonpoint sources of contaminants are the cause (Georgia Environmental Protection Division, 1999). Gwinnett County, in Metropolitan Atlanta, Ga., continues as one of the most rapidly growing areas in the United States. Nonpoint-source pollution is highly complex, because it arises from varied, dynamic, and interrelated sources—especially in areas of urban growth. Nonpoint-source pollution and its relation to rapidly changing land-use conditions is a major concern in Gwinnett County. Water-quality degradation or improvement due to changes in watershed land use and management typically occur over time scales of years. However, water-quality conditions have high variability over the short term, and both acute and chronic conditions are important. Understanding the various changes and processes that affect water quality requires a watershed-monitoring program that includes intensive, long-term monitoring of streamwater quality and watershed characteristics.

The U.S. Geological Survey (USGS), in cooperation with Gwinnett County, Department of Public Utilities, established a water-quality monitoring program in 1996 to assess and analyze the impacts of nonpoint-source contaminants. The program provides water-quality information that can aid land and water-resource managers to make informed resource management decisions that can affect water quality. The Gwinnett County monitoring program includes the development of a network of real-time, continuous water-quality stations augmented with water-quality sampling and analysis of likely contaminants. Long-term monitoring will quantify and describe the fluctuation of pollutants within a stream. Analysis of water quality within a stream, over time, will define possible water-quality trends in the watershed; thereby identifying how land use and development may impact a watershed. Also, the real-time, continuous water-quality network may aid in timely decision making on watershed management. This paper describes the current water-quality monitoring program in Gwinnett County.

Scope and Study Area

Gwinnett County is located in the Piedmont physiographic province of Georgia in one of the most rapidly growing areas in the Unites States (U.S. Bureau of Census, 1991). Gwinnett County is a mostly headwater area where streams drain into one of three major river basins—the Chattahoochee, Ocmulgee, and Oconee. Land use varies greatly throughout the County; however, residential land use is more than 50 percent of the County's total land area when grouping all classes of residential land use. The monitoring network includes 12 monitoring stations located within watersheds of the Chattahoochee, Ocmulgee, and Oconee River basins. These stations will provide real-time continuous, water-quality data in watersheds that represent a wide range of land-use conditions and drain more than 70 percent of Gwinnett County. Six stations have operated since 1996, and six additional stations are being added in 2001.

METHODS

Watershed selection

The Gwinnett County water-quality monitoring network is listed in table 1 and shown in figure 1.

Twelve watersheds were selected for the monitoring network based on watershed characteristics, such as basin size, and land use. Smaller watersheds typically have a dominant land use and fewer total types of land use—this simplifies recognizing relations between observed water quality and land use. Also, smaller watersheds have fewer variables that affect runoff processes including small tributary networks that are minimally affected by widely varied rainfall distribution. However, a watershed should be large enough to have all basic watershed processes, so that water-quality monitoring results can be transferable to other watersheds in the region. Larger watersheds also have longer runoff events making it easier to collect better quality and larger quantity storm samples. Watersheds in the network include North Fork Peachtree Creek where 49 percent of land use is commercial, industrial, and transportation/communications; No Business Creek where 44 percent of land use

Table 1. Water-quality monitoring network, Gwinnett County, Georgia, 2001

Station number	Stream name and location	River basin	Drainage area (square miles)
02207120	Yellow River at State Route 124 near Lithonia, Ga.	Ocmulgee	160
02207185	No Business Creek at Lee Road near Centerville, Ga.	do.	8.7
02207385	Big Haynes Creek at Lenora Road near Snellville, Ga.	do.	17.8
02207400	Brushy Fork Creek at Beaver Road near Loganville, Ga.	do.	8.03
02208150	Alcovy River at New Hope Road near Grayson, Ga.	do.	28.2
02217274	Wheeler Creek at Bill Cheek Road near Auburn, Ga.	Oconee	1.32
02218565	Apalachee River at Fence Road near Dacula, Ga.	do.	5.67
02334480	Richland Creek at Suwanee Dam Road near Buford, Ga.	Chattahoochee	9.35
02334580	Level Creek at Settles Bridge Road near Suwanee, Ga.	do.	8.33
02334885	Suwanee Creek at Buford Highway near Suwanee, Ga.	do.	46.8
02335350	Crooked Creek at Spalding Drive near Norcross, Ga.	do.	6.66
02336030	North Fork Peachtree Creek near Doraville, Ga.	do.	5.05

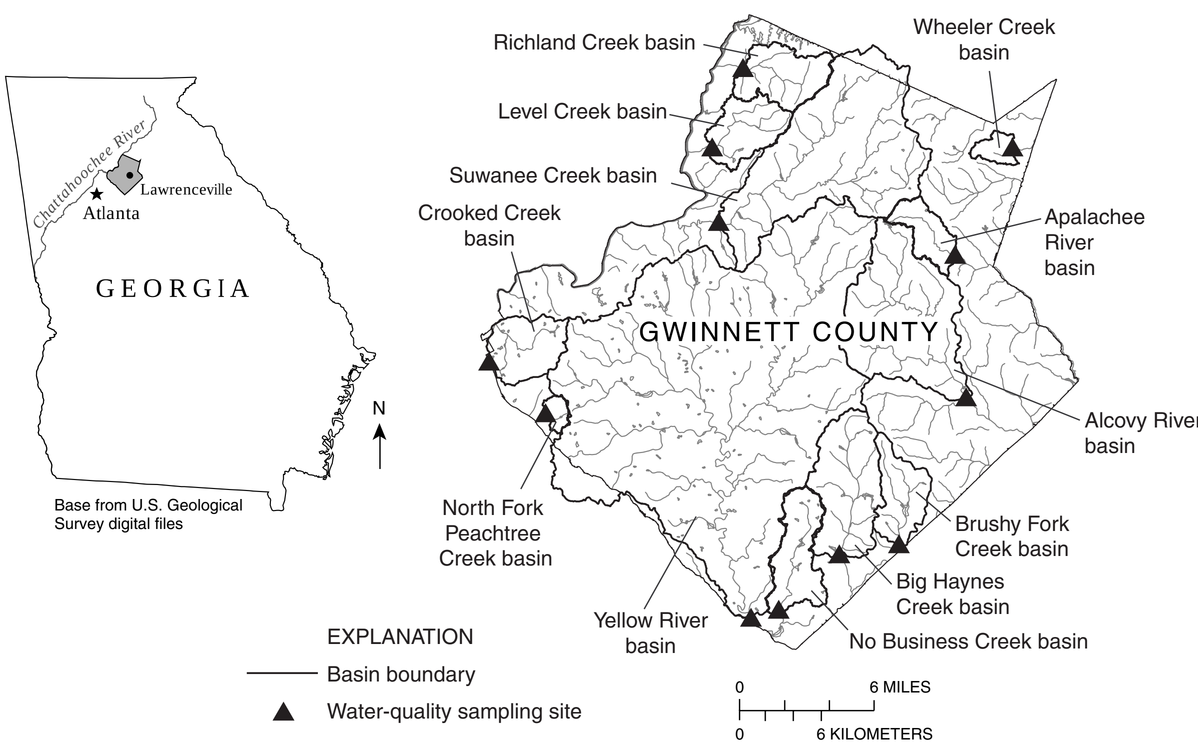

Figure 1. Gwinnett County streamwater-quality monitoring network, 2001.

is established, low density residential areas; and Wheeler Creek where 45 percent of the land is undeveloped. The Wheeler Creek watershed provides an opportunity to begin monitoring before urban land-use changes increase in the basin, and provides a basis for comparisons with more developed watersheds. The percentage of land use for each watershed where water-quality monitoring sites are located, by river basin, is presented in table 2.

Sampling and Monitoring of Watersheds

Long-term monitoring of stream-water quality involves the collection and analysis of baseflow (or dry-weather) samples, stormflow samples, and the continuous measurement of physical and water-quality parameters. Water-quality samples are collected seasonally. During each season—defined as summer or winter season—three stormflow and three baseflow samples are collected. At 6 of the 12 sites, storm-composite samples are collected on a flow-weighted basis using an automatic sampler for the duration of the storm event. At the remaining 6 sites, storm samples are collected using the USGS equal-width increment protocol (Wilde and others, 1998) and typically are obtained during periods when the storm runoff is increasing. Samples are analyzed for the following constituents and parameters:

- Turbidity
- Biological oxygen demand (BOD)
- Chemical oxygen demand (COD)
- Hardness total
- Total suspended solids (TSS)
- Total dissolved solids (TDS)
- Nitrates-nitrites (NO_3-NO_2)
- Ammonia nitrogen (NH_3-N)
- Total Kjeldahl nitrogen (TKN)
- Phosphorus
- Dissolved phosphorus
- Total organic carbon (TOC)
- Cadmium (dissolved)
- Copper (dissolved)
- Lead (dissolved)
- Zinc (dissolved)

Table 2. Percent of land use for monitored watersheds, by river basin, Gwinnett County, Georgia, 2001
[Data derived from Atlanta Regional Commission's 1995 land-use coverage]

River basin	Name of stream tributary	Land use (in percent): Agriculture	Commercial, Industrial, and Transportation, Communications, and Utilities (nonresidential areas)	Estate, Residential	Residential–medium to high density	Residential–low to medium density	Park land	Paved roads, streets, and highways	Undeveloped land	Water
Chattahoochee	Crooked Creek	0	36	0	16	15	0	13	19	0
Do.	Level Creek	0	3	20	3	38	1	9	26	0
Do.	North Fork Peachtree Creek	0	49	0	17	11	1	15	6	0
Do.	Richland Creek	0	15	13	5	23	3	7	34	0
Do.	Suwanee Creek	1	11	21	2	18	2	10	34	0
Ocmulgee	Alcovy River	0	11	25	1	22	0	8	32	0
Do.	Big Haynes Creek	0	4	15	0	50	2	8	20	1
Do.	Brushy Fork Creek	0	5	44	1	24	1	6	18	1
Do.	No Business Creek	0	8	12	1	44	7	9	18	0
Do.	Yellow River	0	14	10	9	35	3	12	17	1
Oconee	Apalachee River	3	2	17	0	23	10	5	38	0
Do.	Wheeler Creek	0	0	28	2	16	0	9	45	0

When water-quality monitoring began in 1996, the Georgia Department of Natural Resources, Environmental Protection Division (GaEPD) water-quality standards required that total (unfiltered sample) metal concentration be reported. However, GaEPD water-quality standards changed in 2000 requiring that dissolved metal concentrations (0.45 micron (μ) capsule filtered sample) be reported (Georgia Environmental Protection Division, 2000). Dry-weather (baseflow) samples collected at Big Haynes Creek and Brushy Fork Creek also will be analyzed for concentrations of chromium, iron, manganese, and color. All sample collection, sample processing, and sample analysis follow quality assurance and control protocols outlined in the National Field Manual for the Collection of Water-Quality Data 1998 (Wilde and others, 1998). In addition to water-quality sampling, the following parameters will be recorded at 15-minute intervals at all 12 sites using an insitu data sonde and data logger—streamflow, rainfall, temperature, specific conductance, and turbidity. Real-time, continuous data are important in watershed management because immediate observation of processes occurring within a watershed can be monitored. Recorded data is transmitted via satellite to the USGS, Atlanta, Ga., and selected parameters are updated on the World Wide Web, Georgia District home page (**http://ga.water.usgs.gov**) every four hours. During extreme storm events, the sites are programmed to transmit data on a more frequent interval. Real-time data will help define current conditions and enable watershed managers to make timely, informed management decisions. USGS personnel also will be able to prioritize sampling efforts during storm events and identify potential water-quality concerns.

Water-Quality Analyses

Water-quality data are used to define the conditions and processes occurring within a watershed and can point to potential sources of water-quality degradation. Determination of pollutant contaminant sources may assist in understanding the impact that various land uses have on a watershed. Also, observing water-quality changes through time may serve to quantify how land-use changes impact water quality and provide a measure of the effectiveness of various Best Management Practices used within a watershed. Water-quality analyses also provide information on background concentrations, short-duration (event), seasonal, and long-duration water-quality changes, and the yield of selected constituents from watersheds having different land uses and characteristics.

SUMMARY

In areas of urban growth, nonpoint-source pollution is highly complex because it arises from varied dynamic, and interrelated sources, especially in areas of urban growth. Nonpoint-source pollution and its relation to rapidly changing land-use conditions is a major concern in Gwinnett County, Ga. In an effort to address this concern, the USGS, in cooperation with Gwinnett County, Department of Public Utilities, developed a long-term watershed-monitoring program in 1996. The program includes watershed selection, long-term monitoring of streamwater quality and watershed characteristics, developing a real-time water-quality network, and analysis. With this plan in place, water-resource managers will have hydrologic data needed to make timely and informed decisions regarding the use of Best Management Practices and other watershed-management practices.

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TRICHLOROETHENE PRESENCE IN ROTTENWOOD CREEK NEAR AIR FORCE PLANT 6, MARIETTA, GEORGIA, SUMMER 2000

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at the University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 586-589.

Abstract. Diffusion samplers were installed at 36 sites along a 2-mile length of Rottenwood Creek, near Air Force Plant 6 (AFP6) at Marietta, Ga., in order to delineate trichloroethene presence in the creek. Water was collected and analyzed for a suite of volatile organic compounds. Trichloroethene was the most frequently detected volatile organic compound followed by cis-1,2-dichloroethene, a common degradation product of trichloroethene. Trichloroethene was detected in two lengths of the creek. The downstream length of the creek contained proportionately more cis-1,2-dichloroethene than the upstream length, indicating the possibility that ground water discharging to these stream lengths moved along pathways with differing degradational histories.

INTRODUCTION

United States Air Force Plant 6 (AFP6) has specialized in aircraft manufacture and repair since its construction in 1942. Various chemicals including trichloroethene (TCE) have been used during plant operation. Within the B-4 area (fig. 1), multiple TCE releases to the environment have occurred resulting in TCE migration to ground water. A plume of TCE detected in ground water from AFP6 is believed to be moving northeast towards Rottenwood Creek. In 1985, the U.S. Environmental Protection Agency (USEPA) declared several parts of the B-4 area and other parts of Dobbins Air Force Reserve Base a Resource Conservation and Recovery Act (RCRA) site. TCE was detected

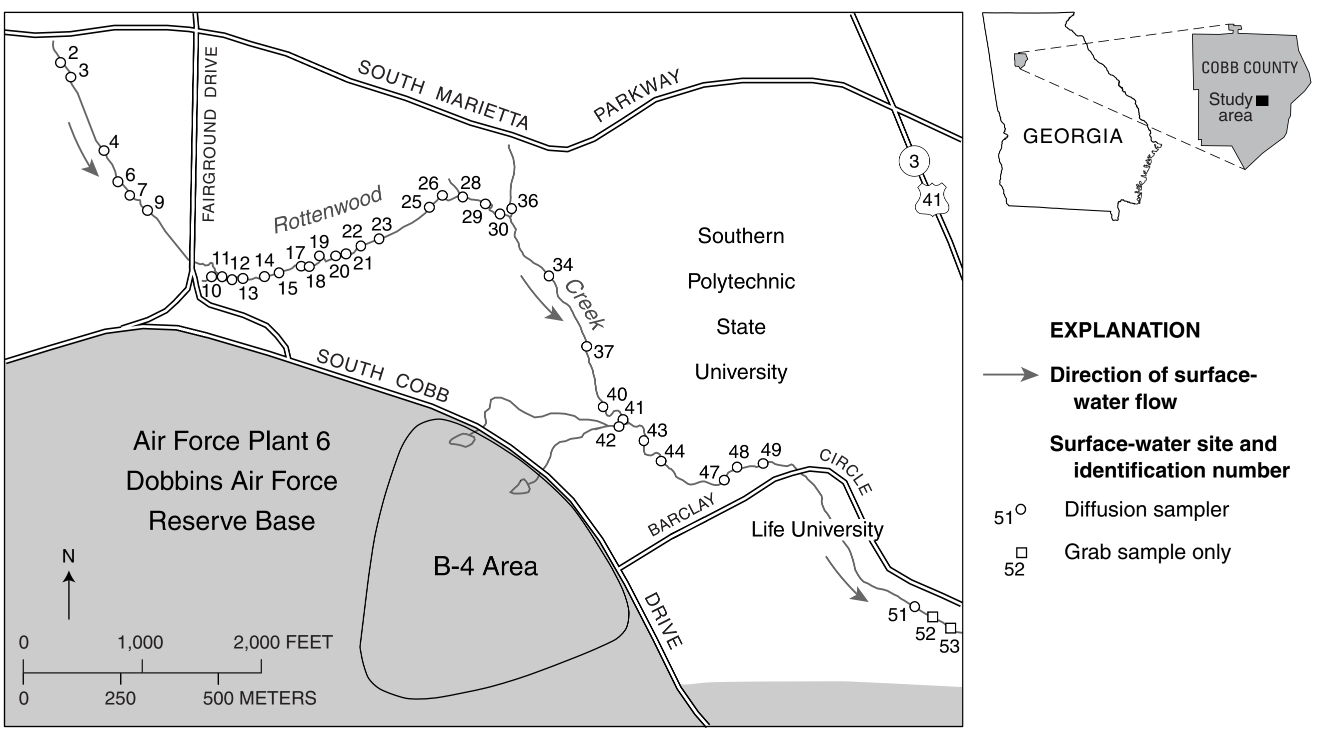

Figure 1. Location of surface-water sites with diffusion samplers in Rottenwood Creek, Summer 2000.

in an irrigation well at Southern Polytechnic State University, northeast of AFP6 and southwest of Rottenwood Creek.

Movement of TCE in the subsurface at AFP6 must be understood in order to effectively remediate contaminated ground water at the plant. Discharge of ground water from the B-4 area most probably is to Rottenwood Creek. Periodic sampling in Rottenwood Creek, performed by private consultants, indicates detectable concentrations of TCE at about 1 microgram per liter (μg/L) (CH2M Hill, written commun., 2000). Diffusion samplers were installed at 36 sites along a 2-mile length of Rottenwood Creek to delineate TCE presence in the creek. A total of thirty-three sites were in the main stem of Rottenwood Creek, and 3 sites were on tributaries to Rottenwood Creek. This paper describes the results of using passive-diffusion samplers to identify where ground water containing TCE may be discharging to Rottenwood Creek.

PHYSICAL SETTING

AFP6 is located in the Central Uplands district of the Piedmont Province of north Georgia (Fenneman, 1938). Topography consists of low semi-linear northeast-trending ridges separated by valleys. Elevation ranges from about 950 to 1,075 feet above mean sea level. AFP6 encompasses about 720 acres of a 3,336-acre military complex that includes Dobbins Air Force Reserve Base (fig. 1). AFP6 is government owned, but operated by a contractor—Lockheed-Martin Aeronautical Systems Corporation. AFP6 is located on a small plateau bounded by Rottenwood Creek to the northeast. The B-4 area is located between the plateau to the southwest and Rottenwood Creek to the northeast.

The Powers Ferry Formation, composed of biotite schist and biotite gneiss, comprises the bedrock beneath the region (Higgins and others, 1988). The contact between the schist and gneiss, and the orientation of foliation strike about N45E, and dip 60 degrees to the southeast. A major joint set in this bedrock strikes about N26W and dips nearly vertical. Many other fractures occur in random orientations. The upper part of the crystalline rock is chemically weathered to saprolite, and consists of resistant grains of minerals, such as quartz and muscovite mica residing in clay. Saprolite also is present as halos adjacent to fractures in the crystalline rock. Much of the saprolite retains the structure of the crystalline rock (structured saprolite).

The hydrogeology of the B-4 area is complex. Three zones with different hydrogeologic properties underlie the surface—overburden, transition zone, and bedrock (table 1). Thicknesses of the three zones vary widely over short horizontal distances and boundaries are commonly gradational. Ground-water flow is faster in fractured rock than in the porous media of the overburden (Freeze and Cherry, 1979). Ground-water flow generally radiates outward from the small plateau where AFP6 is located (International Technology Corporation, 1999). In the B-4 area, ground-water flow is generally to the northeast towards Rottenwood Creek.

Rottenwood Creek flows in a trellis pattern having two dominant flow directions in the study area—southeast and northeast; these two directions are roughly parallel to the trends of the major joint set and orientation of foliation, respectively. Reaches of Rottenwood Creek that flow southeast, cross foliation planes and flow roughly parallel to the major joint set. Bedrock is prevalent in these southeast-flowing reaches of the creek. Reaches of Rottenwood Creek that flow northeast, cross the major joint set and flow roughly parallel to the foliation planes. Bedrock is shallow beneath northeast-flowing reaches, but saprolite and overburden are usually in contact with the creek.

Rottenwood Creek is a perennial stream characterized by long periods of constant, relatively low flow punctuated by brief periods of surface-water runoff in response to moderate rainfall. Urban land use in the Rottenwood Creek watershed has resulted in a large proportion of surface area that consists of impermeable roads, parking lots, or buildings. A 0.5-inch rainfall results in surface-water runoff conditions that end within 4 hours of the rain event. Due to the flashy nature of the flow, Rottenwood Creek is typically at low flow more than 95 percent of the time. Because low-flow conditions persist even during the driest times of the year, ground-water discharge to the creek is most likely the source of low flow to the creek.

Table 1. Lithology and hydrology of conceptual geologic units at Air Force Plant 6, Marietta, Georgia

Geologic unit	Lithologic description	Generalized hydrologic description
Overburden	Reworked saprolite, soil, and fill	Porous media: Relatively homogenous Permeability, high Storativity, high Velocity, low
Transition zone	Structured saprolite and partially weathered metamorphic rock with significant amounts of saprolite	Fractured porous media (dual porosity): Heterogeneous Permeability, variable Storativity, intermediate Velocity, intermediate
Bedrock	Metamorphic rock (biotite schist and biotite gneiss)	Fractured rock: Highly heterogeneous Permeability, low Storativity, low Velocity, high

MOVEMENT AND LOSS OF TRICHLOROETHENE

TCE has many uses including degreasing, painting, dry-cleaning, and producing dyestuffs, textiles, and fumigants. TCE readily volatilizes into the air and is classified as a volatile organic compound (VOC). The density of TCE is approximately 1.46 grams per cubic centimeter, which is greater than the density of water. The solubility of TCE in water is about 1,400 milligrams per liter (mg/L), which exceeds the USEPA drinking-water standard of 0.005 mg/L by several orders of magnitude. Because its density is greater than water, pure-phase TCE in water is referred to as a dense non-aqueous phase liquid (DNAPL).

Migration of a TCE plume is complex and difficult to track. Aquifer assessment and subsurface sampling are currently underway at AFP6 to determine how TCE is moving through the subsurface. As a compound, TCE can occur in the subsurface in the non-aqueous phase (DNAPL) or in the aqueous phase, dissolved in water. How TCE moves in the subsurface largely depends on which phase the TCE is in. The movement of TCE as a DNAPL is density driven, enabling TCE to move across the direction of ground-water flow. Dissolved TCE moves in the same direction as ground-water flow. The subsurface beneath AFP6 is highly heterogeneous, further complicating the movement of TCE. DNAPL movement in fractured geologic media is particularly complex (Pankow and Cherry, 1996). DNAPL that moves across the direction of ground-water flow may allow TCE to migrate into different ground-water flow regimes (local flow, intermediate flow, or regional flow regimes as described in Freeze and Cherry, 1979). DNAPL TCE constantly dissolves into the ground water in the subsurface.

TCE (C_2HCl_3) degrades into less-chlorinated organic compounds such as cis-1,2-dichloroethene, vinyl chloride, ethene, and carbon dioxide. Tetrachloroethene (PCE) (C_2Cl_4) can degrade to TCE. Degradation can occur by reductive dechlorination, aerobic cometabolism, and direct oxidation (Chapelle, 2000; Fetter, 1993; Byl and Williams, 2000). All three of these processes may be accelerated and enhanced by naturally occurring bacteria. The presence of degradation compounds may reveal data about the transport and degradation history of the contaminant. Any TCE that enters Rottenwood Creek volatilizes into the atmosphere. As a result, interpretation of TCE concentrations in diffusion samplers must consider this loss of chemical.

SAMPLING METHODS

Diffusion (surface-water) samplers as described by Vroblesky and Hyde (1997) were installed at sites in Rottenwood Creek. Diffusion samplers were placed in 3-inch-diameter polyvinyl chloride pipes capped with strainers at both ends and tied to 2-foot lengths of rebar secured into the streambed. Originally, diffusion samplers were installed at 50 sites along Rottenwood Creek in late July 2000. Runoff events, however, washed away many of the samplers. As a result, samplers were reinstalled, sometimes repeatedly, at some sites. The most recent installation at several sites including three additional sites occurred in early September 2000. After the most recent installation, another runoff event washed away some samplers. Surface-water samples were extracted from a total of 36 diffusion samplers in early October 2000. During the extraction of water from diffusion samplers, duplicate diffusion samplers, and grab samples also were collected at selected sites. Water from the diffusion samplers and from grab samples was sent to a commercial laboratory and analyzed for 60 VOCs.

TRICHLOROETHENE IN ROTTENWOOD CREEK

Six VOCs were detected in diffusion-sampler water. TCE was detected at 22 sites; cis-1,2-dichloroethene was detected at 8 sites; chloroform at 5 sites; toluene at 4 sites; tetrachloroethene was detected at only 1 site, and cis-1,2-dichloroethane also was detected at only 1 site. The highest concentration of TCE (9.7 µg/L) was detected at site 42, located on a tributary of Rottenwood Creek that flows from the B-4 area (fig. 1). TCE may be entering Rottenwood Creek through fractures in the crystalline rock, as discrete flow paths in the overburden, and/or from surface-water tributaries. The tributary that drains the B-4 area is most likely contributing TCE to Rottenwood Creek; it is undetermined whether the TCE in the tributary comes from ground-water discharge or from surface-water runoff.

TCE was detected in surface-water samples in two lengths of Rottenwood Creek (fig. 2). TCE was not detected at sites upstream from site 11. In the upstream length, concentrations of TCE were 4.6 µg/L at site 11 and steadily declined downstream to 1.4 µg/L at site 20. In the downstream length, concentrations of TCE were detected in almost all samplers from site 34 to site 51. Concentrations of TCE declined from about 4.5 µg/L at site 40, to 1.3 µg/L at site 51. The two stream lengths where TCE was detected are separated by about 2,000 feet of stream length where TCE was not detected.

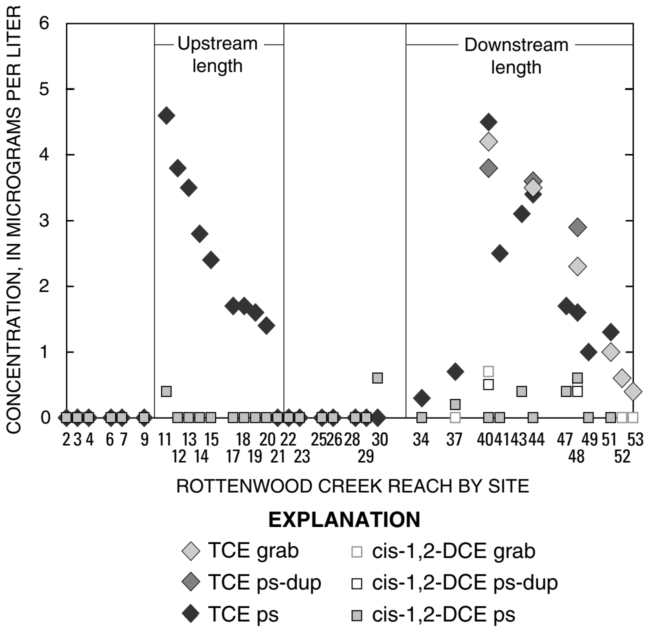

Figure 2. Concentrations of trichloroethene (TCE) and cis-1, 2-dichloroethene (cis-1,2-DCE) in surface water at sites along the mainstem of Rottenwood Creek, Marietta, Georgia, Summer 2000. Distance between sites varies. Samples were collected from passive-diffusion samplers (ps) and from duplicate passive-diffusion samplers (ps-dup), and as grab samples. Nondetects are plotted on the x-axis. Minimum detection limits for the TCE and cis-1,2-DCE are 0.20 and 0.27 micrograms per liter, respectively.

