Ground-Water Flow and Water Quality in the Upper Floridan Aquifer, Southwestern Albany Area, Georgia, 1998–2001

By Debbie Warner and Stephen J. Lawrence

Prepared in cooperation with the
Albany Water, Gas, and Light Commission

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
milliliters (mL)	3.53×10^{-5}	cubic foot (ft^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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

$$°F = (1.8 \times °C)+32$$

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

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

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NAVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Historical data collected and stored as North American Datum 1927 have been converted to NAD 83 for this publication.

Abbreviations

Acid-neutralizing capacity	ANC
Albany Water, Gas, and Light Commission	WGL
Carbon dioxide.	CO_2
Chlorofluorocarbons.	CFC
Communication	commun.
Concentration of nitrogen 15 isotope	$\delta^{15}N$
Concentration of oxygen 18 isotope	$\delta^{18}O$
Confined animal feeding operations	CAFPS
Direct coupled plasma optical emission spectrometry	DCP
Dissolved oxygen	DO
Dougherty County Health Department	DCHD
End-member mixing analysis	EMMA
Georgia Environmental Protection Division	GaEPD
Gypsum	$CaSO_4–H_2O$
Locally weighted scatter-plot smoothing	LOWESS
Mean relative percent difference	MRPD
Micrometer	µm
National Atmospheric Deposition Program	NADP
Nitrate	NO_3
Nitric acid.	HNO_3
Nitrogen	N
Over-the-counter	OTC
Oxidation reduction	redox
Panola Mountain Research Laboratory`	PMRL
Primary maximum contaminant level	PMCL
Quality control	QC
Relative correlation	rho
Relative percent difference	RPD
Secondary maximum contaminant level.	SMCL
Specific conductance	SC
Standard units	SU
The University of Georgia	UGA
U.S. Geological Survey.	USGS
U.S. Environmental Protection Agency	USEPA

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Abstract

During 1997, the Dougherty County Health Department sampled more than 700 wells completed in the Upper Floridan aquifer in Dougherty County, Georgia, and determined that nitrate as nitrogen (hereinafter called nitrate) concentrations were above 10 milligrams per liter (mg/L) in 12 percent of the wells. Ten mg/L is the Georgia primary drinking-water standard. The ground-water flow system is complex and poorly understood in this predominantly agricultural area. Therefore, the U.S. Geological Survey (USGS)—in cooperation with Albany Water, Gas and Light Commission—conducted a study to better define ground-water flow and water quality in the Upper Florida aquifer in the southwestern Albany area, Georgia.

Ground-water levels were measured in the southwestern Albany area, Georgia, during May 1998 and March 1999 (spring), and October 1998 and September 1999 (fall). Ground-water levels measured in 75 wells open only to the Upper Floridan aquifer were used to construct potentiometric-surface maps for those four time periods. These maps show that ground water generally flows from northwest to southeast at gradients ranging from about 2 to greater than 10 feet per mile. During spring and fall 1998, ground-water levels were high and mounding of the potentiometric surface occurred in the central part of the study area, indicating a local recharge area. Water levels declined from December through February, and by March 1999 the mound in the potentiometric surface had dissipated.

Of the 75 wells in the potentiometric network, 24 were selected for a water-quality network. These 24 wells and 1 spring were sampled during fall 1998 and spring 1999. Samples were analyzed for major chemical constituents, selected minor constituents, selected nutrients, and chlorofluorocarbons (CFC). Water-quality field measurements— such as water temperature, pH, specific conductance (SC), and dissolved oxygen (DO)—were taken at each well. During August 2000, a ground-water sample was collected and analyzed for selected sewage tracers. During March 2001, water samples from selected wells were analyzed for nitrogen and oxygen isotopes. Age-dating analysis using CFCs yield apparent ground-water ages that range from modern to greater than 50 years.

The chemistry of ground water in the Upper Floridan aquifer varies widely throughout the southwestern Albany area, Georgia, and in general represents the chemistry commonly found in recharge areas. From fall 1998 through spring 1999, median values of pH, SC, and DO concentration were 7.6 standard units, 266 microsiemens per centimeter at 25 degrees Celsius (µS/cm), and 5.6 mg/L, respectively. The SC is highest (350–400 µS/cm) where mounding of the potentiometric surface exists. Specific DO concentrations indicate an area of anoxic ground water in the north-central part of the study area.

Water samples indicate that ground water in the study area is dominated by calcium and bicarbonate ions, which is consistent with the limestone lithology of the aquifer. About 25 percent of the samples contained sodium and chloride at ratios similar to those in rainfall, indicating a close proximity to recharge areas. The remaining water samples, however, had sodium-chloride ratios less than 0.90, the ratio in Tift County, Georgia, rainfall samples. These low sodium-chloride ratios are consistent with chloride enrichment. Minor constituent and nutrient concentrations typically are below laboratory reporting limits; however, the maximum nitrate concentration measured during the study period was 12.2 mg/L, and the median concentration for the study period was 3.0 mg/L. Samples collected during 1999 had a higher median nitrate concentration than the 1998 samples. Regression analysis indicated that nitrate concentrations are related exponentially to chloride concentrations.

Four distinct groups of ground-water-quality samples, plus four unique samples, were identified using cluster analysis. Water-quality groups I and II occur in the north-central part of the study area and generally are chemically similar. These groups represent an area of anoxic ground water where reducing conditions prevail. Water-quality group III occurs in the central part of the study area and represents a mixing zone where three chemically different ground waters merge. Water-quality group IV occurs in the south-central part of the study area, has nitrate concentrations less than 2.5 mg/L, and probably represents background conditions of the Upper Floridan aquifer in this area. The four unique samples collected from two wells represent ground water with elevated nitrate concentrations. Ground water drawn from one well possibly is contaminated by the application of biosolids in fields upgradient from the study area. Ground water from the other well apparently is influenced by agricultural fertilizer.

Introduction

During 1997, the Dougherty County Health Department (DCHD) collected water samples from a well in the southwestern Albany area, Georgia, that supplies drinking water to a private school. These samples contained concentrations of nitrate greater than 10 milligrams per liter (mg/ L), which is the primary maximum contaminant level (PMCL) for public drinking-water supplies (Georgia Environmental Protection Division [GaEPD], 2003; U.S. Environmental Protection Agency [USEPA], 2000a). Prompted by the high nitrate concentration found in the school well, the DCHD expanded its sampling effort during March 1997 with a goal to collect water samples from more than 700 public and residential wells southwest of Albany. Only nitrate concentrations were analyzed in those samples. The DCHD sampling efforts established the spatial extent of nitrate concentrations and identified elevated nitrate concentrations in many individual wells. Moreover, water samples from 12 percent of the more than 700 wells contained nitrate concentrations above the PMCL (Susan Reyher, Dougherty County Health Department, oral commun., 1999). These wells each tap the Upper Floridan aquifer and are considered contaminated with respect to nitrate.

The presence of elevated nitrate concentrations in the Upper Floridan aquifer is of concern to water providers because the aquifer is the source of drinking water to many urban and rural areas in southern Georgia. Furthermore, the Upper Floridan aquifer supplies water for nearly all irrigation in southern Georgia. Because of the rapid movement of ground water within the aquifer, any potential contamination of the aquifer could disperse widely and impact downgradient water users. In the Upper Floridan aquifer, rapid ground-water flow is facilitated by numerous cavernous zones within the porous limestone that constitutes the aquifer. Because of these cavernous zones, the ground-water flow is complex and not completely understood. Moreover, the complexity of ground-water flow contributes to the difficulty in analyzing and describing the water quality and movement of mobile compounds, such as nitrate, in the aquifer.

The U.S. Geological Survey (USGS) conducted the study described herein in cooperation with the Albany Water, Gas, and Light Commission (WGL) to better define the flow system and possible sources of elevated nitrate in the Upper Floridan aquifer. Results will provide WGL with information necessary to assess the nitrate concentrations in the vicinity of its newly constructed well field. This well field uses the Upper Floridan aquifer to augment the supply of public drinking water for the city of Albany, which previously utilized only deeper aquifers.

Purpose and Scope

This report describes the ground-water flow and ground-water quality and chemistry in the Upper Floridan aquifer in the southwestern Albany area, Georgia. The report: (1) identifies ground-water flow directions and gradients in the Upper Floridan aquifer; (2) discusses how quickly ground-water levels respond to rainfall; (3) identifies recharge areas and apparent ground-water ages for the Upper Floridan aquifer; and (4) describes ground-water quality and chemistry, particularly as they relate to nitrate concentrations.

Water levels were measured in 72 wells during May 1998, in 67 wells during October 1998, and in 71 wells during March 1999. These water levels were used to determine the direction and gradients of ground-water flow under different hydrologic conditions in the study area. Continuous water-level data from six wells and continuous river stage in the Flint River at Albany were collected during the study. These data were compared to precipitation records at Albany, Georgia, to determine whether a hydrologic connection exists between the Upper Floridan aquifer and the Flint River. During September 1998, water samples were collected from 24 wells, 1 spring, and 1 pond and analyzed for major and minor constituents and selected nutrients. Water samples for 22 of the 24 wells were analyzed for chlorofluorocarbons (CFCs) to estimate the apparent year of recharge. During March 1999, water samples were collected from all but one of the locations sampled during September 1998 and analyzed for major and minor constituents and selected nutrients. Selected sewage tracers were analyzed in one sample collected during August 2000. Isotopic concentrations of nitrogen-15 ($\delta^{15}N$) and oxygen-18 ($\delta^{18}O$) were analyzed in water samples collected from six wells during March 2001.

Description of Study Area

The study area encompasses approximately 64 square miles (mi^2) in the Dougherty Plain district of the Coastal Plain physiographic province (Clark and Zisa, 1976) in Dougherty County, southwest of Albany, Georgia (fig. 1). Topography is karstic and relatively flat; altitudes at land surface range from about 160 to 200 feet (ft) above NGVD 29. Surface runoff is minimal because most of the drainage is internal. After heavy rains from Tropical Storm Alberto during July 1994 caused substantial flooding throughout the region, numerous sinkholes developed in the study area. Numerous older sinkholes are identified as depressions on topographic maps, and several of these contain water on a seasonal basis. The major streams are the Flint River near the eastern boundary of the study area and Cooleewahee Creek, a tributary to the Flint River, located near the western boundary of the study area. Streamflow within Cooleewahee Creek is impeded by a large wetland that may recharge the Upper Floridan aquifer.

The primary land use is agricultural and includes cropland, pastures, orchards, and nurseries (fig. 1). The croplands consist mainly of row crops, pastures, and pecan orchards. Residential areas are located primarily within the city limits of Albany and in the central part of the study area. Municipal sewer systems do not extend beyond the Albany city limits; thus, residences outside of the city limits typically have individual septic systems. The Albany airport, a few light industries, and commercial areas are present in the northern part of the study area.

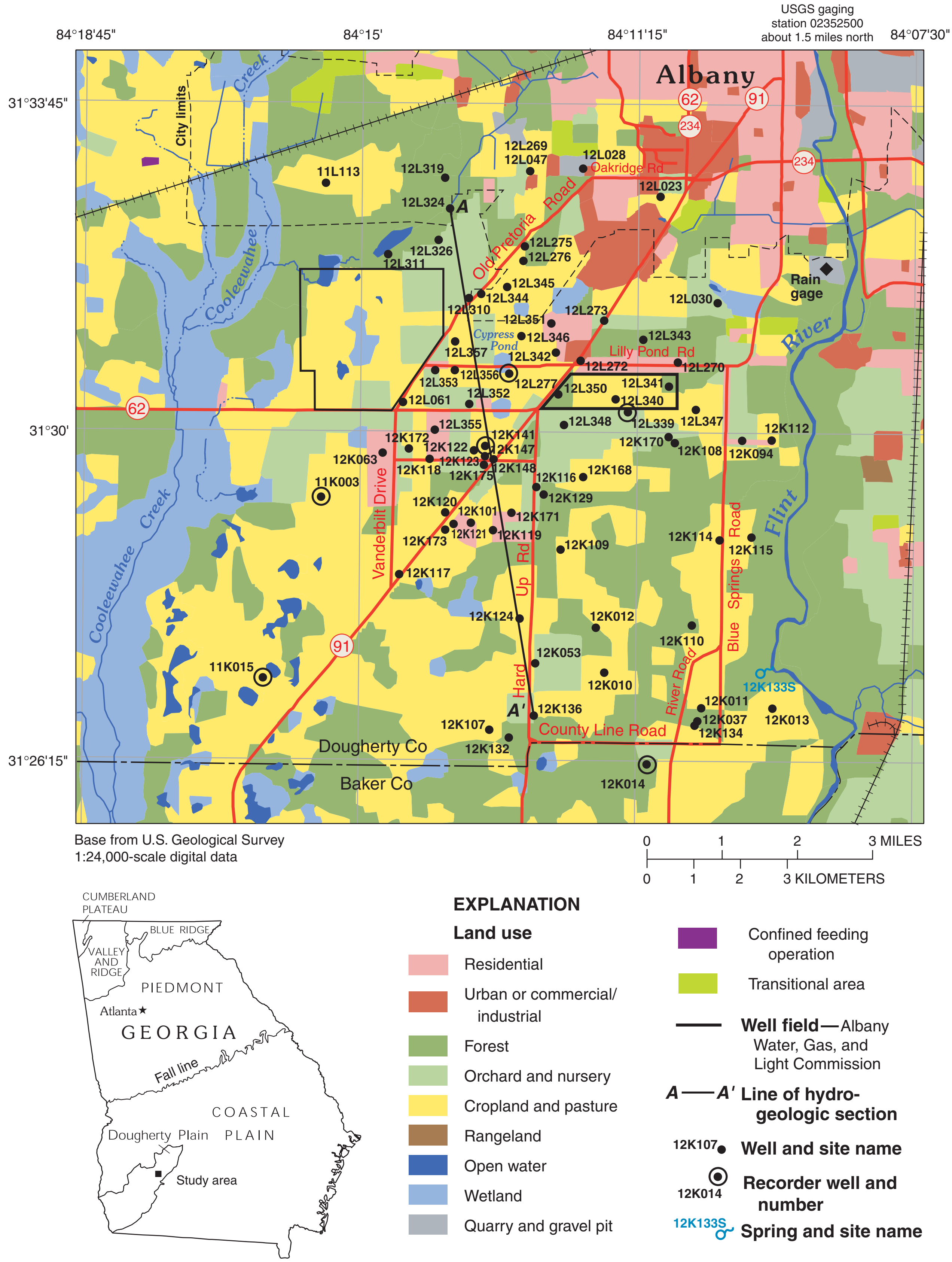


Figure 1. Study area, location of wells used in the study, and land-use delineation in southwestern Albany area, Georgia, 1998–2001.

Previous Investigations

Numerous hydrogeologic investigations have been conducted on the Upper Floridan aquifer in Dougherty County and the Albany, Georgia, area. Wait (1960) described a sampling program to monitor the spatial and temporal water quality of various aquifers in southwestern Georgia, including the Upper Floridan aquifer in the Dougherty Plain. Wait (1963) provided information on the depth, thickness, areal extent, water-bearing properties, and the chemical quality of the water in the principal aquifers in Dougherty County; that report also included a description of the Ocala Limestone, water-level fluctuations, and the potentiometric surface of the Upper Floridan aquifer. Mitchell (1981) described basic climatologic, geologic and hydrologic data—such as specific capacity, transmissivity, and the storage coefficient—for the Upper Floridan aquifer in and adjacent to the Dougherty Plain, including the Albany area. Hicks and others (1981) identified the ground-water development potential and included hydrogeologic, potentiometric-surface, and water-quality data for the Upper Floridan aquifer in the Albany area. Using aquifer-test results, Hayes and others (1983) described the hydraulic properties of the Upper Floridan aquifer and overburden in the Dougherty Plain area. Hicks and others (1987) evaluated the development potential of the Upper Floridan aquifer and identified areas near Albany, Georgia, having the greatest potential for ground-water development; that report delineated the hydrogeology and assessed the ground-water quality in the Upper Floridan aquifer near Albany and concluded that the ground water is dominated by calcium and bicarbonate ions and can be considered “hard” water. Bush and Johnston (1988) described ground-water hydraulics, regional flow direction, and development effects for the entire Floridan aquifer system; several sets of aquifer-test data also are included in that report.

More recent studies focus on the ground-water flow and hydrogeology of the Upper Floridan aquifer in the Albany area. Torak and others (1993) described a ground-water flow model for the Upper Floridan aquifer and reported values of transmissivity and hydraulic conductivity for the lower water-bearing zone in the Upper Floridan aquifer, southwest of Albany. Warner (1997) described the hydrogeology of the Upper Floridan aquifer southwest of Albany, identified cause-and-effect relations between the fluctuations in Flint River stages and ground-water levels, and presented the results of an aquifer test. Stewart and others (1999) depicted the hydrogeologic framework, ground-water quality, and ground-water age in the Upper Floridan aquifer west of Albany.

Several studies described the ground-water quality and geochemistry in the Albany area. Sprinkle (1989) explained the geochemistry of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama; and also summarized the available information on water quality in the Floridan aquifer system and described the principal processes that produce the water chemistry. That report also presented results of mass-transfer modeling for major chemical constituents in the Upper Floridan aquifer.

Since the determination of high nitrate concentrations in domestic wells tapping the Upper Floridan aquifer near Albany, several studies have been conducted in an attempt to identify the source or sources of elevated nitrate concentrations. These studies are described in the Phase III investigation by the GaEPD (1999) and include:

- The delineation of a nitrate plume during a Phase I investigation by GaEPD and the DCHD;
- Identification of several potential nitrate sources in an area northwest of well 12L061 in the GaEPD Phase II investigation;
- Hydrogeologic investigation by a private firm evaluating the impact of biosolid applications on the ground-water quality beneath an area northwest of well 12L061;
- Investigation of abandoned feedlots to assess their impact on nitrate concentrations in Upper Floridan aquifer ground water in the Albany area by The University of Georgia (UGA), Department of Agriculture (1997–98); and
- Source investigation using the isotopic composition of dissolved nitrate in ground water in and downgradient of an area northwest of well 12L061 (UGA and DCHD).

During 2002, an extensive compilation was published for water-quality data collected in southwest Georgia from 1951 to 1999. This report is available on CD–ROM (Warner and others, 2002).

Acknowledgments

The authors thank the many individuals who provided data and information that contributed to the successful completion of this study. Special thanks to Mr. Lemuel Edwards, General Manager, and Mr. Keith Goodin, Assistant General Manager of Operations, of WGL for their support and assistance. Appreciation also is extended to the many cordial landowners who allowed access to their properties for data collection. We also wish to thank the DCHD, including Susan Reyher for providing nitrate data and Carolyn Wood for providing construction records for wells used in the study.

Methods of Investigation

Several methods were used to investigate the hydrology and water chemistry of the Upper Floridan aquifer in the southwestern Albany area. The hydrologic methods included well inventories, measurements of ground-water levels, construction of potentiometric-surface maps, age dating of ground-water samples using CFCs, collection and subsequent chemical analysis of ground-water samples using statistical methods, and analysis of isotopic concentrations of ^{15}N and ^{18}O.

Well and Spring Naming System

In this report, wells and springs are numbered using a system based on USGS 7½-minute topographic quadrangle maps. Each 7½-minute map in Georgia has been assigned a number and letter designation beginning at the southwestern corner of the State. Numbers increase eastward through 39; letters advance northward through "Z," then double-letter designations "AA" through "PP" are used. The letters "I," "O," "II," and "OO" are not used. Wells and springs inventoried in each quadrangle are numbered sequentially beginning with "1." Thus, the 123rd well inventoried in the Baconton North quadrangle (designated 12K) in Dougherty County is designated as well 12K123.

Well Inventory and Measurement of Ground-Water Levels

Since 1977, the USGS and various Dougherty County agencies have cooperated on ground-water monitoring programs within the county. The results of several of these studies—for example, Hicks and others, 1987; and Stewart and others, 1999—initially were used to establish the water-level and water-quality network for this study. The DCHD provided locations and construction records for wells in parts of the study area where additional data were needed. Using this information, the USGS inventoried existing domestic wells to identify those that were suitable for water-level monitoring and the collection of water-quality samples. Suitable wells were identified as those completed in the Upper Floridan aquifer that owner's granted permission for sampling and could be sampled without altering the well. The location of the well was determined using a global positioning system to establish latitude and longitude coordinates. The well was plotted on a 7½-minute USGS topographic map and assigned a number according to the USGS numbering system. With the exception of seven wells that were surveyed, the land-surface altitude at the well was estimated from a USGS topographic map. Comparison of the surveyed altitudes to altitudes estimated from the map indicates that the estimated elevations have an error of +/– 3 ft. As a result of the inventory, the well network used in the study includes 76 domestic, irrigation, and observation wells, and 1 spring (fig. 1; table 1).

Water levels were measured in 72 wells during May 1998, in 67 wells during October 1998, and in 72 wells during March 1999. Continuous water levels were recorded in wells 11K003, 11K015, 12K014, 12K141, 12L339, and 12L277 (fig. 1). These data were used to construct maps of the generalized potentiometric surface within the study area. The maps were then used to estimate ground-water flow directions and ground-water gradients of the Upper Floridan aquifer during different hydrologic conditions.

Geologic and gamma-ray logs were used to construct hydrogeologic section *A–A′* and a contour map showing the altitude of the top of the Upper Floridan aquifer (figs. 2 and 3, respectively). Geologic and gamma-ray logs (where available) were used to determine the top and bottom of the Upper Floridan aquifer and the position of the middle unit (fig. 2).

Collection and Chemical Analysis of Water Samples

During 1998 and 1999, 49 water samples were collected from 24 wells and 1 spring in the monitoring network. These samples were analyzed for major and minor constituents, and selected nutrients at the USGS Panola Mountain Research Laboratory (PMRL) in Atlanta, Georgia. Prior to sample collection, water temperature, pH, specific conductance (SC), and dissolved oxygen (DO) were measured at each well. Replicate samples and an equipment blank were collected for quality-control (QC) purposes. During 2001, water samples from six wells were collected and analyzed for $\delta^{15}N$ and $\delta^{18}O$ at the University of Waterloo, Ontario, Canada.

Field measurements of water temperature, pH, SC, and DO were recorded at all sampled wells using a multiparameter sonde in a flow-through chamber. The flow-through chamber, which is closed to ambient air, prevents the exchange of carbon dioxide (CO_2) and oxygen between the collected water and the atmosphere. The loss of CO_2 from or the gain of oxygen to ground water during field measurements can cause substantial changes in the pH, SC, and DO values—values not typical of water in the aquifer. Inaccurate field measurements can affect the interpretation of water-quality constituents, especially those that are subject to geochemical or biochemical processes.

At domestic wells, the flow-through chamber was connected by Teflon® tubing to a spigot located between the well and holding tank. At observation wells, water was pumped using a stainless-steel, positive-displacement submersible pump. Wells were pumped until a minimum of three casing volumes were removed and field-measured properties became stable (Wilde and others, 1998). All wells were pumped for at least 30 minutes. Water samples were collected into clean polyethylene bottles, packed in ice, and transported to the USGS PMRL in Atlanta, Georgia, for analysis. All samples were analyzed within 14 days of collection.

QC samples are collected routinely to ensure the integrity of water-quality samples. The QC samples used in this study are replicate ground-water samples and equipment blanks. Replicate samples consist of two or more sets of samples collected concurrently or taken from the same composite of water such that both samples are assumed to have identical chemical compositions. Replicate samples are collected to determine the consistency and precision of the laboratory analyses. The other QC sample used in the current study, the equipment blank, identifies the potential for sample contamination from the equipment used to collect a water sample. Contamination from the equipment may arise from inadequate cleaning or from the material or design used in equipment construction. The blank is collected by passing a volume of deionized water through the sampling equipment and into sample bottles, then analyzed in the laboratory for those constituents that are measured in a routine water sample. In this study, an equipment blank and replicate samples from five wells were collected during September 1998. Replicates were collected from four wells during March 1999.

Table 1. Well-construction data for selected wells, southwestern Albany area, Georgia.

[ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; ft bls, feet below land surface; UFA, Upper Floridan aquifer; °, degrees; ', minutes; ", seconds; topo, obtained from USGS topographic map; level, obtained from land survey level; O, observation well; W, withdrawal well; I, irrigation well; H, homeowner well; U, unused; S, spring; —, data not available]

Well name (fig. 1)	Latitude	Longitude	Altitude (ft above NGVD 29)	Method of altitude measurement	Well depth (ft bls)	Casing depth (ft bls)	Altitude at top of UFA (ft)	Well use	Casing diameter (inches)
11K003	31°29'14"	84°15'31"	195	topo	150	63	149	O	4.0
11K015	31°27'09"	84°16'17"	183	topo	177	74	130	O	4
11L113	31°32'51"	84°15'29"	193	level	99	84	—	W	4
12K010	31°29'58"	84°07'46"	198	topo	247	80	—	W	10
12K011	31°26'50"	84°10'21"	181	topo	—	—	—	I	—
12K012	31°27'45"	84°11'47"	192	topo	—	—	—	I	—
12K013	31°26'50"	84°09'23"	185	topo	—	—	—	I	—
12K014	31°26'11"	84°11'05"	183	topo	137	69	—	O	2
12K037	31°26'41"	84°10'24"	178	topo	200	69	115	W	8
12K053	31°27'20"	84°12'36"	189	topo	85	48	165	H	4
12K063	31°29'45"	84°14'41"	190	topo	—	—	—	H	—
12K094	31°29'55"	84°09'49"	180	topo	115	63	160	H	—
12K101	31°28'57"	84°13'29"	204	topo	120	105	119	H	4
12K107	31°26'34’	84°13'13"	190	topo	—	—	—	W	—
12K108	31°29'53"	84°10'44"	179	topo	—	—	—	W	—
12K109	31°28'39"	84°12'16"	182	topo	—	—	—	I	—
12K110	31°27'47"	84°10'29"	182	topo	—	—	—	I	—
12K112	31°29'55"	84°09'25"	177	topo	—	—	—	H	—
12K114	31°28'46"	84°10'07"	174	topo	—	—	—	W	—
12K115	31°28'48"	84°09'41"	172	topo	—	—	—	W	—
12K116	31°29'22"	84°12'36"	189	topo	—	—	—	H	—
12K117	31°28'21"	84°14'27"	192	topo	—	—	—	H	—
12K118	31°29'41"	84°14'03"	190	topo	—	—	—	H	—
12K119	31°28'52"	84°13'11"	190	topo	—	—	—	H	—
12K120	31°29'04"	84°13'50"	193	topo	—	—	—	W	—
12K121	31°28'56"	84°13'43"	195	topo	—	—	—	H	—
12K122	31°29'47"	84°13'27"	190	topo	98	—	—	H	—
12K123	31°29'40"	84°13'18"	201	topo	242	55	149	O	4
12K124	31°27'51"	84°12'49"	185	topo	—	—	—	H	—
12K129	31°29'17"	84°12'30"	196	topo	211	122	152	W	4
12K132	31°26'29"	84°12'57"	184	topo	110	—	—	H	4
12K133S	31°27'15"	84°09'23"	155	topo	—	—	155	S	—
12K134	31°26'38"	84°10'26"	185	topo	—	—	—	W	8
12K136	31°26'44"	84°12'37"	194	topo	215	135	144	W	4
12K141	31°29'50"	84°13'18"	195	level	200	100	132	O	4
12K147	31°29'43"	84°13'18"	195	level	185	105	150	U	—
12K148	31°29'41"	84°13'11"	193	level	200	100	161	O	—
12K168	31°29'29"	84°11'58"	190	topo	180	101	—	I	—

Table 1. Well-construction data for selected wells, southwestern Albany area, Georgia.—Continued

[ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; ft bls, feet below land surface; UFA, Upper Floridan aquifer; °, degrees; ', minutes; ", seconds; topo, obtained from USGS topographic map; level, obtained from land survey level; O, observation well; W, withdrawal well; I, irrigation well; H, homeowner well; U, unused; S, spring; —, data not available]

Well name (fig. 1)	Latitude	Longitude	Altitude (ft above NGVD 29)	Method of altitude measurement	Well depth (ft bls)	Casing depth (ft bls)	Altitude at top of UFA (ft)	Well use	Casing diameter (inches)
12K170	31°29'57"	84°10'49"	180	topo	180	108	119	I	—
12K171	31°29'05"	84°12'56"	193	topo	140	63	153	H	—
12K172	31°29'50"	84°14'21"	190	topo	125	63	127	H	—
12K173	31°28'53"	84°13'49"	195	topo	180	145	157	H	—
12K175	31°29'37"	84°13'19"	195	topo	187	76	—	H	—
12L023	31°32'43"	84°10'57"	192	topo	165	69	132	O	6
12L028	31°33'02"	84°12'00"	190	topo	100	43	166	O	1.5
12L030	31°31'30"	84°10'10"	180	topo	180	84	148	O	4
12L047	31°33'02"	84°12'42"	200	topo	170	100	—	W	—
12L061	31°30'20"	84°14'25"	195	topo	—	—	145	W	—
12L269	31°33'00"	84°12'43"	199	topo	164	100	163	O	4
12L270	31°30'47"	84°10'42"	190	topo	—	75	—	H	—
12L272	31°30'48"	84°12'01"	189	topo	—	—	—	W	—
12L273	31°31'17"	84°11'41"	195	topo	120	105	—	W	—
12L275	31°32'08"	84°12'47"	196	level	—	—	138	O	—
12L276	31°31'58"	84°12'48"	187	level	—	—	167	O	4
12L277	31°30'40"	84°12'59"	186	topo	203	—	142	O	4
12L310	31°31'32"	84°13'32"	206	level	250	—	—	H	4
12L311	31°32'02"	84°14'38"	184	level	100	—	—	W	—
12L319	31°32'55"	84°13'52"	177	topo	90	—	—	H	—
12L324	31°32'34"	84°13'48"	183	topo	154	101	—	O	4
12L326	31°32'12"	84°13'57"	193	topo	115	100	—	O	4
12L339	31°30'14"	84°11'22"	205	topo	187	83	146	O	—
12L340	31°30'23"	84°11'32"	185	topo	178	96	150	O	—
12L341	31°30'32"	84°10'49"	186	topo	153	68	158	O	—
12L342	31°30'55"	84°12'21"	185	topo	100	94	—	H	—
12L343	31°31'04"	84°11'10"	192	topo	200	80	—	I	—
12L344	31°31'35"	84°13'22"	200	topo	160	80	—	I	—
12L345	31°31'40"	84°13'01"	195	topo	160	60	—	I	—
12L346	31°31'06"	84°12'49"	190	topo	160	60	—	I	—
12L347	31°30'16"	84°10'27"	174	topo	160	107	—	I	—
12L348	31°30'05"	84°12'14"	193	topo	180	133	—	W	12
12L350	31°30'26"	84°12'19"	195	topo	191	—	—	O	—
12L351	31°31'16"	84°12'25"	193	topo	165	85	—	H	—
12L352	31°30'21"	84°13'29"	195	topo	100	67	—	H	—
12L353	31°30'42"	84°13'59"	193	topo	120	63	153	H	—
12L355	31°29'60"	84°14'00"	195	topo	155	89	150	H	—
12L356	31°30'43"	84°13'43"	195	topo	160	—	—	I	—
12L357	31°31'02"	84°13'43"	185	topo	160	—	—	I	—

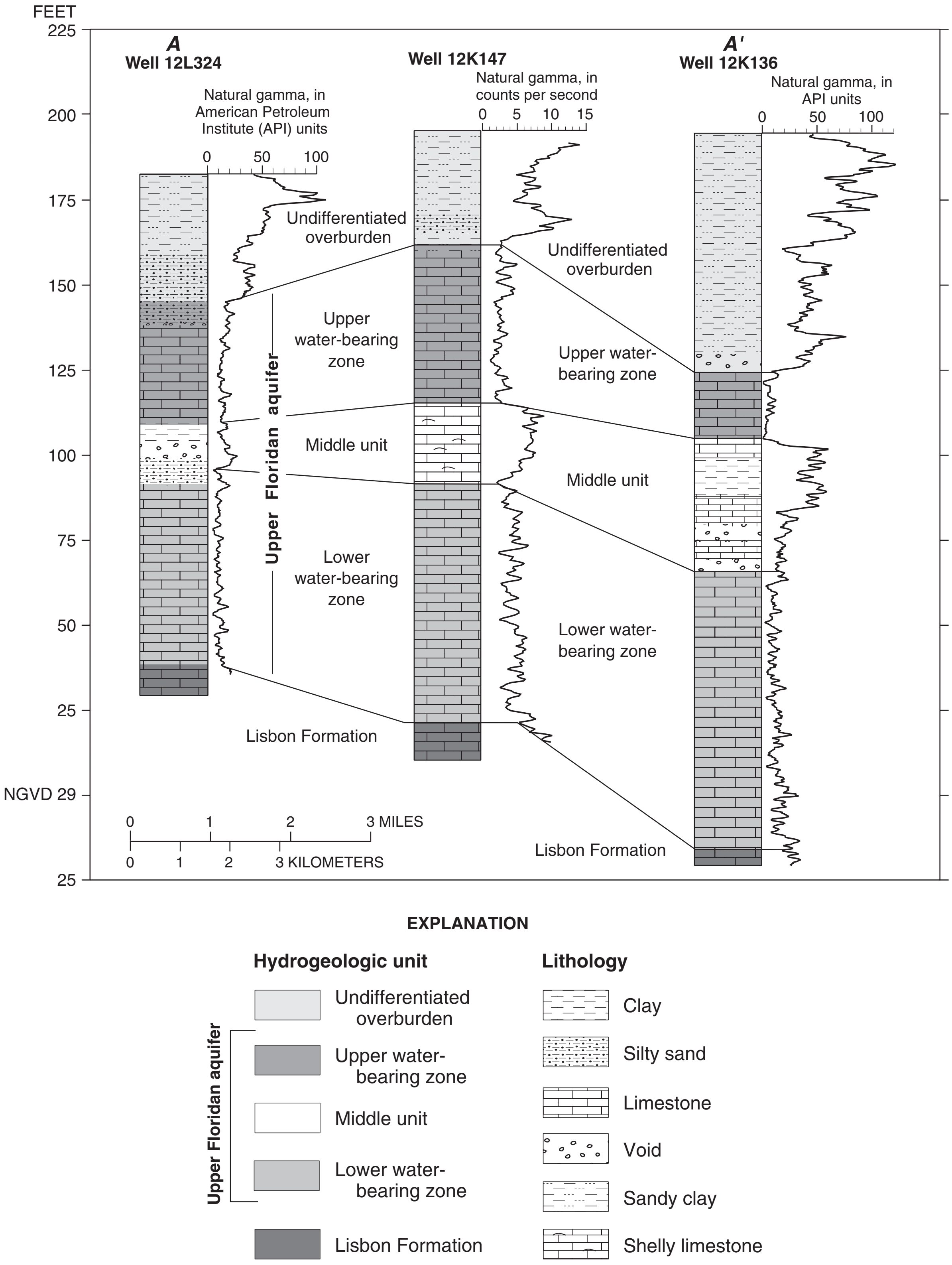
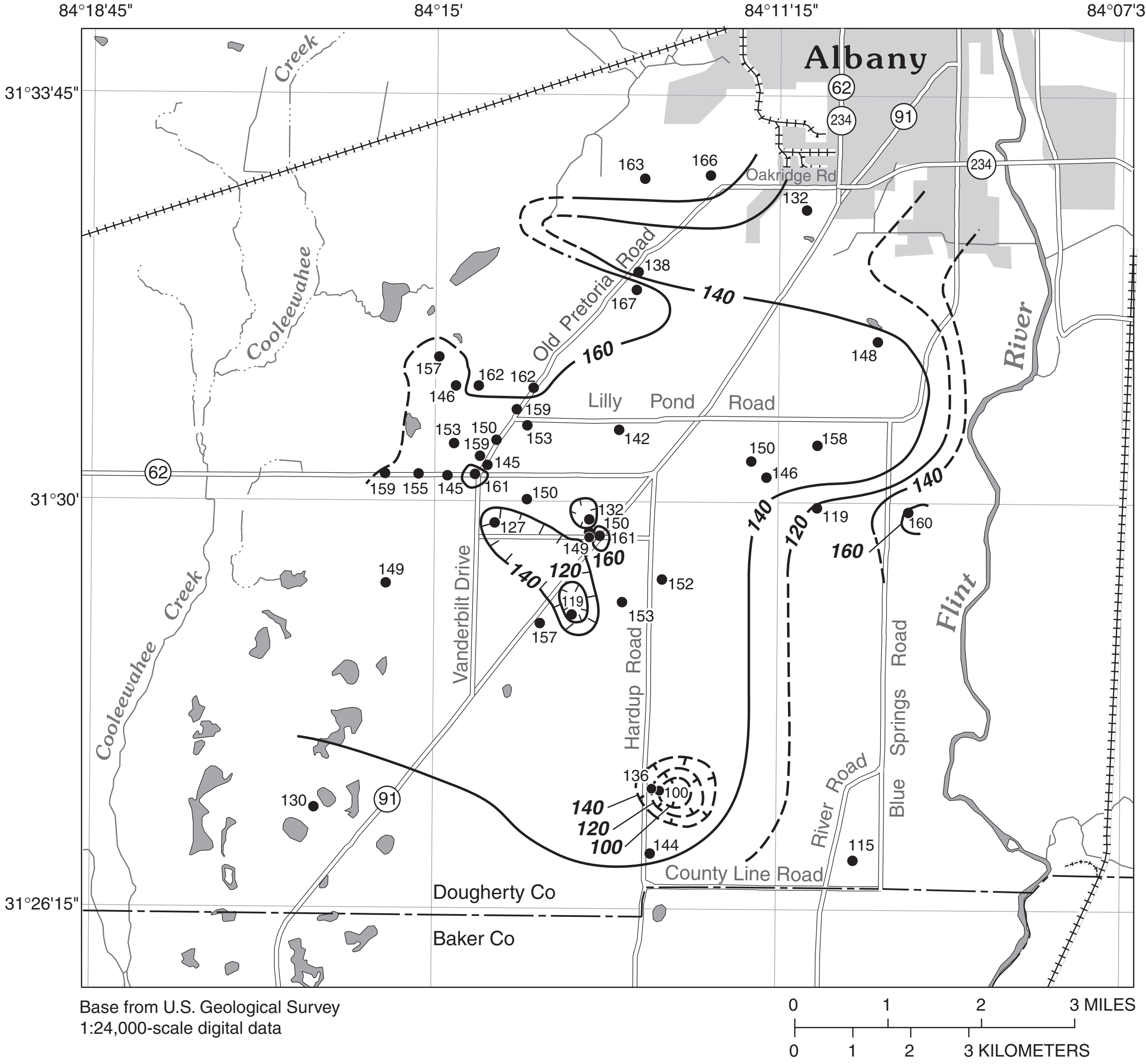


Figure 2. Hydrogeologic section *A–A′* showing geologic and gamma-ray logs of selected wells, southwestern Albany area, Georgia. Line of section shown in figure 1.