Generally, cis-1,2-dichloroethene was detected at surface-water sites where TCE was detected, and it was detected more frequently in the downstream length than in the upstream length of Rottenwood Creek. Similarly, the fraction of cis-1,2-dichloroethene-plus-TCE that is cis-1,2-dichloroethene is higher in the downstream length than in the upstream length of Rottenwood Creek (fig. 3). These results suggest that ground water discharging to these two lengths of the creek move along pathways with differing degradational histories.

DEGRADATION HISTORY OF TRICHLOROETHENE

Differences in the detections of cis-1,2-dichloroethene between two stream lengths indicate that TCE may have two separate pathways to Rottenwood Creek. During travel along these pathways, TCE that moves towards the downstream length of Rottenwood Creek may undergo more degradation to cis-1,2-dichloroethene than TCE that migrates towards the upstream length of the creek. Separate degradational histories along separate pathways may reflect differences in geology or reflect differences in the presence or absence of biodegradative microorganisms.

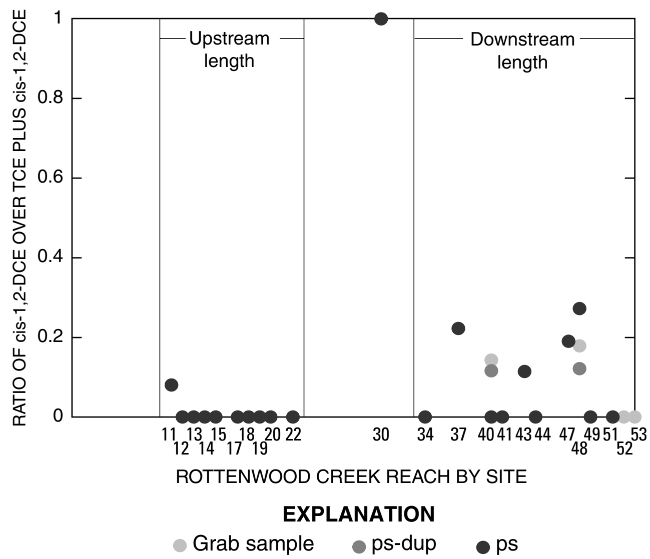

Figure 3. The concentration ratio of cis-1,2-dichloroethene (cis-1, 2-DCE) over trichloroethene (TCE) plus cis-1,2-DCE in surface water at sites along the mainstem of Rottenwood Creek, Marietta, Georgia, Summer 2000. Distance between sites varies. Samples were collected from passive-diffusion samplers (ps) and from duplicate passive-diffusion samplers (ps-dup), and as grab samples. Only sites with a detection of either TCE or cis-1,2-DCE are shown.

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USE OF GROUND-WATER FLOW MODELS FOR SIMULATION OF WATER-MANAGEMENT SCENARIOS FOR COASTAL GEORGIA AND ADJACENT PARTS OF SOUTH CAROLINA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 627-630.

Abstract. Ground-water flow models for the coastal area of Georgia and adjacent parts of South Carolina and Florida were utilized by the U.S. Geological Survey (USGS) for simulation of various water-management scenarios. Results of these simulations were used by the Georgia Department of Natural Resources, Environmental Protection Division (GaEPD) to help develop an interim water-management strategy for coastal Georgia. Results of selected model simulations are presented in this paper.

INTRODUCTION

Water supply in the 24-county coastal area of Georgia and adjacent parts of South Carolina and Florida mainly is withdrawn from the Upper Floridan aquifer. Withdrawal of water has resulted in regional ground-water-level decline and local saltwater intrusion in parts of the coastal area. Seawater encroachment on the northern end of Hilton Head Island, S.C., and saltwater intrusion from deeply buried, connate sources at Brunswick, Ga., have been documented.

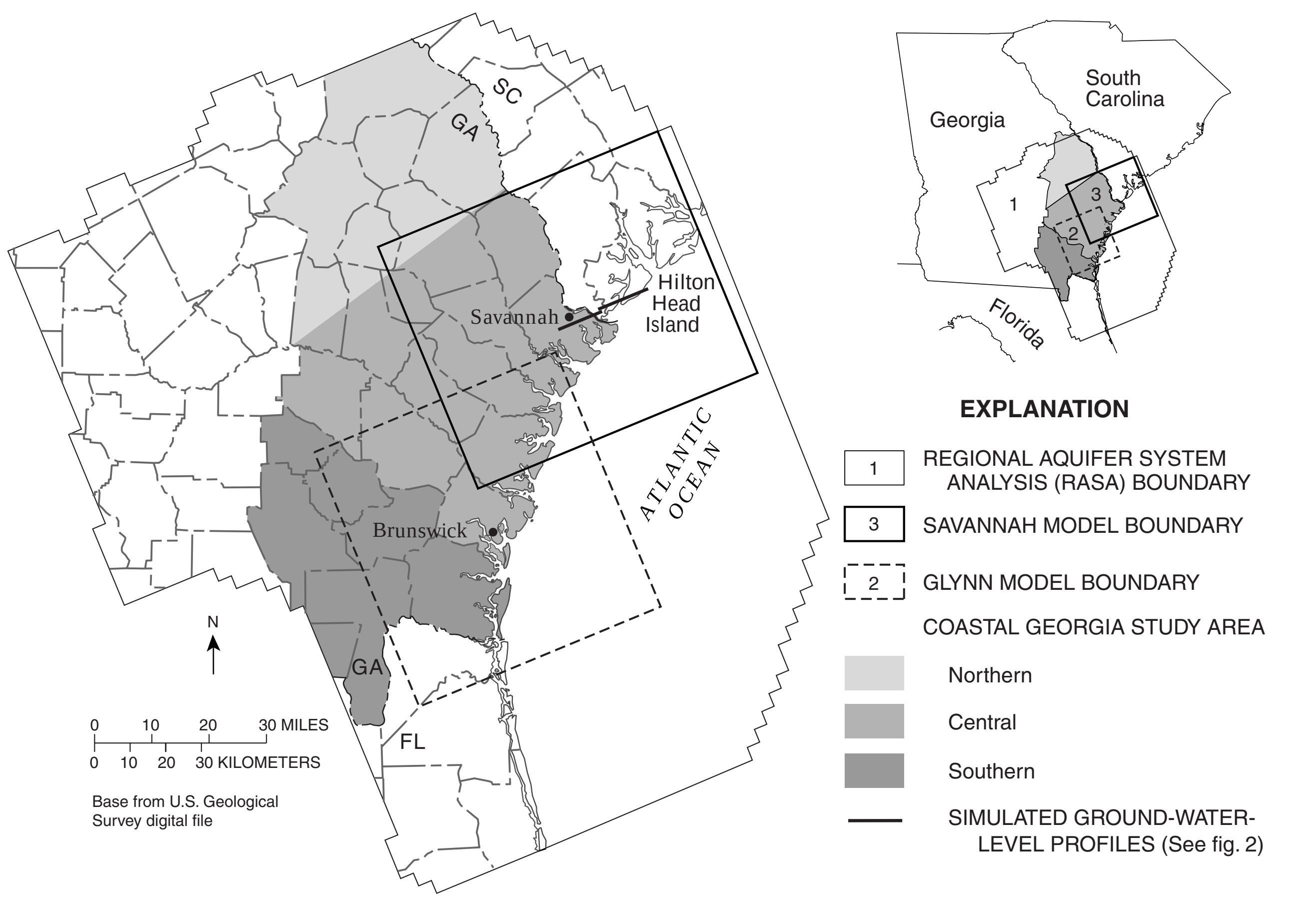

Figure 1. Regional Aquifer-System Analysis (RASA), subregional model boundaries, and coastal Georgia study area (modified from Clarke and Krause, 2000).

Three models, developed as part of regional and areal assessments of ground-water resources in coastal Georgia, were used to simulate water-management scenarios for coastal Georgia: the Regional Aquifer System Analysis (RASA) model, the Glynn County area (Glynn) model, and the Savannah area (Savannah) model (fig. 1). Each model simulates steady-state ground-water flow using the USGS three-dimensional finite-difference MODFLOW code (McDonald and Harbaugh, 1988). Details on model development and calibration are given in Clarke and Krause (2000), Garza and Krause (1996), Randolph and Krause (1990), and Krause and Randolph (1989).

The three models were used to predict effects that hypothetical changes in the distribution and amount of ground-water withdrawal might have on the Floridan aquifer system. The scenarios simulated pumpage changes from 82 million gallons per day (Mgal/d) less to 438 Mgal/d more than the estimated 1985 pumpage (308 Mgal/d).

Results of Water-Management Simulations

The potential for additional withdrawal of from the Upper Floridan aquifer is constrained by water-level declines at locations of saltwater contamination—the northern end of Hilton Head Island and Brunswick. Water-level changes for these areas were simulated to determine if pumpage had any effect on the hydraulic gradient between freshwater and saltwater zones, and the potential for saltwater contamination. Generally, the farther pumping is from the indicator cells at Brunswick and Hilton Head Island, the less is the effect on the ground-water level in the Upper Floridan aquifer and on saltwater contamination.

Effects of pumpage changes on vertical leakage from the Fernandina permeable zone (the source of saltwater) in the area of the Glynn model (fig. 1) also were simulated for each scenario. For scenarios that simulated decreased pumpage, vertical leakage from the Fernandina permeable zone decreased, and water levels at both Hilton Head Island and Brunswick rose, decreasing the hydraulic gradient and potential for saltwater contamination. Conversely, in response to increased pumpage, leakage from the Fernandina permeable zone increased, and water levels at each location declined, increasing the hydraulic gradient and potential for saltwater contamination.

Results from nine scenarios in the Savannah-Hilton Head Island area were used to produce profiles of simulated ground-water levels extending from the point of seawater encroachment on the north end of Hilton Head Island, to the center of the cone of depression at Savannah (fig. 2). These profiles, simulating pumpage reductions in Chatham County of

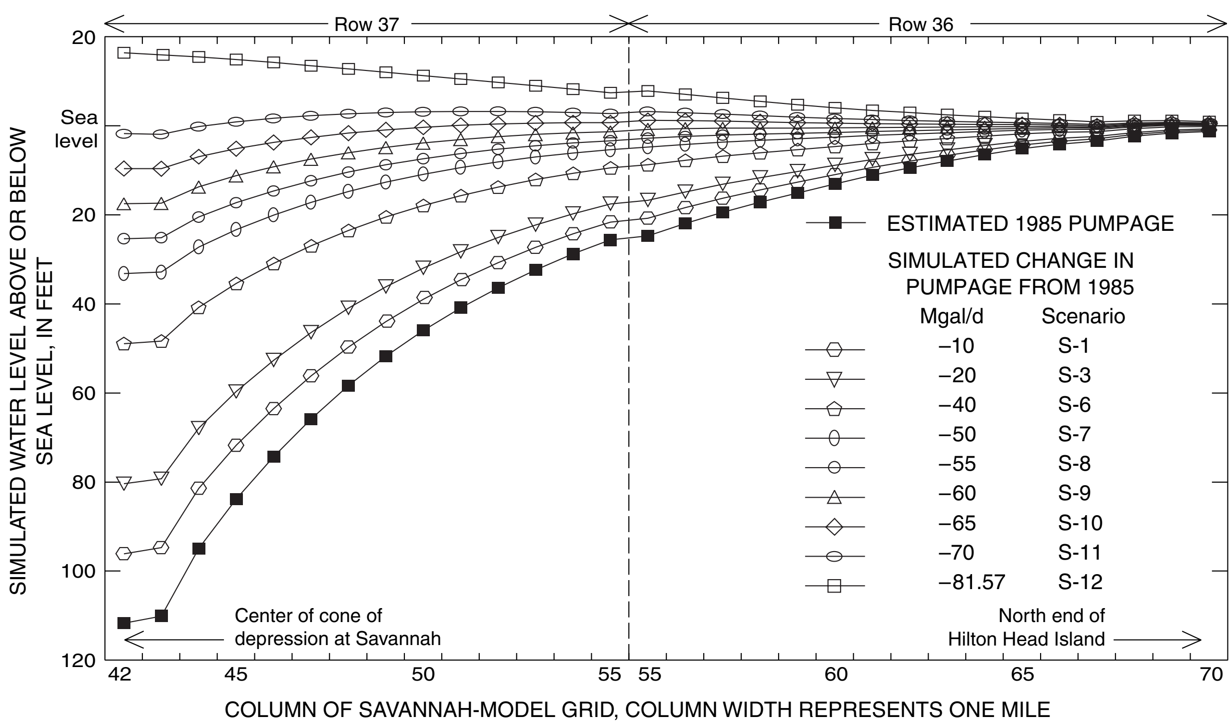

Figure 2. Simulated ground-water-level profiles for the Savannah-Hilton Head Island area for selected water-management scenarios (see figure 1 for location) (modified from Clarke and Krause, 2000).

about 10 to 82 Mgal/d, show the simulated hydraulic gradient toward Savannah is gentler for decreased pumping rates. With reductions in pumpage of 65 Mgal/d or more, the simulated hydraulic profile between Hilton Head Island and Savannah becomes reversed, and has a component of flow in a northeasterly direction from Chatham County toward Hilton Head Island. With cessation of pumpage at Chatham County, the simulated hydraulic gradient along the profile is toward Hilton Head Island and probably is similar to pre-pumping conditions.

Two hydrologic boundaries—the Gulf Trough, separating the northern and central subareas; and the postulated "Satilla Line," separating the central and southern subareas—may affect the development potential of the Upper Floridan aquifer (figs. 3, 4). Model simulations indicate that additional withdrawal may be possible north of the Gulf Trough and south of the "Satilla Line," without producing appreciable drawdown response at Brunswick or Hilton Head Island.

Additional withdrawal may be possible north of the Gulf Trough, as indicated by results from scenario A-4 (fig. 3), which represents a redistribution of pumpage to areas north of the Gulf Trough, and an overall 18 percent increase from the estimated May 1985 rate of withdrawal. Despite this increased pumpage, simulated water levels rose at both Brunswick and Hilton Head Island, and leakage from the Fernandina permeable zone decreased slightly.

South of the hypothesized "Satilla Line," additional withdrawal may be possible, as indicated by results from scenarios G-5 and G-6 (fig. 4), which simulated the effects of a 5 Mgal/d increase in pumpage on the northern and southern sides of the feature. Each scenario resulted in a negligible drawdown response (less than 0.05 ft) at Hilton Head Island. Scenario G-5 resulted in almost twice the drawdown response at Brunswick, as did scenario G-4, suggesting additional withdrawal may be possible south of the Satilla Line without producing an appreciable drawdown response at Brunswick.

Future Studies

Although the three flow models effectively simulate advective ground-water flow, they do not account for effects of variable density and dispersion, and thus

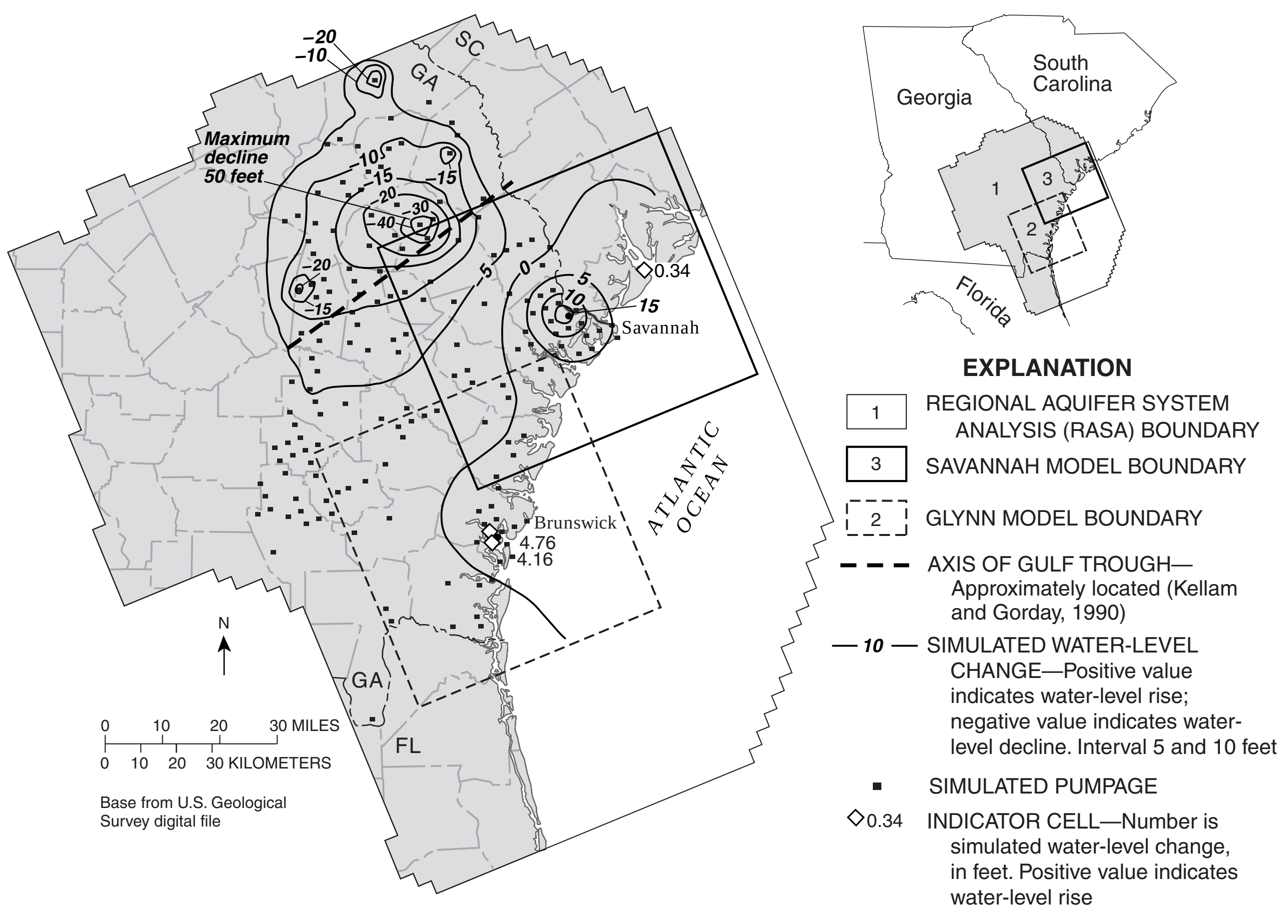

Figure 3. Simulated water-level change from May 1985 conditions for the Upper Floridan aquifer, and location of simulated pumpage and indicator cells (modified from Clarke and Krause, 2000).

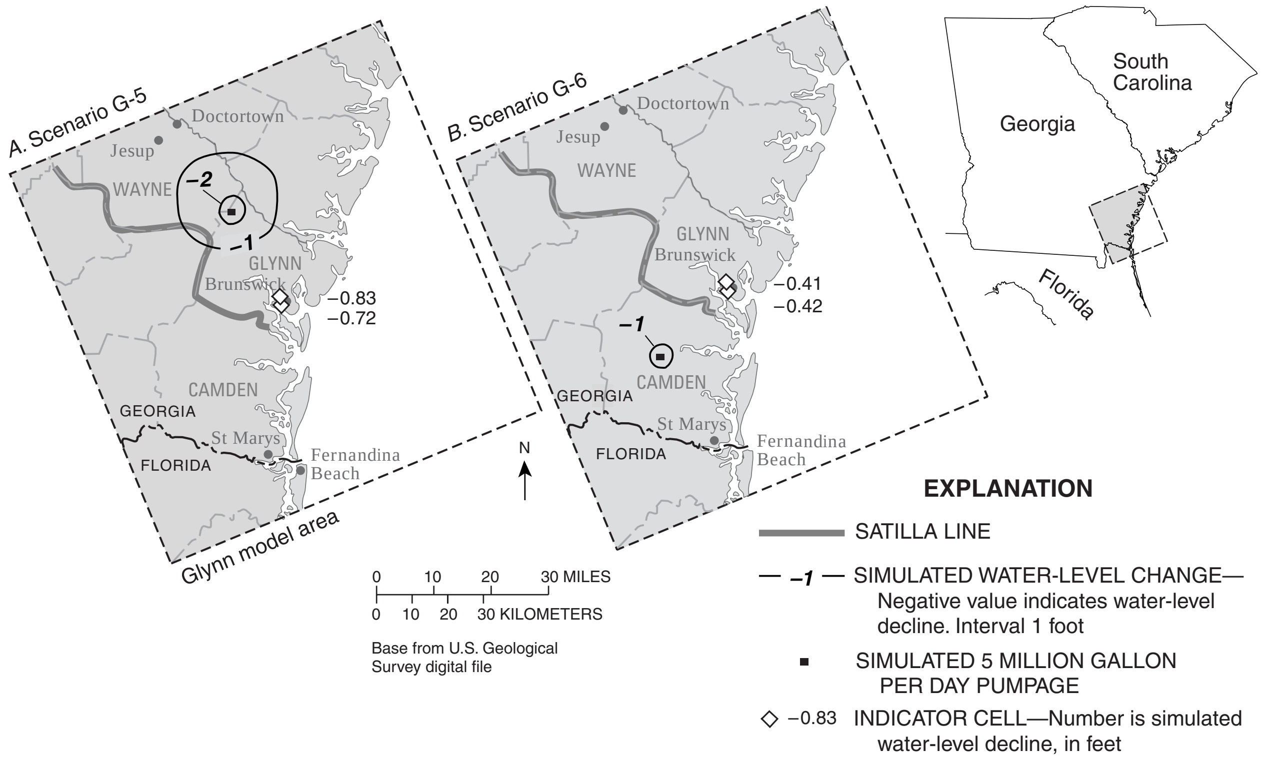

Figure 4. Simulated water-level change from May 1985 conditions for the Upper Floridan aquifer for scenario *(A)* G-5 and *(B)* G-6, and location of simulated pumpage and indicator cells (modified from Clarke and Krause, 2000).

have limited utility to address questions related to seawater encroachment or saltwater intrusion. To better understand and simulate density-dependent flow and solute transport in coastal Georgia, the USGS, in cooperation with the GaEPD, is working on a comprehensive program of data collection and hydrologic simulation (Coastal Sound Science Initiative) that will provide information needed to develop a final water-management strategy for coastal Georgia.

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AQUIFER STORAGE RECOVERY IN THE SANTEE LIMESTONE /BLACK MINGO AQUIFER, CHARLESTON, SOUTH CAROLINA, 1993-2000

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 631-634.

Abstract. The U.S. Geological Survey is investigating the potential for implementation of several Aquifer Storage Recovery systems on the Charleston, South Carolina, peninsula. A pilot study, conducted in the Santee Limestone/Black Mingo aquifer during 1993-95, indicated that the recovery efficiency, based on the national drinking-water standard for chloride, varied between 38 and 61 percent during nine Aquifer Storage Recovery cycles. A second study, initiated in 1998 at a site in downtown Charleston, is evaluating the geochemical and hydrologic effects of storing potable water in the aquifer for 1 to 6 months. Preliminary results from cycles with 1-month storage periods indicate recovery efficiencies as great as 81 percent. Decreased transport time from the production well to observation wells has been observed, indicating a probable increase in the permeability of the aquifer. Analysis and geochemical modeling of water-quality data collected from the site wells are planned to determine the dominant geo-chemical reactions taking place during Aquifer Storage Recovery cycling in the aquifer.

INTRODUCTION

The primary source of potable water for the city of Charleston, S.C., is treated surface water from the Edisto and Back Rivers. Although the Charleston Commissioners of Public Works (CCPW) has a treatment capacity that far exceeds normal demand, there is concern that demand may exceed delivery capacity in the event of damage to the water-distribution system. For this reason, the CCPW, in cooperation with the U.S. Geological Survey (USGS), is evaluating the geochemical and hydrologic effects of an Aquifer Storage Recovery system on the Charleston peninsula.

Aquifer Storage Recovery (ASR) is the concept of storing injected water in an aquifer for later recovery. A typical ASR system consists of at least one production well that is open or screened in the aquifer of interest. The production well is equipped with an injection line to transport water from land surface to the aquifer through the screens or open-hole portion of the well, and a pump to transport the water from the aquifer back to the land surface. Screened or open-hole observation wells are located near the production well to assess the spatial distribution of injected water and to sample injected water.

The feasibility of ASR technology to store potable water was tested at a pilot site located in Charleston, west of the Ashley River (fig. 1) between 1993-95 (Campbell and others, 1997). During this pilot investigation, nine successive cycles (injection, storage, recovery) were conducted to evaluate hydrologic and water-quality changes resulting from injection of treated water into the Santee Limestone/Black Mingo (SL/BM) aquifer.

Pilot study results showed that ASR implementation on the Charleston peninsula is feasible, with recovery of potable water that ranged between 38 and 61 percent of the total volume injected (Campbell and others, 1997; Mirecki and others, 1998). During the pilot project, storage typically was short, with durations less than 6 days. Significant questions, however, remained unanswered after completion of the pilot project involving (1) injectant water-quality changes during long-term storage, (2) changes in hydraulic properties of the SL/BM aquifer resulting from injection, and (3) the feasibility of ASR methods in the SL/BM aquifer on the Charleston peninsula, approximately 2 miles east of the pilot site (fig. 1).

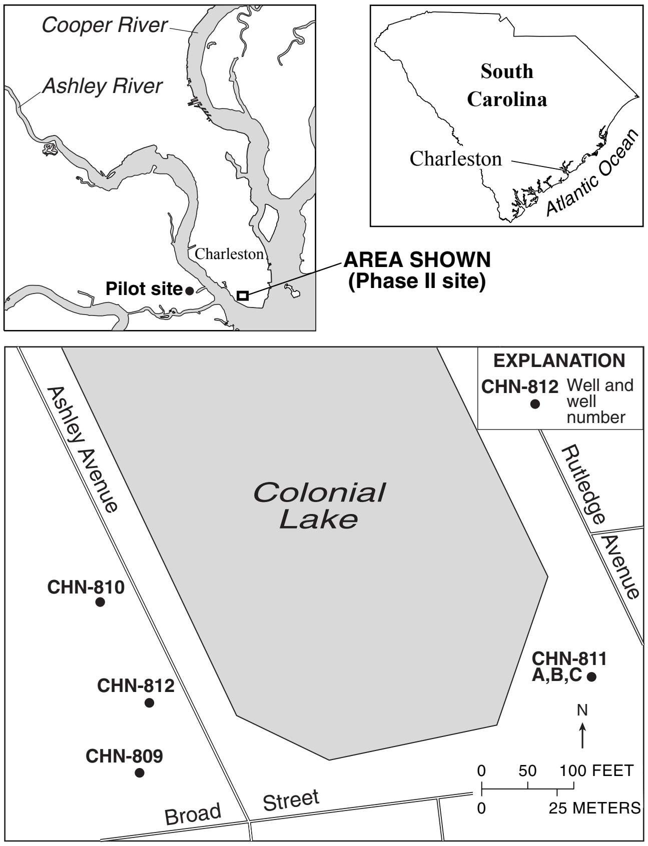

Figure 1. Aquifer Storage Recovery site and well locations, Charleston, South Carolina.

This paper describes the results of an ASR investigation (Phase II) in downtown Charleston. The investigation results include water quality and hydraulic properties for two complete ASR cycles with 1-month storage periods. The Phase II study will define the approximate percentage of potable water that is retrievable with long-term storage in the SL/BM aquifer, and indicate how the mixing of the two water bodies affects the water quality of the recovery water. In addition, this study will evaluate geochemical processes during long-term storage and quantify any changes in the SL/BM aquifer properties in the Charleston area resulting from ASR implementation.

HYDROGEOLOGY

The SL/BM aquifer consists of fracture-dominated semi-consolidated sandstone, and interlayered crystalline limestone characterized by carbonate rock-type solution openings. The aquifer is confined by the underlying Black Creek confining unit and the overlying SL/BM confining unit, which is a 340-foot (ft) thick section comprising the Cooper Group and Cross Formation (fig. 2). The SL/BM aquifer is the northernmost equivalent of the Floridan aquifer system (Park, 1985). Transmissivity of the SL/BM aquifer varies regionally between 130 and 3,700 feet squared per day (Aucott and Newcome, 1986; Campbell and others, 1997; Newcome, 1993; Park, 1985). Storage coefficients between 1.0 x 10^{-4} and 5.5 x 10^{-4} have been reported for this aquifer (Campbell and others, 1997; Newcome, 1993). Overall, aquifer properties of the SL/BM aquifer are not well documented on the Charleston peninsula and these properties can be expected to change during ASR testing. The change and rate of change in aquifer properties requires quantification.

PHASE II INVESTIGATION

In 1998, a second ASR system was constructed on the Charleston peninsula to investigate changing hydraulic properties and water quality during long-term (1- to 6-month) storage of injected water. The second ASR site consists of a single production well (CHN-812) and three observation wells (fig. 1). The production well is equipped with a 4-inch injection line and a 25-horsepower pump, is cased with ductile steel, and is screened at the same intervals as the observation wells. Observation wells CHN-809, CHN-810, and CHN-811 are installed at distances of 76, 122, and 487 ft, respectively, from the production well, specifically to facilitate aquifer hydraulic-property characterization and also to monitor injected water movement and water-quality changes occurring during ASR cycles. Two observation wells are instrumented with probes to measure water-quality properties within the permeable zones. Water-quality samples are obtained from the discharge line at the production well head, and also directly from the permeable zones in the observation wells. A piston-driven submersible pump and low-flow (micropurging) sampling techniques (U.S. Environmental Protection Agency, 1995) were used to ensure the collection of representative ground-water samples.

Each ASR cycle consists of an injection, storage, and recovery period. The length of the injection phase—volume of injected water—is determined by the breakthrough of “fresh” (low chloride concentration) water at the proximal observation well CHN-809 (fig. 1). Water from the SL/BM aquifer contains chloride concentrations of about 2,000 milligrams per liter (mg/L). Treated drinking water, with chloride concentrations of 22 mg/L, is injected at an approximate rate of 11 gallons per minute (gal/min). Injection proceeds until

System	Series	Geologic formation		Aquifer or confining unit	Character of material	Thickness, in feet
Quaternary	Pleistocene	Wando Formation		Surficial aquifer	Gray, fine quartz sand to shelly-clayey sand	40
Tertiary	Miocene	Marks Head Formation		Santee Limestone/ Black Mingo confining unit	Gray, sandy clay to shelly-clayey sand	342
	Oligocene	Ashley Formation	Cooper Group		Greenish-yellow sandy calcareous clay	
	Eocene	Parkers Ferry Formation				
		Harleyville Formation				
		Cross Formation			White fossiliferous calcilutite	
		Santee Limestone		Santee Limestone/ Black MIngo aquifer	Light-gray sandy fossiliferous limestone	70
	Paleocene	Williamsburg Formation	Black Mingo Group	Black Creek confining unit	Gray to black micaceous, calcareous clay; calcareous, silty clay; clayey sand	373
		Rhems Formation				
Cretaceous	Upper	Peedee Formation				

Figure 2. Generalized stratigraphic and geohydrologic correlation chart for Charleston, South Carolina.

the chloride concentration decreases below the U.S. Environmental Protection Agency (USEPA) National Drinking Water Standard, Secondary Maximum Contaminant Level (SMCL) for chloride (250 mg/L) (U.S. Environmental Protection Agency, 1988) at well CHN-809 (fig. 3). Breakthrough curves are defined using specific conductance trends measured by probes placed within the permeable zones, supplemented with water-quality data from ground-water samples collected weekly at depths of 370- and 430-ft below land surface. The duration of storage is 1-month, 3-months, or 6-months, during which water-quality samples are collected biweekly from the observation wells. Injected water is recovered at a pumping rate of about 130 gal/min. Recovery continues until samples show chloride concentrations and specific conductance values equal to pre-test conditions. Water-quality samples are collected biweekly from the observation wells and the production well head during the recovery stage.

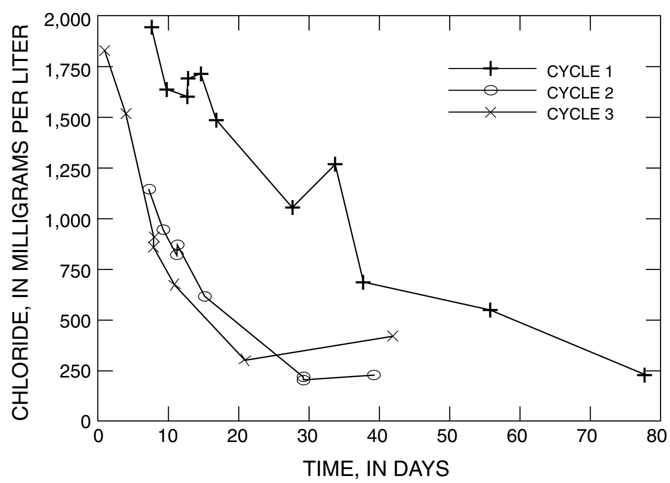

Figure 3. Dissolved chloride concentrations collected from well CHN-809 during the injection phases of Aquifer Storage Recovery cycles 1-3, Charleston, South Carolina.

PRELIMINARY RESULTS

As of December 2000, two complete ASR cycles (with 1-month storage periods) and the injection phase of a 3-month storage cycle have been completed. During the second ASR cycle, chloride concentration decreased to the USEPA SMCL more rapidly (29 days) during breakthrough at well CHN-809 than the first ASR cycle (78 days). Injection during the third ASR cycle required the same amount of injecting time for the freshwater breakthrough as the second cycle. Injected water appears to be moving through the ASR system (from production well to observation well CHN-809) faster with successive injections, suggesting that permeability is enhanced by mineral dissolution. This decreased travel time also was observed during the pilot ASR project (Mirecki and others, 1998).

Enhancement of aquifer permeability is also suggested by increases in recovery efficiency with successive ASR cycles (table 1). Recovery efficiencies during the Phase II investigation are relatively higher than those measured during the pilot study. Whether these higher efficiencies are due to the lower injection rates, greater volume of injected water, differences in the design of the production wells (open-hole well construction at the pilot site), or longer storage periods has yet to be determined.

CONTINUATION OF PHASE II ASR TESTING

Upon completion of ASR cycles at the downtown site, Phase II investigation results will be used to determine whether SL/BM aquifer properties are enhanced or degraded during long-term storage of treated drinking water. Water-quality characteristics measured during storage periods of increasing duration will allow quantification of reaction rates between water and aquifer material. The USGS geochemical model code PHREEQC (pH-redox-equilibrium; Parkhurst, 1995) will be used to quantify the extent and rate of dominant geochemical controls on water quality, including carbonate and silicate mineral dissolution, and sulfate reduction.

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Table 1. Recovery efficiencies during selected aquifer storage recovery cycles (ASR) at the pilot and Phase II study sites, Charleston, South Carolina, June 1994 to September 2000

ASR cycle number	Dates	Volume injected (gallons)	Storage period (days)	Volume of potable water recovered (gallons)	Total volume recovered (gallons)	Recovery efficiency (percent)	Injection rate (gallons per minute)	Withdrawal rate (gallons per minute)
Pilot test 1	06/06/94 – 06/07/94	15,132	0.33	5,789	19,014	38	30	130
Pilot test 9	09/07/94 – 09/17/94	160,154	6	86,186	153,744	54	40	135
Phase II—1	10/26/00 – 04/10/00	1,233,926	30	650,720	8,367,879	53	11	140
Phase II—2	05/08/00 – 09/11/00	623,753	34	508,032	8,970,454	81	11	128

SALTWATER CONTAMINATION IN THE UPPER FLORIDAN AQUIFER AT BRUNSWICK, GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at the University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 644-647.

Abstract. A map and cross section showing the potentiometric surface of the Upper Floridan aquifer, the ground-water flow field, and a plume of saltwater underlying downtown Brunswick, Georgia, depict the ground-water flow system and indicate the response to pumpage for industrial and municipal water use. In 1997, pumpage from the Upper Floridan aquifer in Glynn County, Georgia, the primary source of water supply, was about 65 million gallons per day. In 1998, near centers of pumping in north Brunswick, ground-water levels in the aquifer had declined more than 60 feet from estimated levels prior to the onset of pumpage in the late 1800's, and a cone of depression in the potentiometric surface extended to the Atlantic coast, where ground-water flow had reversed from seaward to landward. Saltwater, which began entering the aquifer in the 1950's in south Brunswick and other locations—apparently from deeper, saline water-bearing zones—has migrated laterally over a 2.5-square-mile area toward the pumping centers. In 1998, the maximum chloride concentration in samples from the aquifer in the Brunswick area was 2,590 milligrams per liter.

INTRODUCTION

The Floridan aquifer system is divided into the Upper Floridan and Lower Floridan aquifers; both are in highly permeable, carbonate sediments ranging in age from Late Cretaceous to Oligocene. In southeast Georgia, the Upper Floridan aquifer is separated into the upper and lower water-bearing zones (Wait and Gregg, 1973) by a low-permeability semiconfining unit. The lower part of the Lower Floridan aquifer includes the Fernandina permeable zone, which contains saline water in the Brunswick area (chloride concentration ranging from about 15,000 to 33,000 milligrams per liter (mg/L)). More detailed descriptions of the geology and hydrogeology of the Floridan aquifer system in southeast Georgia are given in Miller (1986) and Krause and Randolph (1989), and some of the following discussion is based on pumpage rates, water-level and chloride-concentration data, and other observations in Maslia and Prowell (1990).

GROUND-WATER FLOW SYSTEM

Before water was withdrawn from the Floridan aquifer system, the confined parts of the system in coastal Georgia probably were in equilibrium. Recharge from precipitation west-northwest of Brunswick was balanced by discharge to the Atlantic Ocean. In the Glynn County area, ground-water flow was probably very slow and uniformly eastward toward the coast.

By 1942-43, in response to long-term ground-water pumpage (about 40 million gallons per day (Mgal/d) in 1943), small, localized cones of depression had developed in the potentiometric surface of the Upper Floridan aquifer near two pumping centers in north Brunswick, where water levels had declined about 30 ft from pre-development conditions. One pumping center in northeast Brunswick includes municipal water-supply wells and production wells of a chemical-manufacturing plant; the other pumping center in northwest Brunswick includes production wells of a pulp and paper mill and a chemical-manufacturing plant (non-operational since 1994). Away from pumping centers, ground-water flow in the Glynn County area remained very slow and seaward.

Increases in withdrawal at Brunswick between 1943 and 1966 (to about 75 Mgal/d) caused the two small cones of depression to coalesce into a single broad, deep depression that includes the two small cones at the pumping centers. Based on the configuration of the regional potentiometric surface of the Upper Floridan aquifer, in 1966 nearly all ground water entering Glynn County through the aquifer was being withdrawn in northern Brunswick, and the water level had declined an additional 45 feet (ft) near one of the pumping centers (Gregg and Zimmerman, 1974). Also, along the coast, seaward flow of water in the aquifer had reversed direction to landward toward the pumping centers in north Brunswick.

Since 1966, the configuration of the potentiometric surface has remained generally the same, although total withdrawal in the Brunswick area has fluctuated moderately. The depth and steepness of the broad, deep depression vary depending on total pumpage, and the relative size of the two small cones is not constant. Pumpage has caused ground-water level declines in the Upper Floridan aquifer ranging from about 20 ft in southernmost Glynn County to as much as 80 ft near pumping centers in north Brunswick. Pumpage from the Upper Floridan aquifer in Glynn County was about 65 Mgal/d in 1997 (Fanning, 1999). Based on water levels measured in May 1998, the central part of the broad, deep depression in the potentiometric surface of the Upper Floridan aquifer, including the two small cones, is shown in figure 1A.

Water levels in wells that are open only to the lower water-bearing zone of the Upper Floridan aquifer near point *E* on section *D–E–F* are consistently about 5 to10 ft higher than water levels in nearby wells that are open only to the upper water-bearing zone (fig. 1B). The semiconfining unit between the upper and lower water-bearing zones apparently prevents equilibration of water levels between the two zones in this area. Conversely, wells open only to the upper or lower water-bearing zone underlying downtown Brunswick, near point *D*, less than two miles southward, have similar water levels (differing by less than 2 ft; fig. 1B), suggesting the zones may be more hydraulically connected near point *D* than near point *E*.

SALTWATER CONTAMINATION

In the early 1940's, water containing elevated chloride concentration (greater than 50 mg/L) was first detected in the Upper Floridan aquifer in downtown Brunswick (Warren, 1944) between point *D* and Hanover Park (fig. 1A). Although initially isolated, saltwater in the aquifer began to migrate laterally by the 1960's; and by the mid 1970's, a plume of high-chloride water in the Upper Floridan aquifer had migrated toward pumping centers in north Brunswick. In 1998, the plume extended over about a 2.5-square-mile area.

The source of the elevated-chloride water probably is saline water in the Fernandina permeable zone of the Lower Floridan aquifer (Gill and Mitchell, 1979). Saltwater from this zone apparently has migrated upward into overlying zones in response to pumpage. Although the pathway for this upward movement is not known with certainty, it has been suggested that high-angle fractures could allow the upward migration of saltwater from the Fernandina permeable zone, through the upper part of the Lower Floridan aquifer, and finally into the Upper Floridan aquifer (Krause and Randolph, 1989; Maslia and Prowell, 1990). Saltwater apparently has entered the Upper Floridan aquifer at one or more isolated locations and subsequently has moved laterally within water-bearing zones.

During the late 1950's and early 1960's, the highest chloride concentration in ground water sampled near Hanover Park in downtown Brunswick was 860 mg/L, and the plume of elevated-chloride ground water extended downgradient to a few wells about one mile northward. Wells in the vicinity of pumping centers in north Brunswick were not contaminated.

A network of monitoring wells was established in the Brunswick area in the 1960's, and has been sampled periodically to determine the movement of the plume of saltwater. Most wells within the network are open to the upper and/or lower water-bearing zones of the Upper Floridan aquifer. Accurately delineating the vertical distribution of the saltwater plume within the Upper Floridan aquifer is hampered by mixing of ground water in wells open to both zones and a paucity of wells open only to the lower water-bearing zone. Consequently, depictions of the saltwater plume at Brunswick usually are based solely on chloride concentrations in more numerous samples from the upper water-bearing zone of the Upper Floridan aquifer.

By 1965, a few wells near industrial pumping centers in northwest and northeast Brunswick also had become contaminated (chloride concentration of samples greater than 50 mg/L). The location of these contaminated wells suggested that there could be more than one plume of elevated-chloride ground water and possibly several points where saltwater might be entering the Upper Floridan aquifer. By 1975-76, the multiple plumes had coalesced into a single plume that extended from near Hanover Park in downtown Brunswick almost due northward to a point between the two pumping centers, then divided into two branches, one extending eastward toward the pumping center in northeast Brunswick, and one extending westward toward the pumping center in northwest Brunswick.

From 1976 to the present (May-June 1998) (fig. 1A), the plume has maintained the same general areal distribution, originating in downtown Brunswick, extending downgradient, initially northward, and eventually dividing into an eastern and a western branch. Chloride concentrations have increased gradually within the plume during this period (reaching a maximum of 2,590 mg/L in 1998), but the shape of the plume has remained relatively stable because

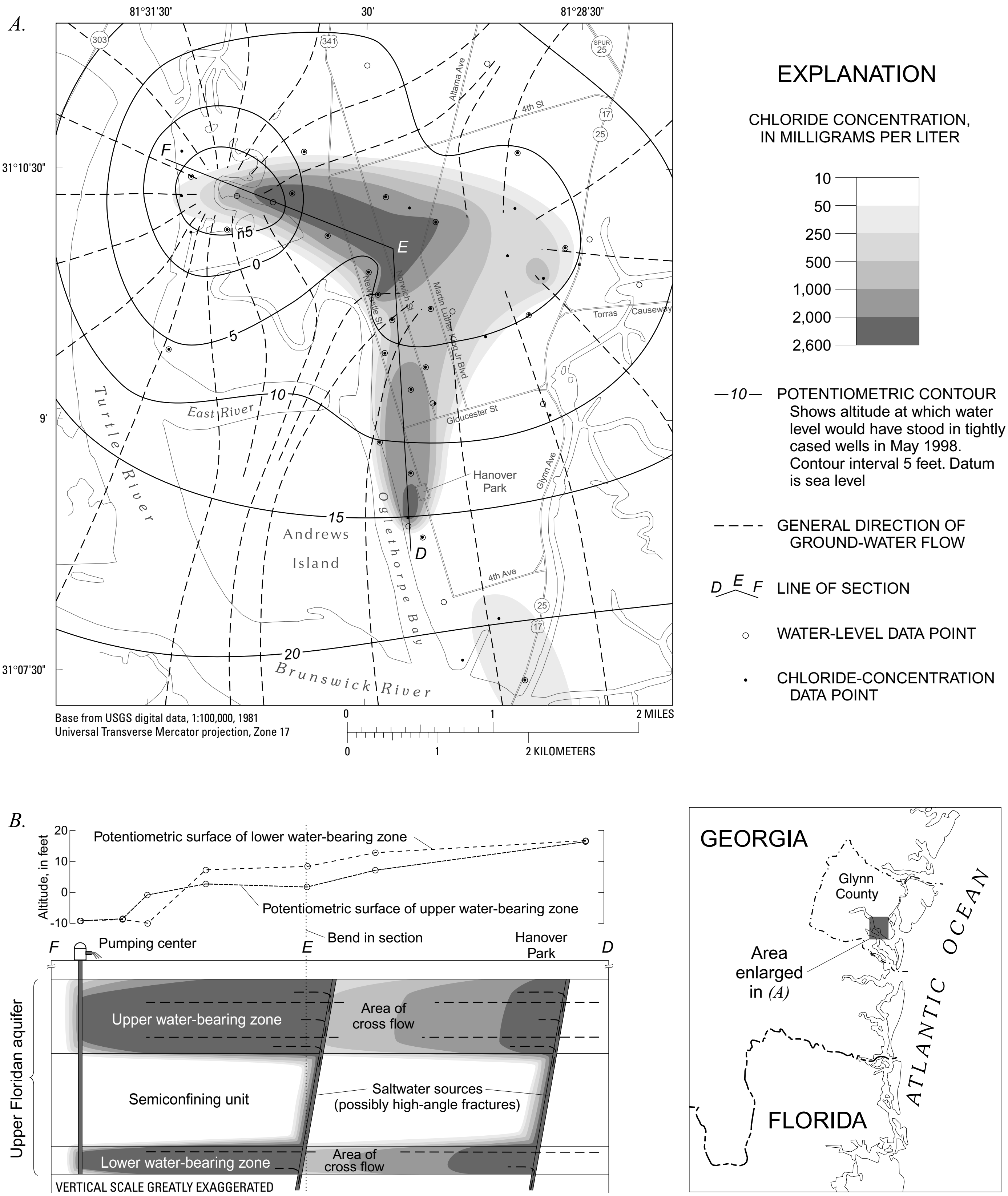

Figure 1. Potentiometric surface, ground-water flow directions, and chloride concentration for the Upper Floridan aquifer at Brunswick, Georgia, May–June 1998; *(A)* plan view of upper water-bearing zone, *(B)* conceptual model of section *D–E–F* from downtown Brunswick to pumping wells in northwest Brunswick.

ground-water flow directions have not substantially changed—saltwater entering the aquifer is withdrawn at pumping centers in north Brunswick.

A conceptual model of the saltwater distribution in both the upper and lower water-bearing zones of the Upper Floridan aquifer across section *D–E–F* is shown in figure 1(B). Decreasing chloride concentrations from point *D* to point *E* probably are due to the eastward flow of uncontaminated ground water across the northern part of plane *D–E*, causing part of the plume to move eastward toward the pumping center in northeast Brunswick (fig. 1A,B). A second source of saltwater near point *E* probably accounts for the high chloride concentrations from near point *E* to the pumping center near point *F* in northeast Brunswick. Earlier maps of the saltwater plume indicate there may be another source of saltwater in the Upper Floridan aquifer near the pumping center in northeast Brunswick.

SUMMARY

Long-term trends in the ground-water flow system in the Upper Floridan aquifer in the Glynn County and Brunswick, Georgia area, include the slow development of two small cones of depression centered in north Brunswick; the eventual coalescence of the two cones, and the deepening and broadening of the resulting depression in response to increased ground-water pumpage; and reversal of ground-water flow from seaward to landward along the coast of Glynn County. Water-level differences in wells open only to the upper or lower water-bearing zones of the Upper Floridan aquifer at Brunswick indicate that the semiconfining unit separating the two zones is more effective in some areas than others. A chloride-concentration map illustrates the downgradient migration of saltwater in the Upper Floridan aquifer from a source near Hanover Park in downtown Brunswick, initially northward, then dividing into an eastward and a westward branch toward pumping centers in northeast and northwest Brunswick. One or more other sources in an area between the pumping centers probably also contributes saltwater to the Upper Floridan aquifer. A thorough understanding of the many complexities of the ground-water flow system in the Upper Floridan aquifer and other parts of the Floridan aquifer system in the area is needed for informed management and protection of the resource.

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HYDROGEOLOGY AND WATER QUALITY OF THE LOWER FLORIDAN AQUIFER, COASTAL GEORGIA, 1999-2000

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 652-655.

Abstract. The Lower Floridan aquifer at Richmond Hill, Brunswick, and St Marys, Ga., has permeable intervals of freshwater to slightly brackish water that could provide water users with an alternative water supply to supplement water use from the Upper Floridan aquifer. Strong similarities in water-level fluctuations for the Upper and Lower Floridan aquifers at Richmond Hill, and similar water-level elevations indicate that both aquifers respond as one saturated unit to regional ground-water withdrawals and recharge. Conversely, at Brunswick and St Marys, abrupt changes in water level and chemistry indicate stronger confinement between permeable zones in the Upper and Lower Floridan aquifers, relative to the Richmond Hill area.

At Richmond Hill, water in the Upper Floridan aquifer is fresh with total dissolved solids (TDS) concentration of 172 milligrams per liter (mg/L) and a chloride concentration of 5 mg/L. Water in the Lower Floridan aquifer at Richmond Hill is slightly brackish, with a TDS concentration of 1,630 mg/L and a chloride concentration of 160 mg/L.

As a result of decades of ground-water withdrawal in downtown Brunswick, water in the Upper Floridan aquifer is brackish with TDS concentrations as high as 5,000 mg/L and chloride concentrations varying from 1,500 to 3,000 mg/L. The Lower Floridan aquifer at Brunswick consists of a freshwater zone from 1,230 to 1,664 ft below sea level with concentrations of 289 mg/L for TDS and 26 mg/L for chloride; a brackish-water zone from 1,664 to 2,176 ft below sea level with concentrations of 1,360 to 4,330 mg/L for TDS and 190 to 1,300 mg/L for chloride; a saline-water zone from 2,176 to 2,675 ft below sea level with concentrations of 33,600 mg/L for TDS and 18,000 mg/L for chloride; and a brine zone from 2,675 ft below sea level to the total borehole depth of 2,710 ft below sea level with concentrations of 48,300 mg/L for TDS and 26,000 mg/L for chloride.

At St Marys, water in the Upper Floridan aquifer is fresh, with a TDS concentration of 463 mg/L and a chloride concentration of 32 mg/L. Water in the Lower Floridan aquifer at St Marys is also fresh, with a TDS concentration of 623 mg/L and a chloride concentration of 28 mg/L.

INTRODUCTION

Ground-water withdrawal from the Upper Floridan aquifer has resulted in substantial water-level declines and the occurrence of—and potential for—saltwater intrusion in coastal areas of Georgia and adjacent areas of South Carolina and Florida (Gill and Mitchell, 1979; Smith, 1993; Krause and Randolph, 1989; Clarke and others, 1990; Spechler, 1994; Landmeyer and Belval, 1996). The U.S. Geological Survey, in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey, is investigating the Lower Floridan aquifer as an alternative ground-water resource along the Georgia coast.

This paper documents the results of an investigation of potential sources of saltwater contamination and the potential of the Lower Floridan aquifer to serve as an alternative water resource. As part of the Georgia Coastal Sound Science Initiative, wells were drilled at Richmond Hill in Bryan County, Brunswick in Glynn County, and St Marys in Camden County, Ga., in 1999 and 2000, to obtain hydrogeologic and water-quality data for the upper permeable zone of the Lower Floridan aquifer and to document the presence or absence of the Fernandina permeable zone below the Lower Floridan aquifer at Richmond Hill, Ga. (fig. 1). Well cuttings and water-quality samples were collected during reverse-air rotary drilling of the boreholes. These data, geophysical logs, and observations of flow and water levels during drilling were used to interpret the hydrogeology and water chemistry of the permeable zones in the Lower Floridan aquifer (fig. 2).

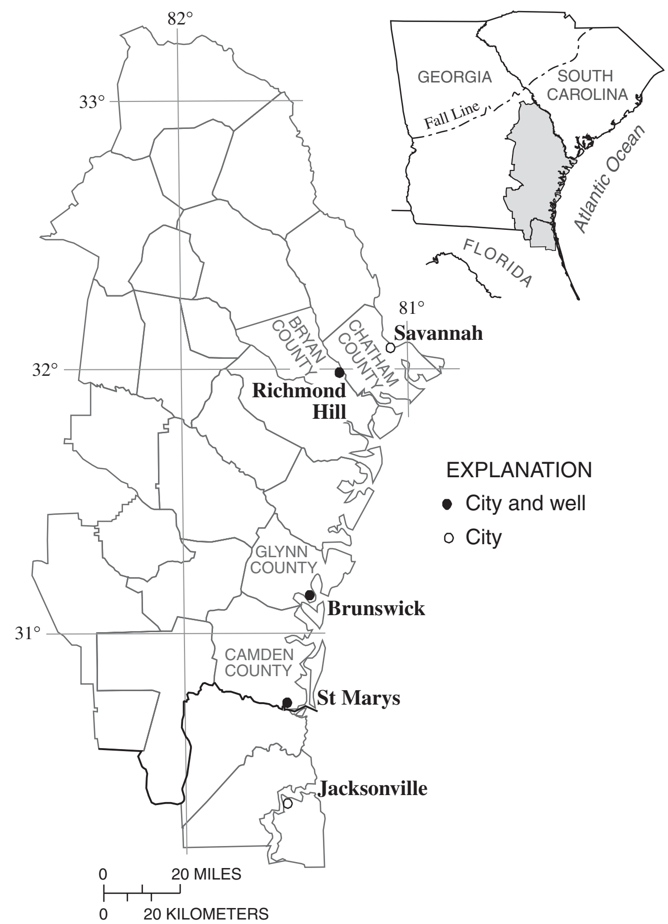

Figure 1. Coastal Georgia study area.

HYDROGEOLOGY AND WATER-QUALITY RESULTS

Richmond Hill—Two wells (35P110 and 35P109) were drilled at the Sterling Creek sewage treatment facility near Richmond Hill in Bryan County, Ga. Test well 35P110 is open to the Upper Floridan aquifer in the interval from 302 to 427 ft below sea level. Test well 35P109 penetrated the base of the Floridan aquifer system at 1,611 ft below sea level; however, the borehole was backfilled with cement to complete the well with an open interval in the Lower Floridan aquifer from 1,002 to 1,262 ft below sea level.