EXPLANATION

— 140 — — **Structure contour**—Shows altitude of top of Upper Floridan aquifer. Dashed where approximately located. Hachures indicate depression. Contour interval 20 feet. Datum is NGVD 29

● 144 **Well and altitude of top of Upper Floridan aquifer**

Figure 3. Approximate altitude and configuration of the top of the Upper Floridan aquifer, southwestern Albany area, Georgia.

During August 2000, a water sample was collected at one well (12L061) to determine the presence and concentration of several organic compounds commonly associated with sewage-contaminated water. These compounds hereinafter will be called wastewater tracers. Wastewater tracers are compounds commonly found in prescription and over-the-counter (OTC) drugs, in caffeinated beverages, and in insect repellants that are either washed off or excreted by humans. Many of these compounds survive unaltered during municipal wastewater treatment or in the primary treatment systems such as septic tanks and may be detected in treated sewage effluent, in septic effluent, or in household or commercial gray water.

During March 2001, additional ground-water samples were collected and analyzed for $\delta^{15}N$ and $\delta^{18}O$ and selected wastewater tracers. Nitrate and dissolved organic carbon concentrations found in samples collected during 1998 and 1999 were used to calculate the volume of water required to obtain the 100–300 micromoles of nitrate needed for isotope analysis. The calculated volume of water was passed through a 0.45-micrometer (µm) capsule filter, then through cation- and anion-exchange columns. The eluant then was checked for nitrate breakthrough using a Hach nitrate test kit. The nitrate-charged columns were shipped on ice to the Environmental Isotope Laboratory at the University of Waterloo, Department of Earth Sciences, Waterloo, Ontario, Canada. Chamberlain and others (2002) described in more detail field extraction and laboratory methods used for the isotope analyses.

In the current study, different analytical methods were used to analyze water samples for major and minor constituents, selected nutrients, and common physical properties. Except for pH, SC, acid-neutralizing capacity (ANC), and ammonia samples, an aliquot of sample was filtered through a 0.45-µm cellulose-nitrate filter at the PMRL. Ground-water samples were analyzed for major and minor cation concentrations (sodium, potassium, calcium, magnesium, barium, and strontium) and dissolved silica. The filtered water was acidified with nitric acid (HNO_3) to a pH of 1–1.5 and stored at room temperature. The cations were determined by direct-coupled argon plasma spectrometry (DCP) (Fishman and Friedman, 1989). The major anions (sulfate, chloride, bromide, fluoride, and nitrate) were determined by ion chromatography (Fishman and Friedman, 1989). All other analyses—such as pH, SC, ANC, and ammonia—were determined from a second unfiltered and untreated aliquot, which was refrigerated prior to the analysis. ANC was determined by a Gran titration (Gran, 1952). Ammonia was analyzed colorimetrically using salicylate hypochlorite. Orthophosphate concentrations were analyzed colorimetrically.

Age-Dating Ground Water Using Chlorofluorocarbons

CFCs measured in water samples are used to determine the approximate time since recharge. Using CFCs to date relatively young ground water is a method generally accepted by the scientific community. Plummer and others (1993) provided a detailed description of CFCs as tracers. CFCs are stable, synthetic, halogenated alkanes (compounds with a linear chain of carbon and hydrogen molecules) that were developed during the 1930s to replace ammonia and sulfur dioxide as refrigerants. The production of CFC-12 began during 1931 followed by CFC-11 during 1936, and many other CFC compounds since, including CFC-113. Atmospheric concentrations of CFCs closely followed production rates, which peaked during the 1970s and 1980s. Those CFCs released into the atmosphere and incorporated into Earth's hydrologic cycle are a valuable tool in assessing the age, or time since recharge, of ground water. By measuring concentrations of CFC-12, CFC-11, and CFC-113, one can determine the apparent year that water entered the aquifer (Plummer and others, 1993). CFCs, however, only can be measured in water that recharges an aquifer after approximately 1941 (CFC-12), 1947 (CFC-11), and 1955 (CFC-113). CFCs also are commonly used to trace sewage effluent in ground-water studies (Busenberg and Plummer, 1991). CFC-12 has proven to be the most reliable of the CFCs because it is more stable and not as easily degraded in anoxic water (Julian E. Wayland, U.S. Geological Survey, written commun., 1999).

Calculating a definitive ground-water age is not possible in this study because water samples collected from wells completed in limestone aquifers typically are mixtures of different waters. These wells typically have large open intervals that tap multiple fractures. As a result, ground water from different depths and with different ages in the aquifer mix when a well is pumped (Julian E. Wayland, U.S. Geological Survey, written commun., 1999). Nevertheless, the apparent age probably represents the age of the major water-producing zone tapped by the well (Eurybiades Busenberg, U.S. Geological Survey, oral commun., 1999). A ground-water sample with CFC concentrations greater than that expected in equilibrium with modern air is considered contaminated and cannot be dated with CFCs. Sources of CFCs to ground water include discharge from septic tanks, leaking sewer lines, leaking underground storage tanks, landfill effluent, discharge of industrial waste, and recharge from rivers carrying effluent from sewage treatment plants (Eurybiades Busenberg, U.S. Geological Survey, written commun., 1998).

Busenberg and Plummer (1992) developed the sampling equipment and procedures used for collection and preservation of water samples for CFC analysis. The sampling equipment establishes a closed path between the well and the sample bottle. The closed system is constructed with refrigeration-grade copper tubing connecting a system of valves for filling and flushing the sample bottle, a 62-milliliter (mL) borosilicate ampoule, with water. A headspace is created in the ampoule with CFC-free ultrapure nitrogen, and the ampoule is fused close using heat (Plummer and Busenberg, 2000). Six ampoules were collected at each site and transported to the Nuclear Regulatory Commission licensed laboratory in Reston, Virginia, for analysis. Three ampoules were analyzed for each site using a purge-and-trap gas chromatography procedure with an electron-capture detector (Busenberg and others, 1993).

Statistical Analysis of Water-Quality Data

Several statistical and pseudo-statistical methods were used to analyze the water quality and ancillary data collected during September 1998 and March 1999. Ancillary data include depth to water below land surface, water temperature, and isotope data. Except for regression analysis, which is a parametric procedure, the statistical methods used are nearly all nonparametric. Nonparametric procedures are not affected by outliers or by sample size limitations, although a minimum number of samples are needed for meaningful conclusions. Spearman rank correlation method is used to construct tables showing the relative correlation (rho) among chemical constituents (Conover, 1980, p. 252). A Wilcoxon Signed-Rank test (Helsel and Hirsch, 1992, p.142) is used to compare the median constituent concentrations among ground-water samples collected during the study. The Wilcoxon test is the nonparametric counterpart to the commonly used parametric t-test. Multiple regression analyses (Montgomery and Peck, 1982, p. 109) are developed to estimate nitrate concentrations.

Exploratory data analysis consists of pseudo-statistical methods such as cluster analysis, boxplots, scatterplots, and end-member mixing analysis (EMMA) to show the underlying patterns in the data. Pseudo-statistical methods are those that do not use hypothesis testing (statistical inference) in the data analysis. An agglomerative, hierarchical-cluster analysis using Euclidean distance with Ward's minimum variance method (Romesburg, 1984, p. 129) is used to identify ground-water samples with similar constituent concentrations. Sample constituents included in the cluster analysis are dissolved magnesium, sodium, potassium, ANC, sulfate, chloride, and silica concentrations. The method uses Euclidean distances in xy-coordinate space to compute the difference between constituent concentrations in multiple samples (Romesburg, 1984, p. 129). Each sample starts out as an individual cluster. By successive iterations, these clusters are combined until an iteration produces a cluster that has the smallest increase in the variance of the Euclidian distances. The samples within each cluster are analyzed using the Wilcoxon Signed-Ranks test (Helsel and Hirsch, 1992, p. 118) to determine which clusters contain statistically different median concentrations of selected constituents. A tree diagram was used to show the hierarchy of similarities or dissimilarities among pairs of water samples. In other words, the tree diagram shows how close the chemistry of one water sample resembles the chemistry in another water sample. The dissimilarity index is a measure of that similarity or dissimilarity among pairs of water samples. The smaller the index value for each pair of water samples, the more alike those samples are with respect to water chemistry.

EMMA was used to determine whether the simple mixing of two or more chemically different ground waters can explain the water chemistry in samples from particular wells. In this study, EMMA is used to determine whether the mixing of high-nitrate ground water with low-nitrate ground water is a plausible explanation for nitrate concentrations found in water samples downgradient from the area with elevated nitrate concentrations. If simple mixing cannot explain nitrate concentrations in wells downgradient from "high nitrate" wells, then nitrate concentrations are the result of unidentified sources or chemical changes to ground-water nitrate concentrations.

The sample domain in EMMA is commonly determined with boundaries described by two conservative constituents, such as deuterium and chloride. Because deuterium was not analyzed in all water samples collected for the current study, the boundaries of a three end-member analysis are described using SC values and chloride concentrations. Chloride is used as the conservative constituent because chloride minerals are not present in the aquifer, chloride is not altered by chemical interactions in the aquifer, and only dilution or evaporation will reduce or increase the chloride concentration in the aquifer (Hem, 1985). Although not considered a conservative constituent, SC is used to define mixing boundaries because it represents an integrated index of major ions (mineral content) in the aquifer. The three end members are water samples collected from wells 12L061, 12L311 (1998), and 12K136. Well 12L061 was selected as the upper end member because it intercepts ground water with high chloride and high nitrate concentrations and represents an area near a source or sources of nitrogen. Well 12L311 is a second end member because 1998 water samples from that well contain elevated chloride concentrations, but undetectable nitrate concentrations. Well 12K136 was selected as the third end member because water samples from that well contain low concentrations of both chloride and nitrate and may represent background chemistry for ground water in this part of the Upper Floridan aquifer.

The mixing fractions of the three end-member samples (f_{061}, f_{311}, and f_{136}) were calculated for each sample in four steps.

1. The chloride concentrations for all samples are plotted against the corresponding SC values. The end-member samples are connected by straight lines to define the mixing domain.
2. A straight line drawn from one end member (called end member C) through a sample in the mixing domain identifies the chloride concentration in a hypothetical sample when that line intersects the line segment connecting the other two end members (called end members A and B). The chloride concentration in the hypothetical sample represents a mixture of the chloride concentration from end-member samples A and B.
3. The linear equations 1 and 2 are solved simultaneously for end-member samples A and B to get the fraction of water in the hypothetical sample represented by the mixing of water from wells A and B

$$C_H = C_A f_A + C_B f_B \tag{1}$$

$$f_A + f_B = 1.0 \tag{2}$$

where

C_H is the concentration of chloride in mg/L in the hypothetical water sample; C_A is the chloride concentration in the ground-water sample from end member A; C_B is the chloride concentration in the ground-water sample from end member B; f_A is the mixing fraction of end member A; f_B is the mixing fraction of end member B.

These mixing fractions are used to determine the ratio of water from end member A to water from end member B in the hypothetical sample as shown in equation 3

$$X = \frac{f_A}{f_B} \quad \text{or} \quad f_A = Xf_B \qquad (3)$$

where

X is the magnitude of the fractional difference between end members A and B when water from wells A and B are mixed to form the hypothetical water sample H.

For example, the fraction contributed by end member A may be X times larger than the fraction contributed by end member B.

4. Using algebraic substitution of equation 3 for the fraction of end member sample A in equation 4, the mixing fraction for end member sample C is determined by simultaneously solving the linear equations 4 and 5

$$C_W = C_C f_C + C_A(2f_B) + C_B f_B \qquad (4)$$

$$f_B + 2f_B + f_C = 1.0 \qquad (5)$$

where

C_C is the chloride concentration in end-member sample C; C_W is the chloride concentration in the ground-water sample; f_C is the mixing fraction of end member C, and C_A, C_B, and f_B are as previously defined.

The results provided by equations 1 through 5 give the relative fractions contributed by each end-member sample to produce a theoretical (predicted) chloride concentration in each ground-water sample. If this predicted chloride concentration is within ±10 percent of the measured chloride concentration, then that ground-water sample is assumed to contain water with a chloride concentration similar to the concentration expected when water from the three end-member wells is mixed in the proportions predicted. An example calculation is provided in Appendix A.

Using the final mixing fractions, nitrate and sodium concentrations and specific conductance values are predicted for each sample using equation 6

$$C_W = C_{L061} f_{L061} + C_{K136} f_{K136} + C_{L311} f_{K311} \qquad (6)$$

where

C_W is the predicted nitrate, sodium, or SC value in the ground-water sample in milligrams per liter, C_{L061} is the measured nitrate, sodium, or SC value in the water sample from well 12L061,C_{K136} is the measured nitrate, sodium, or SC value in the water sample from well 12K136 (background); C_{L311} is the measured nitrate, sodium, or SC value in the water sample from well 12L311; f_{L061} is the fraction of water that is chemically similar to the water sample from well 12L061 and assumed to contribute to the nitrate concentration in C_W; f_{K136} is the fraction of water that is chemically similar to the water sample from well 12K136 and assumed to contribute to the chloride concentration in C_W; and f_{K311} is the fraction of water that is chemically similar to the water sample from well 12L311 and assumed to contribute to the chloride concentration in C_W.

The relative percent difference (RPD) between measured and predicted SC values is used to determine the validity of the chloride-derived mixing model. Those samples with a RPD beyond the critical value of ±15 percent from the measured SC are those that did not fit the mixing model. This critical value is determined by the analytical uncertainty in the chloride and SC measurement. These uncertainties commonly range between 5 and 10 percent. The samples that do not fit the model may be mixtures of one or more end members that are not identified in the study area or are those that may exist outside of the study area (for example, nitrate enrichment in ground water moving into the study area from an unknown source). Poorly predicted nitrate or sodium concentrations indicate that those constituents are probably determined or altered by geochemical or biochemical processes such as cation exchange, denitrification, or nitrate reduction.

Hydrogeology of the Upper Floridan Aquifer

By Debbie Warner

In the southwestern Albany area, the Upper Floridan aquifer primarily consists of the upper Eocene Ocala Limestone. The aquifer is confined above by low-permeability sediments of the undifferentiated Quaternary overburden and below by the middle Eocene Lisbon Formation (fig. 2). Regionally, the Ocala Limestone and the Lisbon Formation dip slightly and thicken to the southeast.

Ground water in the Upper Floridan aquifer generally moves from the northwest to the southeast in the study area. Maps of the potentiometric surface were constructed for three time periods to show the general hydrology of the aquifer during the study period (1998–2001).

Undifferentiated Overburden

The undifferentiated overburden is the uppermost hydrogeologic unit in the study area. The overburden ranges in thickness from about 30 to 70 ft and consists of fine to coarse quartz sand, silty sand, sandy clay, and clay (fig. 2). At the base of the overburden, an areally extensive 10- to 15-ft-thick layer of sand, sandy clay and clayey limestone directly overlies the Ocala Limestone. This clayey zone probably is residuum derived from weathering of the Ocala Limestone. This zone of low-permeability material comprises the upper semiconfining unit of the Upper Floridan aquifer. At well 12K147 (figs. 1 and 2), the upper 25 ft of overburden consists of silty clay and sandy clay, underlain by 10 ft of silty sand, and about 10 ft of sandy clay and clay containing weathered limestone (Warner, 1997).

Laboratory analyses of sediment samples collected at various depths in the undifferentiated overburden indicate that the vertical hydraulic conductivity at well 12K123 (fig. 1) ranges from 0.011 to 11.3 feet per day (ft/day) (Torak and others, 1993). The low end of the range represents values for the clays in the semiconfining unit above the Upper Floridan aquifer, and the high end of the range is characteristic of sediments that make up the surficial aquifer.

The surficial aquifer consists of high permeability sandy sediments within the undifferentiated overburden. The surficial aquifer provides recharge to the Upper Floridan aquifer; however, in the study area the semiconfining layer decreases the rate of vertical infiltration into the Upper Floridan aquifer.

Upper Floridan Aquifer

Previous studies in the Albany area have subdivided the Upper Floridan aquifer into an upper water-bearing zone, a confining or semiconfining middle unit, and a lower water-bearing zone based on differing hydrologic properties (Hicks and others, 1987). Hydrogeologic section *A-A′* shows the general position, thickness, and extent of the hydrogeologic units in the study area (fig. 2). Sprinkle (1989, fig. 11) suggests that the Upper Floridan aquifer in the southwestern Albany area is unconfined or has a thin confining layer present.

The top of the Upper Floridan aquifer, determined from geologic and geophysical logs, ranges from an altitude of about 166 ft (above NGVD 29) in the northern part of the study area (at well 12L028) to an altitude of about 115 ft (above NGVD 29) in the southeastern part of the study area (at well 12K037) (figs. 1 and 3). The top of the aquifer is an erosional surface that changes in altitude more than 40 ft within a short distance. In general, the top of the aquifer dips to the southeast at a gradient that ranges from about 5 feet per mile (ft/mi) in the northern part of the study area (between wells 12L269 and 12L030) to about 10.6 ft/mi in the central part of the study area (between wells 12L353 and 12K170, fig. 1).

In well 12K147, the upper 10 ft of the upper water-bearing zone consists of sandy, clayey, friable, chalky limestone, underlain by about 21 ft of sandy, friable limestone, and about 24 ft of less friable limestone and minor quartz sand (fig. 2) (Warner, 1997). The middle unit was included within the lower water-bearing zone by Warner (1997), but has been identified as a separate unit in this report because of increased thickness in the southern part of the study area (fig. 2). In well 12K147 (fig. 2), the middle unit consists of about 20 ft of shelly limestone, and the lower water-bearing zone consists of 70 ft of slightly weathered limestone (Warner, 1997).

The upper water-bearing zone is less permeable than the lower water-bearing zone (Hicks and others, 1987), which reduces the ability of the aquifer to transmit ground water (Torak and others, 1993). The thickness of the upper water-bearing zone controls the extent to which this zone acts as a hydrologic barrier for transmitting water vertically between the undifferentiated overburden and the lower water-bearing zone (Torak and others, 1993). The upper water-bearing zone often is used for domestic supply, even though yields from wells tapping this zone generally are low (Torak and others, 1993).

The lower water-bearing zone is highly permeable with numerous caverns. A zone of potentially high flow is located near the top and the bottom of the lower water-bearing zone (Warner, 1997). Aquifer tests conducted in the study area indicate that the transmissivity of the lower water-bearing zone ranges between about 120,000 and 506,000 feet squared per day, and the storage coefficient is between 1.4×10^{-4} and 6.3×10^{-4} (Warner, 1997).

Lisbon Confining Unit

The Lisbon Formation—a tan to green glauconitic, argillaceous limestone—is the lower confining unit of the Upper Floridan aquifer (fig. 2). The formation is about 100 ft thick at Albany (Hicks and others, 1987). The Lisbon confining unit acts as a nearly impermeable boundary to the Upper Floridan aquifer; no substantial leakage occurs through this formation in the southwestern Albany area (Torak and others, 1993).

Ground-Water Flow in the Upper Floridan Aquifer

To characterize the ground-water flow system of the Upper Floridan aquifer in the southwestern Albany area, water-level and precipitation data were collected, the water level in the Flint River was monitored, and ground-water samples were collected for age-dating purposes. Continuous water-level data were recorded in wells 11K003, 11K015, 12K014, 12K141, 12L339, and 12L277 (figs. 4 and 5) and in the Flint River at USGS gaging station 02352500 Flint River at Albany (located 1.5 miles north of the study area) (fig. 6). Daily precipitation data were obtained from the National Weather Service station rain gage located 3 miles southeast of the main U.S. Post Office in Albany (fig. 1). Water-level data were collected in 67–72 wells throughout the study area (table 2) to construct potentiometric-surface maps of the Upper Floridan aquifer for May 1998, October 1998, and March 1999. A few of the wells were pumping during each time period and could not be measured. Water samples were collected from 21 wells, 1 spring, and 1 pond for age dating.

Water Levels

Ground-water levels in the southwestern Albany area are affected by pumping, rainfall, evapotranspiration, and water-level fluctuations in the Flint River (figs. 4–6). Land use in the area is primarily agricultural, with widespread irrigation withdrawal from the Upper Floridan aquifer from May through September. These withdrawals, coupled with decreased precipitation and increased evapotranspiration typical during summer, produce a corresponding water-level decline in the Upper Floridan aquifer. Following the irrigation season and with winter rain, water levels rise. Water-level declines from May to September 1998 ranged from about 13.5 (well 12L339) to about 8.5 ft (well 11K015) (figs. 5 and 4, respectively). Water-level change in response to irrigation pumpage is especially pronounced in well 11K003, which is located about 400 ft from an irrigation well (fig. 4). Water levels in this well show a large decline and subsequent rise each time the irrigation well is turned on and off.

Water levels in the Upper Floridan aquifer show a pronounced response to rainfall, especially during the nonirrigation period. Following the end of the irrigation-pumping season, substantial precipitation (greater than or equal to 1 inch of rainfall) contributes to increases in water levels. For example, in 1998 water levels in the recorder wells increased by about 3.5 ft following 6.55 inches of rain on September 3–4 and rose 0.5–3 ft following 4.17 inches rain on September 30 (table 3, figs. 4–6). During January 1999, ground-water levels increased from less than 0.5 ft to about 4 ft following a storm that produced 1.12 inches of rain on January 18 and 1.65 inches of rain on January 23 (table 3; figs. 4–6). During the summer, precipitation does not produce substantial water-level response because of the more pronounced response to irrigation pumping and evapotranspiration. For example, substantial precipitation during May, July, and August of 1998 did not cause substantial water-level increases.

Substantial precipitation also causes increases in the stage of the Flint River. The river stage rose about 2.4 ft following the 6.55 inches of rainfall on September 3–4, 1998; 3 ft following the 4.17 inches of rainfall on September 30, 1998; and about 10 ft following the 3.9 inches of cumulative rainfall during January 1999 (fig. 6, table 3). The Flint River appears to be hydraulically connected to the Upper Floridan aquifer. This effect was evident during an Upper Floridan aquifer test conducted in the study area during 1995 (Warner, 1997). During pumping, water levels declined about 49 ft in the pumped well, declined as much as 2.4 ft in nearby observation wells, and rose as much as 3.2 ft in wells located within 4 miles of the Flint River. The stage of the Flint River rose 3.5 ft during the test, causing a decrease in the natural discharge from the Upper Floridan aquifer to the river and a subsequent increase in ground-water levels in the Upper Floridan aquifer. The hydrograph of well 12K014 is similar to the hydrograph of the Flint River, reflecting changes in the Flint River water levels during September 1998, and through the early part of 1999 (figs. 4 and 6). Well 12K014 is located about 2.5 miles west of the river. Additional ground-water data near the river are needed to better define the hydraulic connection between the Upper Floridan aquifer and the Flint River.

Flow Directions and Gradients

The potentiometric surface, ground-water flow directions, and gradients were estimated for the Upper Floridan aquifer using water-level data collected during May and October 1998, and March 1999 (figs. 7–9). The potentiometric surface varies seasonally throughout the study area in response to changes in pumping, precipitation, stage of the Flint River, and evapotranspiration. Ground-water altitudes ranged from 137 to 188 ft during May 1998, from 132 to 182 ft during October 1998, and from 134 to 181 ft during March 1999 (table 2). The general direction of regional ground-water flow in the study area is from northwest to southeast (Stewart and others, 1999, figs. 18 and 19).

During May 1998, water levels generally were high and a large mound (encompassed by the 175-ft contour) in the potentiometric surface was observed in the central part of the study area (fig. 7). In this area, the hydraulic gradient is nearly flat and the aquifer may receive more recharge than in surrounding areas.

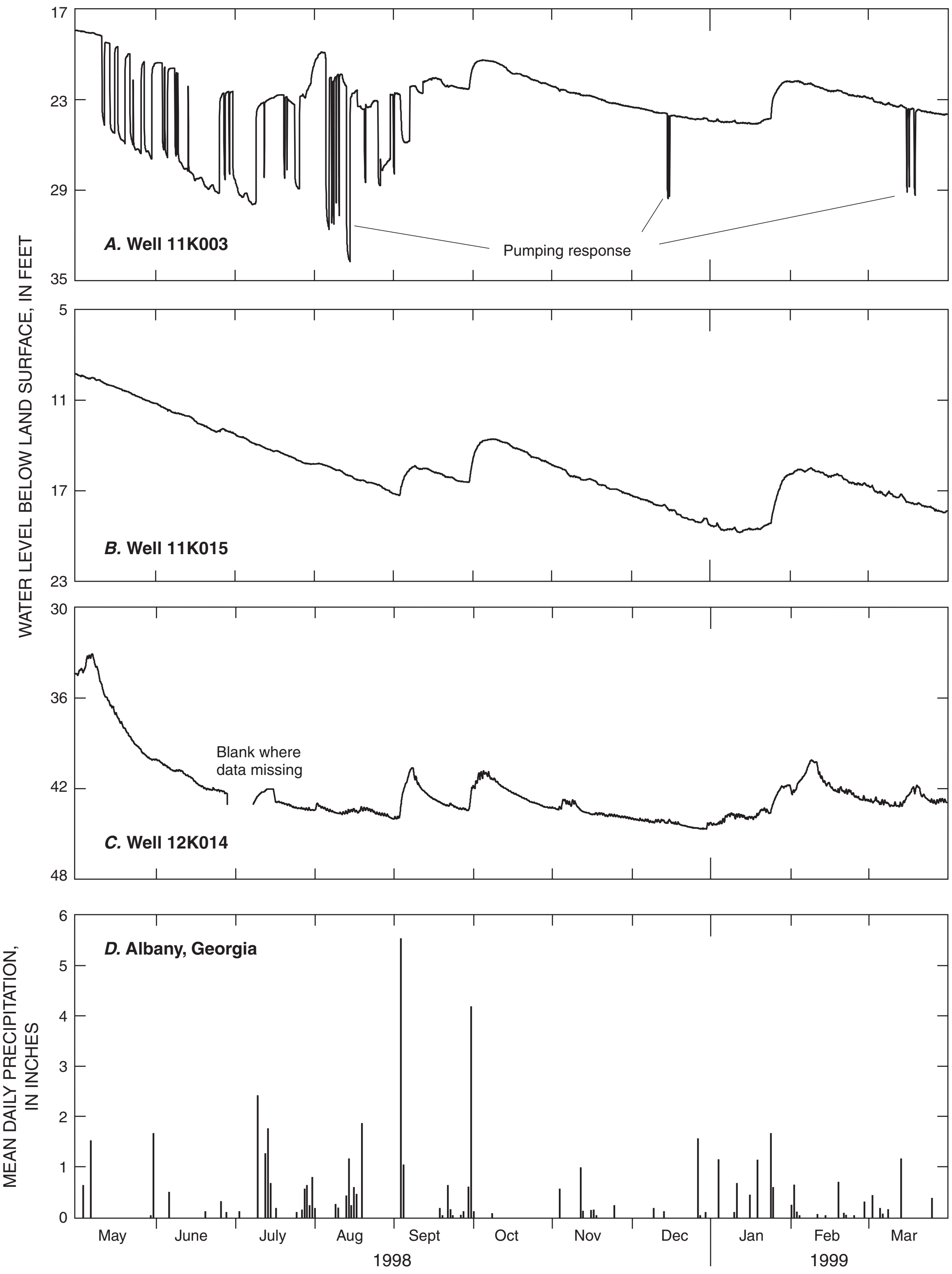


Figure 4. Water levels in wells *(A)* 11K003, *(B)* 11K015, and *(C)* 12K014, southwestern Albany area, Georgia; and (*D*) mean daily precipitation at Albany, Georgia, May 1998–March 1999 (see figure 1 for locations).

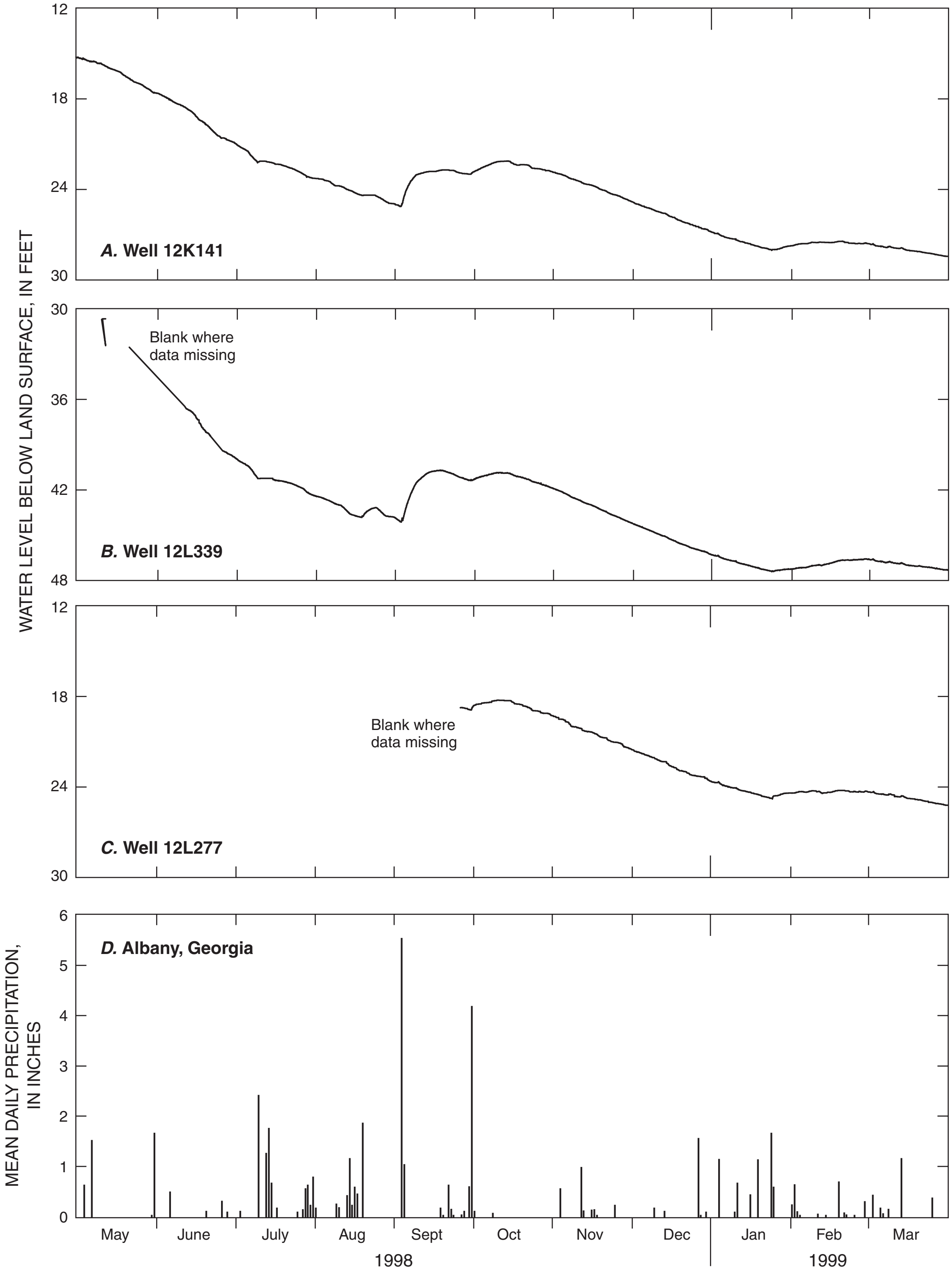


Figure 5. Water levels in wells *(A)* 12K141, *(B)* 12L339, and *(C)* 12L277, southwestern Albany area, Georgia; and *(D)* mean daily precipitation at Albany, Georgia, May 1998–March 1999 (see figure 1 for locations).