Carbonates of the Floridan aquifer system consist of limestone from 317 to 1,611 ft below sea level. The limestone is dolomitic in several intervals; however, beds of dolomite were not present. The Upper Floridan aquifer consists of a porous, permeable zone of limestone from 317 to 677 ft below sea level. The Lower Floridan aquifer includes a porous, permeable zone of mostly limestone with some dolomitic limestone from 937 to 1,063 ft below sea level. Strata below the permeable zone of the Lower Floridan aquifer consist of fine-grained limestone from 1,063 to 1,280 ft below sea level, clay from 1,280 to 1,305 ft below sea level, and clayey limestone with chert nodules from 1,305 to 1,611 ft below sea level. A permeable zone was not identified in the fine-grained lithologies below 1,305 ft below sea level.

Hydrographs for wells completed in the Upper and Lower Floridan aquifers at this site for the period from June–October 2000, have nearly identical trends with water levels ranging between 17 and 22 ft below sea level. No abrupt changes in water level were observed during drilling.

At Richmond Hill, water in the Upper Floridan aquifer is fresh with TDS concentration of 172 mg/L and a chloride concentration of 5 mg/L.Water in the Lower Floridan aquifer at Richmond Hill is slightly brackish, with a TDS concentration of 1,630 mg/L and a chloride concentration of 160 mg/L. The change from freshwater to slightly brackish is gradational and occurs from 1,002 to 1,063 ft below sea level in the permeable zone of the Lower Floridan aquifer. Hydrogen sulfide concentrations are less than 1.0 mg/L in both aquifers at this site. Formation water collected below the clay at 1,305 ft below sea level has a TDS concentration of 2,100 mg/L and chloride concentrations of 280 mg/L, which exceeds the secondary drinking water standard for chloride of 250 mg/L (U.S. Environmental Protection Agency, 1988).

Brunswick—Two wells were drilled at the Georgia Ports Authority Mayor Point facility in downtown Brunswick, Glynn County, Ga. Test well 34H500 is open to a permeable zone of the Lower Floridan aquifer in the interval from 1,207 to 1,390 ft below sea level. Test well 34H495 is open to the Fernandina permeable zone of the Lower Floridan aquifer in the interval from 2,079 to 2,710 ft below sea level.

The Floridan aquifer system beneath Brunswick consists of the upper and lower permeable zones of the Upper Floridan aquifer, and the upper and Fernandina permeable zones of the Lower Floridan aquifer. The Upper Floridan aquifer consists of limestone from 520 to 873 ft below sea level and interbedded limestone and dolomite from 873 to 1,183 ft below sea level. The Lower Floridan aquifer consists of interbedded limestone and dolomite from 1,230 ft below sea level to the bottom of the borehole at 2,710 ft below sea level.

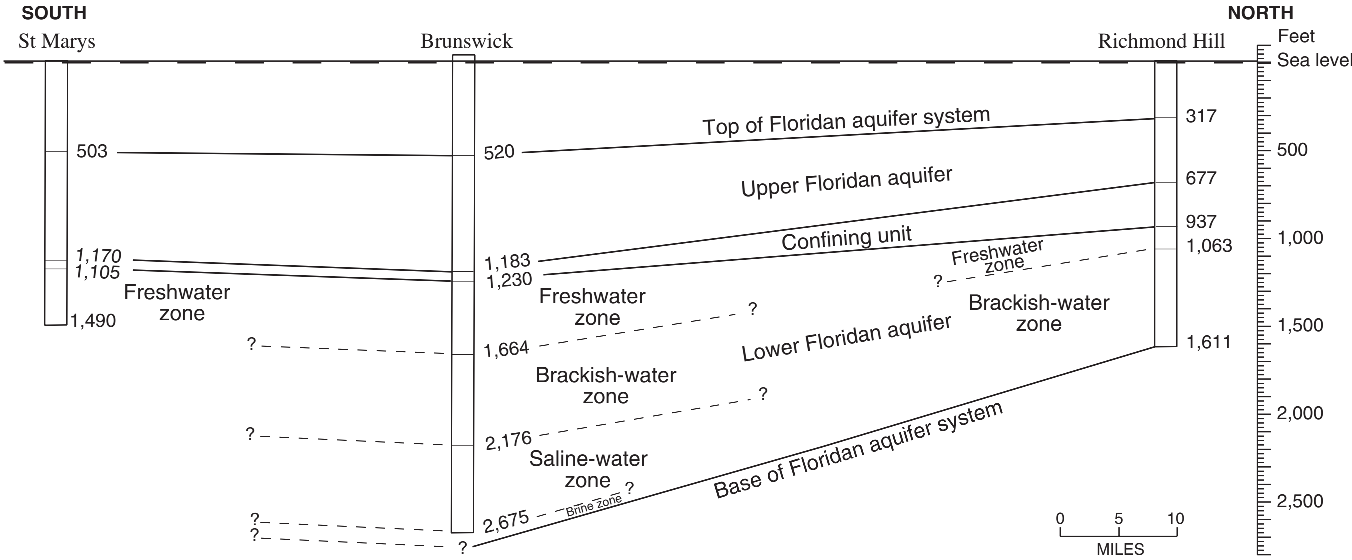

Figure 2. Hydrogeology of Floridan aquifer system and water-quality zones of the Lower Floridan aquifer.

The Upper Floridan aquifer at this site has a water-level altitude at or just above land surface, or 10 to 12 ft above sea level. Water-level altitudes in the permeable zones of the Lower Floridan aquifer range from 10 to 75 ft above sea level. Abrupt changes in water-level altitudes and/or flow were observed during drilling at depths of 1,664, 2,064, 2,176, and 2,675 ft below sea level.

As a result of decades of ground-water withdrawal in downtown Brunswick, water in the Upper Floridan aquifer at this site is brackish with TDS concentrations as high as 5,000 mg/L and chloride concentrations varying from 1,500 to 3,000 mg/L. The Lower Floridan aquifer contains a freshwater zone from 1,230 to 1,664 ft below sea level, a brackish-water zone from 1,664 to 2,176 ft below sea level, a saline-water zone from 2,176 to 2,675 ft below sea level, and a brine zone from 2,675 ft below sea level to the total borehole depth of 2,710 ft below sea level (table 1). Hydrogen sulfide concentrations are less than 2.2 mg/L for all sample intervals. Immediate changes in flow to the well bore and changes in water chemistry observed at depths of 1,664, 2,064, 2,176, and 2,675 ft below sea level during drilling most likely reflected penetration of confining units between permeable intervals in the Lower Floridan aquifer.

St Marys—One well was drilled at the Gallop Road ballpark in St Marys, Camden County, Ga. Test well 33D073 is open to the Lower Floridan aquifer in the interval from 1,355 to 1,490 ft below sea level.

The Upper Floridan aquifer at St Marys consists of limestone from 503 to 1,105 ft below sea level with two intervals of interbedded limestone and dolomite from 804 to 1,105 ft below sea level. The Lower Floridan aquifer at the St Marys site was penetrated at a depth of 1,170 ft below sea level and consists of thick beds of dolomite and interbedded limestone and dolomite. Measurements during drilling indicate the water-level altitude of the Upper Floridan aquifer ranged between 2 and -5 ft, and the water-level altitude in the Lower Floridan aquifer was about 10 ft in December 1999. The difference in water levels may reflect water-level declines in the Upper Floridan in response to ground-water withdrawal. Water from the Upper and Lower Floridan aquifers has TDS concentrations of 463 and 623 mg/L, respectively, chloride concentrations of 32 and 28 mg/L, respectively, and hydrogen sulfide concentrations of 4.3 and 3.4 mg/L, respectively.

Table 1. Water-quality characteristics of water zones of the lower Floridan aquifer in the Brunswick area
[mg/L, milligrams per liter]

Water zone	Altitude below sea level (feet)	Total dissolved solids (mg/L)	Chlorides (mg/L)
Freshwater	1,230 to 1,664	289	26
Brackish	1,664 to 2,064	1,360	190
Brackish	2,064 to 2,176	4,330	1,300
Saline	2,176 to 2,675	33,600	18,000
Brine	2,675 to 2,710	48,300	26,000

DISCUSSION

The Lower Floridan aquifer at all three coastal sites consists of permeable intervals of freshwater to slightly brackish water that could provide additional water for municipal and industrial supply. Dense, low permeability layers of dolomite interbedded with dense limestone are more abundant in the Brunswick and St Marys areas than in the Richmond Hill area. As a result, confinement between the Upper and Lower Floridan aquifers is greater at Brunswick and St Marys compared to Richmond Hill.

The Richmond Hill site is within the potentiometric cone of depression that results from decades of ground-water withdrawal from the Upper Floridan aquifer in Chatham County and the surrounding area (Clarke and others, 1990). Strong similarities in water-level trends for the Upper and Lower Floridan aquifers, and similar water-level elevations indicate that both aquifers in this area respond as one saturated unit to regional ground-water withdrawal and recharge. Wells completed in the Upper and Lower Floridan aquifers would distribute the stress of withdrawal over a thicker interval, in comparison with wells completed only in the Upper Floridan aquifer; however, mixing waters from both aquifers in the well bore would likely increase the TDS and chloride concentrations. Completing wells in the carbonates below 1,305 ft below sea level would provide little additional yield to the well, and could increase chloride concentrations above the secondary drinking-water standard. It does not appear that the Fernandina permeable zone is present in the Floridan aquifer system at this site.

Previous investigations in the Brunswick area suggest that saltwater from the Lower Floridan aquifer moves to the Upper Floridan aquifer by way of vertical fractures, and then moves laterally through the permeable zones of the Upper Floridan aquifer in response to ground-water withdrawal (Krause and Randolph, 1989; Maslia and Prowell, 1990). The freshwater and slightly brackish-water zones of the Lower Floridan aquifer have chloride concentrations less than the secondary drinking-water standard. These intervals could be used as potential sources of drinking water; however, ground water withdrawn from these intervals of the Lower Floridan aquifer could reduce the local pressure head and potentially induce saltwater to migrate along the same vertical fractures that serve as pathways for migration to the Upper Floridan aquifer.

Although the water chemistry of the Lower Floridan aquifer at St Marys is similar to that of the Upper Floridan aquifer, water-level differences suggest that the aquifers are separated by an interval of dense, low porosity limestone and dolomite, which serve as a confining unit in the St Marys area. The upper permeable zone of the Lower Floridan aquifer may provide a source of freshwater comparable in water quality to the Upper Floridan aquifer. The Fernandina permeable zone is known to be present to the southeast at Fernandina Beach, Florida (Spechler, 1994) and to the north near Brunswick (Gill and Mitchell, 1979); however, the well drilled at St Marys did not penetrate the Fernandina zone.

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PRELIMINARY NUMERICAL MODELS OF SALTWATER TRANSPORT IN COASTAL GEORGIA AND SOUTHEASTERN SOUTH CAROLINA

By D.F. Payne[1/], A.M. Provost[2/], and C.I. Voss[3/]

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 656-659.

Abstract. Two preliminary saltwater transport models of the Savannah, Georgia—Hilton Head Island, South Carolina area and the Brunswick area were developed as part of a cooperative investigation by the U.S. Geological Survey (USGS) and the Georgia Department of Natural Resources, Environmental Protection Division (GaEPD) to assist the GaEPD in the development of management strategies for coastal ground-water resources. The Savannah-Hilton Head Island model was designed to test the effect of concentrated pumping on the steady-state, offshore, saltwater-freshwater interface. Results show that saltwater moves laterally from offshore and vertically downward through the confining unit toward the pumping site on a scale of 100,000 years. The Brunswick model was designed to test the movement of saltwater along a complex flow path toward a pumping well. Results show that saltwater moves upward from the source at depth through a vertical conduit, then laterally across the aquifer unit toward the pumping center, while mixing with freshwater. Future models will be refined to more accurately represent actual conditions.

INTRODUCTION

The Upper Floridan aquifer is the primary ground-water resource in coastal Georgia and adjacent parts of South Carolina and Florida; the aquifer is extremely permeable and high-yielding. Saltwater has encroached into the Upper Floridan aquifer on the northern end of Hilton Head Island, S.C.; and a saltwater plume exists in the Upper Floridan aquifer beneath downtown Brunswick, Ga., as a result of pumping and consequent reduction in hydraulic head. At some locations, the Upper Floridan aquifer contains dissolved chloride concentrations exceeding the U.S. Environmental Protection Agency secondary maximum contaminant level of 250 milligrams per liter (mg/L) (U.S. Environmental Protection Agency, 1994).

As part of the Georgia Coastal Sound Science Initiative, the USGS, in cooperation with the GaEPD, is developing numerical models of the regional ground-water flow system and intrusion of saltwater in coastal Georgia and South Carolina to: (1) better define mechanisms of ground-water flow and saltwater intrusion in the Floridan aquifer system, and in aquifer units that affect the Floridan aquifer system or that may be considered as alternative ground-water supplies; (2) delineate paths and rates of ground-water flow and changes in chloride concentration in water in the Upper Floridan aquifer; and (3) evaluate various water-management scenarios that may alleviate saltwater contamination.

Preliminary saltwater transport models in the Savannah—Hilton Head Island and Brunswick areas are part of the first phase of the modeling program that will include development of a regional flow model and refined, predictive models of the focus areas. The preliminary models are designed to generally test the sensitivity to model input and boundary conditions, and the physical controls on the system. Results of the preliminary models are presented herein.

Approach

Saltwater transport models of the Savannah, Ga.–Hilton Head Island, S.C., area and Brunswick, Ga., area are being developed using the SUTRA3D simulator, a three-dimensional version of the SUTRA program (Voss, 1990). A concurrently developed regional-scale flow model will provide boundary conditions for and encompass these two smaller-scale models. SUTRA3D is a three-dimensional variable-density finite-element model that simulates density-dependent saturated-unsaturated ground-water flow and transport of a solute in ground water. SUTRA3D calculates fluid pressures and solute concentrations as they vary with time. These preliminary models are not calibrated and should not be used to evaluate saltwater movement. Subsequent models will be refined from the preliminary models, calibrated, and used to test the effects of various management scenarios.

Savannah-Hilton Head Island Model

Chloride concentration in ground water in the Upper Floridan aquifer beneath Port Royal Sound—north of Hilton Head Island—indicates that saltwater has intruded into the aquifer (Smith, 1988). Recent unpublished chloride concentrations in the aquifer on the north end of the island suggest that saltwater is moving south toward Hilton Head Island (Camille Ransom III, South Carolina Department of Health and Environmental Control, oral commun., 2000). Withdrawal of water from the Upper Floridan aquifer in the Savannah area since the late 1800's has resulted in the development of a large cone of depression in the potentiometric surface that extends from Savannah northeastward across Hilton Head Island. This situation, combined with pumping on Hilton Head Island, has resulted in reversal of the normally seaward hydraulic gradients (fig. 1). Offshore of the Savannah-Hilton Head Island area, erosion has partially or completely removed the confining unit overlying the Upper Floridan aquifer (Vernon Henry, Clark Alexander, and Anthony Foyle, Georgia Southern University, written commun., 1999) exposing the aquifer directly to seawater. These conditions allow seawater to enter the aquifer and migrate laterally downgradient toward pumping centers (fig. 1).

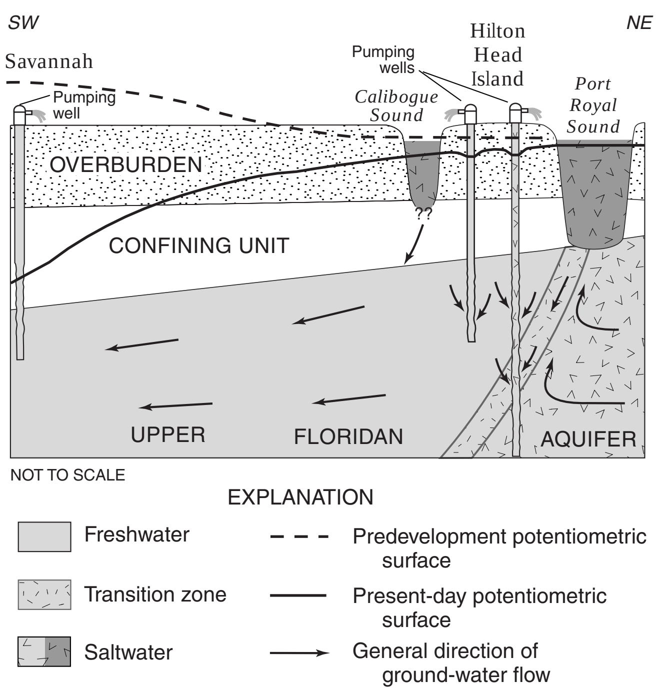

Figure 1. Conceptualization of saltwater contamination in the Upper Floridan aquifer near Hilton Head Island, South Carolina (R.E. Krause, written commun., 2000).

The saltwater transport model for the Savannah-Hilton Head Island area represents five aquifers and three confining units, and includes Chatham and surrounding Counties in Georgia and South Carolina and the adjacent offshore area—an area of approximately 11,000 square miles (mi^2). The model vertically represents aquifer units with five cell layers and confining units with three cell layers. Horizontally, each layer consists of 40 rows by 35 columns of cells. Intrinsic permeability values assigned to the layers range from 10^{-16} feet squared (ft^2) for the confining units, to 10^{-9} ft^2 for the aquifer units. The hydraulic boundary conditions are as follows: the bottom boundary is no flux; the top offshore boundary is hydrostatic seawater; the top onshore boundary is atmospheric or zero pressure; the northwest vertical boundary is hydrostatic freshwater; the southeast vertical boundary is hydrostatic seawater; and the southwest and northeast vertical boundaries are no flux. A stress is applied to three vertical cells representing a pumping site that withdraws 80 million gallons per day (Mgal/d) from the Upper Floridan aquifer at Savannah. This preliminary model is designed to test the effect of concentrated pumping on the steady-state offshore saltwater-freshwater interface and is not intended to simulate actual conditions.

The model was run to simulate steady-state conditions prior to development, and transient conditions after 100,000 years of pumping. The steady-state simulation was used as the initial condition for transient simulations. Preliminary modeling results after simulated pumping for 100,000 years simulation time from the initial condition are shown in figure 2. For the preliminary model, this time scale is required to move the saltwater-freshwater interface to the pumping site. Over the course of the simulation, the saltwater-freshwater interface migrates toward the Savannah pumping center as saltwater moves both laterally from the offshore steady-state position and downward through the confining unit. The preliminary model was designed with a grid resolution that does not capture local areas where the confining unit above the Upper Floridan aquifer is thin or has been eroded. In spite of this, the simulated saltwater intrusion is partly the result of downward vertical transport of seawater through the confining unit. As the model is refined, these areas of thinning confining unit will be more precisely and accurately simulated, and it is expected that these will act as more direct conduits for seawater entry into the Upper Floridan aquifer, and thus decrease the time scale of saltwater intrusion.

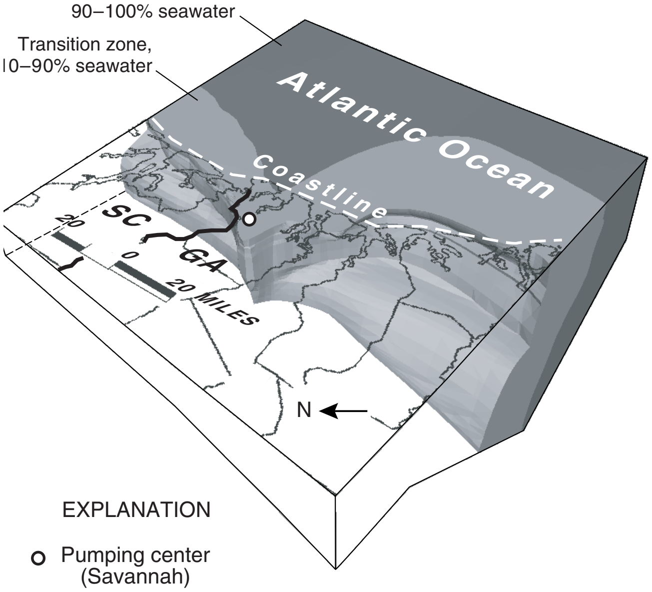

Figure 2. Preliminary modeling results, Savannah-Hilton Head Island model, after simulated pumping for 100,000 years.

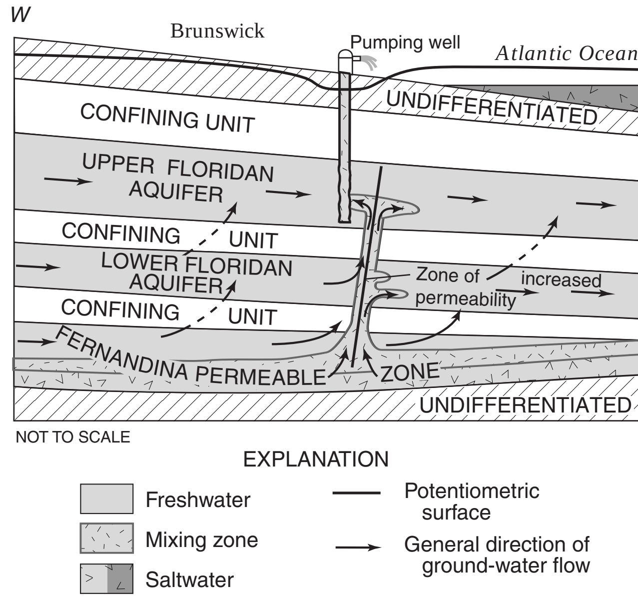

Figure 3. Conceptualization of saltwater contamination in the Floridan aquifer system at Brunswick (R.E. Krause, written commun., 2000).

Brunswick Model

Beneath downtown Brunswick, the occurrence of saltwater in the Upper Floridan aquifer has been known for several decades (Krause and Randolph, 1989). Water from about 2,400 feet below land surface in the lower part of the Lower Floridan aquifer (Fernandina permeable zone) has chloride concentrations greater than 30,000 mg/L, suggesting that this is brine or connate water and is a likely source of saltwater in the Upper Floridan aquifer at Brunswick (Krause and Randolph, 1989). The presence of steeply dipping fractures and zones of abundant solution features in the Floridan aquifer system in one of these wells (Maslia and Prowell, 1990) suggests that saltwater is transported vertically upward into the Upper Floridan aquifer from depth (fig. 3). The geometry and distribution of possible conduits that allow saltwater to move upward are poorly defined in this area, limiting the model's ability to accurately predict future movement of the plume. The model, however, may be used to test conceptual models for the area.

The saltwater transport model for the Brunswick area represents four hydrologic units and covers an area of about 50 mi^2 encompassing downtown Brunswick. The model is discretized into 19 cell layers, with increased cell layer density in the Upper Floridan aquifer. A narrow vertical zone of increased permeability extends from the lowermost unit into the upper aquifer unit; inclusion of this feature in the model roughly simulates conduits probably present in the Floridan aquifer system (Maslia and Prowell, 1990). In plan view, the model area is discretized into 437 cells with increased cell density in the vertical zone of increased permeability. Intrinsic permeability values assigned to the layers range from 10^{-16} ft^2 in the confining units to 10^{-10} ft^2 in the Upper Floridan aquifer. The vertical zone of increased permeability is represented by five closely spaced rows of cells assigned a permeability of 10^{-7} ft^2. Vertical boundaries are all hydrostatic for freshwater conditions for the upper three units, and for saltwater conditions at the sides of the lowermost unit. The top and bottom boundaries are no-flux. These boundaries allow the lowermost unit to supply unlimited saltwater, and the other units to supply unlimited freshwater. Initially, the lowermost unit contains saltwater (35,000 mg/L total dissolved solids), and the other units contain freshwater. The model simulates 36 and 9 Mgal/d withdrawal from the Upper Floridan aquifer at two locations in downtown Brunswick. This model is designed to test the movement of saltwater along a complex flow path toward a pumping well, and is not intended to accurately represent all aspects of the flow system.

After a 47-year simulated pumping period, the saltwater in the lowermost unit mixes with freshwater as the saltwater migrates upward through the vertical zone of increased permeability, then laterally within the Upper Floridan aquifer toward pumping centers (fig. 4). The total dissolved-solids concentration of the water reaching the pumping center is 250 mg/L. The lower-most unit continues to supply saltwater, so as pumping continues, the saltwater continues to follow the indirect path toward the pumping sites. Despite the uncertainty in the geometry and transport properties of the zones of increased permeability, these preliminary results suggest that this conceptual model may result in the type of saltwater contamination observed at Brunswick.

DISCUSSION

These models are preliminary—future models will require considerable refinement of input data and model construction. Boundary conditions will need to be refined by imposing flow conditions calculated from a larger, regional-scale flow model that encompasses the areas in the saltwater transport models. More accurate and precise distributions of aquifer properties will need to be assigned, as appropriate. Once developed, the models will be calibrated against water-level and chloride-concentration data within acceptable ranges of uncertainty. Finally, changes in water level and chloride concentration may be estimated based on scenarios of future changes in pumping rates or aquifer-management practices.

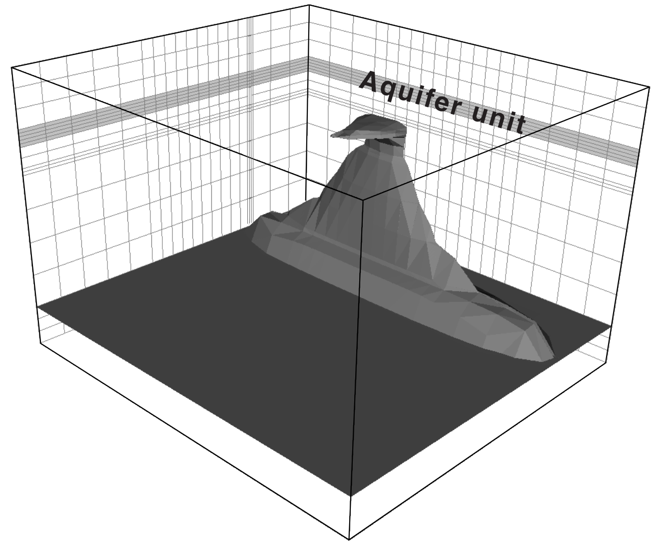

Figure 4. Preliminary modeling results, Brunswick model, after simulated pumping for 47 years. The gray isosurface represents approximately 250 mg/L total dissolved solids.

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PRELIMINARY SIMULATION OF POND-AQUIFER FLOW AND WATER AVAILABILITY AT A SEEPAGE POND NEAR BRUNSWICK, GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 669-672.

INTRODUCTION

The Upper Floridan aquifer is the principal source of water in coastal Georgia, but declining water levels and local saltwater contamination have resulted in restricted withdrawals from the aquifer in some areas, and prompted interest in developing supplemental sources of ground water. In the coastal area, seepage ponds are sometimes constructed at golf courses, farms, or communities by excavating through sandy surface soils until the water table is reached. These ponds commonly are used to supply water for irrigation; however, the water-supply potential of such ponds is poorly understood.

To better define the water-supply potential of seepage ponds, the U.S. Geological Survey (USGS) in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, is evaluating ground-water flow in the vicinity of two seepage ponds in coastal Georgia. Ground-water-flow models are being developed to better understand pond-aquifer flow. This paper describes results of preliminary simulations at a seepage pond at Brunswick, Ga.

Study Area

The study pond described herein is a 3-acre pond located on the campus of Coastal Georgia Community College, at Brunswick, Georgia (fig. 1). The study pond was excavated about 30 years ago to about 15 feet (ft) below sea level into the upper part of a fine-grained quartz sand layer that is part of the surficial aquifer (fig. 2). The surficial aquifer is underlain by a dense clay layer at a depth of about 40 ft below sea level. The pond is isolated from streams and drainage structures.

The surficial aquifer is recharged by rainfall in the vicinity of the pond. Ground-water flow generally is northwest to southeast toward Cyprus Mill Creek, part of a major estuary system about 2,500 ft east of the pond. Ground water seeps into the pond from the west-northwest and seeps out of the pond to the east-southeast.

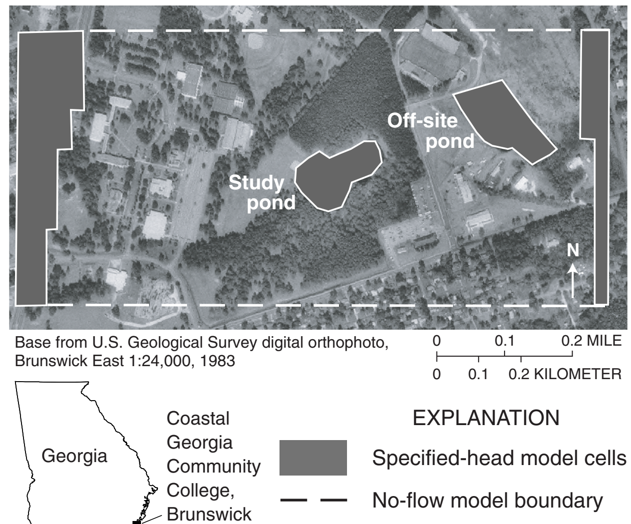

Figure 1. Location of study area and model boundaries.

Ground-Water Seepage

Ground-water inflow (seepage) to the pond results from hydraulic gradients from the aquifer toward the pond. The following relation (Darcy's Law) applies:

$$Q = K\ I\ A \qquad (1)$$

where

Q = the seepage rate in ft^3/day;

K = the hydraulic conductivity in ft/d;

I = the hydraulic gradient in ft/ft; and

A = is the cross-sectional area in ft^2.

Hydraulic conductivity is a constant; both hydraulic gradient and cross-sectional area may change as pond stage or ground-water level changes. Under non-pumping conditions, the regional hydraulic gradient is toward the western and northern shore of the pond, and away from the pond along the southern and eastern shore. Under pumping conditions, a depression in the water-table surface develops, and ground water flows toward the pond from all shorelines.

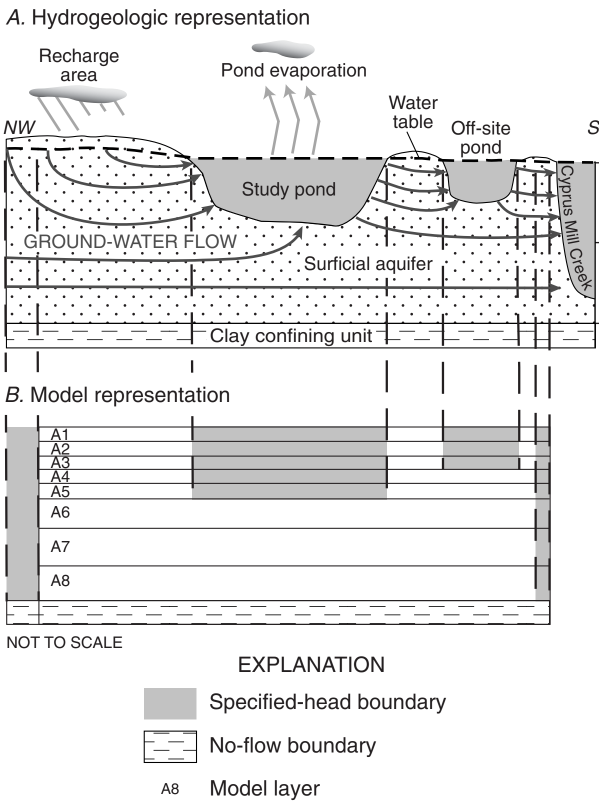

Figure 2. Diagram showing *(A)* hydrogeologic framework and pond-aquifer flow, and *(B)* model layers and boundary conditions for the Coastal Georgia Community College pond-site model.

Seepage represents ground water either entering or leaving the pond. When positive, more ground water enters than leaves the pond; when negative, more water leaves than enters the pond. Ground-water seepage can be estimated using the following volumetric relation:

Seepage = Change in stage + Pumping –
Precipitation + Evaporation + Transpiration (2)

Data from a continuous-monitoring weather station at the site provided information on precipitation and evaporation (transpiration was not considered).

During a 33-hr pumping test in May 2000, pond stage was lowered 2 ft by pumping at an average rate of 1,000 gallons per minute (gal/min). During the same period, there was no precipitation, estimated evaporation was about (10 gal/min), and transpiration was unknown. Thus, changes in pond stage during the pumping test mainly are due to the volume of water removed by pumping and contributed by ground-water seepage. Seepage estimates are limited by the accuracy of evaporation and transpiration estimates, and to pond-volume estimates determined using pond-stage and bathymetric data. Because transpiration is unknown, seepage estimates derived for the pond are lower than actual rates.

Rates of ground-water seepage vary depending on pond stage and related changes in hydraulic gradient and cross-sectional area. Decreasing pond stage results in an increased hydraulic gradient toward the pond and increased rates of seepage to the pond. During the pumping test, however, estimated seepage was about – 280 gal/min, indicating a losing condition. This discrepancy results from errors in pond-volume and evaporation estimates, and from a lack of transpiration data. Following the pumping test, pond stage recovered about 0.1 ft in 25.5 hours corresponding to rate of about 90 gallons per minute gal/min, which combined with the estimated evaporation rate of 10 gal/min, equals a seepage rate of 100 gal/min.

Preliminary Simulation of Pond-Aquifer Flow

Pond-aquifer flow is being simulated using the USGS digital, three-dimensional, finite-difference ground-water flow model—MODFLOW (McDonald and Harbaugh, 1988). Steady-state and transient simulations are being used to evaluate changes in ground-water level and seepage to and from the pond prior to, and during the 33-hr pumping test. Initial conditions are simulated as steady state, followed by simulation of transient changes in recharge, pond stage, ground-water levels, and seepage.

The model consists of a variably spaced grid having 75 rows and 106 columns, encompassing an area of 0.4 square mile. Cell size ranges from 20 by 20 ft near the pond, to 100 by 120 ft at the outer margins of the model grid. Smaller cell sizes were used near the pond to better simulate steeper hydraulic gradients. In the model, the surficial aquifer is divided into eight layers—layer A1 is simulated as a water-table layer, whereas layers A2–A8 are simulated as confined layers (fig. 2).

Initial estimates of horizontal hydraulic conductivity (Kh) are within estimated ranges for a silty sand and are near values derived from aquifer-test data (Gregory Schultz and Carolyn Ruppel, Georgia Institute of Technology, written commun., 2000) at Sapelo Island, about 20 miles north of the site, but in a similar geologic setting. Initial Kh values range from 30 to 60 feet per day (ft/d). Vertical hydraulic conductivity (Kv) was assigned an initial value of 20 ft/d, which is about 1.5 to 3 times less than horizontal values. Pond bed sediments occur mostly in layer A6, and were assigned an initial value of 30 ft/d, or a vertical to horizontal ratio of 1:1. The uppermost layer (A1), simulated under water-table conditions, was assigned a specific yield of 0.04. Layers A2-A8, simulated as confined layers, were assigned a specific storage of 0.0003. Hydraulic property values are being adjusted as part of the calibration process.

The study pond is simulated as a constant-head boundary in the first five layers of the model. The depth and geometry of the pond bottom was determined from a bathymetric survey conducted during summer 1999. Pond-stage changes recorded by a continuous gage were applied to each stress period of the transient model. A second pond, located about 750 ft east of the study pond, is simulated as a constant-head boundary in the first three layers of the model.

Lateral boundary conditions for the model were selected to coincide as closely as possible with natural no-flow boundaries (figs. 1 and 2). No-flow boundaries are assigned to the northern and southern sides of the model and correspond to flow lines in the surficial aquifer. The eastern and western boundaries are simulated as specified head layers located at least 0.3 mile from the pond site to minimize influence on simulation results. The base of the model (layer A8) is bounded by a no-flow boundary at the top of the basal clay layer.

Recharge applied to the uppermost layer of the model for the initial steady-state simulation ranges from zero in the vicinity of impermeable surfaces such as parking lots, to 0.03 ft/d in unlined drainage ditches adjacent to impervious surfaces. Because there was no rainfall during the pumping test, recharge was zero during the transient simulation.

For the initial steady-state simulation of pre-test conditions, ground-water flow directions are from the western boundary and into the pond along the western and northern shores (fig. 3A). Ground water seeps from the pond along the southeastern shoreline. Some water moving from the pond seeps into the second pond site, with the remaining water moving toward Cyprus Mill Creek, east of the simulated area. These flow patterns compare favorably to water-table maps derived from test-well data.

Following the initial steady-state simulation, the model was discretized into one stress period divided into 33 time steps of one-hour duration for simulation of transient conditions. A map showing the preliminary simulated water table after 33 hours of pumping is shown in figure 3B. The simulated water table indicates a depression surrounding the study pond, with a steepened hydraulic gradient that captures flow along all shorelines. This depression resulted in the development of a ground-water divide between the study pond and the off-site pond located east of the site. Simulated flow is similar to that shown on water-table maps derived from test-well data.

Water Availability

Ground-water seepage rates control the availability of water in the pond. Seepage rates vary in response to changes in hydraulic gradient and pond area. Availability of water supplies from seepage ponds in coastal Georgia is constrained by the fact that water flowing into the pond is derived from a water-table aquifer and, thus, is highly dependent on climatic conditions. Any water removed from the water table is lost from ground-water storage until replenished by rainfall recharging the aquifer. Because seepage ponds are used largely for irrigation during the dry season, the quantity of water available is limited by ground-water seepage and the size of the reservoir (pond storage) during dry periods. This limitation is demonstrated at the study pond by the time required for water levels to recover from the pumping test. For several weeks following the pumping test, water levels in wells surrounding the pond continued to decline, and remained low until rainfall recharged the aquifer; during the same period, the pond stage showed a similar pattern.

DISCUSSION

Model results presented in this paper are preliminary and subject to change pending final calibration and sensitivity testing. Calibration will consist of adjusting hydraulic properties and boundary conditions to provide improved matches of hydraulic head and ground-water seepage. The calibrated model will be used to estimate the rate of ground-water seepage into the pond under varying stage observed before and during the 33-hour pumping test.

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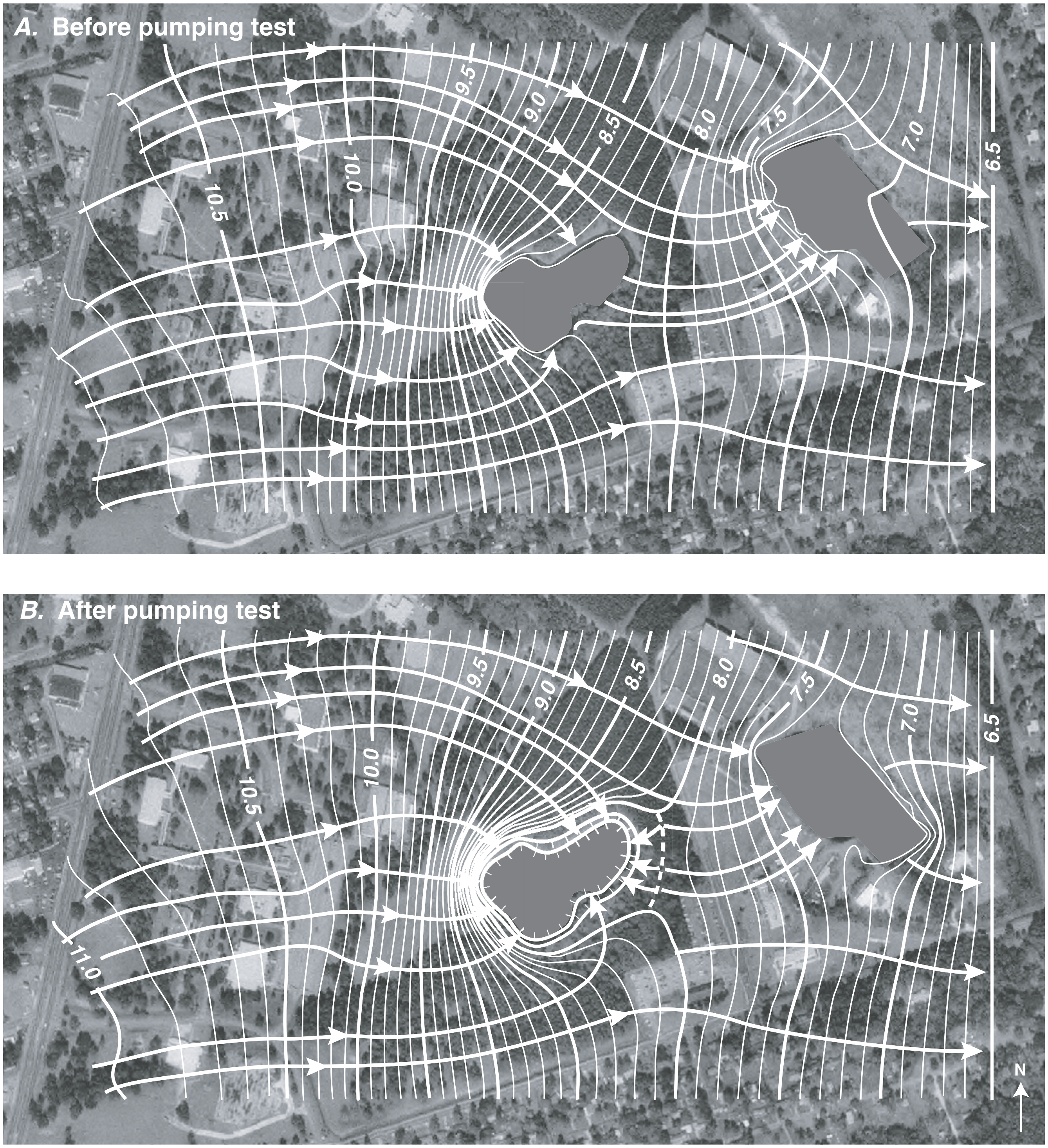

Base from U.S. Geological Survey digital orthophoto, Brunswick East 1:24,000, 1983

0 0.1 0.2 MILES

0 0.1 0.2 KILOMETERS

EXPLANATION

— **10.5** — SIMULATED WATER-TABLE CONTOUR—Shows altitude of water table in surficial aquifer. Hachures indicate depression. Contour interval 0.1 and 0.5 feet. Datum is sea level

→ DIRECTION OF GROUND-WATER FLOW

- - - - - GROUND-WATER DIVIDE

Figure 3. Simulated water-table contours in the surficial aquifer *(A)* before pumping test on May 1, 2000 and *(B)* after the pumping test on May 3, 2000.

SUMMARY OF SELECTED U.S. GEOLOGICAL SURVEY WATER-RESOURCES ACTIVITIES IN GEORGIA

By Steven D. Craigg and Debbie Warner

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p.677-680.

Abstract. The U.S. Geological Survey (USGS) is the Nation's largest natural sciences and civilian mapping agency and provides reliable and impartial scientific information to natural-resource managers, planners, the public, and other customers and stakeholders throughout the Nation. This information contributes to sound conservation and management of natural resources; enhances the quality of life by monitoring water, biological, energy, and mineral resources; and minimizes losses from numerous natural hazards. The USGS disseminates results of data-collection programs and technical investigations in a wide variety of formats—including numerous scientific reports, maps, various databases, CD-ROMs, World Wide Web sites, and other products.

USGS water-resources activities in Georgia are conducted in cooperation with numerous local, State, and Federal agencies. Cooperating agencies include, but are not limited to, the City of Brunswick and Glynn County; Albany Water, Gas, and Light Commission; City of Lawrenceville; Georgia Department of Natural Resources; Georgia Department of Agriculture; University System of Georgia; U.S. Army Corps of Engineers; U.S. Department of Defense; U.S. Environmental Protection Agency; U.S. Fish and Wildlife Service; and National Park Service. In addition, some projects are funded through direct Congressional appropriation of Federal funds.

USGS WATER-RESOURCES INVESTIGATIONS IN GEORGIA

The USGS has collected water-resources data and conducted technical investigations in Georgia since the 1890's. Currently (2001) surface-water data are collected at about 135 continuous-record and 75 partial-record streamflow-gaging stations, 18 reservoir stage-and-contents gaging stations, 20 continuous-record water-quality stations, and 135 water-quality stations that are sampled monthly. Many of the continuous-record stations are being upgraded to include rain gages, meteorologic instrumentation, and satellite telemetry that relay hydrologic data to the USGS office in Atlanta. Ground-water-level data are collected at about 175 continuous-record monitoring wells—during a typical year, ground-water levels are measured periodically in about 150 wells; however, this number varies depending on requirements of ongoing hydrologic investigations. USGS data are used in various interpretive hydrologic studies; by water-resources managers to make decisions concerning water supplies, flood control, drought effects, irrigation, bridge design and scour, and pollution abatement; and by recreational users (see USGS papers and abstracts by S.J. Alhadeff and others; T.R. Dyar and others; A.J. Gotvald and M.N. Landers; Landers and others; B.E. McCallum and J.K. Joiner; B.E. McCallum and A.J. Horowitz, K.B. McSwain and N.L. Barber; and T.C. Stamey and others, *this volume*).

Numerous water-resources investigations are being conducted by the USGS in Georgia. The objectives of these studies vary widely; summaries of selected investigations follow:

- *Coastal Ground-Water Investigations*—Cooperative projects to evaluate effects of ground-water pumpage on water quality (saltwater intrusion) in the Upper Floridan aquifer; determine mechanisms of ground-water flow and saltwater movement; delineate areas where saltwater is entering the aquifer in the Savannah, Ga.—Hilton Head Island, S.C., and Brunswick, Ga., areas; evaluate water-management alternatives through digital simulation; assess alternative water supplies from seepage ponds and supplemental aquifers; and monitor long-term ground-water levels and quality (see USGS papers by J.S. Clarke and R.E. Krause; W.F. Falls and others; L.E. Jones; R.E. Krause and J.S. Clarke; M.T. Laitta; D.F. Payne and others; Malek Abu-Ruman and J.S. Clarke; M.F. Peck and others; and M.D. Petkewich and others, *this volume*). Cooperators: Georgia Department of Natural Resources, City of Brunswick, Glynn County, St Johns River Water Management District.

- *Ground-Water Resources of the Piedmont in the vicinity of Lawrenceville*—Cooperative project to delineate the hydrogeologic characteristics of fractured crystalline-rock aquifers, and evaluate effects of ground-water withdrawal in a rapidly developing urban area (see USGS abstract by L.J. Williams and Marcel Belaval, *this volume*). *Cooperato*r: City of Lawrenceville.
- *Hydrogeologic Monitoring and Evaluation in the Albany area*—Cooperative program to define ground-water resources, monitor ground-water levels and quality, establish and maintain a hydrogeologic database, and assess water chemistry and recharge mechanisms. *Cooperator*: Albany Water, Gas, and Light Commission.
- *Water Use in Georgia*—Cooperative program to collect and compile water-use data, and conduct assessments to improve the methodology for estimating irrigation water use (see USGS abstract by J.L. Fanning, *this volume*). *Cooperator*: Georgia Department of Natural Resources.
- *National Water-Quality Assessment (NAWQA) Program*—Federally funded program to provide consistent description of current water-quality conditions for surface- and ground-water resources; define long-term trends (or lack of trends) in water quality; and identify, describe, and explain the major factors that affect water-quality conditions and trends. Three NAWQA studies are being conducted in Georgia: (1) *Apalachicola-Chattahoochee-Flint River basin and related investigations*—study began in 1991 and is based in Atlanta, Ga. (see papers by M.B. Gregory and E.A. Frick; N.E. Peters and Seth Rose, *this volume*); (2) *Georgia-Florida Coastal Plain*—study began in 1991 and is based in Tallahassee, Fla.; and (3) *Mobile River basin*—study began in 1997 and is based in Montgomery, Ala.
- *Surface-Water Quality of Gwinnett County*—Cooperative study to describe water-quality status and trends for twelve streams, evaluate relations between water quality and watershed characteristics, and assess potential use of these relations to develop techniques to predict water quality from watershed characteristics (see USGS paper by P.D. Ankcorn and others, *this volume*). *Cooperator*: Gwinnett County.
- *Chattahoochee Riverway Bacteria ALERT*—Cooperative program to monitor coliform bacteria levels at two sites on the Chattahoochee River. Water samples are collected Monday through Thursday, analyzed for total coliform bacteria and E coli, and the results posted to the USGS Georgia Home page (**http://ga.water.usgs.gov/bacteria**) within 24 hours of sample collection. *Cooperators*: U.S. National Park Service, Georgia Department of Natural Resources, The Georgia Conservancy, Upper Chattahoochee River Keeper.
- *Department of Defense (DOD) Environmental Contamination Program*—Program to provide sound technical assistance to DOD facilities in Georgia, so that DOD can make appropriate science-based decisions to remediate current contamination and prevent future contamination. Sites currently being evaluated include the Naval Submarine Base Kings Bay; Marine Corps Logistics Base near Albany; U.S. Army Signal Center at Fort Gordon near Augusta; and U.S. Air Force Plant 6, Marietta (see USGS paper by G.J. Gonthier and J.P. Waddell, *this volume*).
- *Effect of Impoundment of Lake Seminole on Water Resources of Lower Apalachicola–Chattahoochee–Flint-River Basin*—Cooperative project to develop a water budget for the Lake; compare current and pre-impoundment ground- and surface-water flow conditions; evaluate the possibility of a substantial amount of lake water entering the ground-water system, flowing beneath Jim Woodruff Lock and Dam, and entering Florida downstream; and assess the likelihood of a sinkhole collapse in the lake bottom, resulting in partial or complete lake drainage (see USGS abstracts by P.N. Albertson; and USGS papers by M.S. Mosner; and L.J. Torak, *this volume*). *Cooperator*: Georgia Department of Natural Resources.
- *Pesticide Monitoring in Ground Water, Southwest Georgia*—Cooperative project to monitor ground-water quality by collecting and analyzing annual samples from 40 shallow wells in southwest Georgia. These samples are analyzed for the following classes of

pesticides—organochlorine pesticides, chlorophenoxyacid herbicides, carbamate insecticides, organophosphorus pesticides, and triazine herbicides. *Cooperator*: Georgia Department of Agriculture.

- *Water, Energy, and Biogeochemical Budgets at Panola Mountain State Park*—Federally funded-research study to investigate processes controlling movement and solute composition of water in a forested watershed; determine relative contributions of various sources including primary mineral weathering, ion exchange, and atmosperic deposition to solutes in streamwater; and investigate biogeochemical processes controlling the regulation of soil chemistry (see USGS paper by N.E. Peters and others, *this volume*).
- *Geographic Information Systems*—Cooperative program to develop environmental and ancillary spatially referenced databases for use in hydrologic investigations (see USGS abstracts by S.J. Alhadeff and others, *this volume*). *Cooperator*: Georgia Department of Natural Resources.

DISSEMINATION OF USGS INFORMATION AND PRODUCTS

The results of USGS data-collection programs and technical investigations are disseminated in a wide variety of formats, including numerous scientific reports, maps, CD-ROMs, World Wide Web sites, and other products. For further information about USGS water-resources activities in Georgia, visit the USGS Georgia Home Page at **http://ga.water.usgs.gov/**; for further information about the USGS, visit the USGS Home Page at **http://www.usgs.gov/**.

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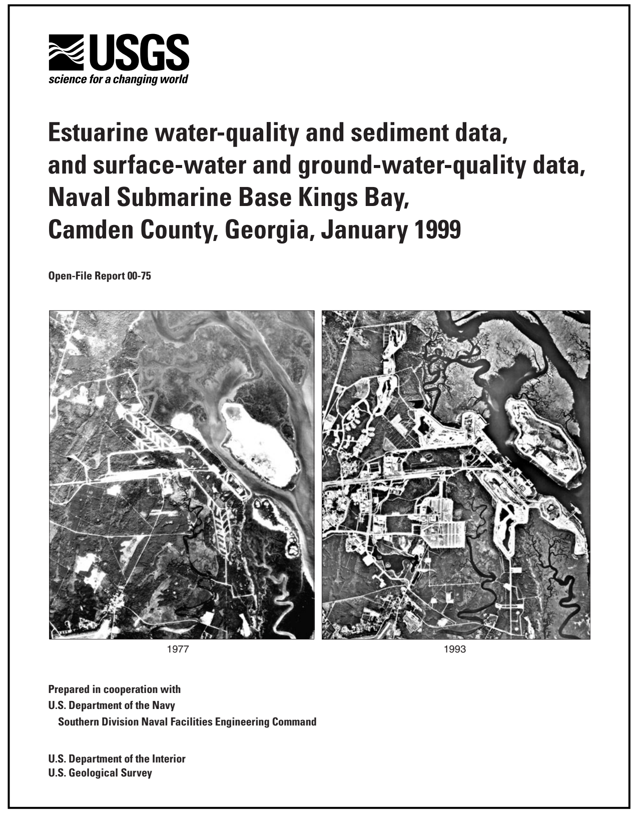
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science for a changing world

Estuarine water-quality and sediment data, and surface-water and ground-water-quality data, Naval Submarine Base Kings Bay, Camden County, Georgia, January 1999

Open-File Report 00-75

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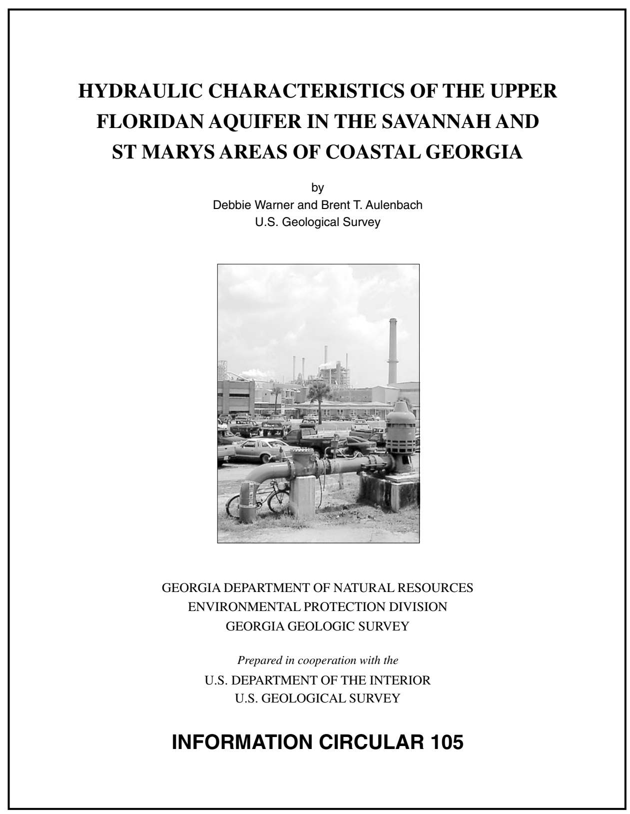
HYDRAULIC CHARACTERISTICS OF THE UPPER FLORIDAN AQUIFER IN THE SAVANNAH AND ST MARYS AREAS OF COASTAL GEORGIA

by
Debbie Warner and Brent T. Aulenbach
U.S. Geological Survey

GEORGIA DEPARTMENT OF NATURAL RESOURCES
ENVIRONMENTAL PROTECTION DIVISION
GEORGIA GEOLOGIC SURVEY

Prepared in cooperation with the
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

INFORMATION CIRCULAR 105

NEW WATERSHED BOUNDARY MAP FOR GEORGIA

By Mark N. Landers[1/], Keith W. McFadden[2/], and Jimmy R. Bramblett[3/]

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 681.