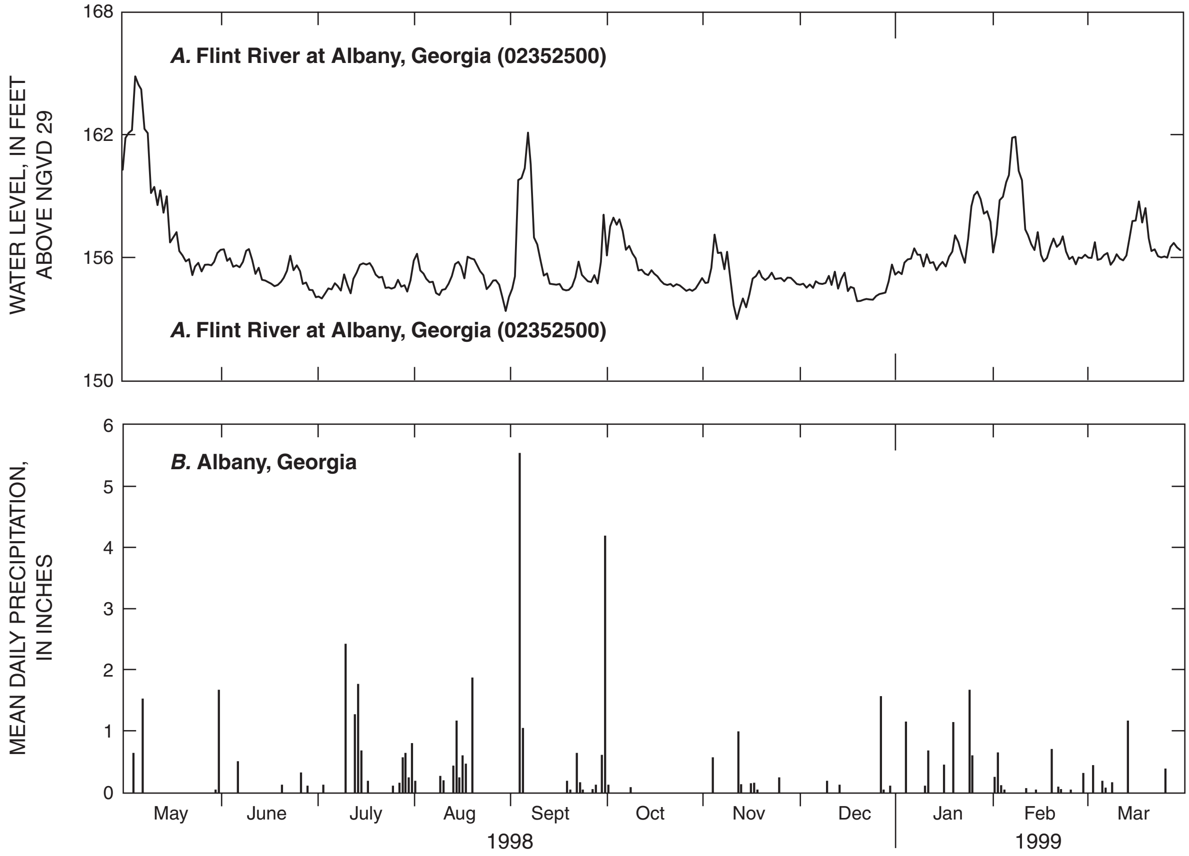


Figure 6. *(A)* Water-level fluctuations in the Flint River, at Albany, Georgia, USGS station number 02352500, and *(B)* mean daily precipitation at Albany, Georgia, May 1998–March 1999 (see figure 1 for locations).

The recharge mound, when present, alters the regional flow of ground water (Stewart and others, 1999, figs. 18 and 19) toward the Flint River and decreases southeast ground-water flow through the study area. The water flows outward from the mound in all directions. As water levels increase in this area, the hydraulic gradient steepens on the west side of the mound, and ground water flows toward Cooleewahee Creek (fig. 7). During most of this study period, the area was in drought conditions (figs. 4–6). During May 1998, however, the study area was not in a drought, so the mound was present and had an effect on the ground-water flow through the study area. During the drought, which began during late 1998, the recharge mound had much less of an effect on ground-water flow in the area. Water levels declined during summer 1998, and by October 1998 were less than 1–13 ft lower than during May 1998 (figs. 7–8). During October 1998, the recharge mound was still present, but much smaller in areal extent than during May. North and south of the mound, ground-water flow generally was northwest to southeast. Water levels remained low through winter 1999 and, during the study period, were lowest during March 1999 (fig. 9). The recharge mound was not present in March 1999, and ground water flowed from northwest to southeast.

The hydraulic gradients were calculated and compared from the central part of the study area to the southeastern part of the study area along the flowpath during May 1998, October 1998, and March 1999. Water levels in well 12K141 in the central part of the study area and well 12K110 in the southeastern part of the study area (fig. 1) were used for the calculations. The hydraulic gradients calculated for May 1998 (fig. 7), October 1998 (fig. 8), and March 1999 (fig. 9) were 8.7, 9.3, and 6.8 ft/mi, respectively. Although the data are limited, they indicate that the hydraulic gradient steepens through the summer when precipitation is low and irrigation pumping is high.

All three potentiometric-surface maps indicate that ground water flows westward away from the Flint River in the extreme southeastern part of the study area near the Flint River (figs. 7–9). As previously documented by Warner (1997) and as indicated by the hydrograph of well 12K014 (fig. 4), when the stage of the Flint River is high (relative to the potentiometric surface near the river), the hydraulic gradient between the aquifer and the river is decreased or reversed, resulting in local westward ground-water flow.

Table 2. Water-level altitudes in selected wells completed in the Upper Florida aquifer, southwestern Albany area, Georgia, May 1998, October 1998, and March 1999.

[NGVD 29, National Geodetic Vertical Datum of 1929; —, not measured]

Well name (fig. 1)	Water-level altitude, feet above NGVD 29		
	May 1998	Oct. 1998	Mar. 1999
11K003	170	173	172
11K015	173	160	167
11L113	179	180	181
12K010	156	152	149
12K011	141	—	141
12K012	156	151	149
12K013	157	150	155
12K014	147	137	139
12K037	138	132	134
12K053	161	150	147
12K063	171	165	163
12K094	152	143	142
12K101	177	170	166
12K107	171	—	155
12K108	164	153	151
12K109	173	162	159
12K110	148	139	143
12K112	152	145	145
12K114	156	147	147
12K115	158	150	150
12K116	177	168	163
12K117	178	—	—
12K118	175	169	165
12K119	174	—	162
12K120	182	175	171
12K121	184	178	174
12K122	177	170	165
12K123	182	176	172
12K124	164	155	151
12K129	173	165	160
12K132	166	154	150
12K134	137	—	137
12K136	165	154	151
12K141	179	172	168
12K147	180	173	168
12K148	179	172	167
12K168	177	168	163
12K170	164	154	152
12K171	175	168	163
12K172	174	169	165
12K173	183	177	173
12K175	—	168	—
12L023	164	—	155
12L028	181	172	169
12L030	171	162	159
12L061	180	181	178
12L269	177	171	168
12L270	168	158	154
12L272	178	170	—
12L273	181	174	169
12L275	176	169	169
12L276	173	171	167
12L277	181	174	169
12L310	181	178	175
12L311	179	177	176
12L319	171	—	171
12L324	177	—	173
12L326	181	178	176
12L339	174	163	158
12L340	172	163	158
12L341	168	158	154
12L342	177	166	165
12L343	172	168	164
12L344	188	182	178
12L345	178	174	170
12L346	177	172	167
12L347	167	157	154
12L348	182	171	166
12L350	183	175	170
12L351	179	172	167
12L352	181	172	170
12L353	178	174	171
12L355	181	178	171
12L356	—	179	175
12L357	—	173	170

Table 3. Water-level rise in selected wells and stage of the Flint River following substantial precipitation during 1998–99, southwestern Albany area, Georgia.

[—, no data available; <, less than, water-level rise less than 0.5 ft following rainfall event; water-level increases refer to the peak water level following a significant rain (greater than or equal to 1 inch); in parentheses are dates when rainfall began]

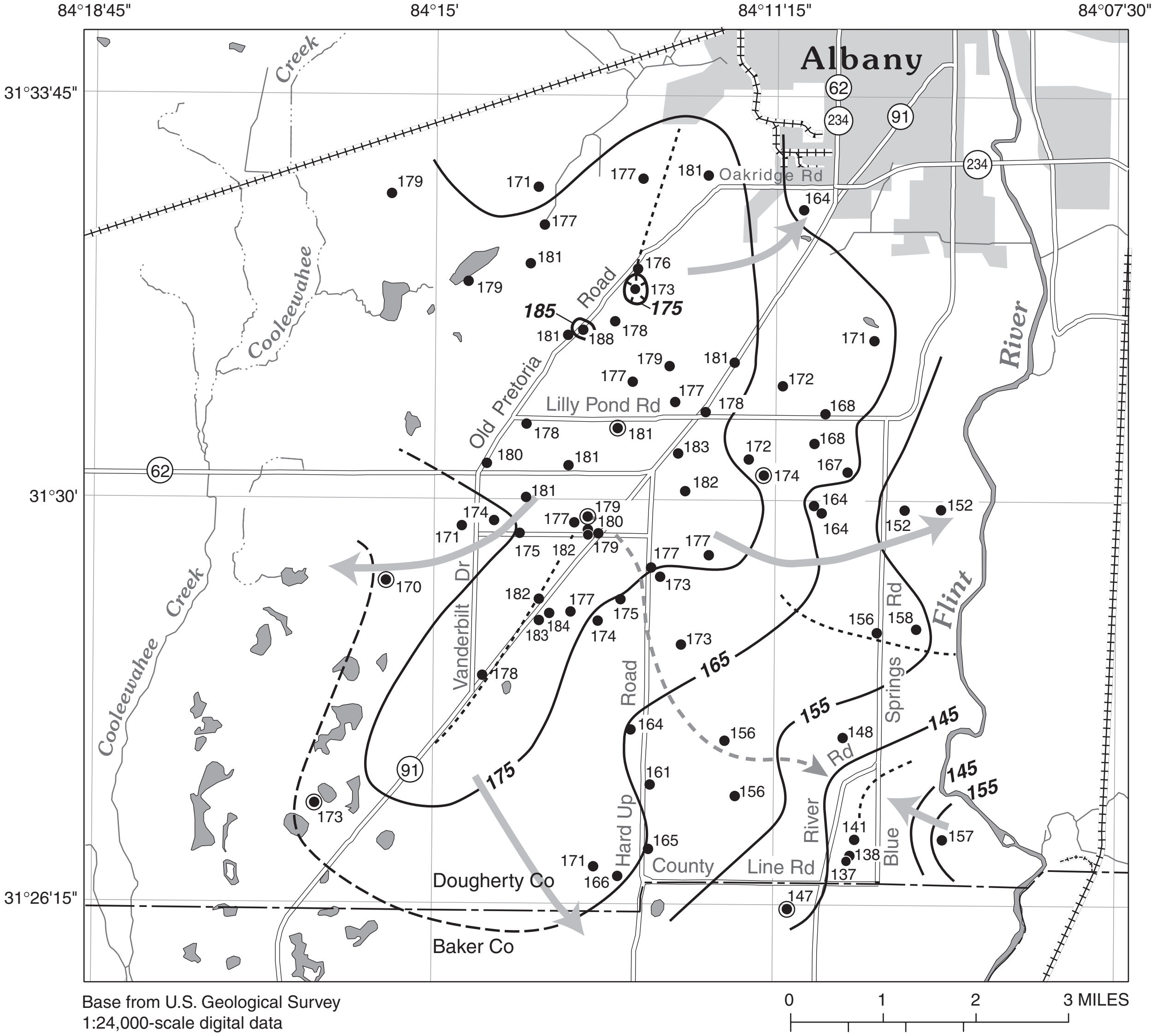
Date of rainfall	Rainfall (inches)	Maximum rise in water level after rainfall (feet) (Date of maximum rise in water level)						
		Well names (fig. 1)						
		11K003	12K014	11K015	12K141	12L277	12L339	Flint River
Sept. 3–4, 1998	6.55	<0.5	3.5 (09/07)	2.0 (09/08)	2.3 (09/13)	—	3.4 (09/17)	2.4
Sept. 30, 1998	4.17	1.9 (10/05)	2.5 (10/01)	3.0 (10/08)	.6 (10/14)	—	.5 (10/10)	3.0
Dec. 26, 1998	1.60	—	—	<.5	—	—	—	1.5
Jan. 3, 1999	1.13	<.5	.7 (01/04)	<.5	<.5	<.5	<.5	1.3
Jan. 18, 1999	1.12	.2	1.7 (01/24)	.2	<.5	.5 (01/29)	<.5	3.4
Jan. 23, 1999	1.65	2.5 (01/29)	1.3 (01/30)	3.8 (02/02)	.7 (02/10)	<.5	1.0 (02/21)	5.2
Mar. 14, 1999	1.20	—	1.5 (03/15)	—	—	—	—	2.8

Recharge and Ground-Water Ages

This study and previous studies indicate that recharge to the Upper Floridan aquifer occurs through the undifferentiated overburden in the central part of the study area. Vertical hydraulic conductivities for the undifferentiated overburden (Torak and others, 1993), static water-level data from the undifferentiated overburden and the Upper Floridan aquifer (Warner, 1997), and ground-water age data from this study indicate that the mound in the central part of the study area is the result of recharge.

The Upper Floridan aquifer may receive more recharge in areas where the undifferentiated overburden has a higher vertical hydraulic conductivity. The vertical hydraulic conductivity of the undifferentiated overburden in the area of the mound ranges from about 1×10^{-5} to 2.5×10^{-5} ft/day; whereas, in the area surrounding the mound, the overburden has a vertical hydraulic conductivity of about 1×10^{-8} to 1×10^{-9} ft/day (Torak and others, 1993). Static water levels in three of six undifferentiated overburden wells drilled as part of well-cluster sites in the center of the study area indicate recharge to the Upper Floridan aquifer (Warner, 1997). These well clusters were drilled for an Upper Floridan aquifer test during which all of the undifferentiated overburden wells showed response to pumping of the Upper Floridan aquifer, indicating a hydraulic connection (Warner, 1997).

Apparent ground-water ages (time of recharge) were determined in 21 wells, 1 spring, and 1 pond by measuring the concentration of CFCs in samples collected during September 1998. The apparent ground-water age in the study area ranges from modern (less than 2 years since recharge) to greater than 50 years (fig. 10, table 4). Most of the water ranges in age from 10 to 20 years, with water younger than 20 years located in the central and the southeastern parts of the study area, and water older than 20 years present in the northwestern and southern parts of the study area (fig. 10). In this report, with the exception of well 12L326 (+/– 5 years), the reported uncertainty in apparent ground-water ages is +/– 2 years (Leonard N. Plummer, U.S. Geological Survey, oral commun., 1999). These age data are consistent with the apparent ages determined in the study area during 1993 using CFC and tritium concentrations (Stewart and others, 1999), which indicates no major changes in the flow system between 1993 and 1998 (fig. 10). The younger water in the central part of the study area is coincident with the position of the ground-water mound (figs. 7 and 8), indicating that the aquifer receives more recharge in the area of the mound than in the northwestern and southern parts of the study area. Water from two samples collected in the northern part of the study area (wells 12L324 and 12L326) were dated at 44 years or greater, indicating less rapid recharge (or longer flowpaths) in that area. This water also is anoxic, further indicating little recharge or older water.



EXPLANATION

— *155* – – **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells during May 1998. Dashed where approximately located. Hachures indicate depression. Contour interval 10 feet. Datum is NGVD 29

Direction of ground-water flow

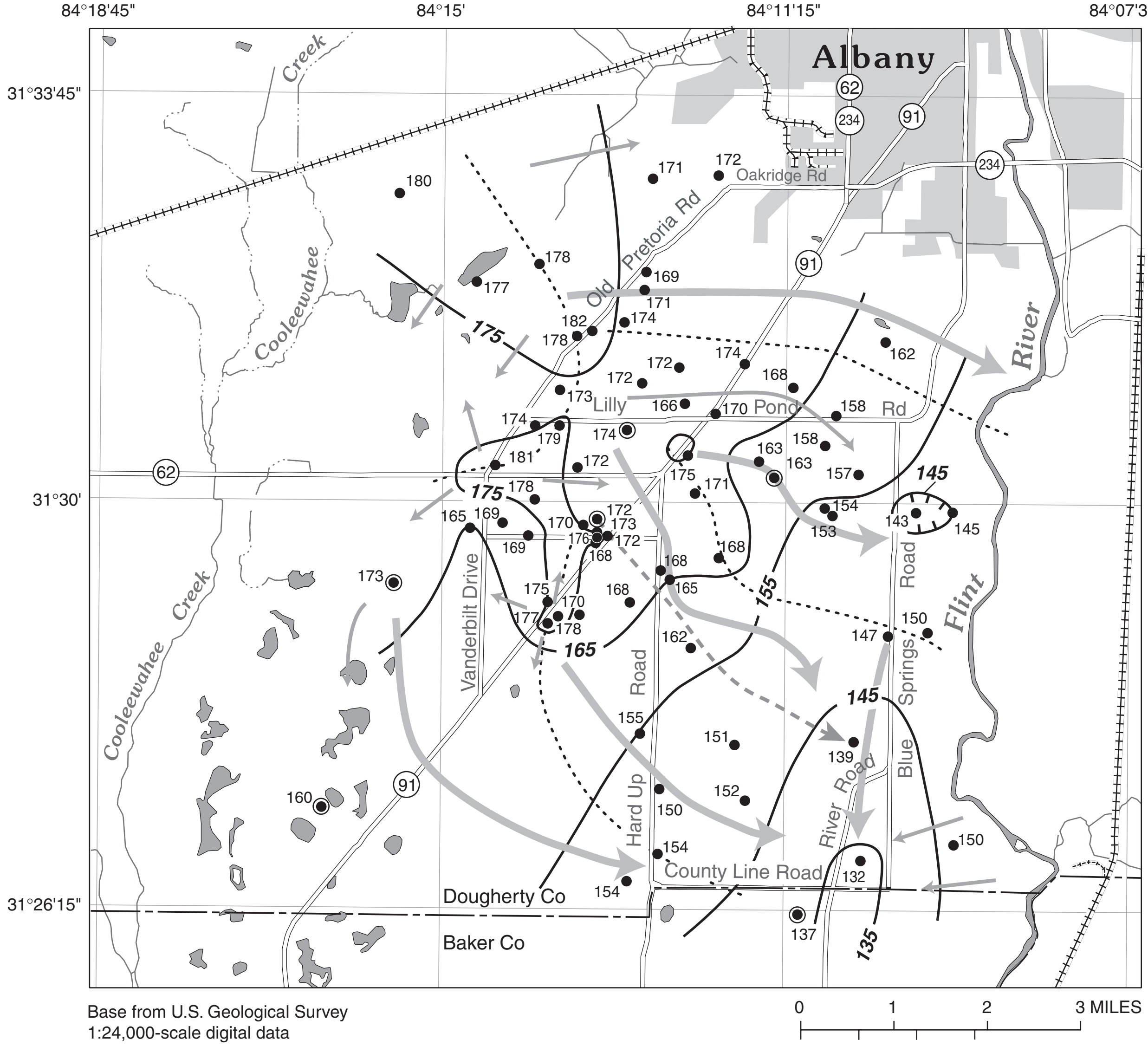
Flowpath used for hydraulic-gradient calculation

Ground-water divide

●164 **Well and water level**

◉179 **Continuous recorder well and water level**

Figure 7. Potentiometric surface of the Upper Floridan aquifer, southwestern Albany area, Georgia, May 1998.



EXPLANATION

— *155* — — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells during October 1998. Hachures indicate depression. Contour interval 10 feet. Datum is NGVD 29

➞ → **Direction of ground-water flow**—Thick arrow indicates major flowpath

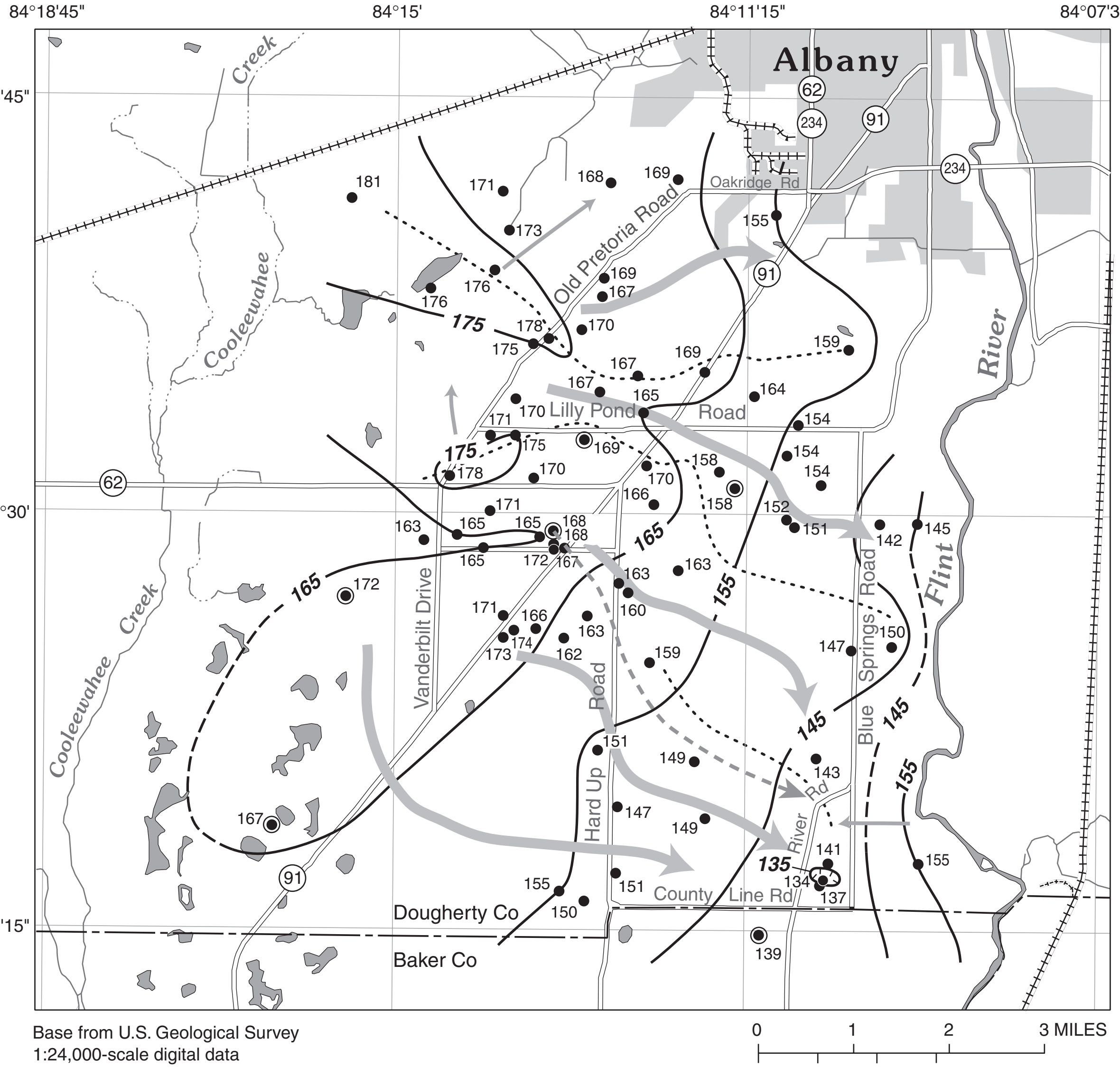
- - - ➤ **Flowpath used for hydraulic-gradient calculation**

-------- **Ground-water divide**

●154 **Well and water level**

◉172 **Continuous recorder well and water level**

Figure 8. Potentiometric surface of the Upper Floridan aquifer, southwestern Albany area, Georgia, October 1998.



EXPLANATION

— *155* – – **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells during March 1999. Dashed where approximately located. Hachures indicate depression. Contour interval 10 feet. Datum is NGVD 29

➡ → **Direction of ground-water flow**—Thick arrow indicates major flowpath

- - -➤ **Flowpath used for hydraulic-gradient calculation**

······ **Ground-water divide**

● 151 **Well and water level**

◉ 167 **Continuous recorder well and water level**

Figure 9. Potentiometric surface of the Upper Floridan aquifer, southwestern Albany area, Georgia, March 1999.

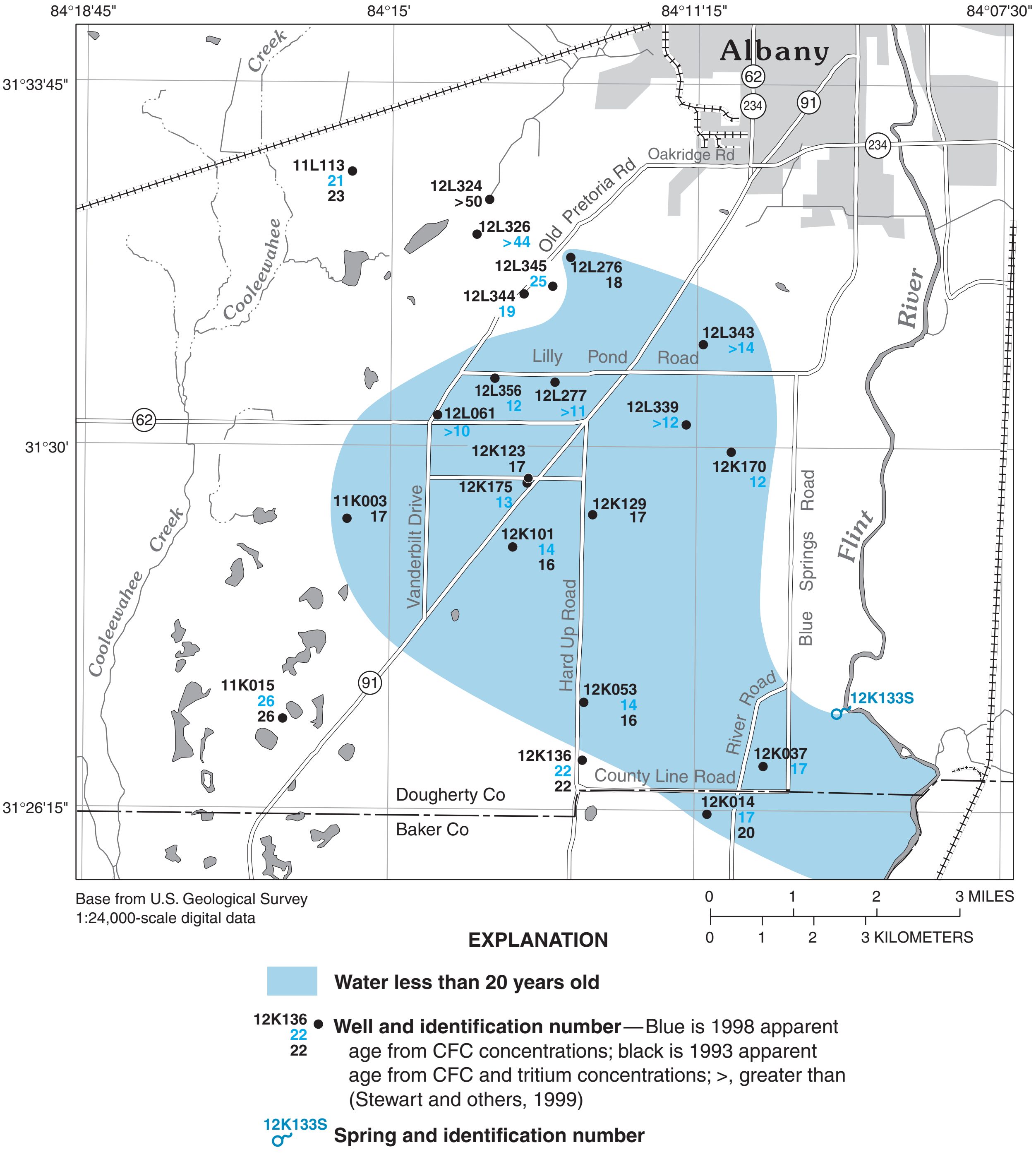


Figure 10. Apparent ground-water age at selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, September 1998.

Table 4. Apparent ground-water ages at selected wells, a spring, and a pond, southwestern Albany area, Georgia, September 1998.

[CFC, chlorofluorocarbon; the production of CFC-12 began during 1931 followed by CFC-11 during 1936, and many other CFC compounds since, including CFC-113; contaminated, refers to CFC concentrations greater than that possible for equilibrium with modern air; modern, less than 2 years; since recharge; >, greater than]

Well name (fig. 1)	Sampling period		Apparent year of recharge			Apparent[2] age, in years before 1998
	Date	Time[1]	CFC-11	CFC-12	CFC-113	
11K015	Sept. 1, 1998	1653	1970	1973	1980	26
		1703	1970	1972	1979	
		1713	1969	1970	1980	
11L113	Sept. 8, 1998	1340	1955	1975	1994	23
		1356	1955	1977	1990	
		1405	1961	1981	contaminated	
12K014	Sept. 1, 1998	1915	1983	1981	1985	17
		1925	1984	1981	1983	
		1945	1984	1986	1983	
12K037	Sept. 2, 1998	1520	1982	1982	1984	17
		1535	1980	1980	1983	
		1545	1982	1981	1984	
12K053	Sept. 2, 1998	1756	1980	contaminated	1984	14
		1821	1978	modern	1984	
		1815	1980	contaminated	1985	
12K101	Sept. 9, 1998	1020	contaminated	contaminated	1984	14
		1042	contaminated	contaminated	1984	
		1050	contaminated	contaminated	1985	
12K123	Aug. 31, 1998	1825	contaminated	1994	1991	contaminated
		1800	contaminated	contaminated	1992–1998	
		1815	contaminated	modern	1991	
12K133S	Sept. 2, 1998	1400	contaminated	1988	contaminated	contaminated
		1328	contaminated	1988	contaminated	
		1406	contaminated	1989	contaminated	
12K136	Sept. 9, 1998	1225	1974	1978	1986	22
		1310	1974	1976	1985	
		1323	1974	1976	1994	
12K170	Sept. 2, 1998	1618	contaminated	1993	1986	12
		1625	contaminated	1994	1986	
		1601	contaminated	1992	1986	
12K175	Sept. 8, 1998	1613	contaminated	contaminated	1983	13
		1625	modern	1985	1982	
		1640	modern	1986	1985	
12L061	Sept. 2, 1998	1815	contaminated	contaminated	contaminated	contaminated (>10)
		1830	contaminated	contaminated	modern	
		1150	contaminated	contaminated	1989	

Table 4. Apparent ground-water ages at selected wells, a spring, and a pond, southwestern Albany area, Georgia, September 1998.—Continued

[CFC, chlorofluorocarbon; the production of CFC-12 began during 1931 followed by CFC-11 during 1936, and many other CFC compounds since, including CFC-113; contaminated, refers to CFC concentrations greater than that possible for equilibrium with modern air; modern, less than 2 years; since recharge; >, greater than]

Well name (fig. 1)	Sampling period		Apparent year of recharge			Apparent[2] age, in years before 1998
	Date	Time[1]	CFC-11	CFC-12	CFC-113	
12L269	Sept. 8, 1998	1108	contaminated	contaminated	contaminated	contaminated
		1140	contaminated	contaminated	contaminated	
		1150	contaminated	contaminated	contaminated	
12L277	Sept. 1, 1998	1020	contaminated	contaminated	1988	contaminated >11
		1040	contaminated	contaminated	1987	
		1055	contaminated	contaminated	1987	
12L326	Sept. 2, 1998	1130	1953	1960	<1955	[3]>44
		1045	1954	1954	1980	
		1125	1952	1959	1976	
12L339	Sept. 1, 1998	1350	contaminated	contaminated	1986	>12
		1410	contaminated	contaminated	1987	
		1420	contaminated	contaminated	1986	
12L343	Sept. 1, 1998	1757	contaminated	contaminated	1984	>14
		1738	contaminated	contaminated	1984	
		1802	contaminated	contaminated	1984	
12L344	Sept. 1, 1998	1258	1972	1978	1981	19
		1218	1972	1980	1984	
		1250	1972	1979	1983	
12L345	Sept. 1, 1998	1040	1971	1973	1981	26
		1046	contaminated	contaminated	contaminated	
		1020	1972	1977	1984	
12L350	Aug. 31, 1998	1520	contaminated	1997	contaminated	modern or contaminated
		1545	contaminated	1997	contaminated	
		1600	contaminated	modern	contaminated	
12L351	Sept. 9, 1998	1620	contaminated	contaminated	modern	modern or contaminated
		1645	contaminated	contaminated	modern	
		1700	contaminated	contaminated	contaminated	
12L356	Sept. 1, 1998	1610	1986	1988	1986	12
		1551	1986	1991	1988	
		1617	1986	1990	1986	
Cypress Pond	Sept. 2, 1998	1109	1985	contaminated	modern	modern
		1103	1978	contaminated	1991	
		1115	1973	contaminated	contaminated	

[1] Military time

[2] ± 2 years

[3] ± 5 years

Ground-Water Chemistry and Water Quality in the Upper Floridan Aquifer

By Stephen J. Lawrence

Ground-water quality is a qualitative description of how the concentration of chemical constituents in ground water, either acquired naturally or anthropogenically, compare to drinking-water or other water-quality standards or criteria. Water-quality standards relevant to the current study are legislated by the GaEPD (Georgia Environmental Protection Division, 2003). The standards are based on criteria recommended by the U.S. Environmental Protection Agency (USEPA) (U.S.Environmental Protection Agency, 2000a, b) as either primary or secondary maximum contaminant levels (PMCLs and SMCLs, respectively). These MCLs are thresholds beyond which ground water cannot be used for a specific purpose, such as drinking water or irrigation. Drinking water and agricultural irrigation are the primary uses of ground water from the Upper Floridan aquifer in the southwestern Albany area, Georgia. Specific MCLs that are applicable to the current study include those for nitrate as nitrogen (N) (PMCL, 1 mg/L), nitrate as N (PMCL, 10 mg/L), sulfate (SMCL, 250 mg/L), chloride (SMCL, 250 mg/L), iron (SMCL, 0.3 mg/L), manganese (SMCL, 0.05 mg/L), and fluoride (SMCL, 2.0 mg/L) (Georgia Environmental Protection Division, 2003, p. 655 and 664). Because water-quality standards are based on the concentration of chemical constituents in the water, assessing ground-water quality depends on an analysis of ground-water chemistry.