Abstract. Watersheds are units for surface-water runoff and are broadly used to define the spatial extent of surface-water investigations and management programs. A standardized, digital data base of accurately and consistently defined watershed boundaries, or hydrologic units, has been developed to support water resources programs in Georgia. This new watershed boundary map is a cooperative effort of the Georgia Department of Natural Resources, the U.S. Geological Survey (USGS), the Georgia Geographic Information System Clearinghouse, and the Natural Resources Conservation Service (NRCS). Watershed boundary development also was coordinated with adjacent States, and with Federal Geospatial Data Committee efforts to create a National guideline for watershed boundary—or hydrologic unit—mapping. The map is complete and a digital copy may be obtained from the USGS, the Georgia GIS Clearinghouse, or the NRCS. A hard copy of the map and supporting report also is being produced by the NRCS and the USGS.

The principal characteristic of the new Georgia watershed boundary map is that its pour points and boundaries are based solely on hydrologic considerations. The map defines watershed boundaries at the fourth through sixth levels (8-, 10- and 12-digit hydrologic units). Watershed boundaries selected for definition on this map were delineated on 1:24,000 scale USGS topographic maps, using the most recent edition available. The maps were scanned and digitized at a scale of 1:12,000 or larger. The new map defines parts of 54 8-digit watersheds; 395 10-digit watersheds with an average area of 174 square miles, and 1,964 12-digit watersheds with an average area of 35 square miles. The new Georgia watershed boundary map will support scientific investigations and management efforts on topics such as non-point and point source contaminant loading, ecosystem function, and coordinated partnerships among stakeholders whose interests are joined by a shared watershed.

SUMMARY OF FECAL-COLIFORM BACTERIA CONCENTRATIONS IN STREAMS OF THE CHATTAHOOCHEE RIVER NATIONAL RECREATION AREA, METROPOLITAN ATLANTA, GEORGIA, MAY-OCTOBER 1994 AND 1995

By M. Brian Gregory[1/] and Elizabeth A. Frick[2/]

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at the University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 718-721.

Abstract. As part of a 2-year U.S. Geological Survey (USGS) and National Park Service (NPS) project to better define microbial contamination in and near the Chattahoochee River National Recreation Area (CRNRA), the USGS analyzed fecal-coliform bacteria data collected from May to October of 1994 and 1995, by the Georgia Environmental Protection Division. This data set included 14 Chattahoochee River and 22 tributary stream sites in the vicinity of the CRNRA and the reach of the Chattahoochee River downstream of the CRNRA and Metropolitan Atlanta. This paper summarizes the distribution and occurrence of fecal-coliform bacteria concentrations based on these data and is a condensed version of a USGS and NPS publication by Gregory and Frick (2000).

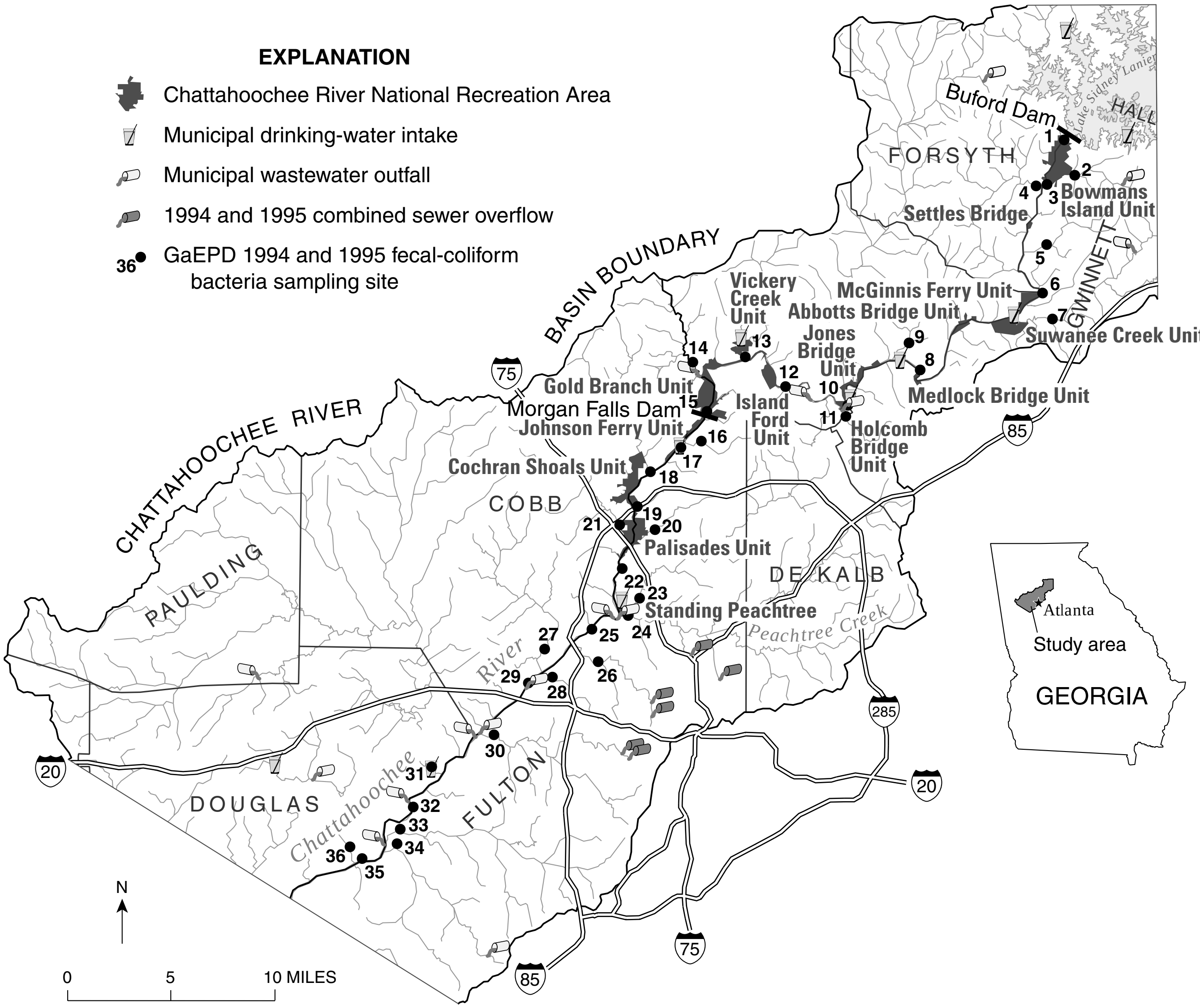
INTRODUCTION

The Chattahoochee River is the most utilized water resource in Georgia. The rapid growth of Metropolitan Atlanta and its location downstream of the headwaters of the drainage basin make the Chattahoochee River an important resource for drinking-water supplies, recreation, and wastewater assimilation (fig. 1). The CRNRA was created by the U.S Congress in 1978 and contains about three-fourths of all public green space in the 10-county area of Metropolitan Atlanta (Kunkle and Vana-Miller, 2000). The CRNRA attracted about 2.9 million visitors in 1999, with nearly 30 percent of the visitors participating in water-based activities (William J. Carroll, National Park Service, oral commun., 2000).

During 1994 and 1995, elevated concentrations of fecal-coliform bacteria were the most common reason that the Chattahoochee River and its tributaries did not meet designated uses of drinking-water supply, recreation, and fishing. According to the Georgia Department of Natural Resources (1997), during 1994 and 1995, 67 of 77 stream reaches assessed in Metropolitan Atlanta did not meet or only partially met water-quality requirements for designated uses. High concentrations of fecal-coliform bacteria were a contributing factor in ninety-four percent (63 of the 67) of stream reaches that did not meet or only partially met designated uses. Although the presence of indicator bacteria does not prove that disease-causing bacteria, viruses, or protozoa are present in the environment, their presence does show that contamination by fecal material has occurred. High concentrations of fecal-coliform bacteria have the potential to reduce the recreational value of the Chattahoochee River by posing an increased risk of exposure to harmful bacteria and the associated adverse effects to humans who come in contact with the water.

Data Collection

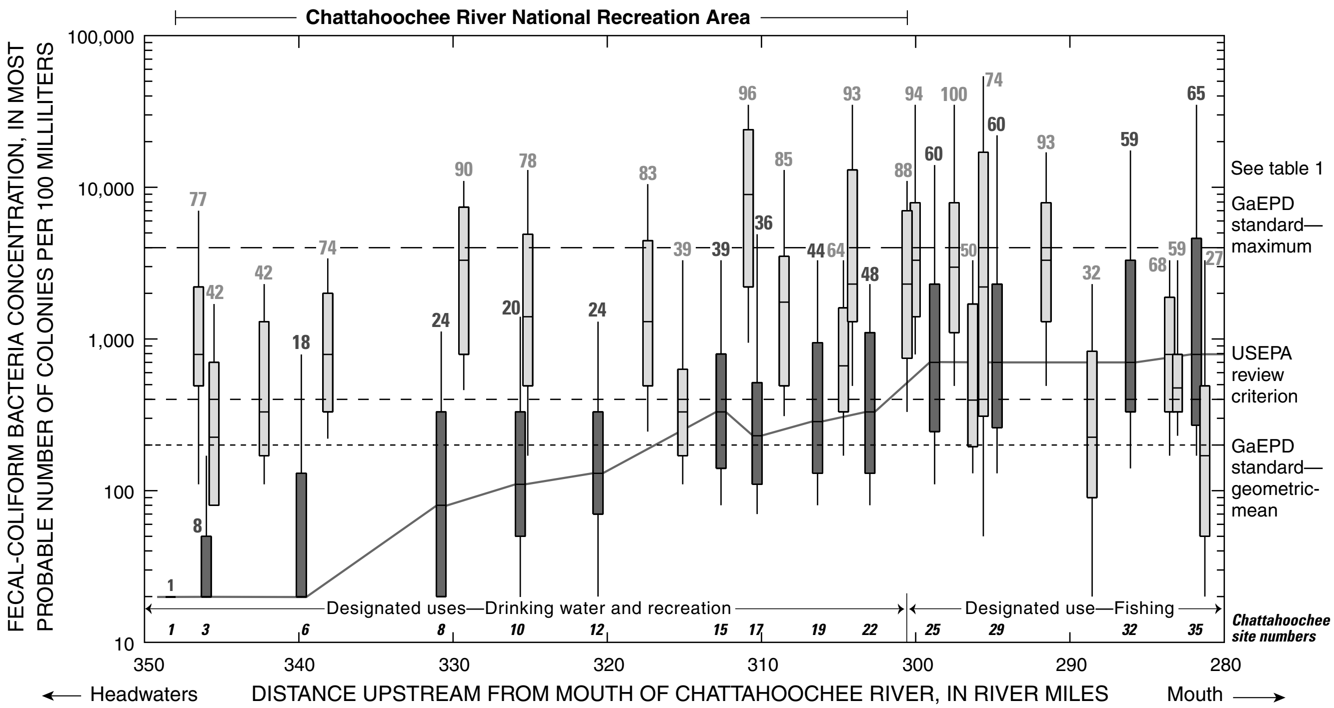
The Georgia Environmental Protection Division (GaEPD) collected a spatially extensive water-quality data set from May to October in 1994 and 1995 as part of their Chattahoochee River Modeling Project (Georgia Department of Natural Resources, 1994a). Water-quality samples consisted of single grab samples collected midstream at 14 Chattahoochee River and 22 tributary stream sites in the vicinity of and immediately downstream of the CRNRA (fig. 1). Fecal-coliform bacteria concentrations were determined using the Multiple Tube Fermentation Technique (American Public Health Association and others, 1985) and expressed as the Most Probable Number of fecal-coliform colony forming units per 100 milliliters (MPN col/100 mL). As part of a 2-year USGS and NPS project to better define microbial contamination in and near the CRNRA, the USGS analyzed these historical data.



Georgia Environmental Protection Division (GaEPD) 1994 and 1995 fecal-coliform bacteria sampling sites within the study area

Site number	Site name	Site number	Site name
1	Chattahoochee River—Buford Dam tailwater near Buford	19	Chattahoochee River—Powers Ferry Road & I-285 near Atlanta
2	Richland Creek	20	Long Island Creek
3	Chattahoochee River—State Road 20 near Suwanee	21	Rottenwood Creek
4	James Creek	22	Chattahoochee River—Paces Ferry Road at Atlanta
5	Level Creek	23	Nancy Creek
6	Chattahoochee River—McGinnis Ferry Road at Suwanee	24	Peachtree Creek
7	Suwanee Creek	25	Chattahoochee River—South Cobb Drive near Atlanta
8	Chattahoochee River—Medlock Bridge Road near Norcross	26	Proctor Creek
9	Johns Creek	27	Nickajack Creek
10	Chattahoochee River—Holcomb Bridge Road near Norcross	28	Sandy Creek
11	Crooked Creek	29	Chattahoochee River—Martin Luther King Jr. Blvd. near Mabelton
12	Chattahoochee River—Eves Road above Roswell	30	Utoy Creek
13	Big Creek	31	Sweetwater Creek
14	Willeo Creek	32	Chattahoochee River—State Road 166 near Ben Hill
15	Chattahoochee River—Morgan Falls Dam Forebay at Sandy Springs	33	Camp Creek
16	Marsh Creek	34	Deep Creek
17	Chattahoochee River— Johnson Ferry Road near Atlanta	35	Chattahoochee River—State Road 92 near Fairburn
18	Sope Creek	36	Anneewakee Creek

Figure 1. Location of the Chattahoochee River National Recreation Area and Georgia Environmental Protection Division fecal-coliform bacteria sampling sites in the study area, May–October 1994 and 1995.



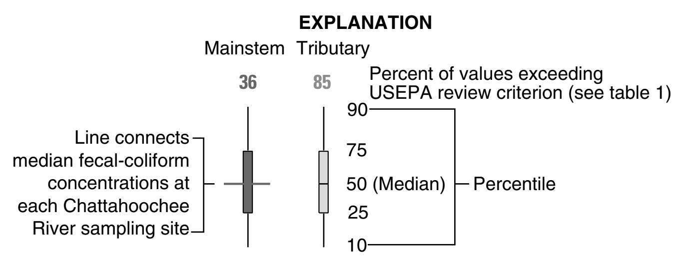


Figure 2. Fecal-coliform bacteria concentrations in the Chattahoochee River and tributary streams, Metropolitan Atlanta, May–October 1994 and 1995 (data from Georgia Environmental Protection Division).

Table 1. Georgia Environmental Protection Division (GaEPD) fecal-coliform bacteria standards and U.S. Environmental Protection Agency (USEPA) review criterion

[All standards and criterion are in Most Probable Number of colonies per 100 milliliters (MPN col/100 mL); —, no standard or criterion. Modified from Georgia Department of Natural Resources, 1994b]

Designated use	Time of year that standards and criterion apply	GaEPD standards		USEPA (1997) recommended review criterion to evaluate once-per-month samples[2]
		30-day geometric mean[1]	Maximum single sample[2]	
Drinking-water supply	May–October[3]	200	—	400
	November–April	1,000	4,000	—
Recreation	Year round	200	—	400
Fishing	May–October[3]	200	—	400
	November–April	1,000	4,000	—

1/ Based on at least four samples collected from a given site over a 30-day period at an interval not less than 24 hours. The geometric mean of a series of N terms is the N[th] root of their product. For example, the geometric mean of 2 and 18 is 6—the square root of 36.

2/ Waters are deemed **not supporting** designated uses (impaired) when 25 percent or more of the samples have fecal-coliform bacteria concentrations greater than the applicable review criterion or standard (400 or 4,000 MPN col/100 mL) and **partially supporting** when 11 to 25 percent of the samples exceed the review criterion or standard.

3/ May–October is defined as the summer recreation season—the season when most water-contact activities are expected to occur. The State of Georgia does not encourage swimming in any natural surface waters because a number of factors beyond the control of any State agency contribute to elevated concentrations of fecal-coliform bacteria.

RESULTS

During the 1994 and 1995 summer recreational seasons, fecal-coliform bacteria concentrations in the Chattahoochee River were lowest downstream from Buford Dam—especially nearest the dam—because of dilution from water released from near the bottom of Lake Sidney Lanier. Median fecal-coliform bacteria concentrations in the Chattahoochee River increased steadily from less than 20 MPN col/100 mL in the tailwaters of Buford Dam on Lake Sidney Lanier to 790 MPN col/100 mL downstream of Metropolitan Atlanta (fig. 2). During the 1994 and 1995 summer recreational seasons, from 27 to 100 percent of samples collected at 22 tributary stream-monitoring sites exceeded the U.S. Environmental Protection Agency (USEPA) review criterion of 400 col/100 mL and from 1 to 65 percent of samples collected at 14 Chattahoochee River monitoring sites also exceeded this criterion (fig. 2; table 1). GaEPD standards and the USEPA review criterion for fecal-coliform bacteria (table 1) were commonly exceeded during wet-weather conditions in most Metropolitan Atlanta tributary streams and during most streamflow conditions in several tributaries that drain areas dominated by urban and suburban land uses.

OVERVIEW

Although concentrations of fecal-coliform bacteria that exceed GaEPD standards and the USEPA review criterion are common in Metropolitan Atlanta streams, this situation is not unique to the Metropolitan Atlanta area. According to a recent nationwide study, bacterial contamination was ranked as the third most common cause for water-body impairment in the United States during 1996 (Armitage and others, 1999). Whereas waterborne diseases were once a greater threat to human health in the United States, currently the threat of waterborne disease exists for humans living in densely populated areas (Burke, 1993). These risks have the potential to be even greater in areas where under-treated or untreated wastewater effluent and runoff from highly urbanized areas contribute to drinking-water-source supply intakes, or where recreational contact with contaminated water may occur.

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SALTWATER CONTAMINATION OF GROUND WATER AT BRUNSWICK, GEORGIA AND HILTON HEAD ISLAND, SOUTH CAROLINA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at the University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 756-759.

Abstract. Sustained pumping from the Upper Floridan aquifer in the coastal area of Georgia and adjacent lowcountry of South Carolina has resulted in substantial reductions in artesian pressure in the aquifer, which has resulted in saltwater intrusion at two locations in the area. At Brunswick, Georgia, brine from deeply buried paleokarst zones has intruded the aquifer by migrating upward through solution-enlarged breaks in the confining units. At the northern end of Hilton Head Island, South Carolina, lateral encroachment of seawater has occurred. Understanding the conditions under which these types of intrusion occur is of importance to managing the water resources of the coastal area.

INTRODUCTION

Ground water is the main source of water supply in coastal Georgia. The first "deep" well in the coastal area was completed in 1885 in the water-bearing zone now known as the Upper Floridan aquifer, an extremely permeable, carbonate sequence. (The zone was considered "deep" at that time, because existing wells generally tapped one of three overlying aquifers.) The Upper Floridan became the water supply of choice because of its capacity to yield extremely large quantities of fresh water and the simplicity of well construction, including not having to use well screen. By 1900, more than 200 wells had been completed in the aquifer in coastal Georgia, and pumpage was more than 10 million gallons per day (Mgal/d). This apparent plentiful water supply attracted numerous industries that required large quantities of fresh water. Pumpage increased at varying rates, and today (2000), more than 300 Mgal/d is pumped from the aquifer in the coastal area of Georgia and adjacent lowcountry of South Carolina. Pumping is widespread throughout the area, but is concentrated at several pumping centers. This pumping has resulted in substantial reduction in artesian pressure regionally, and has caused large, deep, cones of depression in the potentiometric surface at pumping centers.

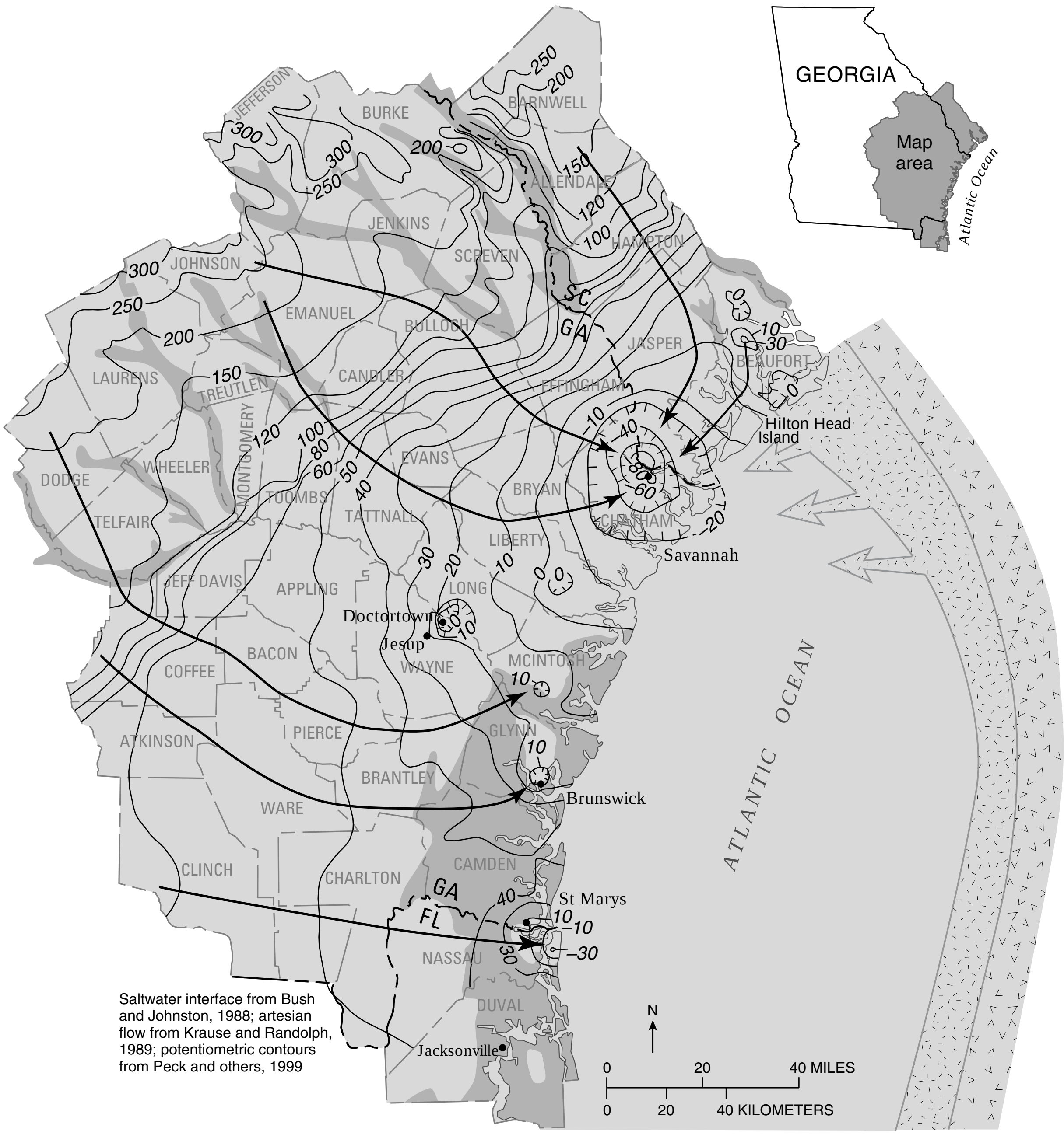
As a result of the heavy pumpage and resulting reduction in pressure, saltwater intrusion of the aquifer was observed in the 1950's at Brunswick, and in the early 1970's at Hilton Head Island, South Carolina (fig.1). Saltwater contamination at these two coastal locations has constrained further development of the Upper Floridan aquifer in the coastal area and created competing demands for the limited supply of water. The Georgia Department of Natural Resources, Environmental Protection Division (GaEPD) has capped permitted withdrawal of water from the Upper Floridan aquifer in parts of the coastal area (including the Savannah and Brunswick areas) at 1997 rates, and also has restricted permitting of additional pumpage in all 24 coastal-area counties to 36 Mgal/d above 1997 rates. This strict management action has prompted interest in alternative management of the aquifer and in the development of alternative, supplemental sources of water supply, including supply from the shallower Miocene and surficial aquifers and the underlying Lower Floridan aquifer.

GEOLOGY AND GROUND-WATER RESOURCES

The coastal area of Georgia and adjacent lowcountry of South Carolina is blanketed and underlain by unconsolidated sedimentary strata that overlie carbonate rocks—limestone and dolostone—at varying depth. The sedimentary strata are thickest and most deeply buried in the Brunswick area and south into northeastern Florida, where more than 500 feet of sand and clay overlie more than 2,000 feet of carbonate rocks. The sequence is thinner and at shallower depth toward the north in the Savannah, Georgia—Hilton Head Island, South Carolina, area where the top of the carbonate rocks are 50-150 feet below land surface and the thickness is less than 500 feet.

Predevelopment Ground-Water Flow System

Prior to development of the Upper Floridan aquifer in the 1880's, recharge to the aquifer system was roughly offset by natural discharge. The Upper Floridan aquifer



EXPLANATION

Freshwater—Darker color shows area of artesian flow (modern day May 1980)

Transition zone

Saltwater

—*10*– – **Potentiometric contour of Upper Floridan aquifer**—Shows altitude at which water level would have stood in tightly cased wells (modern day May 1998). Dashed where approximately located. Hachures indicate depression. Contour interval variable

→ **General direction of ground-water flow**

Figure 1. Modern-day (1998) ground-water flow system, coastal Georgia and adjacent parts of South Carolina and Florida.

was replenished (recharged) by rainfall in areas where aquifer sediments are at or near land surface, generally west and northwest of the coast.Water flowed from the recharge area in the western and northwestern part of the area downgradient toward the coast. This downgradient flow with increasing depth and decreasing land-surface altitude, together with confinement exerted by low-permeability sediments overlying the aquifer, resulted in increasing artesian pressure toward the coast and offshore. The aquifer was under confined, or artesian conditions, and the water level was sufficient that wells flowed at land surface throughout most of the coastal area. The artesian water level was about 65 feet above sea level at Brunswick, and 35 feet above sea level at Savannah. Ground water discharged naturally to springs; as seepage to rivers, ponds, wetlands, and other surface-water bodies; and as diffuse upward leakage into adjacent aquifers and offshore to the Atlantic Ocean.

Modern-Day Ground-Water Flow System

Ground-water pumping has caused the water level in the Upper Floridan aquifer to decline throughout the entire coastal area, and has resulted in the development of cones of depression in areas of heavy, concentrated pumpage, such as the Savannah, Brunswick, Jesup, and St Marys, Georgia–Fernandina Beach, Florida areas (fig.1). Wells have ceased to flow at land surface throughout much of the coastal area. Many freshwater springs and seeps have ceased to discharge; freshwater wetlands and ponds that prior to development were fed by flow from the Upper Floridan are no longer sustained by that flow. Although the cones of depression are deep, they do not intercept the top of the Upper Floridan aquifer; thus, dewatering or "mining" of the aquifer is not taking place. The aquifer is still fully saturated, but because of the large, sustained withdrawal of water, the artesian pressure in the aquifers has been reduced. This pressure reduction has allowed saltwater under higher pressure to intrude the freshwater part of the aquifer in at least two locations—Brunswick, Georgia, and Hilton Head Island, South Carolina.

Freshwater-Saltwater Interface

Freshwater in the Upper and Lower Floridan aquifers flows seaward until it comes in contact with seawater along the freshwater-saltwater interface. Freshwater is less dense than saltwater and tends to flow on top of it. The interface is not sharp and distinct, but is a diffuse zone in which freshwater and saltwater mix through the processes of chemical diffusion and mechanical dispersion. Data from the offshore area, hydrologic conceptual models, and results of simulation indicate that the freshwater-saltwater interface in the upper part of the aquifer system is at the coastline just north of Hilton Head Island; arcs eastward under the Atlantic Ocean, reaching a maximum distance of about 55 miles offshore; then arcs back to the coast south of Jacksonville, Florida.

The freshwater-saltwater interface is relatively flat-lying and at considerable depth in and under the Floridan aquifer system along the central part of the Georgia coast and northeastern Florida. In the Brunswick area, saltwater (hypersaline connate water) occurs naturally below freshwater in the lower part of the Fernandina permeable zone. Saltwater in the Fernandina permeable zone is at a depth of about 2,400 feet below sea level.