Sprinkle (1989) presented a thorough analysis of regional ground-water chemistry in the Upper Floridan aquifer; that report gives good, baseline descriptions of the ground-water chemistry in the Upper Floridan aquifer for Alabama, Georgia, South Carolina, and Florida. The ground-water chemistry described in the text that follows is often referenced to the ground-water chemistry described by Sprinkle (1989).

Description of Ground-Water Chemistry and Water Quality

The ground-water chemistry in any aquifer is a complex mixture determined by the interplay of water, microbes, and minerals. The effect on water chemistry is determined by aquifer and overburden geology, rates of ground-water flow, rates and locations of recharge, the presence or absence of DO, the dissolution rates of aquifer minerals, the types of microbes, the impact of human influences, and the physics, chemistry, and other interactions among chemical elements and compounds in the water.

Because ground-water chemistry is complex, statistical analyses commonly are used to identify patterns or trends in the chemistry. Patterns or trends in the ground-water chemistry of the Upper Floridan aquifer may point to a potential source or several potential sources of elevated constituent concentrations in the study area. The statistical relations described in the discussion that follows are primarily derived from cluster analysis, correlation analysis, multiple regression analysis, and nonparametric t-tests.

The analytical results of QC samples are listed in tables 5 and 6. Major and minor constituent concentrations in the equipment blanks are from 10 to 500 times lower than concentrations found in ground-water samples, indicating adequate cleaning of the sampling equipment and no impact from equipment construction. Ammonia, however, is present in blank samples, but at concentrations below the laboratory reporting limit of 0.01mg/L. Replicate samples show excellent precision and indicate laboratory bias is minimal.

pH, Specific Conductance, and Dissolved Oxygen

Measures of pH, SC, and DO provide a relatively quick, general indication of the chemical and water-quality conditions of ground water. Apart from human influences, low pH levels and low DO concentrations within an aquifer are uncommon, but when present can markedly affect the concentration of many major and minor constituents, and several nutrients in ground water (Hem, 1985, p. 61 and 62). Low pH values, less than 6, or DO concentrations less than 1 mg/L, are commonly associated with substantial changes in aquifer geochemistry. Aquifer geochemistry typically dictates the presence and chemistry of dissolved elements and compounds (ions) in ground water. The magnitude of those constituents commonly is measured indirectly by the electrical conductivity of the water. This electrical conductivity, in microsiemens per centimeter, typically is measured and reported as SC—the electrical conductivity normalized to 25 degrees Celsius (°C).

In the current study, pH, SC, and DO values (tables 7 and 8) measured during September 1998 are statistically similar to those measured during March 1999 (p-value <0.001). Collectively, the pH measurements in all ground-water samples collected during this study range from 7.0 to 8.1 standard units (SU) (tables 7 and 8). The median pH measured during the study period is 7.6 (table 9). Because the measured pH values in this study are between 7.0 and 8.1, pH is not expected to substantially affect the concentration of chemical constituents, especially minor constituent and nutrient concentrations in the study area.

Various levels of correlation are observed among pH, SC, DO, and depth to water below land surface, and the chemical constituents in ground-water samples. The results of Spearman correlation analysis between pH and all constituents in all samples are presented in tables 10 and 11. The correlation analysis shows that pH has a statistically significant, inverse relation to all major chemical constituents measured during the study. A moderate, inverse relation exists between pH and magnesium, sodium, potassium, sulfate, chloride, and silica (table 10).

Table 5. Analytical results from an equipment blank sample and from duplicate ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998.

[ID, identification; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; ANC, acid-neutralizing capacity; <, less than; —, not applicable]

Well name or sample ID (fig. 1)	pH (standard units)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Dissolved concentration (mg/L)						
				Calcium	Magnesium	Sodium	Potassium	ANC as bicarbonate	Sulfate	Chloride
Equipment blank	6.0	<1	—	00.2	<0.1	<0.1	<0.1	<1	<0.1	0.2
11L113	7.4	330	<.5	69.0	.5	3.1	.1	160	6.4	7.9
		330	<.5	67.6	.5	3.0	.2	160	6.1	7.5
12K014	7.7	180	8.5	35.0	.5	1.4	.1	82	.3	2.8
	7.7	180	8.5	34.4	.5	1.5	.2	82	.4	2.7
	7.7	180	8.5	34.4	.5	1.5	.1	81	.2	2.7
12K133S	7.6	190	8.6	36.1	.5	1.6	.2	82	.4	3.6
		190	8.6	37.1	.5	1.6	.3	83	.3	3.7
12K136	8.1	160	7.2	29.3	.9	1.6	.3	70	.5	2.8
	8.1	160	7.2	29.6	.9	1.6	.3	70	.5	2.9
12K170	7.7	250	6.8	45.1	.9	2.4	.4	79	.5	8.5
		250	6.8	43.8	.9	2.4	.4	79	.5	8.4

Well name or sample ID (fig. 1)	Dissolved concentration (mg/L)									
	Iron	Manganese	Barium	Strontium	Silica	Ammonia	Fluoride	Bromide	Nitrate	Orthophosphate
Equipment blank	<.04	<.04	<.01	<.01	.01	.01	<.02	<.02	<.02	<.02
11L113	.08	.11	<.01	.04	3.48	<.01	<.02	<.02	<.02	<.02
		.12	<.01	.04	3.45	<.01	<.02	<.02	<.02	<.02
12K014	<.04	<.04	<.01	.02	3.27	<.01	<.02	<.02	1.50	<.02
	<.04	<.04	<.01	.02	3.47	<.01	<.02	<.02	1.50	.10
	<.04	<.04	<.01	.02	3.40	<.01	.10	<.02	1.50	<.02
12K133S	<.04	<.04	<.01	.02	3.32	<.01	<.02	<.02	2.50	<.02
		<.04	<.01	.02	3.30	<.01	.10	<.02	2.50	.10
12K136	<.04	<.04	<.01	.05	3.69	<.01	<.02	<.02	1.90	.10
	<.04	<.04	<.01	.05	3.66	<.01	<.02	<.02	2.00	<.02
12K170	<.04	<.04	<.01	.03	3.53	.01	<.02	<.02	7.00	<.02
		<.04	<.01	.03	3.51	<.01	<.02	<.02	7.40	<.02

Table 6. Analytical results from duplicate ground-water samples from selected wells, southwestern Albany area, Georgia, March 1999.

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; ANC, acid-neutralizing capacity; <, less than]

Well name (fig. 1)	pH (standard units)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Dissolved concentration (mg/L)						
				Calcium	Magnesium	Sodium	Potassium	ANC as bicarbonate	Sulfate	Chloride
11K015	7.7	270	3.4	52.1	0.6	1.8	0.4	130	0.5	3.9
	7.7	270	3.4	52.6	.6	1.7	.4	130	.5	3.9
12K037	7.2	310	3.8	53.2	1.3	2.8	.7	130	.8	5.8
		310	3.8	54.1	1.3	2.8	.7	130	.8	5.6
12K053	8.0	170	5.8	32.7	.4	1.5	.2	77	.7	3.4
	8.0	170	5.8	32.4	.4	1.4	.2	77	.7	3.4
12L343	7.6	270	6.8	43.8	3.9	2.4	1.0	110	1.3	5.0
		270	6.8	45.2	3.8	2.3	.9	110	1.2	5.1

Well name (fig. 1)	Dissolved concentration (mg/L)								
	Barium	Bromide	Fluoride	Iron	Manganese	Strontium	Ammonia	Nitrate	Orthophosphate
11K015	<.01	<.02	<.02	<.04	<.04	.03	<.01	.46	<.02
	<.01	<.02	<.02	<.04	<.04	.03	<.01	.45	<.02
12K037	.01	<.02	.07	<.04	<.04	.04	<.01	3.05	.03
		<.02	<.02	<.04	<.04	.04	<.01	2.98	.02
12K053	<.01	<.02	.02	<.04	<.04	.02	<.01	2.18	<.02
	<.01	.02	.02	<.04	<.04	.02	<.01	2.20	<.02
12L343	<.01	.02	.11	<.04	<.04	.18	<.01	6.04	<.02
		<.02	<.02	<.04	<.04	.17	<.01	6.02	<.02

Table 7. Results of field and laboratory measurements for selected water-quality constituents in ground-water samples from selected wells, southwestern Albany area, Georgia, August 31–September 9, 1998.

[ft bls, feet below land surface; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligrams per liter; ANC, acid-neutralizing capacity; <, less than; —, not determined]

Well name (fig. 1)	Depth to static water (ft bls)	Water temperature (°C)	pH (standard units)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Dissolved concentration (mg/L)							
						Calcium	Magnesium	Sodium	Potassium	ANC as bicarbonate	Sulfate	Chloride	Silica
11K015	17.3	20.8	7.5	248	4.3	52	0.6	1.6	0.38	157	0.6	2.6	3.6
11L113	192.7	20.8	7.4	331	<.5	69	.5	3.1	.14	197	6.4	7.9	3.5
12K014	47.0	20.7	7.7	177	8.5	35	.5	1.4	.14	100	.3	2.8	3.3
12K037	47.1	20.4	7.3	269	5.7	52	1.1	2.6	.47	156	.7	4.4	3.5
12K053	40.0	20.9	7.8	181	6.6	35	.4	1.4	.23	93	.8	3.0	3.0
12K101	34.0	20.3	7.8	193	7.7	36	.4	1.8	.25	103	.3	3.7	3.5
12K123	26.5	20.7	7.6	241	11.1	44	.5	3.2	.34	129	.5	4.5	3.8
12K129	32.0	20.1	7.9	194	7.7	38	.5	2.0	.25	103	.4	4.5	3.6
12K133S	0	20.6	7.6	190	8.6	36	.5	1.6	.25	100	.4	3.6	3.3
12K136	40.1	20.4	8.1	162	7.2	29	.9	1.6	.28	85	.5	2.8	3.7
12K170	28.8	21.4	7.7	251	6.8	45	.9	2.4	.37	97	.5	8.5	3.5
12K175	27.3	20.3	8.0	225	9.4	43	.6	3.0	.34	114	.5	5.4	3.6
12L047	—	19.5	7.3	355	1.4	75	.9	3.1	.38	223	2.8	4.7	4.3
12L061	18.7	20.8	7.0	356	5.0	68	1.9	4.6	1.07	149	1.1	10.0	4.5
12L277	20.9	20.7	7.4	315	7.7	61	1.0	2.9	.80	147	1.0	8.9	4.0
12L311	9.5	21.9	7.3	321	<.5	64	1.5	2.5	.60	198	1.2	3.7	6.1
12L326	17.4	20.3	7.3	319	<.5	66	.8	3.3	.65	193	5.9	5.8	3.6
12L339	43.9	20.9	7.7	251	7.2	48	.8	2.3	.43	120	.9	6.6	3.8
12L343	25.0	21.0	7.6	280	2.1	46	4.0	2.5	.99	131	1.1	4.8	6.8
12L344	18.7	20.4	7.2	363	.9	70	1.2	3.2	.50	187	2.1	6.6	4.2
12L345	23.9	21.4	7.5	266	4.2	53	.7	1.8	.27	144	.7	3.9	4.0
12L350	21.6	20.6	7.5	257	5.6	51	.7	2.4	.55	141	1.2	5.0	3.6
12L351	19.3	20.6	7.8	283	5.0	52	.8	2.3	.39	143	.8	6.0	3.8
12L356	19.8	20.6	7.4	284	5.1	54	.8	2.3	.39	144	.9	5.2	4.0
12L357	15.0	20.4	7.2	400	1.6	79	1.3	3.5	.91	206	5.4	8.3	4.1
Median	**23.9**	**20.6**	**7.5**	**266**	**6.2**	**52**	**.8**	**2.4**	**.38**	**143**	**.8**	**4.8**	**3.7**

Table 7. Results of field and laboratory measurements for selected water-quality constituents in ground-water samples from selected wells, southwestern Albany area, Georgia, August 31–September 9, 1998.—Continued

[ft bls, feet below land surface; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligrams per liter; ANC, acid-neutralizing capacity; <, less than; —, not determined]

Well number (fig. 1)	Dissolved concentration (mg/L)								
	Ammonia as nitrogen	Nitrite plus nitrate as nitrogen	Orthophosphate as phosphorus	Barium	Bromide	Fluoride	Iron	Manganese	Strontium
11K015	<0.002	0.40	<0.02	<0.01	<0.02	<0.02	<0.04	<0.04	0.03
11L113	<.010	<.02	<.02	<.01	<.02	<.02	.08	.11	.04
12K014	<.010	1.50	<.02	<.01	<.02	<.02	<.04	<.04	.02
12K037	<.010	2.20	<.02	<.01	<.02	<.02	<.04	<.04	<.02
12K053	<.002	2.10	<.02	<.01	<.02	<.02	<.04	<.04	.02
12K101	<.010	1.80	<.02	<.01	<.02	<.02	<.04	<.04	.02
12K123	<.010	2.00	<.02	<.01	<.02	<.02	<.04	<.04	.03
12K129	<.010	2.60	<.02	<.01	<.02	<.02	<.04	<.04	<.02
12K133S	<.010	2.50	<.02	<.01	<.02	<.02	<.04	<.04	.02
12K136	<.010	1.90	.03	<.01	<.02	<.02	<.04	<.04	.05
12K170	<.002	7.00	<.02	<.01	<.02	<.02	<.04	<.04	.03
12K175	<.010	3.80	<.02	<.01	<.02	<.02	<.04	<.04	.03
12L047	<.010	.70	<.02	<.01	<.02	<.02	<.04	<.04	.05
12L061	<.010	11.00	<.02	.01	<.02	<.02	<.04	<.04	.05
12L277	<.002	7.50	<.02	<.01	.10	<.02	<.04	<.04	.04
12L311	.060	<.02	<.02	.01	<.02	<.02	<.04	.09	.07
12L326	.040	.20	<.02	.01	<.02	<.02	<.04	.07	.04
12L339	<.002	5.90	<.02	<.01	<.02	<.02	<.04	<.04	.03
12L343	<.010	6.50	<.02	<.01	<.02	<.02	<.04	<.04	.20
12L344	<.010	6.00	<.02	<.01	<.02	<.02	<.04	<.04	.04
12L345	<.010	3.10	<.02	<.01	<.02	<.02	<.04	<.04	.03
12L350	.020	3.00	<.02	<.01	<.02	.10	<.04	<.04	.03
12L351	<.010	5.20	.03	<.01	<.02	.10	<.04	<.04	.03
12L356	<.002	4.50	<.02	<.01	<.02	<.02	<.04	<.04	.03
12L357	.010	5.90	<.02	.01	.10	<.02	<.04	<.04	.05
Median	**<.010**	**2.60**	**<.02**	**<.01**	**<.02**	**<.02**	**<.04**	**<.04**	**.03**

Table 8. Results of field and laboratory measurements for selected water-quality constituents in ground-water samples from selected wells, southwestern Albany area, Georgia, March 1–4, 1999.

[ft bls, feet below land surface; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligrams per liter; ANC, acid-neutralizing capacity; —, not determined; <, less than]

Well name (fig 1.)	Depth to static water level (ft bls)	Water temperature (°C)	pH (standard units)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Dissolved concentration (mg/L)							
						Calcium	Magnesium	Sodium	Potassium	ANC as bicarbonate	Sulfate	Chloride	Silica
11K015	16.4	20.8	7.7	266	3.4	52	0.63	1.8	0.42	164	0.6	3.9	3.6
12K014	43.8	20.7	8.0	181	8.5	34	.48	1.5	.16	101	.3	3.0	3.3
12K037	44.2	20.3	7.2	309	3.8	53	1.28	2.8	.66	162	.8	5.8	3.4
12K053	41.7	20.6	8.0	170	5.8	33	.42	1.5	.23	94	.7	3.4	3.0
12K101	38.1	20.5	8.0	184	6.9	37	.41	1.9	.29	104	.3	4.2	3.5
12K123	25.4	20.7	7.8	233	9.5	44	.44	3.3	.35	131	.4	4.8	3.7
12K129	36.4	20.0	8.0	200	9.1	37	.49	1.9	.23	104	.2	5.0	3.4
12K133S	0	19.5	8.1	201	7.1	37	.54	1.7	.26	104	.4	4.1	3.4
12K136	42.7	20.8	8.1	162	6.4	29	1.12	1.6	.28	87	.5	3.2	3.7
12K175	28.8	20.1	7.7	250	9.2	46	.64	3.5	.41	114	.3	7.6	3.4
12L047	—	19.7	7.2	354	.9	70	.88	3.1	.34	221	3.1	5.2	4.0
12L061	12.3	20.7	7.6	371	5.5	64	1.48	4.5	1.12	152	1.2	10.8	4.4
12L277	17.4	21.0	7.6	246	6.5	51	.80	2.6	.70	130	.9	8.0	3.6
12L311	8.0	20.5	8.0	297	<.5	56	1.07	2.5	.58	184	1.3	4.4	4.7
12L326	16.7	20.4	7.3	342	<.5	67	.75	2.9	.61	213	1.8	5.1	4.2
12L339	46.6	21.3	7.7	223	5.5	47	.76	2.2	.40	124	.8	6.9	3.5
12L343	28.3	20.4	7.6	270	6.8	44	3.89	2.4	.99	132	1.3	5.0	6.5
12L344	21.8	19.7	7.4	358	.7	66	1.10	3.0	.45	193	1.7	6.6	3.9
12L345	25.4	20.1	7.5	294	4.2	54	.85	2.2	.31	158	.9	5.7	3.9
12L348	26.8	20.0	7.6	286	7.5	53	.98	2.8	.37	134	.6	7.6	3.8
12L350	24.9	20.5	7.5	224	3.8	51	.61	2.2	.45	145	1.4	4.9	3.4
12L351	25.8	20.7	7.8	234	6.2	44	.59	2.5	.30	118	.6	6.1	3.4
12L356	20.3	20.0	7.9	282	5.6	51	.81	2.4	.37	151	1.2	5.6	3.9
12L357	14.8	19.9	7.7	386	.9	76	1.12	3.4	.96	217	5.6	7.4	4.0
Median	**25.4**	**20.4**	**7.7**	**258**	**6.0**	**51**	**.78**	**2.4**	**.39**	**133**	**.8**	**5.1**	**3.6**

Table 8. Results of field and laboratory measurements for selected water-quality constituents in ground-water samples from selected wells, southwestern Albany area, Georgia, March 1–4, 1999.—Continued

[ft bls, feet below land surface; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25° Celsius; ANC, acid-neutralizing capacity; —, not determined; <, less than]

Well name (fig. 1)	Dissolved concentration (milligrams per liter)								
	Ammonia as nitrogen	Nitrite plus nitrate as nitrogen	Orthophosphate as phosphorus	Barium	Bromide	Fluoride	Iron	Manganese	Strontium
11K015	<0.01	0.46	<0.02	<0.01	<0.02	<0.02	<0.04	<0.04	0.03
12K014	<.01	1.55	<.02	<.01	<.02	.03	<.04	<.04	.02
12K037	<.01	3.05	.03	.01	<.02	.07	<.04	<.04	.04
12K053	<.01	2.18	<.02	<.01	<.02	<.02	<.04	<.04	.02
12K101	<.01	1.93	<.02	<.01	<.02	<.02	<.04	<.04	.02
12K123	<.01	2.08	<.02	<.01	<.02	<.02	<.04	<.04	.03
12K129	<.01	2.94	.02	<.01	<.02	<.02	<.04	<.04	.02
12K133S	<.01	2.56	.04	<.01	<.02	<.02	<.04	<.04	.03
12K136	<.01	2.07	<.02	<.01	<.02	.05	<.04	<.04	.06
12K175	<.01	5.70	<.02	<.01	<.02	.04	<.04	<.04	.03
12L047	<.01	.58	<.02	<.01	.05	.06	<.04	<.04	.05
12L061	<.01	12.20	<.02	.01	<.02	<.02	<.04	<.04	.05
12L277	<.01	6.94	<.02	<.01	<.02	<.02	<.04	<.04	.03
12L311	.06	<.01	<.02	.01	<.02	.06	<.04	.13	.05
12L326	.10	<.01	<.02	.01	.10	<.02	<.04	.14	.04
12L339	<.01	5.42	<.02	<.01	.05	<.02	<.04	<.04	.03
12L343	<.01	6.04	<.02	<.01	<.02	.11	<.04	<.04	.18
12L344	<.01	5.06	<.02	<.01	<.02	<.02	<.04	<.04	.04
12L345	<.01	4.40	<.02	<.01	<.02	<.02	<.04	<.04	.03
12L348	<.01	6.46	<.02	<.01	<.02	<.02	<.04	<.04	.04
12L350	.02	2.86	.02	<.01	<.02	<.02	<.04	<.04	.03
12L351	<.01	4.40	<.02	<.01	<.02	<.02	<.04	<.04	.03
12L356	<.01	3.80	<.02	<.01	.02	<.02	<.04	<.04	.03
12L357	.01	3.13	.02	.01	.02	<.02	<.04	<.04	.05
Median	**<.01**	**3.02**	**<.02**	**<.01**	**<.02**	**<.02**	**<.04**	**<.04**	**.03**

Table 9. Median and third-quartile concentrations[1] of major chemical constituents, and selected nutrients in rainfall samples (wet deposition), and ground-water samples from regional (Sprinkle, 1989) and local (southwestern Albany area) studies of the Upper Floridan aquifer.

[°C; degrees Celsius; pH, negative log of hydrogen ion concentration in standard units; SC, specific conductance; µS/cm, microsiemens per centimeter at 25 degrees Celsius; DO, dissolved oxygen; Ca, calcium ion, Mg, magnesium ion; Na, sodium ion; K, potassium ion; ANC, acid-neutralizing capacity as bicarbonate ion; SO_4, sulfate ion; Cl, chloride ion; Si, silica, NH_4, ammonia; NO_3, nitrate ion; —, not determined; <, less than]

Source	Water temperature (°C)	pH (standard units)	SC (µS/cm)	Dissolved concentration in milligrams per liter (mg/L) Median (third quartile)											Na/Cl ratio	K/Cl ratio	SO_4/Cl ratio
				DO	Ca	Mg	Na	K	ANC	SO_4	Cl	Si	NH_4	NO_3			
Rainfall, Tift County, Ga.[2]	—	4.8	12.8	—	0.07 (.14)	0.03 (.06)	0.19 (.37)	0.03 (.06)	—	1.05 (1.82)	0.33 (.62)	—	0.12 (.24)	0.79 (1.38)	0.90 (.98)	0.07 (.14)	2.3 (4.3)
Sprinkle (1989, various plates)[3]	21.1 (21.7)	7.0 to 8.5	<455 (—)	—	60 (—)	<6 (—)	<12 (—)	<3 (—)	183 (—)	<25 (—)	<125 (—)	13.4 (20.2)	.05 (.12)	.99 (.05)	1.0 to 3.0	.03 to.06	.16 (—)
Albany, Georgia[4]	20.6	7.6	266 (315)	5.6 (7.2)	51 (61)	.78 (1.07)	2.40 (2.99)	.38 (.58)	141 (162)	.80 (1.22)	5.0 (6.6)	3.7 (4.0)	<.01 (<.01)	2.90 (5.4)	.71 (.79)	.07 (.10)	.12 (.19)

[1] Top number is median and bottom number, in parentheses is third-quartile concentration

[2] U.S. Geological Survey National Atmospheric Deposition station (Chula) (USGS, 2000)

[3] Data from unconfined recharge areas in Upper Floridan aquifer

[4] Data from this current study, 1998–99

Table 10. Spearman rank correlation coefficients and p-values[1] for pH, dissolved oxygen, water temperature, and major constituents in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999.

[pH, negative log of hydrogen ion concentration; °C, degrees Celsius; DO, dissolved oxygen; SC, specific conductance; Ca, dissolved calcium; Mg, dissolved magnesium; Na, dissolved sodium; K, dissolved potassium; ANC, acid-neutralizing capacity as dissolved bicarbonate in mg/L; SO_4, dissolved sulfate; Cl, dissolved chloride; SiO_2, dissolved silica; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; DWLS, depth to water in feet below land surface; –, minus; NS, not significant at alpha = .05; <, less than; —, not determined]

	Age[2]	pH (standard units)	Water temperature (°C)	Spearman rank correlation coefficients and p-values									
				DO (mg/L)	SC (µS/cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	ANC (mg/L)	SO_4 (mg/L)	Cl (mg/L)	SiO_2 (mg/L)
DWLS	–0.190 NS	0.340 .015	0.180 NS	0.470 <.001	–0.540 <.001	–0.540 <.001	–0.310 .032	–0.350 .014	–0.430 .002	–0.570 <.001	–0.440 .001	–0.140 NS	–0.540 <.001
Age[2]	1.000 —	–.280 NS	.030 NS	–.680 <.003	.220 NS	.300 NS	.240 NS	–.040 NS	.060 NS	.360 NS	.360 NS	–.130 NS	–.030 NS
pH		1.00 —	–.010 NS	.612 <.001	–.760 <.001	–.820 <.001	–.500 <.001	–.570 <.001	–.570 <.001	–.760 <.001	–.660 <.001	–.410 .004	–.450 .001
Water temperature				.012 NS	–.190 NS	–.150 NS	–.020 NS	–.230 NS	.060 NS	–.230 NS	–.080 NS	–.070 NS	–.010 NS
DO				1.000 —	–.700 <.001	–.760 <.001	–.500 <.001	–.300 .038	–.460 .001	–.800 <.001	–.810 <.001	–.190 NS	–.480 <.001
SC						.960 <.001	.680 <.001	.770 <.001	.670 <.001	.900 <.001	.790 <.001	.640 <.001	.720 <.001
Ca						1.000 —	.580 <.001	.710 <.001	.630 <.001	.940 <.001	.800 <.001	.580 <.001	.650 <.001
Mg								.490 <.001	.750 <.001	.510 <.001	.580 <.001	.440 .001	.720 <.001
Na								1.000 —	.620 <.001	.630 <.001	.530 <.001	.730 <.001	.530 <.001
K										.580 <.001	.600 <.001	.550 <.001	.640 <.001
ANC										1.000 —	.790 <.001	.380 .006	.610 <.001
SO_4												.440 .002	.610 <.001
Cl												1.000 —	.320 .025

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[1] The top number in a cell is the correlation coefficient and the bottom number is the p-value; the correlation coefficient ranges from –1.0 to 1.0. The closer the number is to 1.0 the greater the positive relation between two constituents; the closer the coefficient is to –1.0 the greater the inverse relation between two constituents. The p-value is the probability that the two constituents are related only by chance; thus, a p-value of 0.0001 indicates a 0.01-percent probability that the correlation has happened by chance alone, a very slim possibility; number of samples in correlation analysis is 49

[2] Age, apparent ground-water age determined using chlorofluorocarbon dating; number of samples used in any correlation with age is 17

Table 11. Spearman rank correlation coefficients and p-values[1] for relations among depth to water, apparent ground-water age, pH, water temperature, dissolved oxygen, specific conductance, major constituents, selected minor constituents, and nutrients in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999.

[DWLS, depth to water in feet below land surface; pH, negative log of hydrogen ion concentration; °C, degrees Celsius; DO, dissolved oxygen; SC, specific conductance; Ca, dissolved calcium; Mg, dissolved magnesium; Na, dissolved sodium; K, dissolved potassium; ANC, acid-neutralizing capacity as bicarbonate; SO_4, dissolved sulfate; Cl, dissolved chloride; SiO_2, dissolved silica; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; —, minus; NS, not significant at alpha = .05; <, less than]

	DWLS	Age[2]	pH (standard units)	Water temperature (°C)	Spearman rank correlation coefficient and p-values									
					DO (mg/L)	SC (µS/cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	ANC (mg/L)	SO_4 (mg/L)	Cl (mg/L)	SiO_2 (mg/L)
Iron	0.250 NS	0.210 NS	–0.130 NS	0.130 NS	–0.224 NS	0.150 NS	0.190 NS	–0.140 NS	0.130 NS	–0.240 NS	0.180 NS	0.270 NS	0.200 NS	–0.150 NS
Manganese	–.190 NS	.440 NS	–.210 NS	.070 NS	–.524 <.001	.320 .023	.370 .010	.090 NS	.210 NS	.140 NS	.420 <.002	.420 <.003	.010 NS	.210 NS
Strontium	–.360 .010	.380 NS	–.510 <.001	–.004 NS	–.587 <.001	.700 <.001	.630 <.001	.860 <.001	.550 <.001	.630 <.001	.600 <.001	.680 <.001	.320 .024	.830 <.001
Ammonia as nitrogen[3]	–.160 NS	.170 NS	–.010 NS	–.210 NS	–.187 NS	.110 NS	.120 NS	.020 NS	.190 NS	.020 NS	.180 NS	.110 NS	–.030 NS	.050 NS
Nitrite plus nitrate as nitrogen	–.020 NS	–.430 NS	–.110 NS	.090 NS	.190 NS	.230 NS	.110 NS	.420 .003	.300 .037	.430 .002	–.110 NS	.060 NS	.690 <.001	.240 NS
Orthophosphate as phosphorus	.160 NS	.260 NS	.240 NS	–.270 .015	.336 .020	–.350 .010	–.350 .015	–.260 NS	–.200 NS	–.240 NS	–.320 .024	–.360 .010	–.27 NS	–.390 .006

[1] The top number in a cell is the correlation coefficient and the bottom number is the p-value; the correlation coefficient ranges from –1.0 to 1.0. The closer the number is to 1.0 the greater the positive relation between two constituents; the closer the coefficient is to -1.0, the greater the negative relation between two constituents. The p-value is the probability that the two constituents are related only by chance; thus a p-value of 0.0001 indicates a 0.01-percent probability that the correlation has happened by chance alone, a very slim possibility

[2] Age, apparent ground-water age determined using chlorofluorocarbon dating; number of samples used in correlation is 17

[3] Number of samples used in correlation is 48

Moreover, pH has a strong, inverse relation to SC, calcium, and ANC (table 10). However, pH is not statistically related to the minor constituents (such as iron and manganese) and nutrient concentrations ($p<0.05$; table 11). Moreover, pH has a strong, inverse relation to SC (−0.76) and a moderate, positive relation with DO (rho = 0.612). Although, the correlation coefficients (Spearman's rho) for the relation between pH and depth to water below land surface is minor, the relation is statistically significant and positive (rho = 0.34).

Ground-water samples collected during the current study have a wide range of SC values. These values range from 162 to 400 microsiemens per centimeter (μS/cm) (tables 7 and 8). The median value for all SC measurements, 266 μS/cm (table 9), is similar to the median SC measured nearly 20 years ago in the Upper Floridan aquifer near Albany, Georgia (250 μS/cm; Hicks and others, 1987). Because SC provides an indirect measure of chemical ion concentrations (elements with a positive or negative electrical charge) in water, one would expect that SC is strongly correlated to the concentrations of chemical constituents in that water. Indeed this is true for the ground-water samples collected during the current study. The SC is highly correlated with calcium (rho = 0.96, table 10) and ANC concentrations (rho = 0.90, table 10) in the ground-water samples collected in the study area. In addition, SC is statistically related to most of the other chemical constituents measured in ground-water samples except for apparent ground-water age, water temperature, iron, ammonia, and nitrate concentrations (tables 10 and 11).

DO measurements in ground water at 24 sampled wells indicate that four wells in each sample event have DO concentrations below 1.0 mg/L (tables 7 and 8). Individual DO measurements range from less than 0.5 mg/L (reporting level) to 11.1 mg/L (tables 7 and 8). The median DO measured at all wells is 5.6 mg/L (table 9). The low DO concentrations are important because at concentrations below 1.0 mg/L, nitrogen processing by soil and aquifer bacteria shifts from aerobic (nitrification) to anaerobic reactions (denitrification and nitrate reduction; Snoeyink and Jenkins, 1980, p. 409). Under anaerobic conditions, trace elements that commonly are sorbed to aquifer minerals are released to ground water and nitrate is converted to volatile nitrous compounds or ammonia. Such a condition can increase substantially the ground-water concentrations of several minor constituents, such as iron and manganese, or ammonia, but substantially decrease nitrate concentrations.

The Spearman correlation coefficients between DO and all chemical constituents measured during the study period are given in tables 10 and 11. The correlation analysis shows that DO has a moderate correlation with depth to water below land surface and pH (table 10). Moreover, DO has a strong, inverse correlation with SC, calcium, ANC, and sulfate concentrations. These relations indicate that low DO is associated with shallow ground water, low pH and elevated SC, calcium, ANC, and sulfate concentrations. Although DO shows a small, inverse correlation with the apparent ground-water age, magnesium, sodium, potassium, and silica concentrations, the relation is statistically significant, indicating that these constituents are slightly elevated where DO is low (table 10). DO concentrations, however, are not related statistically to chloride concentration (table 10). This lack of a relation indicates that the source of chloride to the Upper Floridan aquifer does not affect the overall DO concentrations in the study area.

Major Chemical Constituents

Major constituents are defined as inorganic chemical elements-or compounds that exist in water at concentrations greater than 1 mg/L (Hem, 1985). Tables 7 and 8 list the major constituent concentrations and median values measured in ground-water samples collected during the two sampling periods. A nonparametric t-test shows that major constituent concentrations from the September 1998 samples are statistically similar to those collected during March 1999. Because of this, the samples from these two sampling periods are combined for subsequent analyses.

According to Sprinkle (1989), water that moves into and replenishes most of the Upper Floridan aquifer generally is of two types: recharge water and upward leakage from deeper aquifers. Sprinkle (1989) showed that these two potential sources of ground water can have substantially different water chemistries. Upward leakage of water into the Upper Floridan aquifer from a deeper, water-bearing unit beneath the study area is unlikely however, because the Lisbon Formation (a dense, confining unit) is present below the Upper Floridan aquifer (fig. 2). Thus, recharge is the primary source of ground water in the Upper Floridan aquifer (Sprinkle, 1989). Recharge water may be derived from several sources such as infiltrating rainfall, seepage from rivers, streams, or lakes, or runoff from human activities (sewage effluent, irrigation, landscape runoff, artificial recharge). Although infiltrating rainfall is the primary source of water to the Upper Floridan aquifer, agricultural irrigation, and seepage from the Flint River or Cooleewahee Creek also may contribute a substantial amount, as discussed previously. Different sources of recharge to the Upper Floridan aquifer may contain markedly different concentrations of major constituents.

Initially, infiltrating rainfall contains low concentrations of chemical constituents. Rainfall samples collected between 1983 and 2000 in Tift County, Georgia (National Atmospheric Deposition Program, 2000 [NADP]), have a median SC less than 13 μS/cm (table 9). The chemistry of that water changes substantially however, between the recharge area and the ground water at sampled wells completed in the Upper Floridan aquifer within the study area. The median SC in ground-water samples is 20 times greater than the median SC in rainwater (table 9). This geochemical change is facilitated by the low pH in rainfall and its interaction with minerals, mostly calcite, in the overburden and Upper Floridan aquifer. The median pH of rainwater in the NADP samples is 4.8. This pH is acidic enough to produce dissolution of minerals as rainwater moves through the overburden in the study area and enters the Upper Floridan aquifer. The closer a well is to an area recharged by rainwater, the thinner the overburden, and the faster the recharge rate, the greater the chemical similarity between rainfall and ground water intercepted by that well. Water samples from such a well are expected to contain relatively low major constituent concentrations because of the limited amount of spatial and temporal contact with overburden and aquifer minerals.

The composition of major constituents in ground-water samples collected near Albany, Georgia, and analyzed for the current study are listed in tables 7 and 8. Calcium and bicarbonate are the dominant constituents in ground water collected from the Upper Floridan aquifer because calcite is the dominant mineral in the aquifer (Sprinkle, 1989, p. 129). Calcite consists of calcium carbonate, with minor amounts of magnesium, sodium, and potassium. The median ground-water concentration of calcium in the study area, 51 mg/L, is 70 times greater than the median concentration in rainwater and within the 40 to 60 mg/L range reported by Sprinkle (1989, p. 131) (table 9). In the current study, the median ANC concentration is 141 mg/L (table 9), slightly lower than that reported by Sprinkle (1989, p. 131). Although calcite chemistry determines the concentrations of calcium and bicarbonate in the Upper Floridan aquifer, Sprinkle (1989) described a zone in which the chemistry of recharge water has a substantial influence on ground-water chemistry. In this zone, the Upper Floridan aquifer is intermittently confined, the overburden is thin, and ground water is undersaturated with respect to calcite (Sprinkle, 1989, p. 131). The current study area lies within that recharge zone. Overburden in the study area consists of fine quartz sand, sandy silt, and sandy clay (fig. 2)—a geologic profile that may be favorable for local recharge.

Depending on the source of water, local recharge areas influence the concentrations of other major constituents in ground water, such as magnesium, sodium, potassium, sulfate, chloride, and silica (table 9). In the current study, magnesium, sodium, potassium, sulfate, chloride, and silica are substantially lower than the median values reported by Sprinkle (1989), and substantially higher than those measured in rainfall (table 9). The median magnesium concentration, 0.78 mg/L, is markedly lower than the median concentration reported for the Upper Floridan aquifer (Sprinkle, 1989, p. 136–137), but about 10 times greater than in rainfall. Sprinkle (1989, p. 136) reported that magnesium concentrations typically are less than 1.0 mg/L in the Upper Floridan aquifer recharge zone. Magnesium concentrations are low in the recharge zone because dolomite, the primary source of magnesium in the Upper Floridan aquifer, is not present in that part of the aquifer (Sprinkle, 1989, p. 137). Rather, the magnesium measured in the current study probably is derived from the dissolution of calcite containing small amounts of magnesium.

Like magnesium, the median sodium and potassium concentrations measured in the current study (2.4 and 0.38 mg/L, respectively) are substantially lower than the median values reported by Sprinkle (1989) and slightly higher than those measured in rainfall (table 9). In the recharge zone described by Sprinkle (1989, p. 144), however, typical concentrations of sodium and potassium in the Upper Floridan aquifer recharge zone are near 1.0 and 0.2 mg/L, respectively. The dissolution of calcite in the Upper Floridan aquifer does not add appreciable amounts of sodium and potassium to ground water in the southwestern Albany area, Georgia, because mineral sources of sodium or potassium such as halite or albite are not present in the aquifer. Nevertheless, small amounts of aluminosilicate minerals or clays such as glauconite may exist in the overburden or shallow parts of the aquifer and contribute small amounts of sodium or potassium to ground water (Sprinkle, 1989, p. 144). If ground water interacts with clay minerals, sodium and potassium concentrations may increase by cation exchange (Sprinkle, 1989, p. 145; Hem, 1985, p. 104). In cation exchange, sodium or potassium ions that are sorbed to clay particles change places with calcium ions in the water. Therefore, ground water may be enriched with sodium or potassium ions, but depleted in calcium. Moreover, sodium or potassium may be enriched in ground water when sewage effluent from septic systems enters the aquifer. Other human activities such as confined animal feeding operations (CAFOS), land applications of animal waste or biosolids, or fertilizer applied to agricultural fields also may be important sources of sodium and potassium in the study area. Because land use near Albany is primarily agricultural, applications of fertilizer containing potassium chloride may leach into ground water near areas of active farming, thus increasing potassium concentrations. The land application of biosolids in an area west-northwest of the study area, upgradient from well 12L061, is a well-known and documented potential source of chemical constituents in Upper Floridan aquifer ground water (Wenner and Reyher, 1999).

Because the electrical neutrality must be maintained in a water sample, major cation concentrations (in equivalent weight) are balanced by major anion concentrations. The most important of these anions in Upper Floridan aquifer ground-water samples is bicarbonate. Bicarbonate commonly is estimated by measuring alkalinity. In most routine water analyses, the total alkalinity is determined by titration of a water sample with dilute sulfuric acid, usually to a fixed-pH endpoint of 4.5. The theoretical basis for the total alkalinity measurement assumes that the only ions available to buffer changes in pH are the carbonate or bicarbonate species in the water (Snoeyink and Jenkins, 1980, p. 183). The total alkalinity measured in surface and ground water, however, usually does not provide a true alkalinity because other noncarbonate constituents generally are present in the water. Any chemical constituent that is capable of accepting a hydrogen ion from the acid during titration will be counted in the total alkalinity value. Thus, an alkalinity measure may not only consist of bicarbonate ion, but also other ions such as ammonia, borate, nitrate, sulfate, silica, or orthophosphate (Hem, 1985, p. 106). For this reason, the alkalinity value is really a measure of the acid-neutralizing capacity of water. Therefore, alkalinity herein is called the acid-neutralizing capacity (ANC) as bicarbonate in milligrams per liter.

The range in ANC for the study period is 85–223 mg/L (tables 7 and 8), and the median for the study is 141 mg/L (table 9). Correlation analyses show that the ANC is highly correlated with SC (rho = 0.90) and calcium (rho = 0.94), but shows a strong, negative correlation with pH (rho = –0.76), and DO (rho = –0.80; tables 10 and 11). Furthermore, the ANC is moderately correlated with depth to water, magnesium, sodium, potassium, sulfate, silica, and strontium (tables 10 and 11). Only a slight, but statistically significant, correlation exists between the ANC and chloride, manganese, and orthophosphate concentrations. In contrast, a statistical relation does not exist between the ANC and apparent ground-water age, water temperature, iron, ammonia, or nitrate concentrations (tables 10 and 11). The relations between ANC and sulfate, silica, and orthophosphate indicate that these constituents may contribute to the ANC and overinflate the measured value. Because the bicarbonate ion was not analyzed specifically, it cannot be differentiated from the ANC measurement.

The sources of sulfate and chloride concentrations in the study area are either nonmineral or caused by dissolution of minor minerals that are present within the Upper Floridan aquifer or the overburden. Sulfate concentrations in the study area range from 0.2 to 6.4 mg/L (tables 7 and 8). The median sulfate concentration in the current study is 0.80 mg/L, which is slightly lower than the sulfate concentrations measured in rainfall near Tifton, Georgia (table 9). Moreover, the sulfate concentrations measured are 20 to 30 times lower than the median Upper Floridan aquifer concentration described by Sprinkle (1989, p. 151) (table 9). According to Sprinkle (1989, p. 151), the dissolution of either gypsum ($CaSO_4{-}H_2O$) or anhydrite (noncrystalline $CaSO_4$) is the primary source of sulfate concentrations in water from the Upper Floridan aquifer; however, these minerals are either nonexistent or are present as thin, intermittent lenses in the area of the current study (Sprinkle, 1989). Thus, the only other potential sources of sulfate in ground water near Albany are rainwater, sewage effluent from septic systems, animal waste, or fertilizer.

In contrast to sulfate, minerals containing chloride, such as halite, are not present in the Upper Floridan aquifer near Albany, Georgia (Sprinkle, 1989, p. 145). Therefore, the only possible sources for chloride concentrations measured in the current study are rainfall, sewage effluent from either septic systems, animal waste, or fertilizer. The median chloride concentration in this study, 5.0 mg/L, is markedly lower than the values reported by Sprinkle (1989, p. 145) and about 15 times greater than concentrations in rainfall samples (table 9).

The ratio of a chemical constituent to a conservative constituent in a water sample, such as chloride, commonly is used to identify the source of or the processes that determine the measured chemical composition of that water. The average sodium-chloride ratio in rainfall samples from Tift County, Georgia, is 0.90 (table 9), which indicates that sodium is slightly depleted with respect to chloride in those samples. In contrast, the ground-water samples collected in the current study have an average sodium-chloride ratio of 0.71 (table 9). This ratio indicates that many of the ground-water samples collected in the study area are either substantially depleted in sodium or substantially enriched in chloride (fig. 11). Chloride probably is enriched because sodium only can be depleted by precipitation from solution. Sodium salts are among the most soluble compounds in water and will not precipitate until the salts become concentrated at many times the salinity of seawater (Snoeyink and Jenkins, 1980). In most cases, cation exchange between ground water and clay minerals results in sodium enrichment and calcium depletion. About 25 percent of the samples in this study have sodium-chloride ratios that are consistent with the ratios in rainfall, indicating that the ratio has not been altered since recharge (table 9 and fig. 11). In contrast, 75 percent of the samples are enriched in chloride from an unidentified source other than mineral dissolution or rainfall.

Minor Chemical Constituents

A minor constituent is defined as an element or compound in water at a concentration typically smaller than 1 mg/L (Hem, 1985). In some instances, elements that are considered to be minor constituents, such as iron or manganese, are measured at concentrations greater than 1 mg/L (Hem, 1985). Dissolved concentrations of minor constituents in ground water, especially those called trace metals, primarily are governed by pH and DO values. Natural or anthropogenic influences can reduce the pH or DO levels in ground water to a point where trace metals become more soluble. The greater the solubility of a trace metal, the greater its concentration in ground water. Elevated concentrations of trace metals may exceed drinking-water standards. According to Sprinkle (1989, p. 175), most minor constituent concentrations in the Upper Floridan aquifer recharge zone typically are below laboratory reporting levels; this assessment also is true in the current study.

Among the minor constituents, only strontium has detectable concentrations in more than 90 percent of the samples collected during the study (tables 7 and 8). Median strontium concentrations in ground-water samples from the study area are 0.03 mg/L (tables 7 and 8). A small percentage of strontium commonly is present in calcite because it easily substitutes for calcium and magnesium in the calcite molecule (Hem, 1985, p. 135). Indeed, in the current study, strontium concentrations are strongly correlated to magnesium (rho = 0.86) and silica (rho = 0.83), and moderately correlated with pH, DO (negative relation), SC, calcium, sodium, potassium, ANC, and sulfate (table 11). The correlations between strontium concentrations and depth to water, chloride, manganese, and orthophosphate (negative relation) concentrations are weak, but statistically significant (tables 11 and 12). These relations indicate that the dissolution of calcite with magnesium, silica, and strontium impurities probably are responsible for the strontium concentrations found in ground-water samples from the study area. Strontium is not associated with apparent ground-water age, water temperature, iron, ammonia, or nitrate concentrations.

The remaining minor chemical constituents are detectable in a small percentage of samples probably because mineral sources do not exist in the aquifer. Ten percent of the samples contain manganese concentrations at or above the laboratory reporting limit of 0.04 mg/L (tables 7 and 8). Eighteen percent of the samples contain either barium or fluoride concentrations at or above the laboratory reporting limit of 0.01 and 0.02 mg/L, respectively. Fifteen percent of the samples contain bromide concentrations at or above the laboratory reporting limit of 0.02 mg/L (tables 7 and 8).

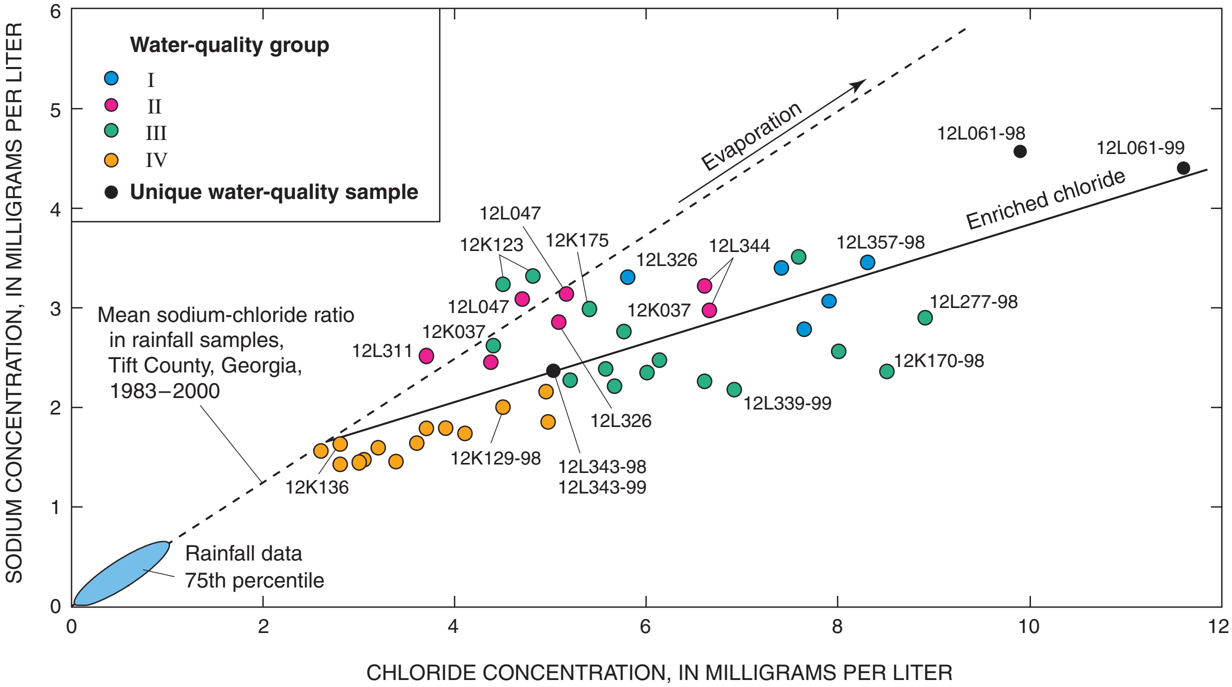


Figure 11. Dissolved chloride and dissolved sodium concentrations in ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, September 1998 and March 1999. Water-quality groups are based on cluster analyses of magnesium, sodium, potassium, chloride, acid-neutralizing capacity, sulfate, and silica. Samples representing the two trends in sodium-chloride ratios are labeled with well number and sample year. (Rainfall data from USGS, 2000.)

Dissolved Nutrient Concentrations

Nutrient analyses are an important component of a ground-water quality assessment because unconfined aquifers commonly are contaminated with nitrates, nitrogen, and phosphorus compounds. These compounds are implicated in accelerated eutrophication in streams and lakes that receive ground water. Nutrients, particularly nitrate, commonly affect drinking-water quality and at elevated concentrations can be detrimental to human health (Train, 1979; Feder and Toth, 1996). During the current study, ground-water samples were analyzed for the following nutrients: ammonia as N, nitrite plus nitrate as N (hereinafter called nitrate), and orthophosphate as phosphorus. Most of the ground-water samples collected during this study contain ammonia and orthophosphate concentrations below the laboratory reporting levels (0.01 and 0.02 mg/L, respectively) (tables 7 and 8). The median ammonia and orthophosphate concentrations are less than 0.01 or 0.02 mg/L for all ground-water samples in the current study (tables 7, 8, and 9). Six samples from three wells contain ammonia concentrations greater than 0.01mg/L. The highest ammonia concentration, 0.1 mg/L, was measured in the March 1999 sample from well 12L326. Ammonia concentrations, however, are typically low in ground water because the ammonium molecule attaches to fine-grained particles (sorption) in the overburden or aquifer. In addition, ammonia is oxidized rapidly to nitrate in water with DO concentrations greater than 1.0 mg/L. This conversion, called nitrification, is catalyzed by nitrifying bacteria that occupy particles in the surficial soil, overburden, or aquifer minerals (particularly within limestone fractures).

Orthophosphate concentrations also are typically low in Upper Floridan aquifer ground water for two reasons: (1) phosphate minerals are not common in the Upper Floridan aquifer (Sprinkle, 1989, p. 115); and (2) phosphate generally is insoluble and rapidly precipitates from ground water within a short distance from its source. Sources of orthophosphate in the Upper Floridan aquifer can be either mineral (primarily calcium apatite), sewage effluent, animal waste or biosolids, or fertilizers. In 86 percent of the water samples collected during the study period, orthophosphate concentrations are less than the laboratory reporting limit, 0.02 mg/L. The median orthophosphate concentration for the current study is below the laboratory reporting limit (tables 7 and 8).

Table 12. Spearman rank correlation coefficients and p-values[1] for selected minor constituent and nutrient concentrations in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999.

[Fe, dissolved iron; Mn, dissolved manganese; Sr, dissolved strontium; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; –, minus; —, not determined; NS, not significant at alpha = .05; <, less than]

	Spearman rank correlation coefficients and p-values					
	Fe (mg/L)	Mn (mg/L)	Sr (mg/L)	NH_4N	NO_3N	PO_4P
Iron (Fe)	1.000 —	0.430 .002	0.080 NS	0.130 NS	–0.230 NS	–0.090 NS
Manganese (Mn)			.320 <.020	.520 <.001	–.520 <.001	–.210 NS
Strontium (Sr)			1.000 —	.130 NS	.130 NS	–.340 .017
					–.370 .009	.190 NS
Nitrite plus nitrate as N (NO_3N)					1.000 —	–.110 NS

[1] The top number in a cell is the correlation coefficient and the bottom number is the p-value; the correlation coefficient ranges from –1.0 to 1. The closer the number is to 1.0 the greater the positive relation between two constituents; the closer the coefficient is to negative 1.0 the greater the negative relation between two constituents. The p-value is the probability that the two constituents are related only by chance; thus a p-value of .0001 indicates a .01-percent probability that the correlation has happened by chance alone, a very slim possibility.

Nitrate

Many of the water samples analyzed in this study contain nitrate concentrations greater than 2 mg/L, the presumed background concentration (tables 7 and 8). Nitrate concentrations in uncontaminated ground-water samples typically are below 2 mg/L, whereas those above 2 mg/L typically are associated with either sewage effluent, animal waste, or fertilizer applications (Mueller and others, 1995). The Georgia drinking-water standard and the USEPA PMCL for nitrate concentrations in ground and surface water is 10 mg/L as nitrogen (Georgia Environmental Protection Division, 2003, p. 655; U.S. Environmental Protection Agency, 2000a).

In the current study, two water samples from well 12L061 contain nitrate concentrations greater than 10 mg/L (tables 7 and 8). Both samples contain the highest nitrate concentration measured during 1998 and 1999, 11 and 12.2 mg/L, respectively. In contrast, four ground-water samples from three wells contain nitrate concentrations below the laboratory reporting limit of 0.02 mg/L. The median nitrate concentration for all samples collected during 1998 is 2.6 mg/L (table 7) and during 1999 is 3.0 mg/L (table 8). The median nitrate concentration for all samples is 2.9 mg/L (table 9). This median is similar to the median nitrate concentration reported by Nolan (1999) in Upper Floridan aquifer ground-water samples collected from the upper and lower Coastal Plain in southern Georgia. A nonparametric t-test shows that the median nitrate concentration for the 1998 samples is statistically similar to those collected during 1999 ($p>0.10$).

Wenner and Reyher (1999) identified several wells northwest and upgradient from well 12L061 that contained ground water with nitrate concentrations nearly four times higher than those in samples they collected from well 12L061. The high nitrate wells identified by Wenner and Reyher (1999) were not sampled during the current study. Because the direction of ground-water flow near well 12L061 is northwest to southeast (figs. 9 and 10), the elevated nitrate concentrations measured in that well probably originate upgradient in the area sampled by Wenner and Reyher (1999), and then are transported downgradient into the study area. Because water samples for the current study could not be collected in the wells upgradient from well 12L061, the source of elevated nitrate concentrations in the vicinity of well 12L061 cannot be definitively confirmed.

Minerals containing nitrate are not present in the Upper Floridan aquifer (Sprinkle, 1989, p. 171). Therefore, the source of elevated nitrate concentrations in ground water in the southwestern Albany area may come from either nitrogen compounds in rainfall, decomposing organic matter in soils, sewage effluent, animal waste (biosolids), or nitrogen fertilizer. Between 1983 and 2000, nitrate concentrations in rainfall samples collected at Tift County, Georgia, ranged from less than 0.001 to 9.5 mg/L, with a median concentration of 0.79 mg/L (table 9). Although the highest nitrate values in rainfall are higher than most of the concentrations measured in ground-water samples, rainfall is not a plausible source of nitrate in the study area. The high nitrate concentrations measured in Tift County rainwater samples are extreme values that lie outside the concentrations measured in 98 percent of those samples. Moreover, nitrate is an essential plant nutrient that is taken up rapidly by plants and microbes in the soil profile and not likely to enter the aquifer (Hallberg, 1989). Therefore, either animal waste in some form (manure, biosolids, or poultry litter) or human influence (septic systems or inorganic fertilizer applications) or both are the source or sources of elevated nitrate concentrations in the study area.

Nitrate concentrations in the study area are statistically related to several major constituent and ammonia concentrations (tables 11 and 12). Nonparametric correlations between nitrate and magnesium, sodium, and potassium concentrations are weak, but statistically significant (rho from 0.3 to 0.43). Furthermore, the relation between nitrate and chloride concentrations is positive, but modest (rho = 0.69; fig.12), whereas the correlation between nitrate and ammonia is negative and weak (rho = –0.37). Nitrate concentrations also have a modest, but negative, correlation with manganese concentrations (rho = –0.52). The negative correlations among nitrate, ammonia, and manganese are consistent with reducing conditions in the aquifer. Reducing conditions in an aquifer either favor denitrification (conversion of nitrate to nitrous oxides), nitrate reduction (conversion of nitrate to ammonia), or sulfate reduction (conversion of sulfate to sulfide). The chemistry of a water sample collected from a well under reducing conditions with denitrification typically has a DO concentration less than 1.0 mg/L, a nitrate concentration below reporting limits, an elevated manganese concentration, and an elevated ammonia concentration. Furthermore, such a sample under nitrate reduction typically has elevated iron and ammonia concentrations as well (Hem, 1985). As reducing conditions become greater, sulfate reduction may begin. During sulfate reduction, ground-water sulfate concentrations decrease and hydrogen sulfide concentrations increase. All of these processes are catalyzed by bacteria. Multiple linear regression analysis indicates that 96 percent of the variability in nitrate concentration is better explained by the variability in pH (positive relation), calcium and magnesium (positive relations), chloride (positive relation), sulfate (negative relation), bicarbonate (negative relation), and manganese (negative relation) concentrations. This regression analysis indicates that elevated nitrate concentrations correspond to elevated pH, and elevated calcium, magnesium, and chloride concentrations, and to lower alkalinity, manganese, and sulfate concentrations.

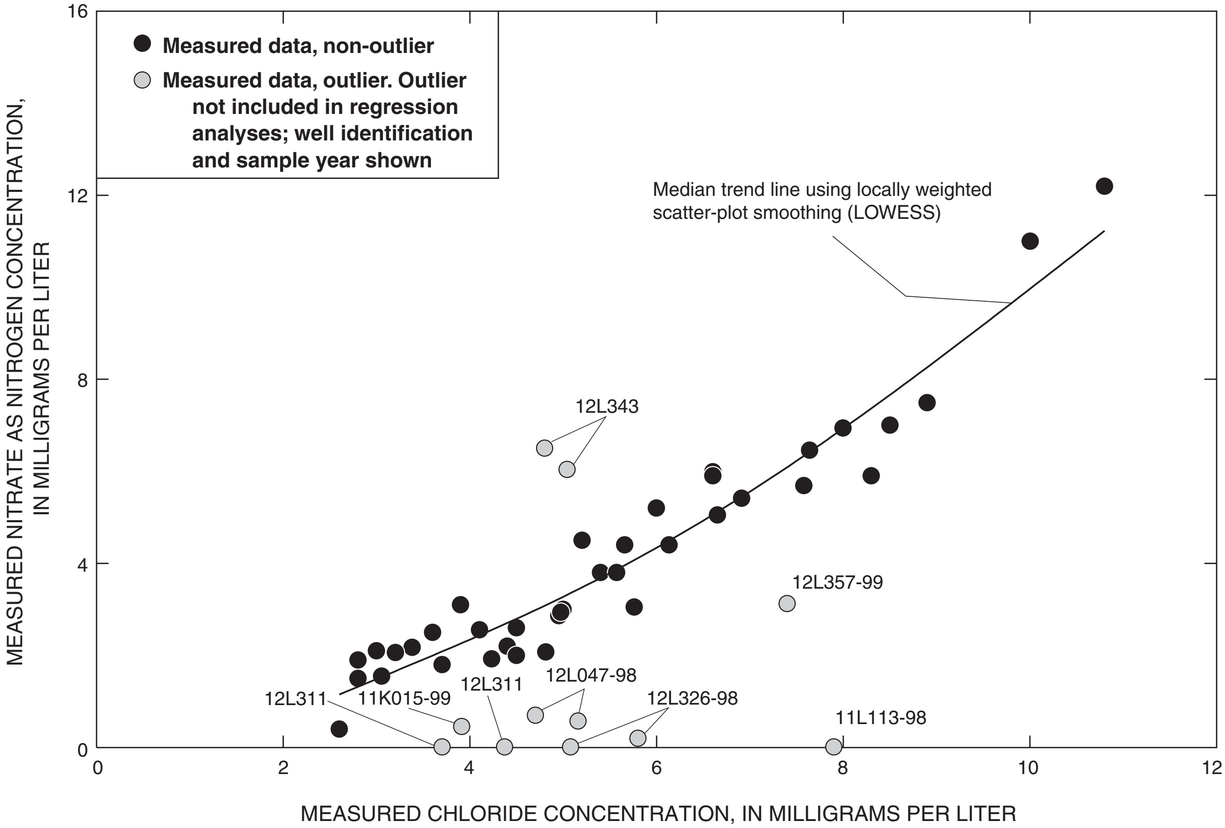


Figure 12. Dissolved chloride and dissolved nitrate as nitrogen concentrations in ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, September 1998 and March 1999. Outlier samples are labeled.

Because of the relation between nitrate and chloride concentration, a regression equation was developed to predict nitrate concentrations from measured chloride concentrations in Upper Floridan aquifer ground water. By using this equation, nitrate concentrations could be estimated in real time by the continuous monitoring of chloride concentrations with a chloride-specific ion probe. Because of the relation between chloride and nitrate and the conservative nature of chloride in most natural waters, chloride can be used as a surrogate for the nitrate concentrations in ground water within the study area. The multiple regression analysis shows that 60 percent of the variability in nitrate concentrations ($R^2 = 0.60$) (Appendix B, fig. B1) is explained by the variability in chloride concentrations. Moreover, with significant outliers removed, 85 percent of the variability in nitrate concentrations is explained by the variability in the chloride concentration ($R^2 = 0.85$) (Appendix B, fig. B2). With significant outliers removed, however, and chloride concentrations squared, 94 percent of the variability in nitrate concentrations is explained ($R^2 = 0.94$) (Appendix B, fig. B3). This relation between the squared chloride concentration and nitrate concentration indicates that the ratio of chloride to nitrate concentration is greater at elevated nitrate concentrations than it is at lower nitrate concentrations (fig. 12).

Leblanc (1984) and Cantor and Knox (1985) show that sewage-contaminated ground water typically contains elevated concentrations of major constituents and nitrate. Clearly, the source of elevated nitrate concentrations in the Upper Floridan aquifer ground water is not rainfall or mineral-based. Rather, sewage effluent, animal waste, and fertilizer applications are the most likely sources of nitrates in the study area. Traditional methods of chemical analyses are unable, however, to distinguish among those three potential nitrate sources in natural water. Thus, more advanced techniques, such as isotope geochemistry, may be useful tools for identifying nitrate sources. Isotope geochemistry may help to identify the primary source of nitrate to the study area because it identifies the isotopic signatures of the nitrogen and oxygen atoms in the nitrate molecule.

Nitrogen and Oxygen Isotopes

Nitrogen and oxygen isotopes in the nitrate compound can be used to differentiate sources of nitrogen in ground water. Research by the USGS (Kendall, 1998) has delineated the isotopic content of nitrogen (δ^{15}N values) from different sources. These sources include rainfall, septic-system effluent, animal waste, soil, and ammonia and nitrate fertilizer (fig. 13).

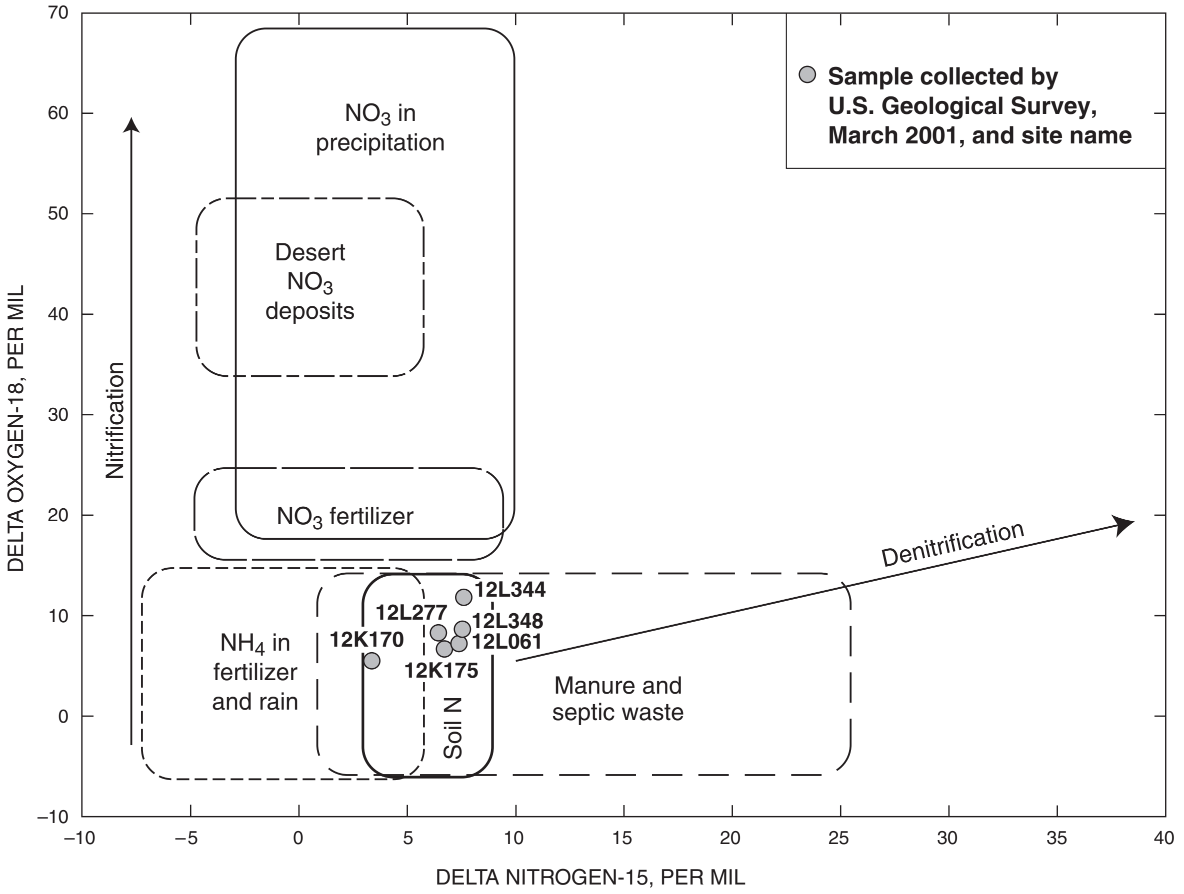


Figure 13. Nitrogen-15 concentration and oxygen-18 concentration in ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, March 2001 (modified from Kendall and McDonnell, 1998, p. 546). [NO_3, nitrate; NH_4, ammonia; N, nitrogen]

Because there is overlap in $\delta^{15}N$ values among nitrate sources, an isotopic content of oxygen ($\delta^{18}O$) also was measured to help further identify the nitrate source or processes affecting nitrate concentrations.

In the current study, ground-water samples from six wells were collected during March 2001 and analyzed for $\delta^{15}N$ and $\delta^{18}O$. In these six samples, the $\delta^{15}N$ values range from 3.37 to 7.66 per mil and $\delta^{18}O$ values range from 5.4 to 11.8 per mil (table 13). Except for wells 12K170 and 12L344, the $\delta^{15}N$ and $\delta^{18}O$ values are not markedly different among the other four wells shown in table 13. These isotopic concentrations are consistent with nitrogen in sewage effluent or animal waste that has been oxidized (nitrification) within soil horizons (fig. 13). Moreover, the similarity in the $\delta^{15}N$ and $\delta^{18}O$ values in four of the six wells indicate all four share a common nitrate source.

Table 13. Values for nitrogen-15 ($\delta^{15}N$) and oxygen-18 ($\delta^{18}O$) isotopes analyzed in samples from selected wells, southwestern Albany area, Georgia, March 2001.

Well name (fig 1.)	$\delta^{15}N$, per mil	$\delta^{18}O$, per mil
12L344	7.66	11.8
12K170	3.37	5.40
12L277	6.32	8.19
12L348	7.55	8.76
12L061	7.38	7.15
12K175	6.70	6.69

The nitrogen and oxygen isotope data in water samples from well 12K170 fall in the range of nitrogen fertilizer, soil nitrogen, sewage, and animal waste (fig. 13). The water sample from well 12L344, however, may represent denitrification at this location in the Upper Floridan aquifer because the nitrogen isotope is slightly and the oxygen isotope is markedly enriched compared to those in the other five samples (table 13 and fig. 13).

The terms *depleted* and *enriched* are commonly used in isotope studies. Water that is isotopically depleted is water with an isotopic concentration that is dominated by the lighter isotope and conveyed as a more negative number. For example, water with an isotopic concentration of +2.8 is isotopically lighter than water with a concentration of +5.2. Water that is isotopically enriched is water that is dominated by the heavier isotope and is conveyed as a more positive number.