Saltwater Contamination at Brunswick, Georgia

Saltwater contamination at Brunswick is the result of upward intrusion of saltwater (chloride concentration greater than 30,000 milligrams per liter) from the lower part of the Fernandina permeable zone into freshwater zones of the Lower Floridan, then Upper Floridan aquifers (fig. 2). Saltwater from the Fernandina permeable zone migrates upward through solution-enlarged fractures and conduits in the limestone and dolostone confining units in response to reduced artesian pressure caused by pumping from the Upper Floridan aquifer. Upon reaching the aquifers in the southern part of the Brunswick peninsula, the diluted saltwater moves northward toward cones of depression caused by pumping in the northern part of Brunswick. Most of this saltwater intrusion and lateral downgradient transport occurs in the Upper Floridan aquifer because of greater pumpage and reduction in pressure than in the Lower Floridan aquifer.

Saltwater intrusion occurs at locations that are laterally away from the centers of pumping and the induced cones of depression. Also, intrusion moves upward through isolated conduits, not symmetrically in the form of an inverted cone as it would through porous media.Therefore, upconing is not occurring. Contamination of the Upper Floridan aquifer in the Brunswick area is not due to lateral encroachment nor downward intrusion of seawater, because the aquifer is deeply buried at Brunswick (greater than 500 feet deep); the freshwater interface with seawater is far from the coastline (more than 50 miles offshore); and most significantly, pressure in the aquifer was greater than sea level when saltwater contamination at Brunswick was first detected in the late 1950's.

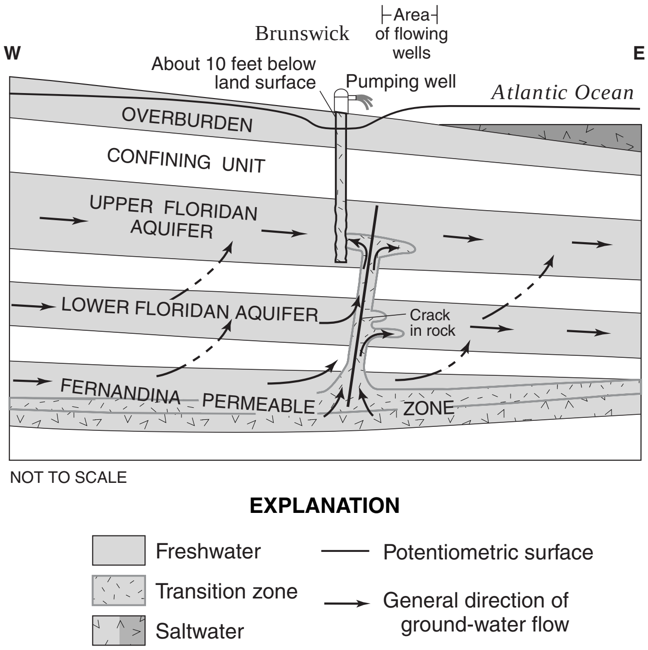


Figure 2. Conceptualization of saltwater contamination in the Floridan aquifer system at Brunswick (modified from Krause and Randolph, 1989).

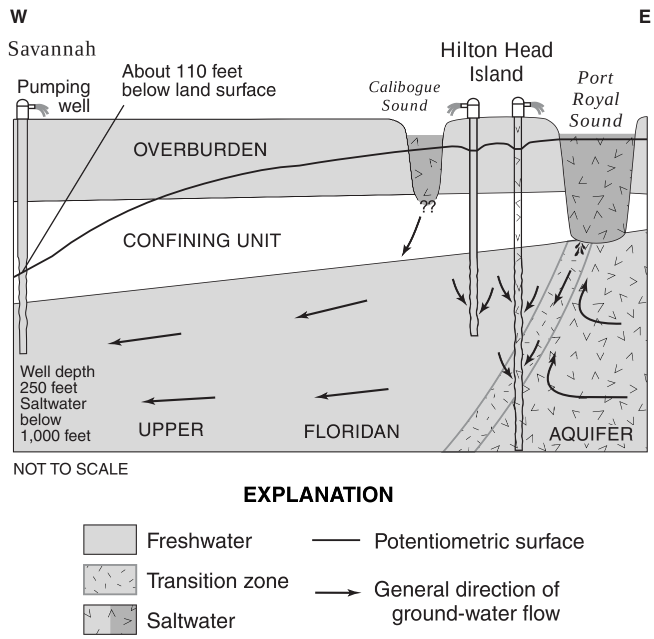


Figure 3. Conceptualization of saltwater contamination in the Floridan aquifer system near Hilton Head Island, South Carolina.

Saltwater Contamination at Hilton Head Island, South Carolina

Saltwater contamination along the northern end of Hilton Head Island probably is the result of lateral encroachment of seawater, combined with some downward vertical leakage of saltwater or brackish water from sounds, estuaries, tidal creeks, and saltwater marshes where the Upper Floridan aquifer is exposed or thinly confined. In the vicinity of Port Royal Sound, and possibly other estuaries, downcutting by ancient river systems during periods of lower ocean levels that existed during the most recent ice age (about 18,000 years BP) has exposed the aquifer to seawater, resulting in a direct connection between salty ocean water and fresh ground water (fig. 3).

Regional pumping, but most significantly, pumping on Hilton Head Island, has locally lowered the water level in the Upper Floridan aquifer and reversed the natural hydraulic gradient, allowing encroachment of saltwater. What had been submarine springs prior to development, now are conduits or sinks where saltwater encroaches from the ocean, sounds, and estuaries.

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LINKAGE OF OFFSHORE AND ONSHORE HYDROGEOLOGIC DATA FOR COASTAL GEORGIA AND ADJACENT PARTS OF SOUTH CAROLINA AND FLORIDA USING A GEOGRAPHIC INFORMATION SYSTEM

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia., p. 764-767.

INTRODUCTION

To characterize ground-water flow and movement of saltwater into freshwater zones, the U.S. Geological Survey (USGS), in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, is developing regional ground-water flow and solute transport models for the Floridan aquifer system and shallower aquifers in coastal Georgia and adjacent parts of South Carolina and Florida. In support of these modeling efforts, structure-contour and thickness maps are being constructed using seismic, geophysical, lithologic, and paleontologic data in a 37,000-square mile (mi^2) area that includes a 8,000-mi^2 offshore region (fig. 1). Constructing these maps is a challenge because (1) the spatial distribution of onshore data is distinctively more dense than that of offshore data; and (2) different types of data are used to identify hydrogeologic units in different areas. Prior to this study, no attempts had been made to integrate and construct a seamless geospatial hydrogeologic framework linking both onshore and offshore interpretations. Objectives of this study include identifying areas with insufficient data coverage; evaluating how well various hydrogeologic interpretations coalesce; and determining the extent to which offshore hydrogeologic data reflect known structural features.

Sources of Hydrogeologic Data

Principle sources of onshore hydrogeologic data include Miller (1986) and Clarke and others (1990). Miller (1986) delineated the hydrogeologic framework of the Floridan aquifer system based on lithologic, paleontologic, geophysical, and hydrologic data for 662 wells in the Coastal Plain Province of Alabama, Florida, Georgia, and South Carolina. The structure-contour and thickness maps of the Floridan aquifer system encompass an area of about 70,000 mi^2 and constitute the basic data for the Floridan aquifer system for this study. Clarke and others (1990) used natural gamma logs as the principal basis to correlate Miocene and younger geologic units that overlie the Floridan aquifer system in 13 percent of the original study area and represent about 10 percent of the area of interest in this study. Clarke and others (1990) described the hydrogeologic framework and water quality of the surficial aquifer and upper and lower Brunswick aquifers and updated earlier interpretations of the Upper Floridan aquifer (Miller, 1986). Clarke and others (1990) used the “A,” “B,” “C,” and “D” (Wait, 1962, 1965) geophysical markers from 500 wells to approximate the altitude of the top of the upper and lower Brunswick aquifers. Other sources used to supplement this investigation include more recent paleontologic data (L.E. Edwards and R.E. Weems, U.S. Geological Survey, written commun., 2000; H.E. Gill, U.S. Geological Survey (*retired*), written commun., 2000; and Henry and Foyle, Georgia Southern University, written commun., 2000).

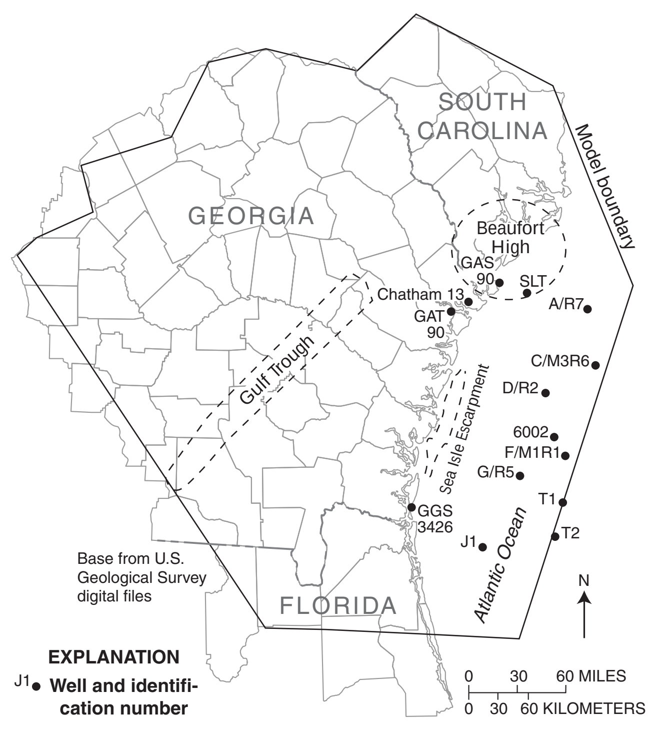

Figure 1. Study area, locations of onshore and offshore borehole data, and location of major structural features.

In the offshore region, sources of data include (1) seismic data from Henry and Idris (1992); (2) borehole data from McClelland Engineers, Inc. (1984—*report to the U.S. Department of the Navy*); and (3) biostratigraphic data from Huddlestun (1993). Seismic data collected by Henry and Idris (1992) were correlated with biostratigraphic data obtained from eight Tactical Air Command Test Sites (TACTS) offshore drilling sites (Manheim, 1992) and from AMCOR 6002 exploratory borings (Hathaway and others, 1981). Seismic records were interpreted to identify time-stratigraphic (geologic) units bound at the top and bottom by unconformities. Key reflectors, assumed to represent formational contacts, were traced along the grid and correlated with contacts identified in the TACTS, Savannah Light Tower (SLT), and AMCOR 6002 offshore borings (fig. 1). Offshore structure contours then were linked to four onshore boreholes—GAS 90 (Chatham County), GAT 90 (Chatham County), Chatham13 (Chatham County) and Cumberland Island 1 (GGS 3426) (Camden County).

Method of Study

Onshore and offshore data were compiled into a Geographic Information System data base by scanning and digitizing contour maps and manually entering altitudes of the tops of hydrogeologic units based on the distribution of borehole data. Digital data sets then were projected into an Albers Equal Area projection and adjusted to the North American Datum of 1983 (NAD83). Contour data sets then were clipped to the model boundaries and edited to remove areas of overlap. Each data set was gridded to form a digital elevation model (DEM) at a resolution of 1,000 square meters, and was contoured using a consistent contour interval of 500 feet. In order to create a seamless surface, the gridded models were combined to form one triangulated irregular network (TIN) surface, which was then re-gridded and contoured. To estimate the degree of fit between offshore seismic data (Henry and Idris, 1992) and onshore geophysical data (Clarke and others, 1990), stratigraphic horizons from four boreholes common to both data sets were correlated with biostratigraphic horizons (L.E. Edwards and R.E. Weems, written commun., 2000) and in an earlier study conducted by Huddlestun (1993) (fig. 2).

Preliminary Results–Upper Floridan Aquifer

The previously described procedure was attempted for the Upper Floridan aquifer, for which substantial data are available in the form of previous map interpretations and abundant borehole data. Initial results indicate a reasonable match between the three input interpretations (fig. 3). The merged interpretations produced a seamless structure-contour surface that retained known structural features such as the Gulf Trough, Beaufort High, and the offshore Sea Isle Escarpment (Huddlestun, 1993) (figs. 1, 3). Correlation between the four onshore boreholes show general agreement in all but the Cumberland Island 1 (GGS3426) borehole (fig. 2).

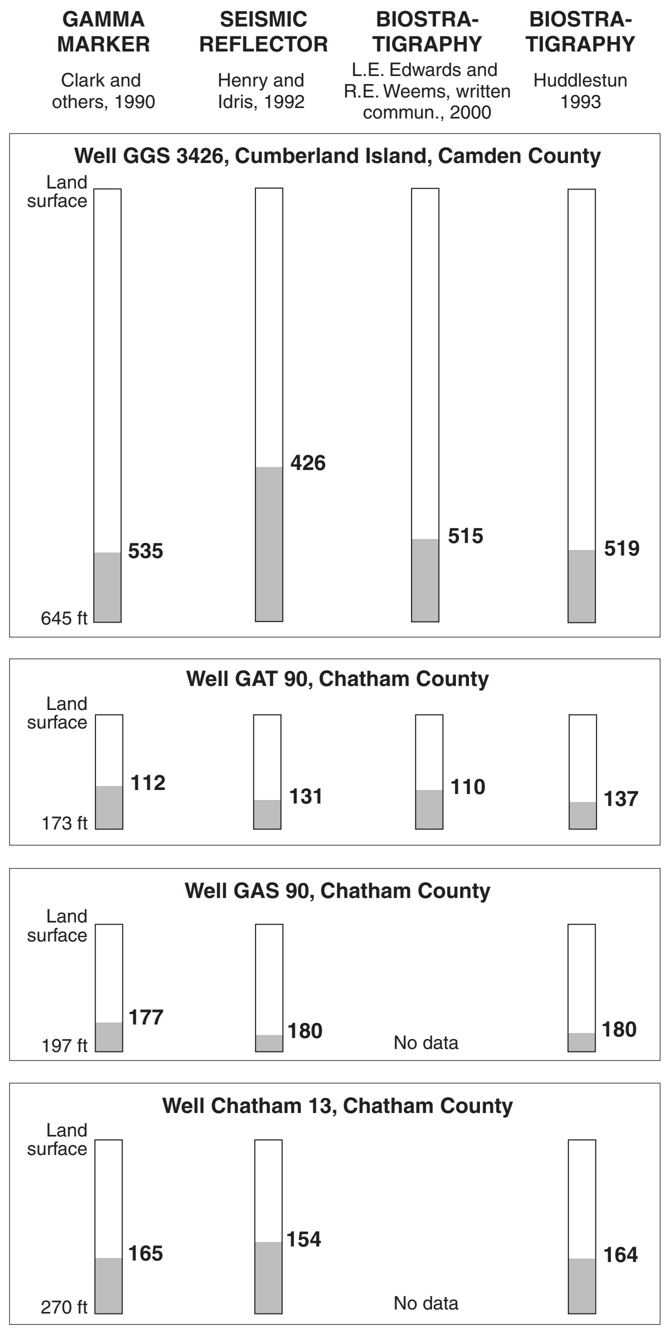

Figure 2. Correlation of the four wells used to link onshore and offshore interpretations. Numbers in bold show depth, in feet below land surface, to the top of the Upper Floridan aquifer.

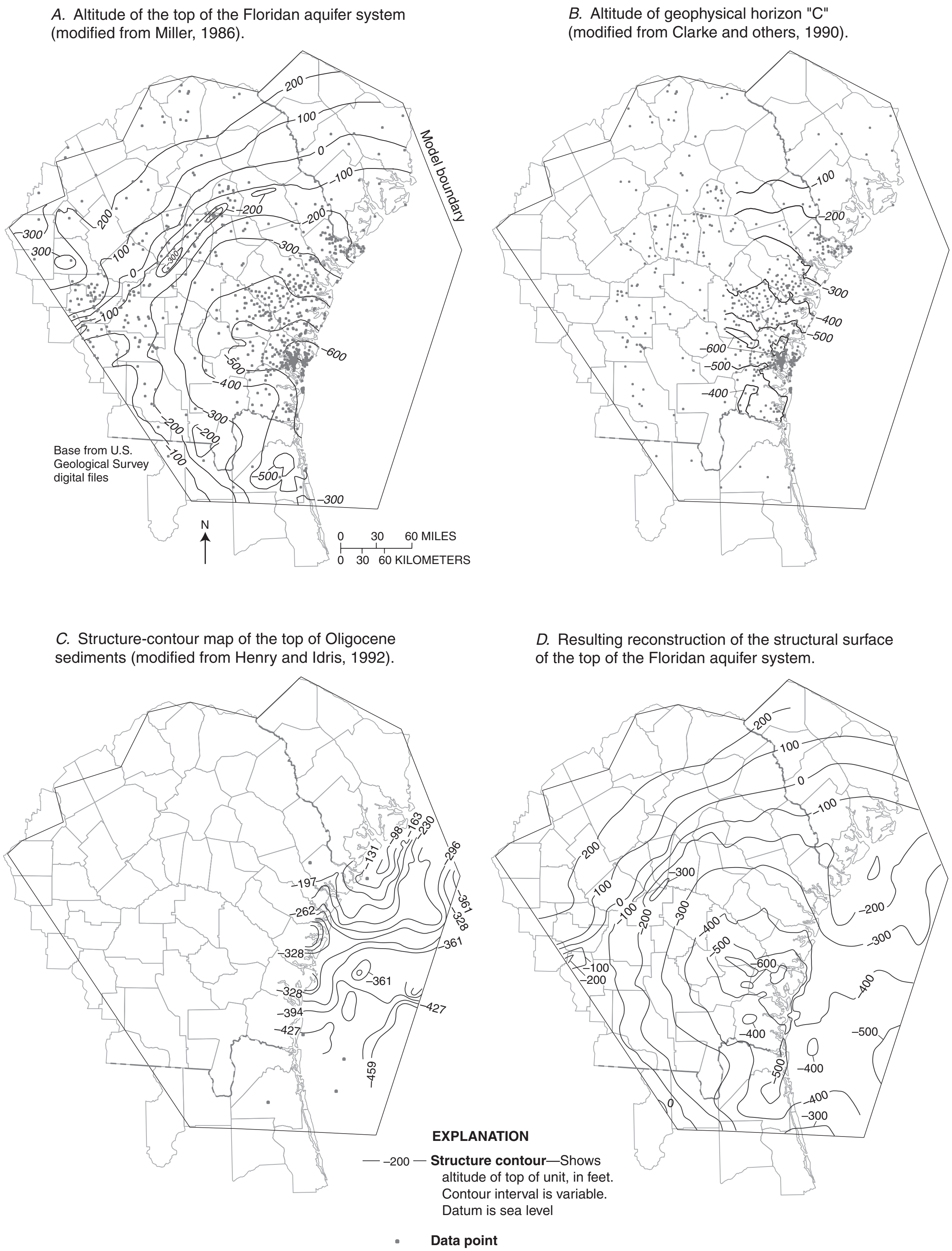

Figure 3. Three interpretations *(A–C)* used to construct a *(D)* seamless onshore/offshore structure-contour map of the top of the Floridan aquifer system.

Ongoing Work

This same procedure is currently being used to estimate the configuration of the altitude of the upper and lower Brunswick aquifers. The objective of this ongoing work is to produce a three dimensional, seamless onshore–offshore distribution of selected geologic units within the study region.

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HYDROGEOLOGIC CONDITIONS AT TWO SEEPAGE PONDS IN THE COASTAL AREA OF GEORGIA, AUGUST 1999 TO FEBRUARY 2001

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 768-771.

INTRODUCTION

The Upper Floridan aquifer is the principal source of water in the coastal area of Georgia, but declining water levels and localized saltwater contamination have resulted in restricted ("capped") withdrawals from the aquifer, and have prompted interest in developing supplemental sources of ground water. In the coastal area, seepage ponds are sometimes excavated at golf courses, farms, or communities by digging through sandy surface soils until the water table is reached. Because these ponds are largely cut off from surface-water runoff, water is largely derived from ground water seeping into the pond. Seepage ponds are often used to supply water for irrigation; however, the water-supply potential of such ponds is poorly understood. The U.S. Geological Survey (USGS), in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, is evaluating hydrogeologic conditions and pond-aquifer relations at two pond test sites in coastal Georgia to determine their potential as supplemental sources of water for irrigation. This paper describes and contrasts hydrogeologic conditions at seepage pond sites at Brunswick, Glynn County, and in southern Bulloch County, Georgia (fig. 1).

Study Areas

To assess the water-supply potential of seepage ponds, two sites located in areas of contrasting hydrologic, physiographic, and soil conditions were selected to evaluate pond-aquifer relations and maximum potential yield (fig. 1). The Glynn County site is located in the Coastal Lowlands physiographic division near the Atlantic Ocean in an area characterized by flat topography and high-permeability sandy soil. The Bulloch County site is located in the Coastal Terraces physiographic division in an area characterized by flat topography and low-permeability clayey soils. Rainfall at the Glynn County site averages 54 inches per year and at the Bulloch County site averages about 47 inches per year (Krause and Randolph, 1989).

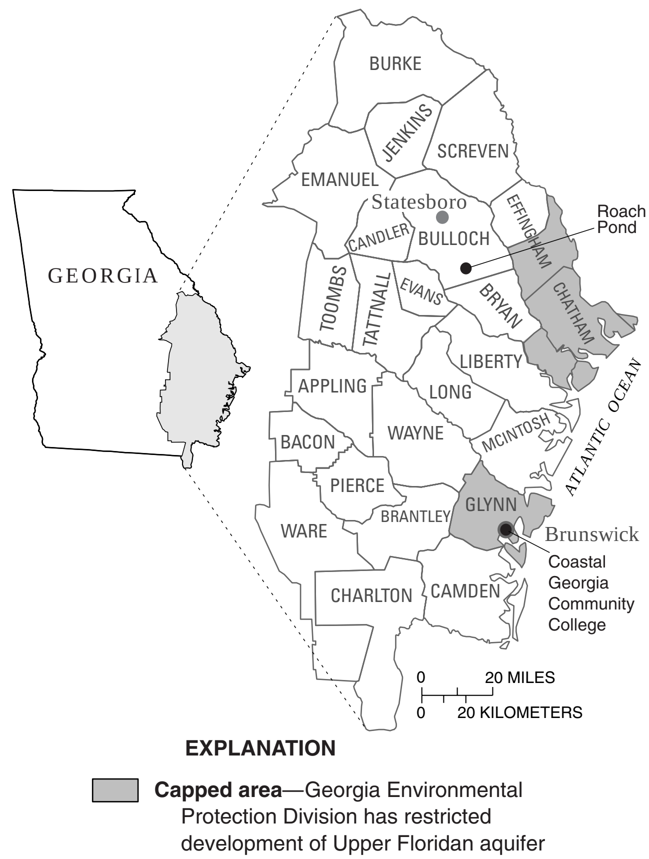


Figure 1. Location of Glynn County and Bulloch County pond study sites.

Approach

Each pond test site is being characterized by constructing test wells, conducting pond bathymetric surveys, and monitoring ground-water levels, pond stage, and climatic conditions. Long-term aquifer tests are being conducted at each pond to estimate ground-water seepage and to evaluate effects on ground-water levels.

Water budgets are being developed at each site to evaluate the annual exchange of water between the surficial aquifer, pond, and atmosphere. Automated weather stations were installed at each site by the University of Georgia, Department of Biological and

Agricultural Engineering, as part of the Georgia Automated Environmental Monitoring Network (**http://www.griffin.peachnet.edu/bae**). Sensors at each weather station measure air temperature, relative humidity, wind speed and direction, net and total solar radiation, barometric pressure, precipitation, and soil temperature at 2-, 4-, and 8-inch depths. From these data, rates of recharge and evaporation are computed using the Penman equation (Winter and Rosenberry, 1995).

GROUND-WATER SEEPAGE

Seepage represents ground water either entering or leaving the pond. When positive, more ground water enters than leaves the pond; when negative, more water leaves than enters the pond. Ground-water seepage can be estimated using the following volumetric relation:

Seepage = Change in stage + Pumping - Precipitation + Evaporation + Transpiration

In a preliminary investigation, Beck (1979) used hydraulic conductivity derived from grain-size analyses of sediments in coastal Georgia to estimate rates of ground-water seepage. Beck (1979) concluded that a yield of 100,000 gallons per day or 69.4 gallons per minute (gal/min) could be obtained from a 15-foot-(ft) deep pond having a 100-ft radius.

Glynn County Study Site

The first study site is a 3-acre pond located on the campus of Coastal Georgia Community College at Brunswick, Ga. (fig. 1). The pond was excavated to about 15 ft below sea level into the upper part of a 50- to 55-ft-thick sequence of quartz sand that is part of the surficial aquifer (fig. 2). A dense, low-permeability clay layer was penetrated at about 40 ft below sea level during drilling of several deep wells. Natural gamma logs from wells located within 0.75 mile of the pond site, indicate that the clay layer occurs at similar altitudes throughout the area.

The sandy surficial aquifer is recharged by rainfall near the pond. Data from 14 test wells completed in the uppermost part of the surficial aquifer indicate that ground-water flow varies seasonally, but generally is eastward toward Cyprus Mill Creek, part of a major estuary system about 2,500 ft east of the pond (fig. 3). Locally, ground water seeps from the pond along the northern, southern, and eastern shores. A bottom-temperature survey of the pond water in August 1999 indicates that cooler ground water seeps into the pond along parts of the western shore. Ground water seeps from the pond along the eastern-southeastern shore, toward the estuary.

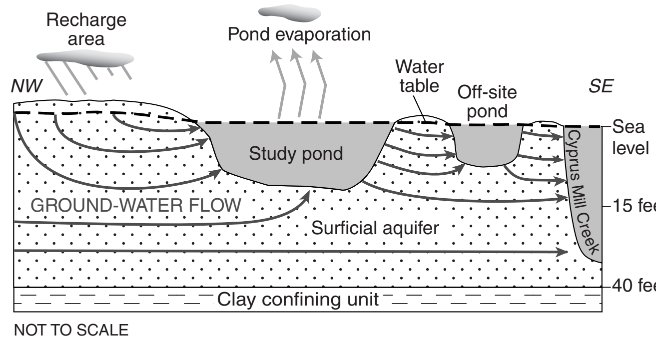
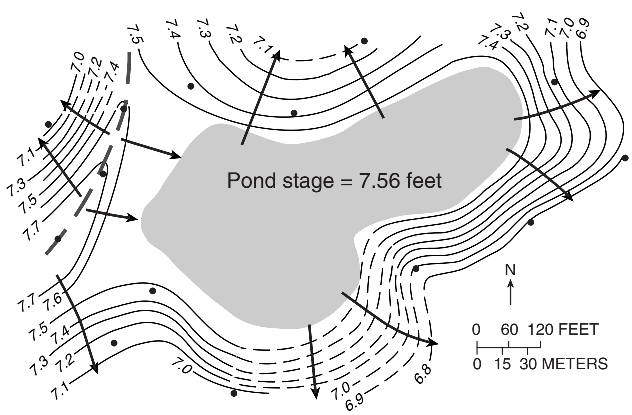


Figure 2. Conceptual model of hydrogeology and pond-aquifer flow at the Glynn County, Georgia, study site.



EXPLANATION

— 7.0 — — **Water-table contour**—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 0.1 foot. Datum is sea level

⟶ **Ground-water flow**

— — **Ground-water divide**

• **Observation well**

Figure 3. Water-table surface of the surficial aquifer at the Glynn County, Georgia, study site, September 19, 1999.