In any geochemical process in which isotopes of elements can be measured, the compounds or elements with the lightest isotopic content are more chemically reactive than the heavier isotope and are processed first (Kendall and Caldwell, 1998, p. 57–66). Therefore, the isotopic content of the remaining elements or compounds will be heavier (more positive) and the resulting compounds lighter (more negative). For example, during nitrification ammonia is converted to nitrate by bacteria. After nitrification, the nitrogen isotope concentration in the remaining ammonia molecules will be heavier (enriched) than it was before nitrification. Similarly, the nitrogen isotope concentration in the nitrate molecule will be lighter (depleted) than it was before nitrification. Denitrification of the nitrate molecule should result in heavier (more enriched) nitrogen and oxygen isotopes in any remaining nitrate molecules.

Emerging Contaminants

Emerging contaminants are chemical compounds present in surface water and ground water as a result of the day-to-day human uses of those compounds or their parent compounds. Many of the emerging contaminants are either pharmaceutical compounds (prescription and OTC drugs) or hormones that are not degraded in wastewater treatment facilities, including septic systems (Halling-Sorensen and others, 1998) (see table 14). This ability to resist degradation elicits concern because these contaminants may enter drinking-water supplies. A large number of municipal water-treatment facilities withdraw surface water at locations downstream from the discharge of tertiary-treated wastewater. Moreover, domestic wells may intercept ground water that is influenced by septic systems (Cantor and Knox, 1985; Hallberg, 1989). Much of this concern reflects a lack of knowledge regarding the acute and chronic affects of the emerging contaminants on the human body. Contaminants, such as estrodial and estrone, are known to disrupt the endocrine systems of animals and fish, and are strongly implicated in reproductive deficiencies in humans (Gilliver and others, 1999).

A ground-water sample collected from well 12L061 during August 2000 was analyzed for 24 pharmaceutical compounds. In this sample, caffeine was the only compound detected, although at a concentration (0.0114 microgram per liter [μg/L]) slightly above the laboratory reporting limit (0.010 mg/L) (table 14). The presence of caffeine indicates that well 12L061 probably intercepts sewage effluent. Indeed, a large septic system containing three septic tanks is located within 250 ft of well 12L061 (Lauren Johnson, Sherwood Christian Academy, oral commun. with Debbie Warner, May 2, 2003). Nevertheless, the small caffeine concentration and the undetectable concentrations of other wastewater tracers may indicate that sewage effluent near well 12L061 is largely diluted, that most of the septic-tank effluent remains in the residuum and has not reached the part of the Upper Floridan aquifer tapped by well 12L061, or the sample was contaminated at the time of collection and the well does not intercept any sewage.

Table 14. Pharmaceutical and wastewater compounds, laboratory reporting limits, and compound concentrations analyzed in ground-water samples from well 12L061, southwestern Albany area, Georgia, August 17, 2000.

[LRL, laboratory reporting limit; µg/L, micrograms per liter; <, less than; e, estimated; —, no data]

Compound	Common usage	LRL (µg/L)	Concentration (µg/L)
1,7-dimethylxanthine	caffeine metabolite	0.018	<LRL
Acetaminophen	analgesic (painkiller)	.009	<LRL
Caffeine	stimulant	.500	e .0114
Cephalexin	antibiotic	—	<LRL
Cimetidine	anti-histamine for gastro-esophageal disorders	.007	<LRL
Codeine	analgesic (painkiller)	.100	<LRL
Cotinine	nicotine metabolite	.023	<LRL
Dehydronifedipine	antianginal metabolite	.010	<LRL
Digoxigenin	digoxin metabolite	.008	<LRL
Digoxin	cardiac stimulant	.260	<LRL
Diltiazem	antihypertensive	.012	<LRL
Enalaprilat	antihypertensive (lowers high blood pressure)	.150	<LRL
Fluoxetine	antidepressant	.018	<LRL
Gemfibrozil	lipid (fat) regulation	.015	<LRL
Ibuprofen	nonsteroidal anti-inflammatory	.018	<LRL
Metformin	antidiabetic drug	.003	<LRL
Paroxetine metabolite	antidepressant	.260	<LRL
Ranitidine	anti-ulcer	.010	<LRL
Salbutamol	bronchodilator (asthma)	.029	<LRL
Sulfamethoxazole	antibiotic	.023	<LRL
Thiabendazole	fungicide	—	<LRL
Trimethoprim	antibiotic	.014	<LRL
Urobilin	urine pigment	—	<LRL

Spatial Patterns in Ground-Water Chemistry and Water Quality

Delineating spatial patterns in ground-water chemistry is important for identifying sources and potential movement of contaminants. In this report, the spatial distributions of SC and nitrate as nitrogen concentrations are mapped for the September 1998 and March 1999 samples (figs. 14 and 15, respectively). In order to further identify spatial patterns in ground-water chemistry, a hierarchical cluster analysis is used to group water samples with similar chemistry. For example, new water (recently recharged) probably is chemically different from older ground water that has been in contact with aquifer minerals for a longer time. In addition, ground water contaminated by human activities are chemically different, in many respects, from uncontaminated water. Therefore, the purpose of cluster analysis in this report is to identify wells that have water samples with similar or contrasting chemical content. Because ground-water samples collected during 1998 and 1999 are statistically similar, both sample sets were combined for the cluster analysis.

Spatial Distribution of Specific Conductance

In the September 1998 map (fig. 14*A*), SC is highest in the northwestern part of the study area. Three discernible "mounds" of high SC ground water were observed in the study area: (1) in the vicinity of well 12L047; (2) in the vicinity of well 12L277; and (3) in an area encompassing wells 12L061, 12L344, and 12L357. Two of the three SC "mounds" correspond to water level highs (shallow ground water) observed during October 1998 (figs. 8 and 14*A*). During March 1999, SC values are highest in the northwestern part and lowest in the southern part of the study area (fig. 14*B*). Furthermore, the SC values in the northwestern part of the study area are lower than those measured during September 1998, whereas concentrations in the southern part of the study area are higher than those measured during September 1998 (fig. 14*A* and *B*). These "mounds" of high SC correspond to water-level highs observed during March 1999 (fig. 9). More important, SC values in or near these potentiometric mounds are highly transient from season to season and across short distances as seen by the differences in SC contours between September 1998 and March 1999 (fig. 14*A* and *B*). This may indicate areas where the Upper Floridan aquifer is under water-table conditions and is an area of recharge. During September 1998 and March 1999, the SC decreases substantially across a short distance from the northwestern to the southeastern part of the study area in the general direction of the Flint River (fig. 14*A* and *B*). The substantial, southeasterly decrease in SC values also corresponds to the steep potentiometric gradients shown in figures 8 and 9.

Spatial Distribution of Nitrate as Nitrogen

Spatially, nitrate concentrations are highest in the west-central and lowest in the northern and southern parts of the study area. The high nitrate concentrations are seen at wells 12K170 (only sampled during 1998), 12L061, 12L277, 12L343, and 12L348. Well 12L061 not only had the highest nitrate concentration during both time periods but also exceeded the MCL of 10 mg/L as nitrogen during both time periods. Some of these elevated nitrate concentrations also correspond to water-level highs and elevated SC values (figs. 8, 9, 14, and 15). Nitrate concentrations in the study area decreases substantially in a southeasterly direction (downgradient).

Identification and Spatial Distribution of Water-Quality Groups

Cluster analysis indicates that four distinct groups of ground-water samples and four unique samples (from wells 12L061 and 12L343) are present in the study area (fig. 16). These unique samples are distinctly different from each other and from all other samples collected during the study. The pattern of chemical similarity among these groups is shown in figure 16, and the spatial pattern is shown in figure 17. The corresponding water-quality data are listed in tables 15 and 16. These water-quality groups consist of samples that represent chemically distinct ground water in the study area. These chemically distinct areas include a zone of anoxic ground water, elevated nitrate concentrations, ground-water mixing and dilution, and background (uncontaminated) water.

EMMA was used to identify ground-water samples whose chemical content may be derived from the simple mixing of two or three different types of ground water. Water samples from three end-member wells were used to identify mixing proportions needed to explain observed water chemistry in other wells. These end-member wells include: (1) background chemistry represented by well 12K136; (2) high SC, moderate chloride, and no detectable nitrate concentrations represented by well 12L311; and (3) high SC, chloride, and nitrate concentrations represented by well 12L061. The mixing domain is defined by the chloride concentrations and SC values in water samples from the three end-member wells (fig. 18). Chloride and SC values are used to define the mixing domain because these two constituents are considered the most conservative in ground water. A conservative constituent is one that does not readily undergo chemical transformation in natural water and, thus, can be used to trace ground-water flow in an aquifer.

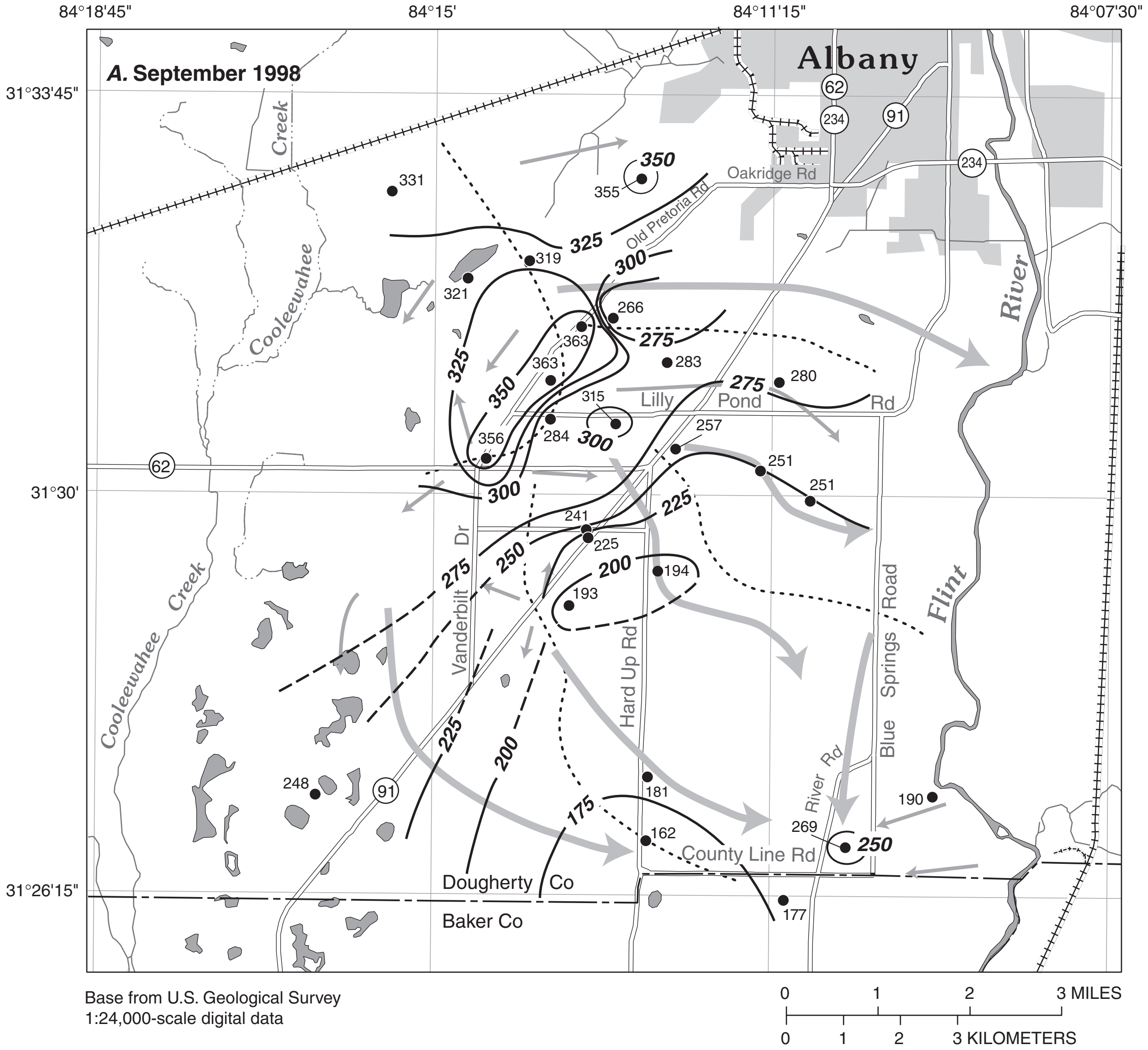
In general, EMMA indicates that the chemical content of selected ground-water samples is plausible when water with chemical compositions similar to those from the three end-member wells (12K136, 12L061, and 12L311) are mixed in various proportions. Ignoring the five end-member samples, 33 of 49 water samples lie within and 12 lie outside of the mixing domain (fig. 18). Seven of these 12 samples contain SC values that are greater than the SC predicted by the mixing analysis (table 17). Thus, the chemical content of the seven samples is not the result of simple mixing of the three end-member samples (tables 17 and 18).

The theoretical mixing of end-member samples using chloride as the index constituent results in a set of mixing fractions for each water sample in the mixing domain (tables 17 and 18). Table 17 shows that when the calculated mixing fractions are used to predict SC values, the mean relative percent difference (mRPD) between measured and predicted SC values is −1.5 percent for those samples within the mixing domain. This negative percentage indicates that the end-member model slightly underpredicts SC values. The range in the relative percent difference (RPD) between measured and predicted SC values for the 33 water samples in the mixing domain range from −42 to 22 percent; however, 93 percent of the predicted values are within +/− 15 percent of the measured values, which is within the acceptable measurement error between field and laboratory SC values (table 17).

For water samples within the mixing domain, EMMA did not predict sodium and nitrate concentrations with the same accuracy as it did for the SC predictions. The mRPD between the measured and predicted nitrate and sodium concentrations is 41.3 and 10.2 percent, respectively (tables 17 and 18). The large difference between the measured and the predicted nitrate concentrations probably are due to biochemical transformations (either nitrification or denitrification) in the ground-water flowpath; whereas, sodium concentrations probably are affected by cation exchange reactions along the ground-water flowpath. Denitrification, and to a limited extent nitrate reduction by facultative bacteria, typically reduces nitrate concentrations in ground water (LeBlanc, 1984; Shedlock and others, 1999; Nolan, 1999). Clay lenses or amorphous minerals are typical sorption sites for cation exchange between calcium and sodium ions (Snoeyink and Jenkins, 1980). The 1998 water sample from well 12L345 appears to be such a situation. The sample from this well has substantially higher measured SC than that predicted by mixing water from the three end-member wells (table 17).

Unique Samples

The hierarchical cluster analysis identified four unique water samples among the samples collected from wells in the southwestern Albany area, Georgia, during September 1998 and March 1999. These samples, two each from wells 12L061 and 12L343, are not closely associated with any other water sample collected during the study. The ground water at well 12L061 is distinctive because of DO concentrations of 5.0 and 5.5 mg/L, nitrate concentrations that exceed the Georgia MCL, and SC values that are the highest measured during the study (table 15). The DO and pH values at well 12L061 are similar to the respective study medians (tables 9 and 15). The SC measured at well 12L061 is between 356 and 371 µS/cm, nearly 100 µS/cm higher than the study median. Moreover, all major chemical constituents in samples from well 12L061 are as much as two times higher than the respective study medians (tables 9 and 15). The sodium-chloride ratios indicate that water samples from well 12L061 are highly enriched in chloride (fig. 11).



EXPLANATION

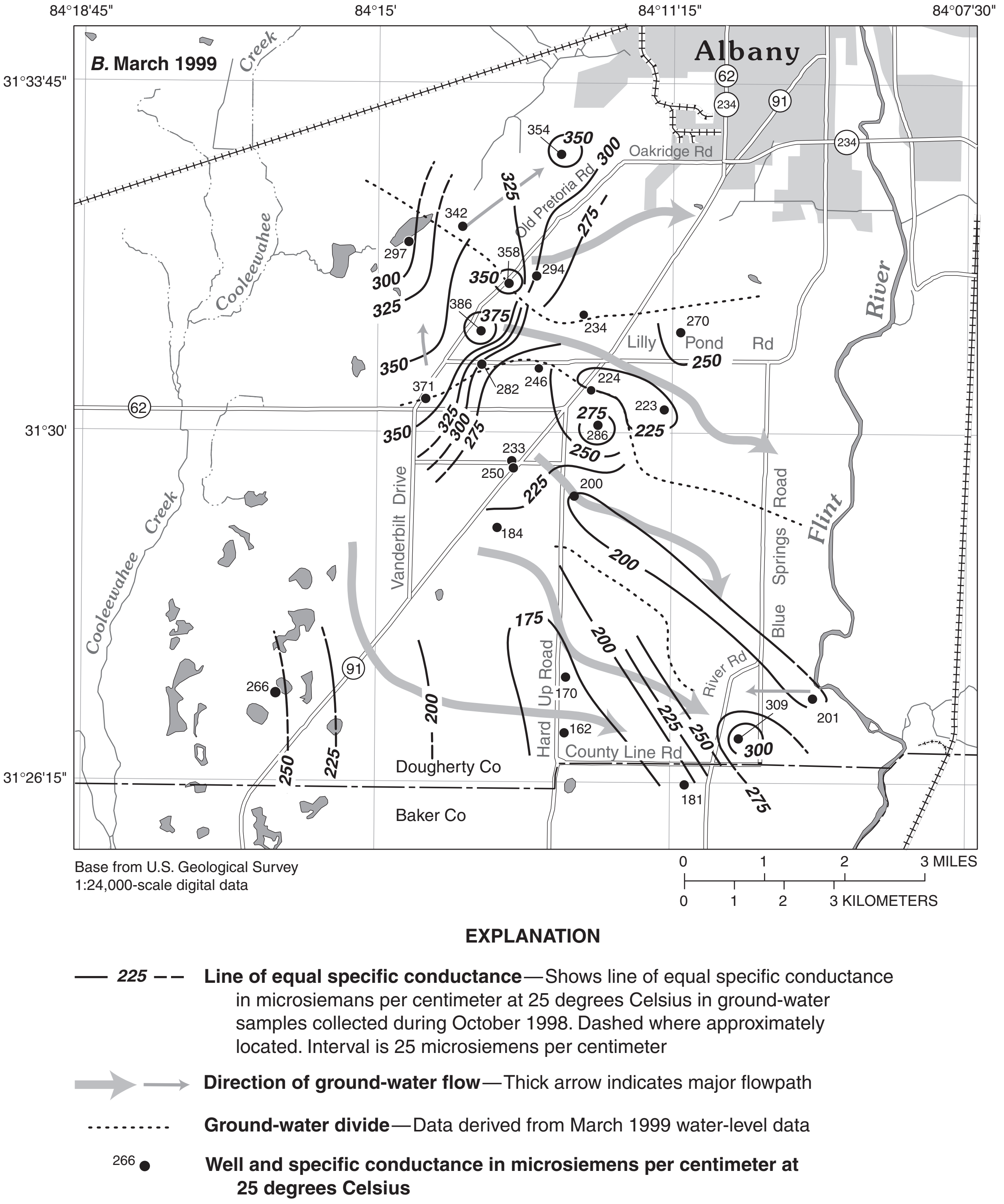
—— *225* – – **Line of equal specific conductance**—Shows line of equal specific conductance in microsiemans per centimeter at 25 degrees Celsius in ground-water samples collected during September 1998. Dashed where approximately located. Interval is 25 microsiemens per centimeter

Direction of ground-water flow—Thick arrow indicates major flowpath

········· **Ground-water divide**

●251 **Well and specific conductance in microsiemens per centimeter at 25 degrees Celsius**

Figure 14. Specific conductance at selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, *(A)* September 1998 and *(B)* March 1999.



EXPLANATION

— *225* — — **Line of equal specific conductance**—Shows line of equal specific conductance in microsiemans per centimeter at 25 degrees Celsius in ground-water samples collected during October 1998. Dashed where approximately located. Interval is 25 microsiemens per centimeter

➡ → **Direction of ground-water flow**—Thick arrow indicates major flowpath

.... **Ground-water divide**—Data derived from March 1999 water-level data

266 ● **Well and specific conductance in microsiemens per centimeter at 25 degrees Celsius**

Figure 14. Specific conductance at selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, *(A)* September 1998 and *(B)* March 1999.—Continued

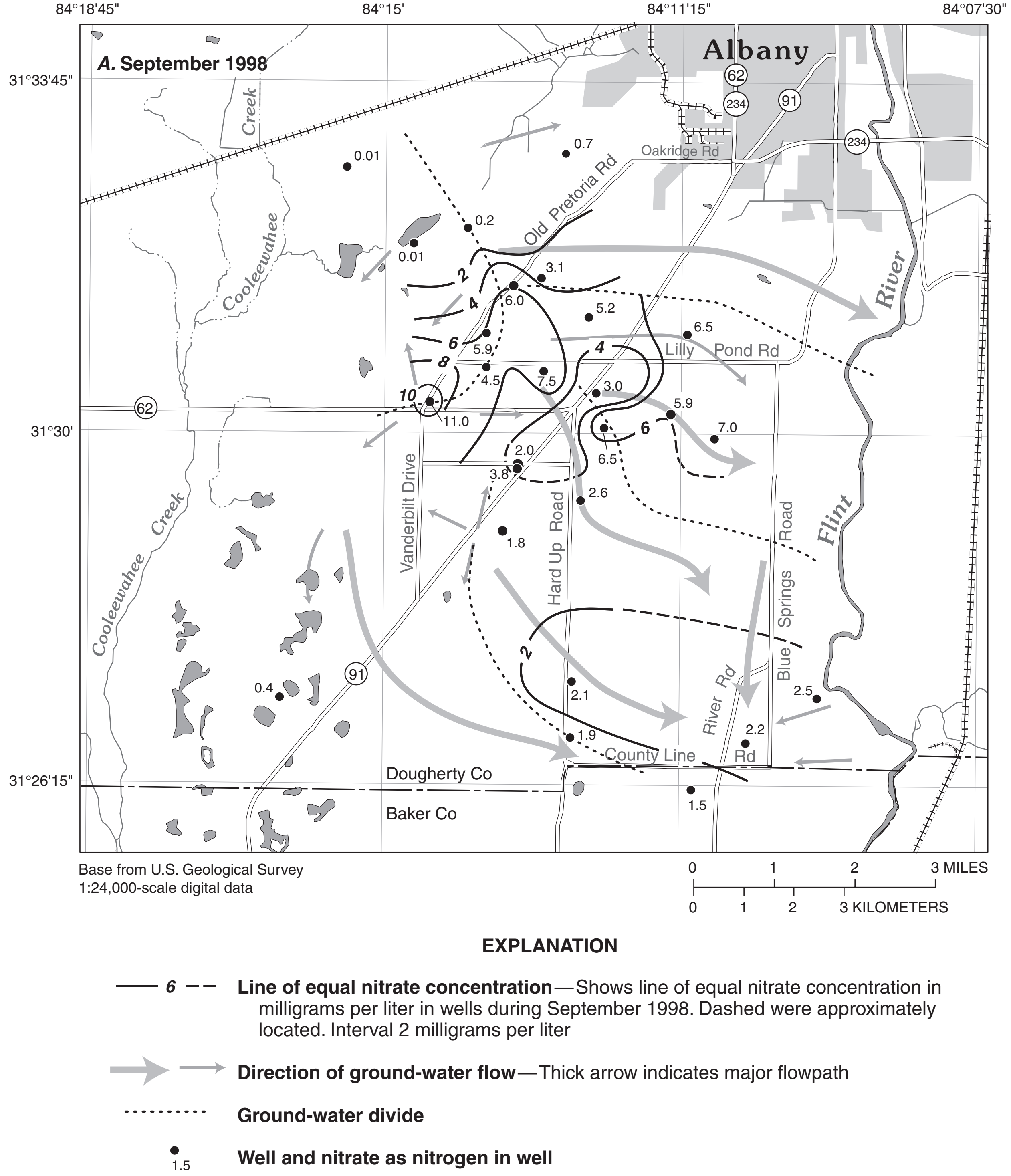
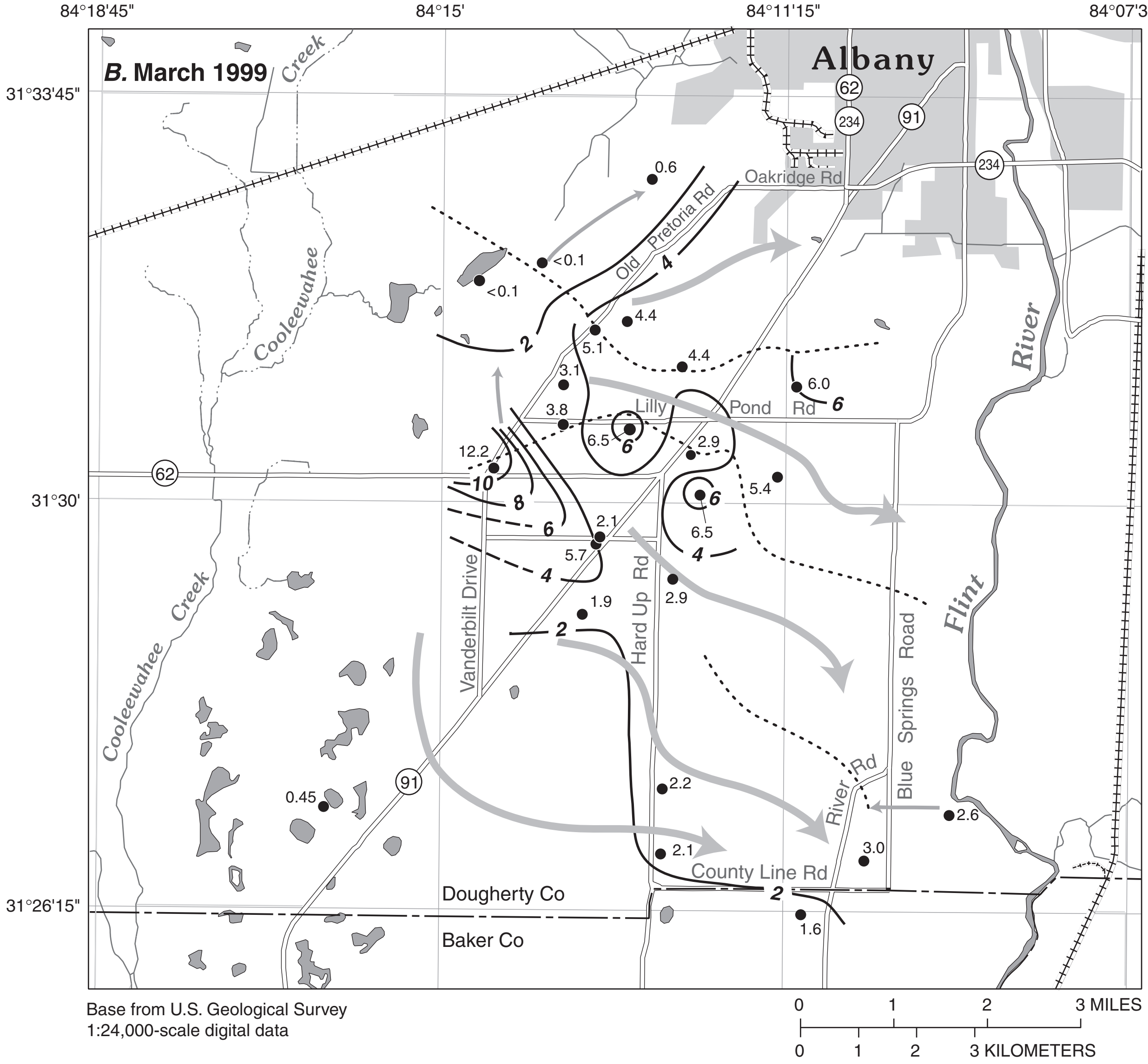


Figure 15. Nitrate as nitrogen concentrations in ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, *(A)* September 1998 and *(B)* March 1999.



EXPLANATION

— 6 – – **Line of equal nitrate concentration**—Shows line of equal nitrate concentration in milligrams per liter in wells during October 1998. Dashed were approximately located. Interval 2 milligrams per liter

➞ → **Direction of ground-water flow**—Thick arrow indicates major flowpath

--------- **Ground-water divide**

● 1.6 **Well and nitrate as nitrogen in well**

Figure 15. Nitrate as nitrogen concentrations in ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, *(A)* September 1998 and *(B)* March 1999.—Continued

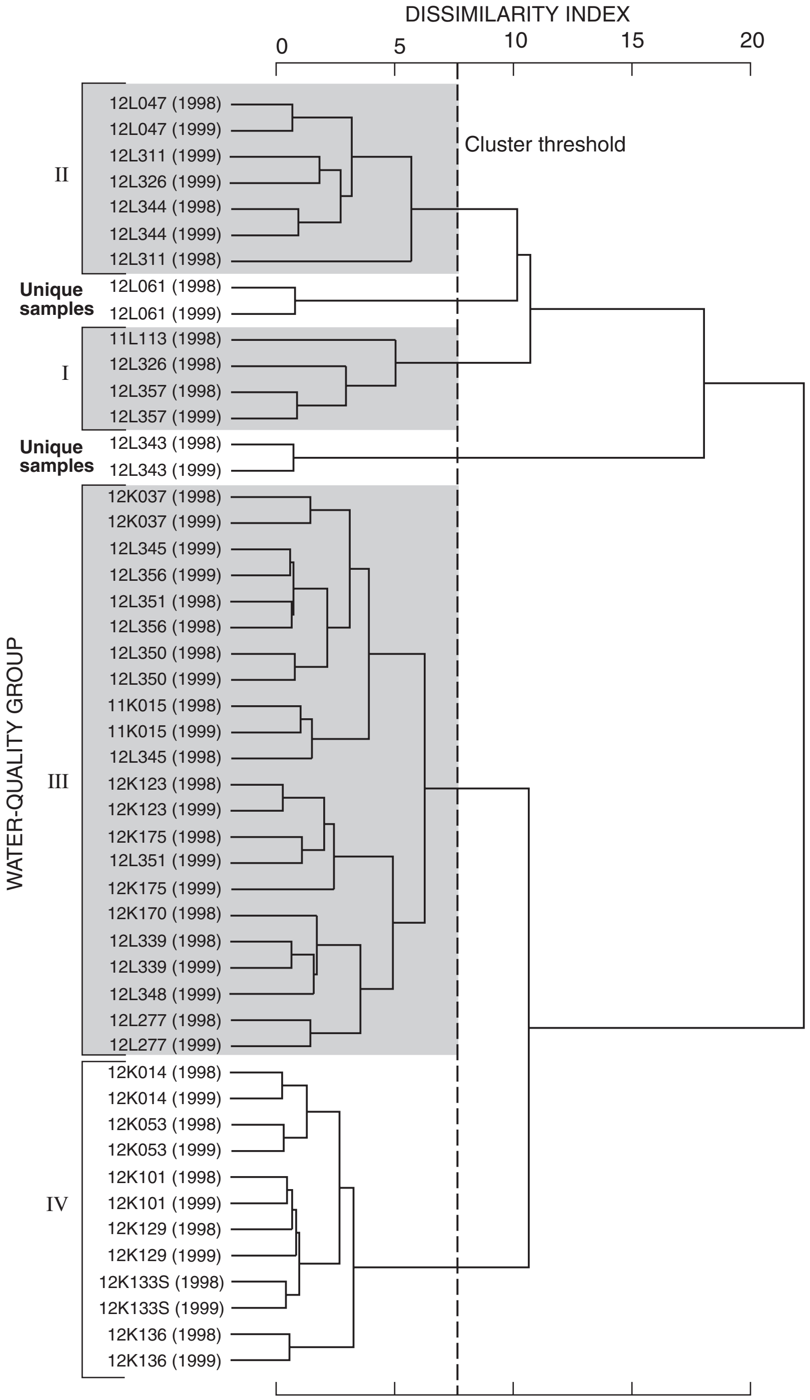


Figure 16. Tree diagram of ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, grouped by similarities in magnesium, sodium, potassium, silica, acid-neutralizing capacity, chloride, and sulfate concentration, September 1998 and March 1999. Samples are grouped using agglomerative hierarchical cluster analysis by Euclidean distance and Ward's minimum-variance method (Romesburg, 1984). See figure 1 for location.

Table 15. Field water-quality measurements and major constituent concentrations in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999. Samples are grouped by similarities in dissolved calcium, magnesium, sodium, potassium, acid-neutralizing capacity, sulfate, chloride, silica, and strontium concentrations.

[ft bls, feet below land surface; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; ANC, acid-neutralizing capacity;—, not measured; <, less than]

Well name (fig. 1)	Sample date	Depth to water (ft bls)	Water temperature (°C)	pH (standard units)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Dissolved concentration (mg/L)						
							Calcium	Magnesium	Sodium	Potassium	ANC as bicarbonate	Sulfate	Chloride
Water-quality group I													
11L113	Sept. 1998	—	20.8	7.4	331	<0.5	69.0	0.52	3.07	0.14	197	6.40	7.9
12L326	Sept. 1998	17.4	20.3	7.3	319	<.5	66.3	.82	3.31	.65	193	5.90	5.8
12L357	Sept. 1998	15.0	20.4	7.2	400	1.6	79.0	1.26	3.46	.91	206	5.40	8.3
	Mar. 1999	14.8	19.9	7.7	386	.9	75.8	1.12	3.40	.96	217	5.59	7.4
Group I median		**15.0**	**20.4**	**7.4**	**359**	**<.5**	**72.4**	**.97**	**3.36**	**.78**	**201**	**5.75**	**7.7**
Water-quality group II													
12L047	Sept. 1998	0.0	19.5	7.3	355	1.4	74.8	0.91	3.09	0.38	223	2.80	4.7
	Mar. 1999	0.0	19.7	7.2	354	.9	7.1	.88	3.14	.34	221	3.11	5.2
12L311	Sept. 1998	9.5	21.9	7.3	321	<.5	64.0	1.45	2.52	.60	198	1.20	3.7
	Mar. 1999	8.0	20.5	8.0	297	<.5	56.3	1.07	2.45	.58	184	1.33	4.4
12L326	Mar. 1999	16.7	20.4	7.3	342	<.5	67.4	.75	2.86	.61	213	1.83	5.1
12L344	Sept. 1998	18.7	20.4	7.2	363	.9	7.2	1.20	3.22	.50	187	2.10	6.6
	Mar. 1999	21.8	19.7	7.4	358	.7	65.8	1.10	2.98	.45	193	1.71	6.7
Group II median		**9.5**	**20.4**	**7.3**	**354**	**.7**	**67.4**	**1.07**	**2.98**	**.50**	**198**	**1.83**	**5.1**
Water-quality group III													
11K015	Sept. 1998	17.3	20.8	7.5	248	4.3	52.0	0.55	1.56	0.38	157	.60	2.6
	Mar. 1999	16.4	20.8	7.7	266	3.4	52.1	.63	1.80	.42	164	.55	3.9
12K037	Sept. 1998	47.1	20.4	7.3	269	5.7	52.3	1.12	2.62	.47	156	.70	4.4
	Mar. 1999	44.2	20.3	7.2	309	3.8	53.2	1.28	2.76	.66	162	.79	5.8
12K123	Sept. 1998	26.5	20.7	7.6	241	11.1	44.3	.46	3.24	.34	129	.50	4.5
	Mar. 1999	25.4	20.7	7.8	233	9.5	43.8	.44	3.32	.35	131	.43	4.8
12K170	Sept. 1998	28.8	21.4	7.7	251	6.8	45.1	.85	2.36	.37	97	.50	8.5

Table 15. Field water-quality measurements and major constituent concentrations in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999. Samples are grouped by similarities in dissolved calcium, magnesium, sodium, potassium, acid-neutralizing capacity, sulfate, chloride, silica, and strontium concentrations.—Continued

[ft bls, feet below land surface; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; ANC, acid-neutralizing capacity;—, not measured; <, less than]

Well name (fig. 1)	Sample date	Depth to water (ft bls)	Water temperature (°C)	pH (standard units)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Dissolved concentration (mg/L)						
							Calcium	Magnesium	Sodium	Potassium	ANC as bicarbonate	Sulfate	Chloride
Water-quality group III—Continued													
12K175	Sept. 1998	27.3	20.3	8.0	225	9.4	42.7	0.59	2.99	0.34	114	0.50	5.4
	Mar. 1999	28.8	20.1	7.7	250	9.2	45.6	.64	3.51	.41	114	.27	7.6
12L277	Sept. 1998	20.9	20.7	7.4	315	7.7	61.4	.97	2.90	.80	147	1.00	8.9
	Mar. 1999	17.4	21.0	7.6	246	6.5	5.8	.80	2.56	.70	130	.85	8.0
12L339	Sept. 1998	43.9	20.9	7.7	251	7.2	47.6	.79	2.26	.43	120	.90	6.6
	Mar. 1999	46.6	21.3	7.7	223	5.5	47.4	.76	2.18	.40	124	.79	6.9
12L345	Sept. 1998	23.9	21.4	7.5	266	4.2	52.6	.74	1.79	.27	144	.70	3.9
	Mar. 1999	25.4	20.1	7.5	294	4.2	53.6	.85	2.21	.31	158	.90	5.7
12L348	Mar. 1999	26.8	20.0	7.6	286	7.5	52.8	.98	2.78	.37	134	.56	7.6
12L350	Sept. 1998	21.6	20.6	7.5	257	5.6	51.4	.66	2.38	.55	141	1.20	5.0
	Mar. 1999	24.9	20.5	7.5	224	3.8	5.8	.61	2.16	.45	145	1.44	5.0
12L351	Sept. 1998	19.3	20.6	7.8	283	5.0	52.2	.78	2.35	.39	143	.80	6.0
	Mar. 1999	25.8	20.7	7.8	234	6.2	43.6	.59	2.48	.30	118	.61	6.1
12L356	Sept. 1998	19.8	20.6	7.4	284	5.1	54.2	.77	2.27	.39	144	.90	5.2
	Mar. 1999	20.3	20.0	7.9	282	5.6	51.3	.81	2.39	.37	151	1.22	5.6
Group III median		**25.4**	**20.6**	**7.6**	**254**	**5.6**	**51.3**	**.76**	**2.38**	**.39**	**142**	**.74**	**5.6**
Water-quality group IV													
12K014	Sept. 1998	47.0	20.7	7.7	177	8.5	35.0	0.48	1.43	0.14	100	0.30	2.8
	Mar. 1999	43.8	20.7	8.0	181	8.5	34.1	.48	1.47	.16	101	.30	3.1
12K053	Sept. 1998	40.0	20.9	7.8	181	6.6	34.7	.44	1.45	.23	93	.80	3.0
	Mar. 1999	41.7	20.6	8.0	170	5.8	32.7	.42	1.46	.23	94	.70	3.4

Table 15. Field water-quality measurements and major constituent concentrations in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999. Samples are grouped by similarities in dissolved calcium, magnesium, sodium, potassium, acid-neutralizing capacity, sulfate, chloride, silica, and strontium concentrations.—Continued

[ft bls, feet below land surface; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; ANC, acid-neutralizing capacity;—, not measured; <, less than]

Well name (fig. 1)	Sample date	Depth to water (ft bls)	Water temperature (°C)	pH (standard units)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Dissolved concentration (mg/L)						
							Calcium	Magnesium	Sodium	Potassium	ANC as bicarbonate	Sulfate	Chloride
Water-quality group IV—Continued													
12K101	Sept. 1998	34.0	20.3	7.8	193	7.7	36.0	0.43	1.79	0.25	103	0.30	3.7
	Mar. 1999	38.1	20.5	8.0	184	6.9	37.4	.41	1.92	.29	104	.27	4.2
12K129	Sept. 1998	32.0	20.1	7.9	194	7.7	37.6	.51	2.00	.25	103	.40	4.5
	Mar. 1999	36.4	20.0	8.0	200	9.1	37.5	.49	1.86	.23	104	.21	5.0
12K133S	Sept. 1998	.0	20.6	7.6	190	8.6	36.1	.53	1.64	.25	100	.40	3.6
	Mar. 1999	.0	19.5	8.1	201	7.1	36.8	.54	1.74	.26	104	.38	4.1
12K136	Sept. 1998	40.1	20.4	8.1	162	7.2	29.3	.93	1.63	.28	85	.50	2.8
	Mar. 1999	42.7	20.8	8.1	162	6.4	29.4	1.12	1.59	.28	87	.53	3.2
Group IV median		**39.0**	**20.5**	**8.0**	**182**	**7.4**	**35.5**	**.48**	**1.63**	**.25**	**100**	**.39**	**3.5**
Unique samples													
12L061	Sept. 1998	18.7	20.8	7.0	356	5.0	68.1	1.38	4.58	1.07	149	1.10	10.0
	Mar. 1999	12.3	20.7	7.6	371	5.5	63.6	1.48	4.45	1.12	152	1.20	10.8
12L343	Sept. 1998	25.0	21.0	7.6	280	2.1	46.2	4.03	2.47	.99	131	1.10	4.8
	Mar. 1999	28.3	20.4	7.6	270	6.8	43.8	3.89	2.40	.99	132	1.26	5.0

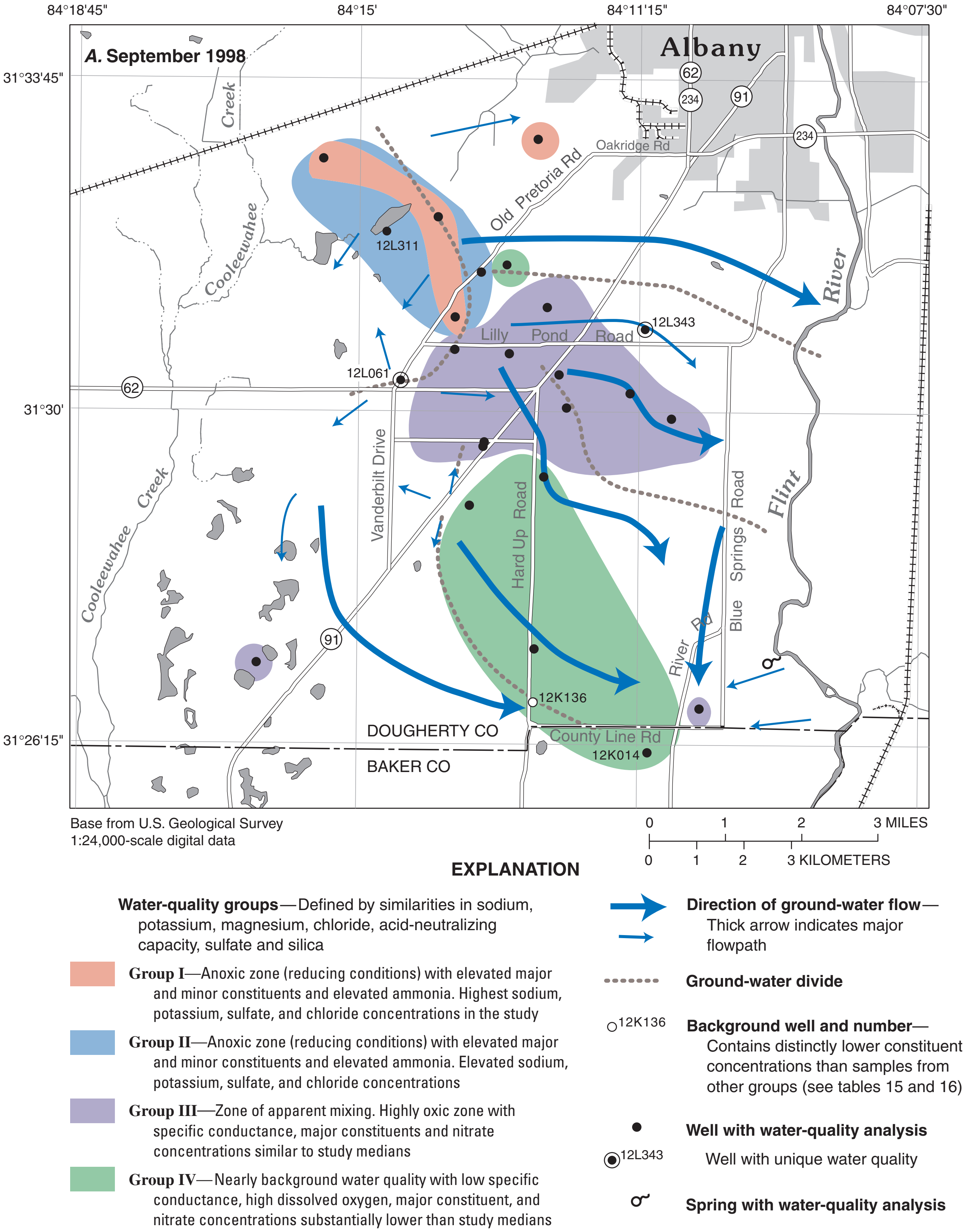


Figure 17. Water-quality groups from a cluster analysis (see figure 16) performed on ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, *(A)* September 1998 and *(B)* March 1999.

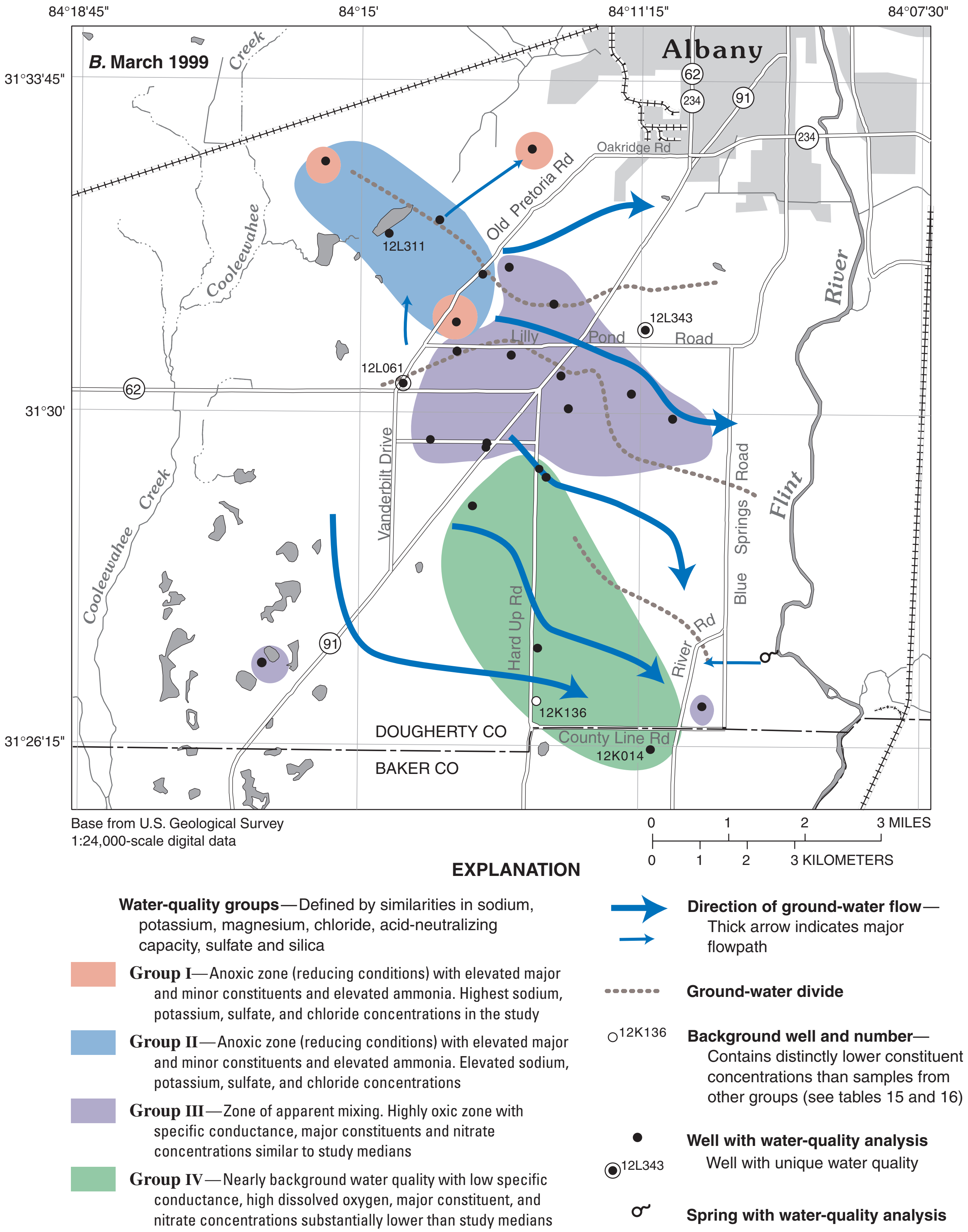


Figure 17. Water-quality groups from a cluster analysis (see figure 16) performed on ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, *(A)* September 1998 and *(B)* March 1999.—Continued

Table 16. Minor constituent and nutrient concentrations measured in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999.

[Samples are grouped by similarities in dissolved calcium, magnesium, sodium, potassium, acid-neutralizing capacity, sulfate, chloride, silica, and strontium; N, nitrogen; P, phosphorus; <, less than]

Well name (fig. 1)	Sample date	Dissolved concentration (milligrams per liter)							
		Silica	Strontium	Bromide	Iron	Manganese	Ammonia as N	Nitrite plus nitrate as N	Orthophosphate as P
Water-quality group I									
11L113	Sept. 1998	3.5	0.04	<0.02	0.08	0.11	<0.01	0.01	<0.02
12L326	Sept. 1998	3.6	.04	<.02	<.04	.07	.04	.20	<.02
12L357	Sept. 1998	4.1	.05	.10	<.04	<.04	<.01	5.90	<.02
	Mar. 1999	4.0	.05	.02	<.04	<.04	<.01	3.13	.02
Group I median		**3.8**	**.04**	**<.02**	**<.04**	**<.04**	**<.01**	**1.70**	**<.02**
Water-quality group II									
12L047	Sept. 1998	4.3	0.05	<.02	<.04	<.04	<.01	0.70	<.02
	Mar. 1999	4.1	.05	.05	<.04	<.04	<.01	.58	<.02
12L311	Sept. 1998	6.1	.07	<.02	<.04	.09	.06	.01	<.02
	Mar. 1999	4.7	.05	<.02	<.04	.13	.06	.01	<.02
12L326	Mar. 1999	4.2	.04	.10	<.04	.14	.10	.02	<.02
12L344	Sept. 1998	4.2	.05	<.02	<.04	<.04	<.01	6.00	<.02
	Mar. 1999	4.0	.04	<.02	<.04	<.04	<.01	5.06	<.02
Group II median		**4.2**	**.05**	**<.02**	**<.04**	**<.04**	**<.01**	**.60**	**<.02**
Water-quality group III									
11K015	Sept. 1998	3.6	.03	<.02	<.04	<.04	<.01	0.40	<.02
	Mar. 1999	3.6	.03	<.02	<.04	<.04	<.01	.46	<.02
12K037	Sept. 1998	3.5	.03	<.02	<.04	<.04	<.01	2.20	.10
	Mar. 1999	3.4	.04	<.02	<.04	<.04	<.01	3.05	.03
12K123	Sept. 1998	3.8	.03	<.02	<.04	<.04	<.01	2.00	.10
	Mar. 1999	3.7	.04	<.02	<.04	<.04	<.01	2.08	<.02
12K170	Sept. 1998	3.5	.03	<.02	<.04	<.04	<.01	7.00	<.02
12K175	Sept. 1998	3.6	.03	<.02	<.04	<.04	<.01	3.80	<.02
	Mar. 1999	3.4	.03	.02	<.04	<.04	<.01	5.70	.03
12L277	Sept. 1998	4.0	.04	.10	<.04	<.04	<.01	7.50	<.02
12L339	Sept. 1998	3.8	.03	<.02	<.04	<.04	<.01	5.90	<.02
	Mar. 1999	3.5	.03	.05	<.04	<.04	<.01	5.42	<.02

Table 16. Minor constituent and nutrient concentrations measured in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999. —Continued

[Samples are grouped by similarities in dissolved calcium, magnesium, sodium, potassium, acid-neutralizing capacity, sulfate, chloride, silica, and strontium; N, nitrogen; P, phosphorus; <, less than]

Well name (fig. 1)	Sample date	Dissolved concentration (milligrams per liter)							
		Silica	Strontium	Bromide	Iron	Manganese	Ammonia as N	Nitrite plus nitrate as N	Orthophosphate as P
Water-quality group III—continued									
12L345	Sept. 1998	4.0	.04	<.02	<.04	<.04	<.01	3.10	<.02
	Mar. 1999	3.9	.04	.03	<.04	<.04	<.01	4.40	<.02
12L348	Mar. 1999	3.8	.04	<.02	<.04	<.04	<.01	6.46	<.02
12L350	Sept. 1998	3.6	.03	<.02	<.04	<.04	.02	3.00	<.02
	Mar. 1999	3.4	.03	<.02	<.04	<.04	<.01	2.86	.04
12L351	Sept. 1998	3.8	.03	<.02	<.04	<.04	<.01	5.20	.10
	Mar. 1999	3.4	.03	.03	<.04	<.04	<.01	4.40	<.02
12L356	Sept. 1998	4.0	.03	<.02	<.04	<.04	<.01	4.50	<.02
	Mar. 1999	3.9	.03	.02	<.04	<.04	<.01	3.80	<.02
Group III median		**3.6**	**.03**	**<.02**	**<.04**	**<.04**	**<.01**	**3.80**	**<.02**
Water-quality group IV									
12K014	Sept. 1998	3.3	.02	<.02	<.04	<.04	<.01	1.50	<.02
	Mar. 1999	3.3	.02	<.02	<.04	<.04	<.01	1.55	<.02
12K053	Sept. 1998	3.0	.02	<.02	<.04	<.04	<.01	2.10	.10
	Mar. 1999	3.0	.02	<.02	<.04	<.04	<.01	2.18	<.02
12K101	Sept. 1998	3.5	.02	<.02	<.04	<.04	<.01	1.80	.10
	Mar. 1999	3.5	.02	<.02	<.04	<.04	<.01	1.93	<.02
12K129	Sept. 1998	3.6	.02	<.02	<.04	<.04	<.01	2.60	.10
	Mar. 1999	3.4	.02	<.02	<.04	<.04	<.01	2.94	.02
12K133S	Sept. 1998	3.3	.02	<.02	<.04	<.04	<.01	2.50	.10
	Mar. 1999	3.4	.03	<.02	<.04	<.04	<.01	2.56	.04
12K136	Sept. 1998	3.7	.05	<.02	<.04	<.04	<.01	1.90	.10
	Mar. 1999	3.7	.06	<.02	<.04	<.04	<.01	2.07	<.02
Group IV median		**3.4**	**.02**	**<.02**	**<.04**	**<.04**	**<.01**	**2.10**	**<.02**
Unique samples									
12L061	Sept. 1998	4.5	.05	<.02	<.04	<.04	<.01	11.00	<.02
	Mar. 1999	4.4	.05	.03	<.04	<.04	<.01	12.20	<.02
12L343	Sept. 1998	6.8	.20	<.02	<.04	<.04	<.01	6.50	<.02
	Mar. 1999	6.5	.18	.02	<.04	<.04	<.01	6.04	<.02

Table 17. Measured and predicted[1] specific conductance values and dissolved sodium concentrations in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999, using end-member mixing analysis.

[µS/cm; microsiemens per centimeter; °C, degrees Celsius; SC, specific conductance in microsiemens per centimeter at 25°C; mg/L, milligrams per liter; –, minus; —, not determined; U, samples with unique water-quality characteristics]

Well[2] name (fig. 1)	Year	Water-quality group	Fraction[3] of water from well 12K136 (back ground water)	Fraction[3] of well 12L311 water	Fraction[3] of well 12L061 water	Specific conductance (µS/cm at 25 °C)		Relative percent difference between measured and predicted SC values	Sodium concentration (mg/L)		Relative percent difference between measured and predicted sodium concentrations
						Measured	Predicted		Measured	Predicted	
11L113	1998	I	0.07	0.26	0.67	331	333	0.5	3.1	3.8	22.2
12L326	1998	I	.12	.53	.35	319	314	–1.5	3.3	3.1	–5.5
12L357	1998	I	.11	.15	.74	[4]400	329	–19.4	3.5	3.9	13.2
	1999	I	.00	.48	.52	[4]386	347	–1.6	3.4	3.5	3.5
12L047	1998	II	.00	.84	.16	[4]355	327	–8.3	3.1	2.8	–8.2
	1999	II	.00	.79	.21	[4]354	332	–6.6	3.1	2.9	–7.2
12L311	1998	II	.00	1.00	.00	321	321	.0	2.5	2.5	.0
	1999	II	.21	.68	.11	297	293	–1.3	2.5	2.5	3.2
12L326	1999	II	.00	.80	.20	342	331	–3.3	2.9	2.9	1.6
12L344	1998	II	.10	.42	.48	[4]363	322	–12.0	3.2	3.4	5.9
	1999	II	.01	.56	.43	[4]358	341	–4.9	3.0	3.3	11.5
11K015	1998	III	1.00	.00	.00	[4]248	162	–42.0	1.6	1.6	4.3
	1999	III	.40	.55	.05	266	260	–2.3	1.8	2.2	21.8
12K037	1998	III	.18	.54	.16	269	259	–3.6	2.6	2.4	–9.5
	1999	III	.18	.51	.31	309	308	–.4	2.8	3.0	6.5
12K123	1998	III	.50	.30	.20	241	249	3.1	3.2	2.5	–26.2
	1999	III	.54	.27	.19	233	245	5.1	3.3	2.4	–32.7
12K170	1998	III	.21	.00	.79	[4]251	315	22.7	2.4	4.0	5.6
12K175	1998	III	.64	.00	.36	225	232	3.0	3.0	2.7	–1.3
	1999	III	.43	.00	.57	[4]250	281	11.7	3.5	3.2	–8.6
12L277	1998	III	.15	.00	.85	315	327	3.7	2.9	4.1	35.2
	1999	III	.37	.00	.63	[4]246	294	17.7	2.6	3.4	27.9
12L339	1998	III	.47	.00	.53	251	265	5.4	2.3	3.2	34.1
	1999	III	.51	.00	.49	[4]223	264	17.0	2.2	3.0	31.6
12L345	1999	III	.37	.32	.31	294	278	–5.7	2.2	2.8	22.5
12L348	1999	III	.26	.20	.54	286	307	7.0	2.8	3.3	17.7
12L350	1998	III	.36	.35	.29	257	274	6.4	2.4	2.8	16.0
	1999	III	.67	.10	0.23	224	226	0.9	2.2	2.3	8.1

Table 17. Measured and predicted[1] specific conductance values and dissolved sodium concentrations in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999, using end-member mixing analysis.—Continued

[µS/cm; microsiemens per centimeter; °C, degrees Celsius; SC, specific conductance in microsiemens per centimeter at 25°C; mg/L, milligrams per liter; –, minus; —, not determined; U, samples with unique water-quality characteristics]

Well[2] name (fig. 1)	Year	Water-quality group	Fraction[3] of water from well 12K136 (back ground water)	Fraction[3] of well 12L311 water	Fraction[3] of well 12L061 water	Specific conductance (µS/cm at 25 °C)		Relative percent difference between measured and predicted SC values	Sodium concentration (mg/L)		Relative percent difference between measured and predicted sodium concentrations
						Measured	Predicted		Measured	Predicted	
12L351	1998	III	0.48	.10	.42	283	259	–8.7	2.3	3.0	23.0
	1999	III	.62	.00	.38	234	241	3.1	2.5	2.7	8.0
12L356	1998	III	.48	.20	.32	284	256	–1.4	2.3	2.8	19.1
	1999	III	.30	.41	.29	282	288	2.0	2.4	2.8	15.9
12K014	1998	IV	1.00	.00	.00	177	162	–8.8	1.4	1.6	13.1
	1999	IV	1.00	.00	.00	181	162	–11.1	1.5	1.6	7.8
12K053	1998	IV	.97	.00	.03	181	167	–8.0	1.4	1.7	16.6
12K133S	1999	IV	.73	.18	.09	201	209	4.1	1.7	2.0	14.9
12K136	1998	IV	1.00	.00	.00	162	162	.0	1.6	1.6	.0
	1999	IV	1.00	.00	.00	162	162	.0	1.6	1.6	.0
12L345	1998	IV	.85	.00	.15	266	191	–32.8	1.8	2.1	14.6
12L061	1998	U	.00	.00	1.00	356	356	.0	4.6	4.6	.0
	1999	U	.00	.00	1.00	371	371	.0	4.5	4.5	.0
12L343	1998	U	.48	.25	.27	280	254	–9.7	2.5	2.6	6.9
	1999	U	.50	.25	.25	270	254	–6.1	2.4	2.5	5.8
Mean[5]								**–1.5**			**10.2**
Standard deviation[5]								**7.9**			**14.6**

[1] Predictions are based on end-member mixing analysis (EMMA) using wells 12L311, 12K136, 12L061 as end members

[2] End-member well names are italicized

[3] Except where noted, fractions are based on a two end-member analysis consisting of water from 12L061 (presumed contaminated with nitrogen) and 12K136 (presumed uncontaminated background), then by substitution using well 12L311

[4] Outside of the mixing domain defined by chloride concentrations in water samples from wells 12K136, 12L061, and 12L311 (1998)

[5] Only the 33 non-end-member samples that lie within the mixing domain are included in the calculation

Table 18. Measured and predicted[1] chloride and nitrite plus nitrate as nitrogen concentrations in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999.

[mg/L, milligrams per liter; N, nitrogen; –, minus; U, unique samples; NO_3, nitrite plus nitrate as N]

Well[2] name (fig. 1)	Year	Water-quality group	Fraction[3] of well 12K136 (background water)	Fraction[3] of well 12L311 water	Fraction[3] of well 12L061 water	Chloride concentration (mg/L)		Nitrate concentration (mg/L as N)		Relative percent difference between measured and predicted nitrate concentrations
						Measured	Predicted	Measured	Predicted[4]	
11L113	1998	I	0.07	0.26	.67	7.9	7.9	0.0	7.5	199.5
12L326	1998	I	.12	.53	.35	5.8	5.8	.2	4.1	181.3
12L357	1998	I	.11	.15	.74	[5]8.3	8.3	5.9	8.4	34.4
	1999	I	.00	.48	.52	[5]7.4	7.4	3.1	6.3	67.9
12L047	1998	II	.00	0.84	.16	[5]4.7	4.7	.7	1.8	86.6
	1999	II	.00	.79	.21	[5]5.2	5.2	.6	2.6	126.3
12L311	1998	II	.00	1.00	.00	3.7	3.7	.0	.0	.0
12L311	1999	II	.21	.68	.11	4.4	4.4	.0	1.8	197.8
12L326	1999	II	.00	.80	.20	5.1	5.1	.0	2.4	196.8
12L344	1998	II	.10	.42	.48	[5]6.6	6.6	6.0	5.5	–9.2
	1999	II	.01	.56	.43	[5]6.7	6.7	5.1	5.3	4.1
11K015	1998	III	1.00	.00	.00	[5]2.6	2.8	.4	1.9	13.4
	1999	III	.40	.55	.05	3.9	3.9	.5	1.4	103.3
12K037	1998	III	.30	.54	.16	4.4	4.4	2.2	2.3	6.0
	1999	III	.18	.51	.31	5.8	5.8	3.1	4.2	3.8
12K123	1998	III	.50	.30	.20	4.5	4.5	2.0	3.2	44.8
	1999	III	.54	.27	.19	4.8	4.8	2.1	3.4	49.1
12K170	1998	III	.21	.00	.79	[5]8.5	8.5	7.0	9.1	26.0
12K175	1998	III	.64	.00	.36	5.4	5.4	3.8	5.2	3.7
	1999	III	.43	.00	.57	[5]7.6	7.5	5.7	7.8	31.7
12L277	1998	III	.15	.00	.85	8.9	8.9	7.5	9.6	24.9
	1999	III	.37	.00	.63	[5]8.0	8.0	6.9	8.5	19.6
12L339	1998	III	0.47	0.00	.53	6.6	6.6	5.9	6.7	13.0
	1999	III	.51	.00	.49	[5]6.9	6.9	5.4	7.0	25.9
12L345	1999	III	.37	.32	.31	5.7	5.7	4.4	4.6	3.4
12L348	1999	III	.26	.20	.54	7.6	7.4	6.5	7.1	9.8
12L350	1998	III	.36	.35	.29	5.0	5.2	3.0	3.9	25.5
	1999	III	.67	.10	.23	5.0	5.0	2.9	4.2	37.8

Table 18. Measured and predicted[1] chloride and nitrite plus nitrate as nitrogen concentrations in ground-water samples from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999.—Continued

[mg/L, milligrams per liter; N, nitrogen; –, minus; U, unique samples; NO_3, nitrite plus nitrate as N]

Well[2] name (fig. 1)	Year	Water-quality group	Fraction[3] of well 12K136 (background water)	Fraction[3] of well 12L311 water	Fraction[3] of well 12L061 water	Chloride concentration (mg/L)		Nitrate concentration (mg/L as N)		Relative percent difference between measured and predicted nitrate concentrations
						Measured	Predicted	Measured	Predicted[4]	
12L351	1998	III	0.48	.10	0.42	6.0	5.9	5.2	5.5	6.2
	1999	III	.62	.00	.38	6.1	6.1	4.4	5.9	29.4
12L356	1998	III	.48	.20	.32	5.2	5.3	4.5	4.4	–1.5
	1999	III	.30	.41	.29	5.6	5.6	3.8	4.2	9.1
12K014	1998	IV	1.00	.00	.00	2.8	2.8	1.5	1.9	23.5
	1999	IV	1.00	.00	.00	3.1	3.2	1.6	2.1	28.7
12K053	1998	IV	.97	.00	.03	3.0	3.0	2.1	2.1	1.9
	1999	IV	.87	.10	.03	3.4	3.5	2.2	2.2	–.6
12K101	1998	IV	.87	.00	.13	3.7	3.7	1.8	3.1	53.0
	1999	IV	.88	.00	.13	4.2	4.2	1.9	3.3	53.4
12K129	1998	IV	.76	.00	.24	4.5	4.5	2.6	4.1	43.7
	1999	IV	.76	.00	.24	5.0	5.0	2.9	4.5	41.1
12K133S	1998	IV	.83	.08	.09	3.6	3.5	2.5	2.6	2.7
	1999	IV	.73	.18	.09	4.1	4.0	2.6	2.6	2.0
12K136	1998	IV	1.00	.00	.00	2.8	2.8	1.9	1.9	0.0
12K136	1998	IV	1.00	.00	.00	3.2	3.2	2.1	2.1	0.0
12L345	1999	IV	.85	.00	.15	3.9	3.9	3.1	3.3	5.2
12L061	1998	U	.00	.00	1.00	10.0	10.0	11.0	11.0	0.0
12L061	1999	U	.00	.00	1.00	10.8	10.8	12.2	12.2	0.0
12L343	1998	U	.48	.25	.27	4.8	5.0	6.5	3.9	–5.4
	1999	U	.50	.25	.25	5.0	5.2	6.0	4.1	–38.6
Mean[6]										**41.3**
Standard deviation[6]										**63.7**

[1] Predictions are based on end-member mixing analysis (EMMA) using wells 12L311, 12K136, 12L061 as end members

[2] End member well names are italicized

[3] Fractions are based on a two end-member analysis consisting of water from well 12L061 (presumed contaminated with nitrogen) and well 12K136 (presumed uncontaminated background), then by substitution using well 12L311

[4] Predictions assume NO_3 concentrations are those under oxic conditions, and therefore not affected by losses due to denitrification or nitrate reduction

[5] Outside of the mixing domain defined by chloride concentrations in water samples from wells 12K136, 12L061, and 12L311 (1998)

[6] Only the 33 non-end-members samples that lie within the mixing domain are included in the calculation

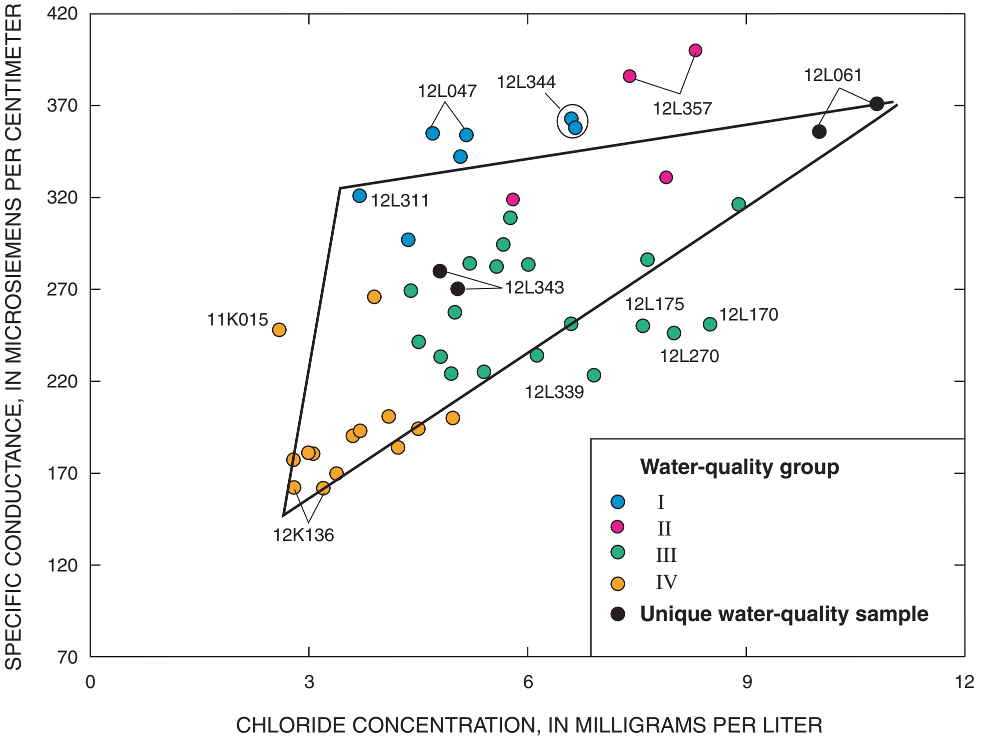


Figure 18. The mixing domain for a three end-member mixing analysis identified in ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, September 1998 and March 1999. Water samples from wells 12K136, 12L061, and 12L311 are the end members defining the mixing domain.