Pond stage and ground-water levels respond rapidly to precipitation events and decline during dry periods when evaporation and transpiration increase. Continuous-recorder data indicate that during October 1999 to May 2000 (immediately prior to a pumping test), pond stage declined about 0.5 ft, and ground-water levels declined about 2 ft.

A bathymetric survey of the pond indicates that the pond depth is about 21 ft at the deepest point, and the bottom of the pond ranges from about 8 ft above sea level to 13 ft below sea level. The volume of water in the pond was calculated using the bathymetric data and the observed range of pond stage. The volume of water in the pond at the highest stage in October 1999 (8.52 ft above sea level) was 17.2 million gallons and decreased to 12.9 million gallons when pond stage was lowest (5.34 ft above sea level) in June 2000.

To estimate rates of ground-water seepage, a long-term pumping test was conducted in the pond during May 1–3, 2000. The water level in the pond was lowered 2 ft during a 33-hour period, pumping at an average rate of 1,000 gal/min. During the same period, there was no precipitation, estimated evaporation was about 10 gal/min, and transpiration was unknown. Thus, changes in pond stage during the pumping test are mainly due to the volume of water removed by pumping and contributed by ground-water seepage. Seepage estimates are limited by the accuracy of evaporation and transpiration estimates, and to pond-volume estimates determined using pond-stage and bathymetric data. Because transpiration is unknown, seepage estimates derived for the pond are lower than actual rates.

Rates of ground-water seepage vary depending on pond stage and related changes in hydraulic gradient and cross-sectional area. Decreasing pond stage results in an increased hydraulic gradient toward the pond and increased rates of seepage to the pond. During the pumping test; however, estimated seepage was about -280 gal/min, indicating water loss. This discrepancy results from errors in pond-volume and evaporation estimates, and from a lack of transpiration data. Following the pumping test, pond stage recovered about 0.1 ft in 25.5 hours, corresponding to a rate of about 90 gal/min, which when combined with the estimated evaporation rate of 10 gal/min, equals a seepage rate of about 100 gal/min. Although this rate compares favorably with the estimated seepage rate reported by Beck (1979) for a 15-ft deep, 100-ft radius pond (69 gal/min), it underestimates the actual seepage because of errors in pond-volume and evaporation estimates and a lack of transpiration data.

Although pond stage showed some recovery following the test in response to rainfall during August and September—as of December 2000, pond stage remained about 0.75 ft below pre-test conditions. Conversely, ground-water levels had recovered to pre-test conditions by early September 2000.

Bulloch County Study Site

The second study site is a 4-acre pond located in southern Bulloch County about 20 miles southeast of Statesboro (fig. 1). The pond was excavated as a borrow pit for road fill material during construction of nearby Interstate 16. The pond was excavated into layers of clay and clayey sand that are underlain by a clayey sand layer at an altitude of about 90 ft above sea level; this clayey sand layer forms the uppermost part of the surficial aquifer (fig. 4). The surficial aquifer is underlain by layers of clay and sandy clay at an altitude of about 60 ft above sea level; these layers act as a semiconfining unit. A bathymetric survey indicates pond depth ranges from about 2 to 6 ft (80 to 86 ft above sea level.

To characterize geologic and hydrologic conditions, nine shallow wells (5 to 16 ft deep) and 7 deep wells (28 to 30 ft deep) were installed. Two of the shallow wells are equipped with recorders to continuously monitor ground-water levels.

The volume of water in the pond was about 4.6 million gallons in October 2000, a period of low precipitation. A continuous weather station was installed to provide climatic data needed to calculate a hydrologic budget. A long-term pumping test is planned for Spring 2001 to provide data needed to estimate rates of ground-water seepage at the pond.

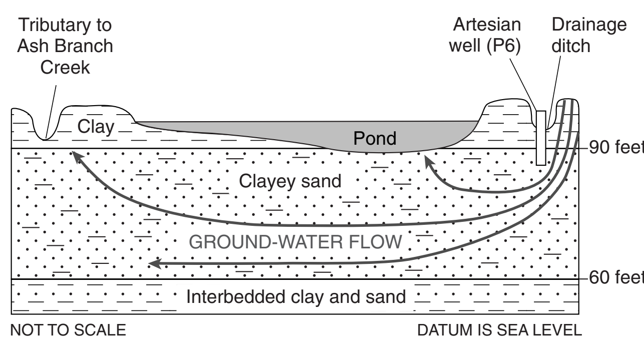
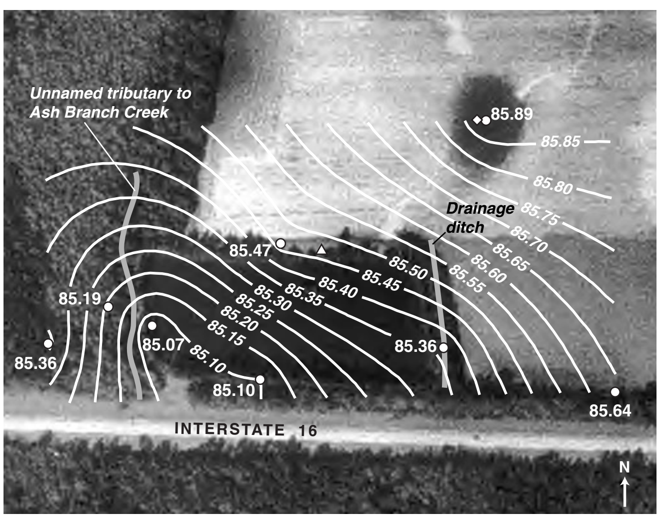


Figure 4. Conceptual model of hydrogeology and pond-aquifer flow at the Bulloch County, Georgia, study site.

The sandy surficial aquifer is recharged by rainfall near the pond. Data from eight shallow test wells indicate that ground-water flow generally is southwestward toward an unnamed intermittent tributary to Ash Branch Creek (fig. 5). Preliminary data indicate that the pond is hydraulically separated from the surficial aquifer over most of its area due to low permeability of the upper soil layer; however, this low permeability layer was breached at the eastern end of the pond. At that location, an excavation cut through the sandy clay layer and into an underlying clayey sand layer of higher permeability resulting in the flooding of, and eventual abandonment of the borrow pit. It appears that most of the water enters the pond in the vicinity of this breach. During the construction of shallow well P-6 (fig. 4), a sand layer was penetrated at a depth of about 9 ft and the water level in the well rose above land surface possibly indicating artesian conditions beneath the pond. The clayey soil apparently acts as a confining or semiconfining unit to the uppermost part of the surficial aquifer in the vicinity of the pond.



Base from U.S. Geological Survey digital orthophoto, Lanier 1:24,000, 1992

0 0.03 0.06 MILE

0 0.03 0.06 KILOMETER

EXPLANATION

—— *85.10* —— **Water-table contour**—Shows altitude at which water level would have stood in tightly cased wells. Contour interval 0.05 foot. Datum is sea level

● **Well**

◆ **Weather station**

▲ **Pond stage**

Figure 5. Water-table surface of the surficial aquifer at the Bulloch County, Georgia, study site, October 19, 2000.

COMPARISON OF HYDROGEOLOGIC CONDITIONS

The Glynn County and Bulloch County seepage pond sites are located in areas of similar topography. Some major differences however, exist in pond area and depth, permeability of the underlying sediments, and conditions under which ground water enters or exits each pond. The Glynn County pond is about 3 acres and has a maximum depth of about 21 ft. Computed pond volume ranges from 17.2 million gallons at maximum stage to 12.9 million gallons at minimum stage. The Bulloch County pond is about 4 acres, but has a maximum depth of only 6 ft. The volume of water in the Bulloch County pond is considerably less than the Glynn County pond, with about 4.6 million gallons in storage during October 2000.

Soil permeability is substantially different at the two sites. At the Glynn County site, the pond is excavated into a highly permeable 50- to 55-ft-thick layer of sand; whereas at the Bulloch County site, the pond is excavated into low-permeability clay throughout most of its extent.

Ground water at the two sites occurs under different conditions. At the Glynn County site, ground water occurs under water-table (unconfined conditions), and thus is highly affected by climatic conditions. Ground water at the Bulloch County site may occur under confined or semi-confined conditions, which may reduce the effects of climatic change on water availability. A long-term pumping test planned for spring of 2001 will provide data needed to further evaluate ground-water conditions at the Bulloch County site.

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USE OF TWO-DIMENSIONAL DIRECT-CURRENT-RESISTIVITY PROFILING TO DETECT FACTURE ZONES IN A CRYSTALLINE ROCK AQUIFER NEAR LAWRENCEVILLE, GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia., p. 772-773.

Abstract. Two-dimensional direct-current resistivity (2D dc-resistivity) profiling was used to detect fracture zones in a crystalline-rock aquifer near Lawrenceville, Georgia. This work—which is a component of a ground-water resource investigation—was conducted by the U.S. Geological Survey in cooperation with the City of Lawrenceville. Profiling using 2D dc-resistivity methods is conducted by laying out an array of electrodes along a straight line and measuring an apparent resistivity. Electrical current is injected into the ground through two current electrodes and the voltage difference is measured at two potential electrodes. A multi-electrode system was used to collect apparent resistivity readings along the linear arrays. A commercially available switching unit was used to automatically select four electrodes along the array; this allowed the collection of several hundred to several thousand measurements along a single profile, depending on the configuration of the array and the number of electrodes used.

Three types of linear arrays were used for profiling. A dipole-dipole and a pole-dipole array appeared to show good horizontal and vertical resolution, whereas a Schlumberger array had poorer resolution, but provided more rapid data acquisition. The pole-dipole had the greatest depth penetration of the three arrays. The 2D dc-resistivity profiles were first conducted at the Rhodes Jordan Wellfield (fig. 1) where subsurface fracture zones have previously been characterized (Chapman and others, 1999). Bedrock resistivity imaging was conducted to a depth of as much as 55-meters (180 feet) using a 4-meter dipole-dipole array and 100 meters (328 feet) using a 4-meter pole-dipole array of 83 electrodes. An electrode spacing of more than 4 meters allows for a greater depth of penetration but with less resolution.

Resistivity profiling was also conducted at a well site where the underlying crystalline-rock aquifer is relatively unfractured. The profile exhibited higher resistivities than those for the Rhodes Jordan Wellfield. Results from the Rhodes-Jordan Wellfield and the unfractured well site provided guidelines that were used to conduct resistivity profiling at other sites being evaluated for ground-water resources in the vicinity of Lawrenceville.

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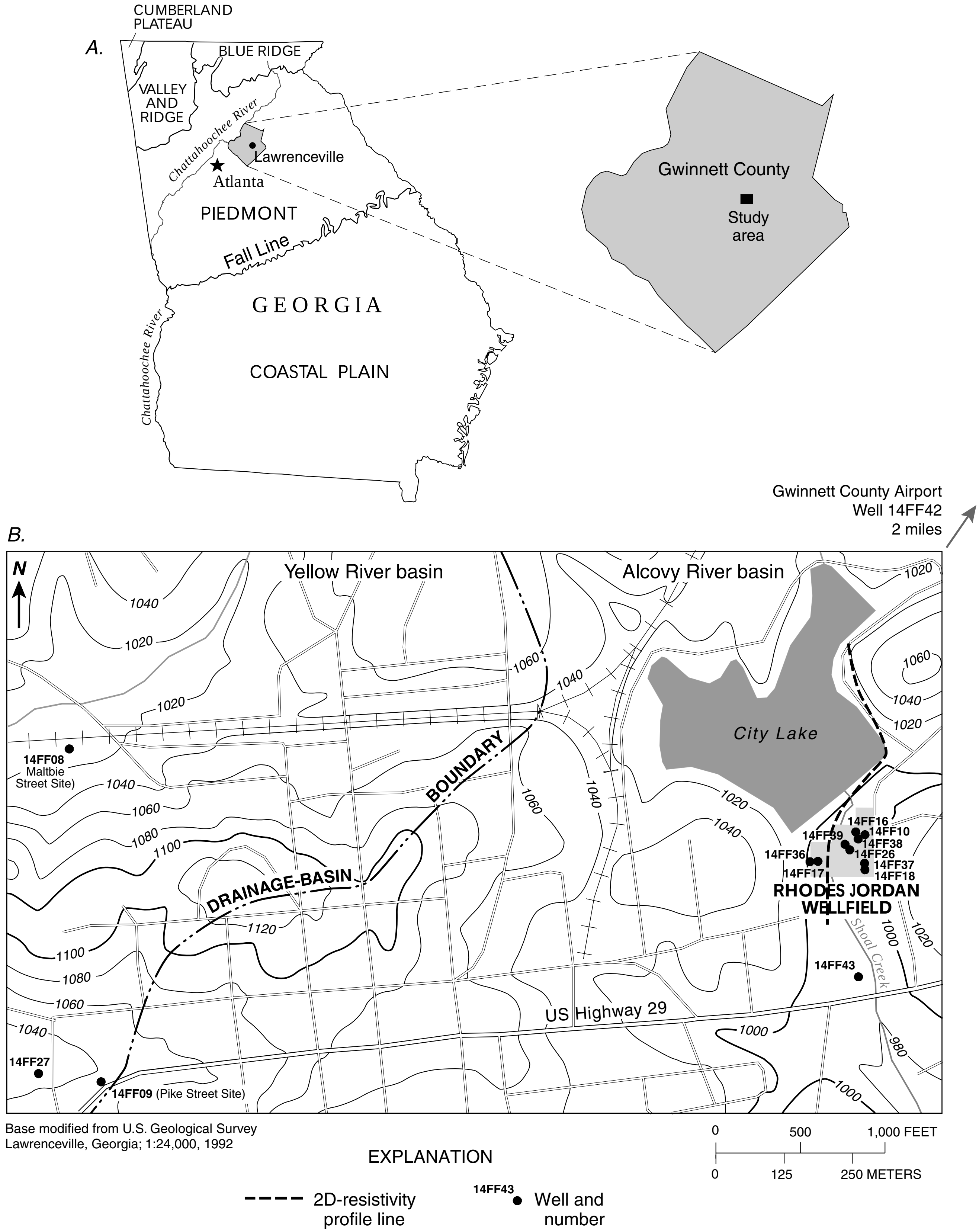

Figure 1. Location of *(A)* the study area in Gwinnett County and physiographic provinces in Georgia, and *(B)* the Rhodes Jordan Wellfield and observation wells in Lawrenceville, Georgia (modified from Chapman and others, 1999).

PUBLIC-SUPPLY WATER USE IN THE METROPOLITAN ATLANTA, GEORGIA AREA, 1995–2000

By Julia L. Fanning

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 782.

Abstract. The Georgia Water-Use Program is a cooperative program of the U.S. Geological Survey and the Georgia Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey. Water-use data on the principal water users in Georgia has been collected and compiled annually since 1978 (including public-supply, industrial, commercial, thermoelectric, and hydroelectric users). Water-use data are stored in a centralized data base known as the Georgia Water-Use Data System (GWUDS).

Monthly water withdrawals for 12 public-supply systems in the Metropolitan Atlanta area, including the City of Atlanta, were compared for the period January 1995 to September 2000. The 1995-2000 period was selected to compare patterns of water use prior to and during drought conditions. Graphical representation of these data depict seasonal and long-term patterns at the public-supply systems during the 6-year period. Eleven of twelve public-supply systems withdraw water from surface-water sources and the remaining system withdraws water from ground-water sources. At most of the systems, patterns in water withdrawal were consistent in 1995 and 1996, with elevated withdrawals during the warmer months (June through August). However, each system showed a steady increase in withdrawals each year beginning in 1998, with continued increases through the height of the drought in September 2000.

SUMMARY OF STREAMFLOW CONDITIONS FOR CALENDAR YEAR 2000 IN GEORGIA

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REFERENCE: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, *editor*, Institute of Ecology, The University of Georgia, Athens, Georgia, p. 783-786.

Abstract. Streamflow conditions for calendar year 2000 in Georgia were monitored at 15 U.S. Geological Survey (USGS) streamflow gaging stations throughout the State as part of the drought-monitoring network. These gaging stations have 30 or more years of record and are useful as drought-index stations (fig. 1, table 1). Data used in these comparisons for the year 2000 are considered “Provisional Data” and subject to change.

During January–April, monthly mean streamflow continued to decline Statewide from the previous year. Many streams were approaching or dropping below long-term monthly mean flows. Streamflow in central and southern Georgia were the lowest levels in the State.

In May, most streams in central and southern Georgia were well below long-term normal (average) monthly flows. Monthly streamflow in the central and southern parts of the State ranged from about 7-40 percent of normal, with the lowest streamflow occurring in south-central and southwestern Georgia. Streamflow gaging stations in the northern part of the State had flows ranging from about 50-65 percent of normal. During May 2000, 6 of the 15-index streamflow stations recorded new minimum monthly flows of record.

- Flint River near Culloden—375 cubic feet per second (ft^3/s);
- Flint River near Montezuma—840 ft^3/s;
- Flint River at Oakfield—1,189 ft^3/s;
- Flint River near Newton—1,934 ft^3/s;
- Ichawaynochaway Creek near Milford—124 ft^3/s;
- Spring Creek near Iron City—25 ft^3/s.

Ichawaynochaway Creek reached an all time minimum daily flow of 38 ft^3/s on May 31. The previous minimum flow was 48 ft^3/s in July 1986.

During June, streamflow continued to decline statewide. Streamflow stations in the northern part of the State showed some decline from the previous monthly flows (50-65 percent of normal), and ranged from about 40-45 percent of normal. Monthly streamflow in the central and southern parts of the State also continued to decline from the previous monthly flows (7-40 percent of normal), and ranged from about 1-35 percent of normal. During June, the lowest flows were still occurring in south–central and southwestern Georgia. For the month, 8 of 15-index streamflow stations recorded new minimum monthly flows of record.

- Flint River near Culloden—147 ft^3/s;
- Flint River near Montezuma—509 ft^3/s;
- Flint River at Oakfield—697 ft^3/s;
- Flint River near Newton—1,211 ft^3/s;
- Ichawaynochaway Creek near Milford—42 ft^3/s;
- Spring Creek near Iron City—1.8 ft^3/s;
- Altamaha River near Doctortown—1,940 ft^3/s;
- Upatoi Creek near Columbus—89 ft^3/s.

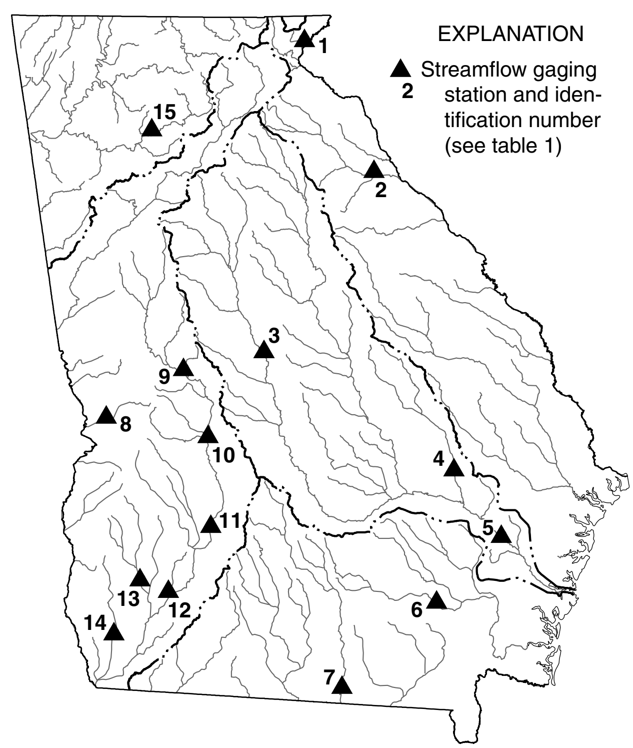

Figure 1. Location of drought-monitoring gaging stations.

Table 1. Minimum daily discharges for period of record at drought monitoring gaging stations
[—, no new minimum; ft^3/s, cubic feet per second; na, no applicable[

Map number	Station name	Minimum daily discharge			
		Previous minimum (ft^3/s)	Year	New minimum in 2000 (ft^3/s)	Month
	Savannah River basin				
1	Chattooga River near Clayton	88	1954	—	na
2	Broad River near Bell	96	1986	—	na
	Altamaha River basin				
3	Ocmulgee River at Macon	128	1954	—	na
4	Ohoopee River near Reidsville	19	1954	—	na
5	Altamaha River at Doctortown	1,430	1954	1,410	August
	Satilla/Alapaha River basins				
6	Satilla River near Waycross	5.5	1990	—	na
7	Alapaha River near Statenville	17	1954	—	na
	Chattahoochee/Flint River basins				
8	Upatoi Creek near Columbus	74	1986	66	July
9	Flint River near Culloden	68	1999	39	July
10	Flint River near Montezuma	448	1986	408	July
11	Flint River at Oakfield	512	1999	—	na
12	Flint River near Newton	832	1999	—	na
13	Ichawaynochaway Creek near Milford	48	1986	6.6	August
14	Spring Creek near Iron City	5.1	1986	0	August
	Coosa River basin				
15	Etowah River near Canton	122	1986	—	na

Ichawaynochaway Creek near Milford and Spring Creek near Iron City reached their all time minimum daily flow of 16 ft^3/s and 0.6 ft^3/s, respectively. The previous minimum daily flow for Ichawaynochaway Creek of 38 ft^3/s occurred at the end of the previous month (May 2000). Prior to the 2000 drought, the previous minimum daily flows for the period of record, for Ichawaynochaway and Spring Creek were 48 ft^3/s and 5.1 ft^3/s, respectively, both of which occurred during the 1986 drought.

During July, streamflow stations in the northern part of the State continued to decline from the previous monthly flows (40-45 percent of normal), and ranged from about 30-35 percent of normal. Monthly streamflow in the central and southern parts of the State also continued to slowly decline from the previous monthly flows (1-35 percent of normal), and ranged from about less than 1-30 percent of normal. The lowest flows were still occurring in south-central and southwestern Georgia. For the month, 5- of the 15-index streamflow stations recorded new minimum monthly flows of record.

- Flint River near Culloden—85 ft^3/s;
- Flint River near Montezuma—477 ft^3/s;
- Flint River at Oakfield—688 ft^3/s;
- Spring Creek near Iron City—0.8 ft^3/s;
- Altamaha River near Doctortown—1,736 ft^3/s.

Three of the 15-index streamflow stations recorded an all time minimum daily flow.

- Flint River near Culloden—39 ft^3/s (previous minimum – 87 ft3/s in 1986);
- Spring Creek near Iron City—0.17 ft^3/s (previous minimum – 0.8 ft3/s in 2000);
- Upatoi Creek near Columbus—66 ft^3/s (previous minimum—74 ft^3/s in 1986).

During August, the monthly declines in streamflow slowed, and in some parts of north and central Georgia, some minor increases in streamflow occurred. Scattered rainfall across most of the State in the first and last weeks of the month helped to sustain streamflow in many areas. Streamflow gaging stations in the northern part of the State showed small increases from the previous monthly flows (30-35 percent of normal), and ranged from about 35-40 percent of normal. Monthly streamflow in the central also increased form the previous monthly flows (15-20 percent of normal), and ranged from about 25-40 percent of normal. Monthly streamflow in the southern part of the State remained about the same as the previous monthly flows (less than 1-30 percent of normal), with only minor increases at a few streamflow stations. The lowest flows were still occurring southwestern Georgia. For the month, 4- of the 16-index streamflow stations recorded new minimum monthly flows of record.

- Flint River near Montezuma—506 ft^3/s;
- Ichawaynochaway Creek near Milford—87 ft^3/s;
- Spring Creek near Iron City—0.14 ft^3/s;
- Altamaha River near Doctortown—1,773 ft^3/s.

Two of the 15-index streamflow stations recorded an all time minimum daily flow.

- Spring Creek near Iron City— 0.0 ft^3/s (previous minimum—0.17 ft^3/s in 2000);
- Ichawaynochaway Creek near Milford—6.6 ft^3/s (previous minimum – 20 ft^3/s in 2000).

During September, the previous monthly declines in streamflow were reversed, with significant increases in streamflow occurring throughout the State. Some streams had above normal monthly flows in parts of central and southern Georgia. Rainfall amounts as much as about 3.5 inches were reported across several areas of the State and in September helped to increase or sustain streamflow in most areas. Streamflow stations in the northern part of the State showed an overall increase from the previous monthly flows (35-40 percent of normal), and ranged from about 40-95 percent of normal. Monthly streamflow in central Georgia also increased from the previous monthly flows (25-40 percent of normal), and ranged from about 55-120 percent of normal. Monthly streamflow in the southern part of the State increased from the previous monthly flows (less than 1-30 percent of normal), and ranged from about less than 1-240 percent of normal. The lowest flows were still occurring in southwestern Georgia. For the month, only 1- of the 15-index-streamflow stations recorded a new minimum monthly flow of record.

- Spring Creek near Iron City—0.08 ft^3/s.

One of the 15 index streamflow stations recorded an all time minimum daily flow that previously occurred in August 2000.

- Spring Creek near Iron City—0.0 ft^3/s.

During October, the previous monthly increases in streamflow were reversed, with significant decreases in streamflow occurring throughout most of the State. No significant amounts of rainfall occurred across the State in October, and most streamflow fell below long-term normal monthly flows throughout the State. Streamflow stations in the northern part of the State showed a drastic decrease from the previous monthly flows (40-95 percent of normal), and ranged from about 25-30 percent of normal. Monthly streamflow in central Georgia also decreased from the previous monthly flows (55-120 percent of normal), and ranged from about 25-55 percent of normal. Monthly streamflow in the southern part of the State decreased from the previous month's flows (less than 1-240 percent of normal), and ranged from about less than 1-70 percent of normal. Overall, the lowest flows were still occurring in southwestern Georgia, with dramatic declines across central and northern parts of the State. For the month, only 1- of the 15-index streamflow stations recorded new minimum monthly flows of record.

- Spring Creek near Iron City—1.1 ft^3/s.

None of the 15-index streamflow stations recorded an all time minimum daily flow, but several stations were approaching the period of record minimum flows.

During November, some areas of the State received as much as about 3 inches of rainfall, but most streams still remained below long-term normal monthly flows throughout the State. Streamflow stations in the northern part of the State showed an increase from the previous monthly flows (25-30 percent), and ranged from about 50-75 percent of normal. Monthly streamflow in central Georgia also increased from the previous monthly flows (25-55 percent of normal), and ranged from about 50-60 percent of normal. Monthly streamflow in the southern part of the State showed some increases, but remained about the same as the previous monthly flows (less than 1-70 percent of normal), and ranged from about 5-75 percent of normal. Overall, the lowest flows were still occurring in southwestern Georgia, with some continued declines across the southeastern part of the State.

For the month, only 1- of the 15-index streamflow stations recorded a new minimum monthly flow of record.

- Spring Creek near Iron City—10 ft^3/s.

None of the 15-index streamflow stations recorded an all time minimum daily flow because baseflow conditions across the State began to stabilize.

During December, additional amounts of rainfall as much as about 2.5 inches occurred across parts of the State, but most streams still remained below long-term normal monthly flows. Streamflow stations in the northern part of the State showed minor decreases from the previous monthly flows (50-75 percent of normal), and ranged from about 35-50 percent of normal. Monthly streamflow in central Georgia also showed an overall decrease from the previous monthly flows (50-60 percent of normal), and ranged from about 35-65 percent of normal. Monthly streamflow in the southern part of the State showed some increases, but remained about the same as the previous monthly flows (5-75 percent of normal), and ranged from about 15-50 percent of normal. Overall, the lowest flows were still occurring in southwestern Georgia, with some continued declines across the southeastern part of the State. During December, none of the 15-index streamflow stations recorded new minimum monthly flows of record or an all time minimum daily flow. December 2000 was the first time since May 2000 that no record low-flows were recorded at any of the index sites. It appears that base-flow conditions across most of the State had begun to stabilize due to some increased precipitation and no extensive irrigation in progress.