The minor constituent, ammonia, and orthophosphate concentrations in water samples from well 12L061 are typical for ground water in karst terrains. Except for silica and strontium, most minor constituents are below laboratory reporting limits and similar to those measured in other water samples collected during the study. The exception is the nitrate concentrations (11.0–12.2 mg/L, table 16), which are about four times higher than the study median and exceed the Georgia PMCL (10 mg/L as N; Georgia Environmental Protection Division, 2003). Wenner and Reyher (1999) showed that a plume of high-nitrate ground water is present west-northwest and upgradient from well 12L061. This nitrate plume, which is intercepted by well 12L061, is assumed to result from the leaching and nitrification of land-applied biosolids on land west-northwest of that well. Moreover, Wenner and Reyher (1999) also showed that the nitrate concentration in water samples from well 12L061 are about 4 mg/L greater than the concentrations expected in the delineated nitrate plume at that well. This elevated nitrate concentration indicates another source of nitrate at the well, probably the septic tank system that services a school at the site.

Further analysis of ground water at well 12L061 using nitrogen and oxygen isotopes failed to identify a specific source of nitrate to that well. Nitrogen and oxygen isotopes in water samples from well 12L061 are consistent with those from either sewage or animal waste (table 13 and fig. 13), but cannot specifically identify if either sewage or animal waste is the dominant source. Perhaps the isotope results indicate both sewage and animal waste are sources of the nitrate measured at well 12L061. This conclusion is supported by the following facts: (1) the Wenner and Reyher study (1999) shows that a plume of high-nitrate ground water is moving from an area west-northwest of well 12L061, an area where biosolids (animal waste) were applied to cropland; (2) the proximity of the well to a large septic tank system serving a school; and (3) caffeine is detected in a water sample collected for the current study from well 12L061. Thus, ground water at well 12L061 probably is contaminated by a mixture of animal and human waste.

The water chemistry in samples from well 12L343 also are markedly different from the chemistry in samples from well 12L061 and the rest of the study samples (tables 15 and 16). The pH and DO measurements, and the calcium, sodium, and chloride concentrations measured at well 12L343 are similar to, and the ANC is slightly lower than, the median values in the study (tables 15 and 16). Moreover, the SC is slightly higher than the study median. In contrast, the magnesium and potassium concentrations are as much as four times greater and sulfate concentrations are nearly two times greater than the respective study medians (tables 9, 15, and 16). The sodium-chloride ratio in the water samples from well 12L343 indicates that ground water near that well is enriched in chloride (fig. 11).

Except for silica and strontium in water samples from well 12L343, the concentrations of minor constituents and most nutrients are below laboratory reporting limits. The silica and strontium concentrations, averaging 6.6 and 0.19 mg/L, respectively, are the highest measured during the study period. Ammonia and orthophosphate concentrations are below laboratory reporting limits in water samples from well 12L343 (table 16). Nitrate concentrations average about 6.3 mg/L, twice the study median.

Although water samples from well 12L343 lie within the mixing domain, EMMA indicates that the nitrate concentrations in those samples are not consistent with the mixing of water from wells 12K136, 12L311, or 12L061 (fig. 18; tables 17 and 18). The EMMA result indicates that ground water near well 12L343 is enriched in nitrate from an unknown source. In addition, samples from well 12L343 are outliers in the relation between chloride and nitrate concentrations (fig. 12). This lack of correspondence further indicates that well 12L343 taps ground water with a water chemistry that is different from ground water in other parts of the study area. Water samples from well 12L343 probably represent ground water from a different source or ground water that is affected by a process or activity not common to other parts of the study area. One possible source of the observed ground-water chemistry at well 12L343 is fertilizer applications on agricultural fields in the study area. Fertilizer use in agricultural areas can cause elevated magnesium, potassium, sulfate, silica, and nitrate concentrations because these constituents are common ingredients in nitrogen fertilizers (Weil and others, 1990; Meister, 2002).

Water-Quality Groups I and II

Water-quality groups I and II are discussed together because of their proximity in the study area (fig. 17*A* and *B*) and because the water samples in both groups show some similarity in chemical composition. Substantial differences also exist, however, in several constituent concentrations in water samples from these two groups. Water-quality groups I and II consist of 11 ground-water samples collected from six wells (11L113, 12L047, 12L311, 12L326, 12L344, and 12L357). These groups represent an anoxic, reducing zone with five typical characteristics: (1) depth to static water level is less than 22 ft; (2) SC, which is an indirect measure of major ion concentrations, is among the highest measured in the study; (3) sodium-chloride ratios are consistent with evapotranspiration; (4) DO concentrations commonly are less than 0.5 mg/L; and (5) nitrate concentrations are low or not detected.

The depth to water can serve as an index of ground-water vulnerability to contaminants in unconfined or semiconfined aquifers. The depths to water at wells in groups I and II range from 0 (land surface) to 21.8 ft. The median depths to water in groups I and II are 15 ft and 9.5 ft, respectively, which are markedly shallower than the depths at other wells in the study area (table 15). Water samples collected from wells that tap the shallowest parts of an unconfined or semiconfined aquifer typically contain higher concentrations of major chemical constituents and nitrate than samples collected from deeper wells (Hallberg, 1989; Lawrence, 1996; Shedlock and others, 1999).

In the current study, the measured pH at wells in group I are similar to those in group II and similar to the study median. Likewise, SC values and DO concentrations at wells in group I are similar to those in group II, but are markedly different than their respective study medians. The SC at wells in groups I and II are the highest measured during the study period and range between 297 and 400 µS/cm (table 15). The median SC for groups I and II, 359 and 354, respectively, are substantially greater than the study median (266 µS/cm; tables 9 and 15). The DO concentration measured at wells in groups I and II ranges from less than 0.5 to 1.6 mg/L with 5 of 11 measurements below 0.5 mg/L, the DO reporting limit (table 15). The median DO concentrations for group I and group II wells, less than 0.5 and 0.7 mg/L, respectively, are markedly lower than the study median (tables 9 and 15). Ground water is considered anoxic when DO concentrations are less than 1.0 mg/L (Snoeyink and Jenkins, 1980).

Most of the major constituent concentrations in water samples from group I wells are similar to those in water samples from group II wells (table 15). All major constituents in samples from groups I and II are greater than the respective study medians (tables 9 and 15). The chloride concentration in group II samples is similar to the study median. Although calcium and sodium concentrations are slightly greater in group I samples than those in group II samples, potassium, sulfate, and chloride concentrations in group I samples are substantially greater than those in water-quality group II samples. The median potassium, sulfate, and chloride concentrations in group I samples, 0.78, 5.75, and 7.7 mg/L, respectively, are 46 to more than 200 percent greater than those concentrations in group II water samples (table 15).

The concentrations of sodium and chloride in water samples from most of the group I wells are at least an order of magnitude greater than samples collected in Tift County, Georgia. The sodium-chloride ratios are similar to those found in rainfall samples collected in Tift County, Georgia (fig. 11 and table 9). Elevated sodium and chloride concentrations coupled with sodium-chloride ratios similar to the ratios in local rainfall are indicative of constituent concentration changes caused by evaporation or evapotranspiration (Drever, 1988, p. 242). In contrast, the sodium-chloride ratios in water samples from wells 11L113, 12L344, and 12L357 indicate that chloride concentrations are enriched in ground water near those wells (fig. 11).

Evaporation or evapotranspiration may influence ground water near wells 12L047, 12L311, 12L326, and 12L344 because these wells are relatively close to either Cooleewahee Creek, one of its tributaries, one of its wetlands, or surface ponds (fig. 1). Furthermore, all four wells are located in a setting of active agriculture where extensive irrigation could also produce an evaporation-evapotranspiration signature in the sodium-chloride ratios. Unfortunately, stable isotopes of hydrogen (deuterium), which are commonly used together with oxygen (oxygen-18) to identify evaporation effects, are not available for water samples collected during the study period. Thus, sufficient data are not available to determine, definitively, whether evaporation is indeed affecting the major constituent concentrations in water samples from wells 12L047, 12L311, 12L326, and 12L344.

Evaporation or evapotranspiration coupled with the slow recharge of water into the Upper Floridan aquifer is a plausible explanation for the observed ground-water quality at wells 12L047, 12L311, 12L326, and 12L344. These four wells may be linked by a common source of ground water or by common geochemical or biochemical processes. This ground water has the following characteristics: slow ground-water flow, an apparent evaporation signature (sodium-chloride ratios), water that may have entered the aquifer more than 40 years ago, low DO concentrations signifying anoxia, similar major ion concentrations, elevated manganese and ammonium, but low to nonexistent nitrate concentrations. These characteristics are consistent with water collected in the saturated zones of freshwater wetlands (Mitsch and Gosselink, 1986, p. 93–101) and heavily irrigated agricultural fields, especially those that commonly are flood irrigated.

The saturated soils and overburden beneath active or paleowetlands or irrigated fields may impede recharge because those soils typically contain high percentages of low-permeability clay (Mitsch and Gosselink, 1986). As water from the land surface slowly moves to the aquifer, evaporation or evapotranspiration concentrates chemical constituents. Although sodium and chloride concentrations typically increase during evapotranspiration, the sodium-chloride ratios are unchanged and remain similar to the ratios in rainfall or background water in the aquifer. Furthermore, wetlands (and possibly agricultural fields) typically contain high amounts of organic matter that decompose (oxidize) under oxic conditions (Mitsch and Gosselink, 1986). In an oxic environment with decomposing organic matter, sulfate concentrations increase in the water (Chappelle and others, 1995). Active organic decomposition in either surface or ground water eventually results in anoxia. This organic decomposition is a possible explanation for the elevated sulfate concentrations in group I wells. Moreover, once the water becomes anoxic (DO less than 1.0 mg/L), the oxidation-reduction (redox) potential increases, denitrification begins, and nitrate is lost as gaseous nitrous oxides. As the redox potential increases, nitrate and sulfate reductions begin, which further reduce nitrate and sulfate concentrations, but increase ammonia, iron, or manganese concentrations in ground water (Trudell and others, 1986; Chappelle and others, 1995). Denitrification, nitrate, and sulfate reduction could explain the presence of low concentrations of ammonia, the lack of nitrate, and the substantial reduction in sulfate concentrations in the group II samples (tables 15 and 16).

The minor constituent concentrations in group I samples generally are similar to those in group II samples (tables 7, 8, and 16). Except for bromide, iron, manganese, silica, and strontium, nearly all minor constituent concentrations in samples from groups I and II are less than laboratory reporting limits (tables 7, 8, and 16). Low but measurable concentrations of bromide are found in water samples from group II wells 12L047 and 12L326 and in samples from 12L357, a group I well. A water sample from well 11L113 (group I) contains the only detectable concentration of iron measured during the study (table 16). Manganese concentrations in water samples from 12L311 and 12L326 range from 0.09 to 0.14 mg/L (table 16). Elevated concentrations of minor constituents in ground water, especially iron and manganese, commonly indicate a reducing environment in the aquifer.

Nutrient concentrations in group I and group II samples also are similar (table 16). Water samples from wells 12L311 (group II) and 12L326 (groups I and II) contain measurable, but low concentrations of ammonia (table 16). The median nitrate concentration in water samples from wells in group I (1.70 mg/L) is nearly three times higher than the median concentration in samples from group II wells (0.60 mg/L; table 16). The highest nitrate concentration measured in group I samples is from well 12L357 (5.90 mg/L) and the highest in group II samples is from well 12L344 (6.0 mg/L, table 16). Elevated chloride and nitrate concentrations commonly indicate either sewage contamination, recent animal waste, or perhaps applications of a nitrogen fertilizer (Cantor and Knox, 1985; Hallberg, 1989). The $\delta^{15}N$ and $\delta^{18}O$ measured during the March 2001 sample from well 12L344 indicates that ^{18}O is enriched, an indication of denitrification (table 13 and fig. 13). Wells 12L344 and 12L357, however, serve as the irrigation supply to agricultural fields or orchards where nitrogen fertilizers probably are routinely applied. The elevated concentrations of calcium, magnesium, potassium, chloride, and nitrate in water samples from well 12L357 are consistent with leaching of nitrogen fertilizer into the Upper Floridan aquifer. Furthermore, a potassium chloride fertilizer may be the source of elevated potassium and chloride concentrations in the group I samples. Low DO concentrations measured at wells in groups I and II and elevated ammonia, iron, and manganese concentrations in samples from those wells are consistent with a strong reducing environment. This reducing environment is conducive to denitrification, sulfate reduction, and nitrate reduction (Chappelle and others, 1995; Hallberg, 1989; Cantor and Knox, 1985).

The results of EMMA to predict SC values and sodium concentrations indicate that the chemical content of water samples from wells in groups I and II is plausible when water samples from wells 12L061 and 12L311 (Sept. 1998) are mixed in varying proportions (fig. 18; tables 17 and 18). When these proportions are used to predict nitrate concentrations in samples from both groups (except samples from well 12L344), however, those predictions are substantially higher than the measured concentrations. This difference between measured and predicted nitrate concentration probably is nitrate lost by either denitrification or nitrate reduction. The DO concentration measurements associated with 9 of 11 water samples in group I and II wells are less than 1.0 mg/L, the threshold where denitrification commonly begins (Cantor and Knox, 1985). The mixtures shown in tables 17 and 18 for groups I and II are plausible given the ground-water flow patterns in the study area (figs. 8 and 9).

The substantial change in the apparent ground-water proportions that determine the chloride and SC values between the 1998 and 1999 samples from wells 12L326, 12L344, and

12L357 illustrates the variability or transient nature of the ground-water chemical composition in this part of the study area. At wells 12L344 and 12L357, the 1998 water sample contains a lower proportion of ground water from the area of well 12L311, and a higher proportion of ground water from wells 12K136 and 12L061 than the apparent 1999 mixtures (tables 17 and 18).

Although EMMA shows that the SC, sodium, chloride, and nitrate concentrations measured at well 12L344 can be explained primarily by the mixing of ground water from wells 12L311 and 12L061, this apparent mixture seems improbable because ground-water flow patterns indicate that wells 12L344 and 12L061 are on opposing sides of a ground-water divide (fig. 17*A* and *B*). Nevertheless, this apparent incongruity might result if ground water with a chemistry similar to that at well 12L061 was mixing with ground water from the area of well 12L311. Given that well 12L344 is in a local recharge area, enriched in chloride (fig. 11) and nitrate, and has a manure/septic isotopic signature (fig. 13), it is possible and perhaps probable that the ground water at this site is influenced by effluent from a septic system, fertilizer applications or a combination of the two.

Water-Quality Group III

Water-quality group III, in the central part of the study area, appears to represent a mixing zone where ground water with different chemical compositions merge. Water-quality group III consists of 22 samples collected from 12 wells (fig. 17*A* and *B*; tables 15 and 16). The median depth to water is nearly 26 ft below land surface, 10 and 16 ft deeper than the median depth to water measured at wells in water-quality groups I and II, respectively. The water quality of group III samples differs substantially from the quality observed in the group I or group II samples. In water-quality group III samples, the SC is more than 30 percent lower, the DO 10 times higher, and major constituents from 20 to 50 percent lower than those found in water samples from groups I or II (table 15). The median concentrations of the major constituents are close to their respective study medians (tables 9 and 15). Chloride concentrations generally are higher in group III samples than concentrations found in samples from group II. With the exception of samples from wells 12K037 (Sept. 1998) and 12K175 (Sept. 1998), the sodium-chloride ratios in group III samples typically are lower than those measured in rainfall in Tift County, Georgia, indicating chloride enrichment (fig. 11 and table 9). The sodium-chloride ratios in water samples from wells 12K037 and 12K175 are similar to the ratios in Tift County rainfall.

Except for silica, strontium, and nitrate concentrations, minor constituent and nutrient concentrations are below laboratory reporting limits (table 16). Ammonia and orthophosphate concentrations in group III samples are either at or below their laboratory reporting limits (0.01 and 0.02 mg/L, respectively). Water samples from wells 12K037, 12K123, 12K350, and 12K351 contain orthophosphate concentrations two to five times the reporting limit (table 16). Nitrate concentrations in group III samples are greater than those in most of the water samples from groups I or II and nearly twice that of the study median (tables 9 and 16), but are similar to the concentration at wells 12L344 (group I) and 12L357 (group II; table 16).

The nitrate concentrations in group III samples and in samples from well 12L061, one of the unique wells, are strongly related to the chloride concentrations in those samples (rho = 0.95). This relation indicates that elevated nitrate and chloride concentrations in water samples from group III and well 12L061 may have a common source.

At the time of ground-water sampling during October 1998 and March 1999, the source of elevated nitrate concentrations in the study area was suspected, but not known with any certainty. As a result, additional water samples were collected from well 12L061 and five other wells during 2001, and the samples were analyzed for δ^{15}N and δ^{18}O. Four of the five wells are in water-quality group III (tables 13 and 15). The isotope analyses are summarized in table 13 and plotted in figure 13. Except for well 12K170, the δ^{15}N and δ^{18}O values are not markedly different among the group III water samples and the water sample from well 12L061 (fig. 13). The similarity in the δ^{15}N and δ^{18}O values among these group III samples and well 12L061 indicates that they share a common source of nitrate. These isotope concentrations are consistent with the isotopic signature of nitrogen and oxygen in nitrifying either sewage or animal waste moving through soil horizons (fig. 13). In contrast, the water sample from well 12K170 has δ^{15}N and δ^{18}O values that plot in the isotopic range commonly attributed to ammonia fertilizer (fig. 13). This well is located in an area of predominantly cultivated cotton and legumes, and the well is used to irrigate those crops.

The potentiometric-surface maps for October 1998 and March 1999 (figs. 8 and 9, respectively), which show the direction of ground-water flow, indicate that some of the group III wells are downgradient from well 12L061, where the ground water has elevated nitrate concentrations. Moreover, group III wells also are downgradient from wells in water-quality groups I and II. Thus, the water chemistry measured in group III wells probably is a mixture of ground water from the area of well 12L061 and from the area delineated as water-quality groups I and II. To address this hypothesis, an EMMA was performed to determine if simple mixing of different ground water can explain the ground-water chemistry in group III.

EMMA indicates that the nitrate concentration in 19 of 22 group III water samples collected during September 1998 can be explained by the simple mixing of water with chemical compositions similar to those in water samples from wells 12K136, 12L311, and 12L061 (table 18). As ground water moves downgradient, the water samples from the group III wells show a progressively higher proportion of background water and lower proportions of water from wells 11L311 and 12L061 (table 18). Because well 12K037 is relatively close to the Flint River and the apparent direction of ground-water flow is from the Flint River toward this well, water samples from this well probably contain a small fraction of Flint River water.

The proportion of water attributed to well 12L311 in water samples from well 12K037 actually may be Flint River water (table 18). Elevated SC values in water samples from well 12K037 indicate this well may be a mixture of water from the Flint River and background ground water (fig. 14*A* and *B*). Water samples from well 12K037 contain higher SC values than those in water samples from neighboring wells, but are lower than those in wells close to the river. The EMMA results also indicate that well 11K015 may intercept ground water that has a different source or is a mixture of water not identified in this report. Indeed, the pattern of ground-water flow indicates that well 11K015 may intercept water moving from Cooleewahee Creek into the Upper Floridan aquifer.

Water-Quality Group IV

Water-quality group IV, in the south-central part of the study area, consists of 12 samples collected from five wells and one spring (fig. 17*A* and *B*, tables 15 and 16). Water samples in water-quality group IV seem to be least affected by ground water moving from the vicinity of wells 12L311 and 12L061 (table 17). The median depth to water is 39.0 ft below land surface and the deepest in the study area. Furthermore, water samples in group IV represent relatively young ground water. The CFC data indicate that ground water in group IV was recharged between 1976 and 1984, from 14 to 22 years before samples were collected (fig. 10).

Measurements of field properties—such as pH, DO, and SC—are markedly different from those in the other water-quality groups. The median pH of 8.0 is the highest measured during the study period and markedly higher than the study median (7.6) (tables 9 and 15). The median DO concentration (7.4 mg/L) is substantially higher than the DO in the other three water-quality groups and substantially higher than the study median (5.6 mg/L) (tables 9 and 15).

The median SC (182 µS/cm) and the median calcium, bicarbonate, and sulfate concentrations in group IV samples are statistically the lowest measured in the study area. The median SC is 86 percent lower than the median SC in water-quality groups I and II, but 32 percent lower than in water-quality group III samples (table 15). Likewise, the median concentrations of major constituents are substantially lower than those found in the other three water-quality groups and the four unique samples (table 15). Figure 13, however, indicates that the sodium-chloride ratios in group IV are below the median ratios found for rainfall at Tift County, Georgia. This ratio indicates that the chloride concentrations in group IV samples are slightly enriched, but still substantially depleted when compared to other samples in the study.

Minor constituent and nutrient concentrations in group IV samples are among the lowest in the study area (table 16). Bromide, iron, manganese, and ammonia concentrations are below laboratory reporting limits. The median nitrate concentration in group IV (2.1 mg/L) is similar to the concentration considered to be the natural, background concentration (2 mg/L in Hallberg, 1989; 2–3 mg/L in Fuhrer and others, 1999).

The direction of ground-water flow shown in figures 8, 9, and 17*A* and *B* indicates that ground water with the highest nitrate concentrations near well 12L061 and high chloride concentrations near well 12L311 flow toward and may influence the water quality in group IV wells. Even so, EMMA indicates that group IV water samples are dominated by ground water with a chemical composition similar to the water samples from well 12K136. Moreover, only a small fraction of ground water (from 2 to 20 percent) with chemical compositions similar to those in samples from wells 12L311 and 12L061 seem to influence nitrate concentrations in group IV wells (table 18 and fig. 17*A* and *B*). EMMA results also indicate that well 12K014 may intercept ground water that has a different source or is a mixture of water not identified in this report. Well 12K014 could intercept ground water that is moving from the south-southwest. This ground water may be a mixture of water that has a substantially different chemical composition than most of the ground water sampled in this study; however, no data were collected south of well 12K014, so flow in that area is uncertain.

Summary and Conclusions

During the mid-1990s, the Dougherty County Health Department (DCHD) collected water samples from selected drinking-water wells in Dougherty County, Georgia, and discovered elevated nitrate as nitrogen concentrations in many of those samples. Among these sampled wells was the drinking-water supply at a school that contained nitrate as nitrogen concentrations exceeding the Georgia primary maximum contaminant level (PMCL) of 10 milligrams per liter. Prompted by the high nitrate concentration found in the well, the DCHD expanded its sampling effort during March 1997 with a goal to collect water samples from more than 700 residential wells in the southwestern Albany area, Georgia. Only nitrate concentrations were analyzed in those samples. The sampling efforts by DCHD established the spatial extent of nitrate concentrations and identified elevated nitrate concentrations in many individual wells. Moreover, water samples from 12 percent of the more than 700 wells contained nitrate concentrations above the PMCL. These wells are considered contaminated with respect to nitrate and each taps the Upper Floridan aquifer.

The U.S. Geological Survey—in cooperation with the Albany Water, Gas, and Light Commission—conducted a study from 1998 to 2001 to better understand the ground-water flow system and water quality of the Upper Floridan aquifer in the southwestern Albany area, Georgia. The study area encompasses about 64 square miles in the highly agricultural area southwest of Albany, in Dougherty County, between the Flint River and Cooleewahee Creek.

Hydrographs from six continuously monitored wells show that the regional trend in ground-water levels for the Upper

Floridan aquifer was decreasing during the study. Following the end of the irrigation season in early September, the six wells showed increases in water levels that corresponded to major rainfall events. The stage of the Flint River also showed increases that correspond to rainfall events. Beginning in November 1998, the Flint River showed a gradual increase in stage. The annual, semiannual, and short-term changes in the stage of the Flint River seem to influence ground-water levels in wells located close to the river.

Following two major rainfall events during September 1998, the Flint River stage rose, but the water levels declined at six continuously monitored wells. The water-level decline at well 12K014 (2.5 miles from the Flint River) was not as substantial as the decline observed at the other five wells. These water-level data indicate that when the Flint River stage is high following a storm and the potentiometric surface of the Upper Floridan aquifer is low, the natural discharge from the aquifer to the river decreases or reverses, causing an increase in the potentiometric surface in that part of the Upper Floridan aquifer closest to the river.

Water-level data collected from 72 wells during May 1998, 67 wells during October 1998, and 72 wells during March 1999 indicate that the potentiometric surface of the Upper Floridan aquifer varies throughout the study area and varies seasonally. The general direction of ground-water flow is from northwest to southeast; however, when water levels are high, as they were during May 1998, the potentiometric surface has a mound of higher potential in the central part of the study area than in surrounding area. The hydraulic gradient east of the mound was southeast at approximately 8.7 feet per mile (ft/mi) during May 1998. Ground water flowed toward Cooleewahee Creek on the west side of the mound. Water levels declined during summer 1998 and by October 1998 were substantially lower than the previous May. Likewise, the mound of high potential was still present on the potentiometric surface, but was much smaller in extent than during the previous May. The hydraulic gradient southeast through the study area was about 9.3 ft/mile. Water levels remained low through winter 1999 and were lowest during March 1999. The mound of high potential was not present during March 1999, and the hydraulic gradient southeast through the study area was about 6.8 ft/mi. All three of the potentiometric-surface maps show ground-water flow from east to west in the southeastern part of the study area near the Flint River. The Flint River seems to have an effect on the potentiometric surface of the Upper Floridan aquifer in this area, especially when the river stage is high.

Recharge to the Upper Floridan aquifer occurs at a greater rate through the undifferentiated overburden in the central part of the study area than in other parts of the study area. The overburden in the central part of the study area has a higher vertical hydraulic conductivity than the overburden in surrounding areas. Rapid recharge to the Upper Floridan aquifer in this area produces a ground-water mound that contains younger ground water than in the surrounding area. Moreover, water levels in wells open to the undifferentiated overburden are affected by ground-water withdrawal from the Upper Floridan aquifer, indicating a hydraulic connection between the overburden and the Upper Floridan aquifer.

During 1998 and 1999, water-quality samples were collected at 24 wells and 1 spring in the study area. Ground water in this part of the Upper Floridan aquifer is dominated by calcium and bicarbonate ions. The pH ranges from 7.0 to 7.9 standard units with a study median of 7.6. The specific conductance (SC) ranges from 162 to 400 microsiemens per centimeter (μS/cm) with a study median of 266 μS/cm. The dissolved oxygen (DO) concentrations in the 24 wells during the study period range from less than 0.5 milligrams per liter (mg/L) to 11.1 mg/L with a study median of 5.6 mg/L.

Nutrient concentrations generally are low in the study area. Ammonia was detected in seven samples from four wells. The highest ammonia concentration measured during the study period is 0.10 mg/L as nitrogen (N). Water samples contained nitrate as N concentrations that range from less than 0.01 mg/L to 12.2 mg/L. Water samples collected from one well (12L061) during 1998 and 1999 contain nitrate as N concentrations that exceed the Georgia and USEPA drinking-water standard of 10 mg/L. At wells with DO concentrations greater than 1 mg/L, nitrate concentrations are strongly related to chloride concentrations. A linear regression analysis shows that 94 percent of the variability in nitrate concentrations can be explained by the variability in the squared chloride concentrations.

Ground-water quality in the study area is divided into four water-quality groups based on similarities in dissolved calcium, magnesium, sodium, potassium, acid-neutralizing capacity (ANC), sulfate, chloride, silica, and strontium concentrations. In addition, water samples from two wells (12L061 and 12L343) are distinctly different from all other samples collected during the study. Each of the four water-quality groups is comprised of water samples with similar chemical characteristics that are unique to that group. Water-quality group I is anoxic ground water containing elevated major chemical constituents (especially potassium, sulfate, and chloride) and generally low nitrate concentrations. Water-quality group II is similar to group I except that group II samples have substantially less potassium, sulfate, and chloride concentrations. Water-quality group III is a mixture, in varying proportions, of ground water with chemical compositions similar to that in water samples from wells 11L113, 12K136, and 12L061; this group is characterized by DO concentrations, pH, SC, and major chemical constituents that are similar to their respective study medians. Water-quality group IV is ground water that is typical of background (uncontaminated) water; samples from these wells have the highest pH values and highest DO concentrations and have markedly lower major ions and nutrients than the other three water-quality groups.

Four general observations are apparent from the analysis of ground-water samples collected in the study area during 1998 and 1999: (1) major ion and nitrate concentrations are elevated where ground-water mounding is evident; (2) elevated dissolved ion and nitrate concentrations rapidly decrease as ground water flows from the recharge areas toward the Flint River; (3) multiple sources of water containing elevated ion and nitrate concentrations are present in the study area; and (4) animal and human waste and nitrogen fertilizers are contributing to elevated nitrate concentrations in the study area. Ground-water flow in this karst region is highly complex and convoluted such that analysis and interpretation of water-quality conditions and identification of contaminant sources may not be possible with the methods and approaches commonly used in nonkarst areas.

This study provided the following insights: (1) additional water-level data near the Flint River would provide a better understanding of how the river influences the potentiometric surface of the Upper Floridan aquifer; (2) given the complexity and karstic nature of the Upper Floridan aquifer, better vertical control would improve the accuracy of potentiometric-surface maps; (3) collecting water-level data in the undifferentiated overburden would allow for better characterization of the hydraulic connection between the overburden and the Upper Floridan aquifer, especially regarding recharge and movement of surface contaminants into the Upper Floridan aquifer; (4) additional water-quality samples from a greater number of wells would provide a better understanding of the hydrologic complexities in the study area; (5) additional constituents—such as isotopes of nitrogen, carbon, oxygen, sulfur, and deuterium—commonly used in geochemical modeling studies would add substantial information to identify nitrate sources; and (6) flow modeling, geochemical modeling, and solute transport modeling would increase the understanding of the interplay between ground-water flow and water quality in the Upper Floridan aquifer in the southwestern Albany area, Georgia.

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Appendix A. Example of End-Member Mixing Calculations

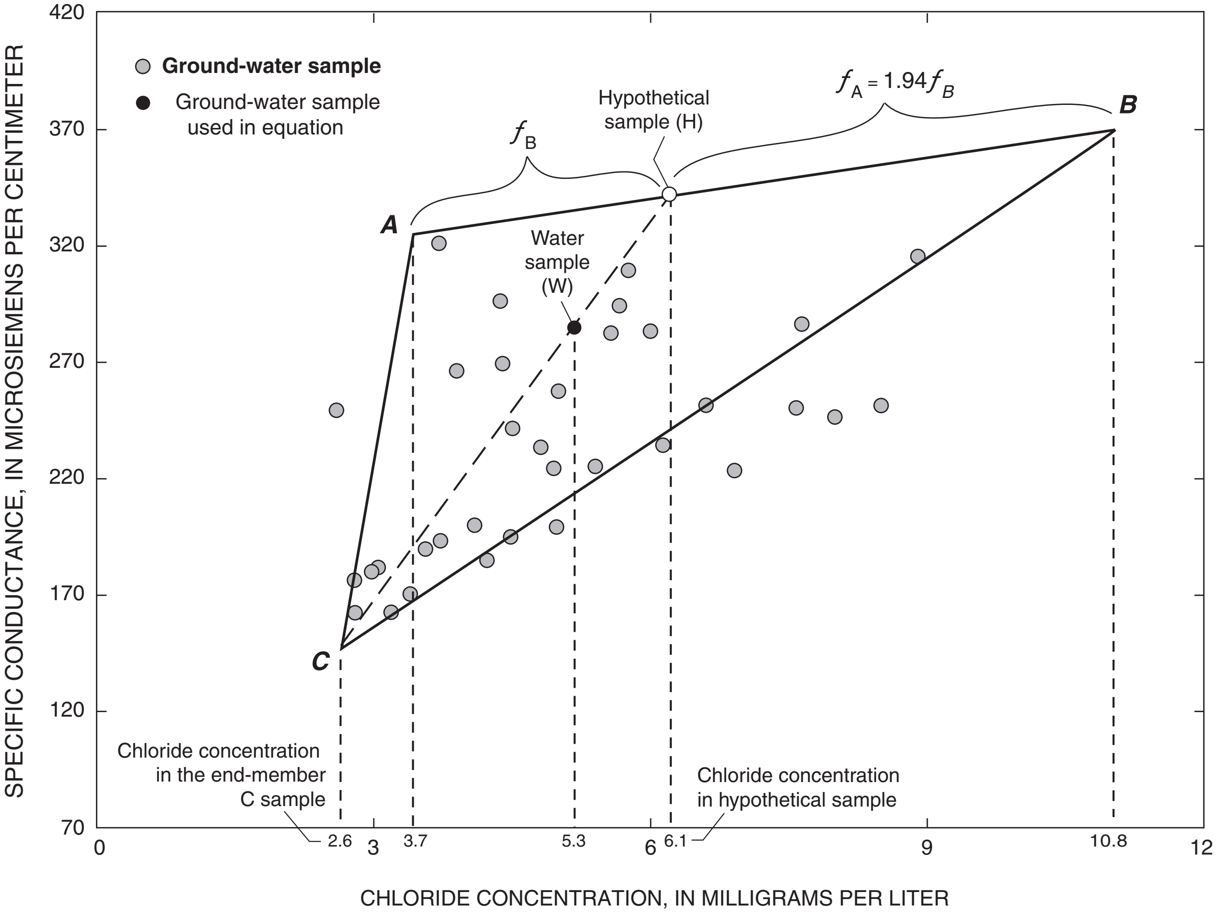

Figure A1. Diagram showing the mixing domain developed from the end-member mixing analysis of ground-water samples from selected wells completed in the Upper Floridan aquifer, southwestern Albany area, Georgia, September 1998 and March 1999. Facing page shows example of end-member mixing analysis.

I. A line drawn from end-member C through a sample intersects the line segment AB at a point that will be called the hypothetical sample H.

II. Determine the fractions *(f)* of water samples A and B in a hypothetical sample H by solving equations (1) and (2) simultaneously. The chloride concentration (C) is the conservative ion used in equation (1).

$$C_H = C_A f_A + C_B f_B \qquad (1)$$

$$1.0 = f_A + f_B \qquad (2)$$

A. Solve for fraction A: multiply equation (2) by $-C_B$, then add equation (2) to equation (1):

1.

$$\begin{array}{rr} C_H = C_A f_A + C_B f_B & (1) \\ \text{plus} \quad -C_B\,(1.0 = f_A + f_B) & (2) \\ \hline C_H - C_B = C_A\, f_A - C_B f_A + C_B f_B - C_B f_B & (3) \end{array}$$

2. Simplify and rearrange equation (3): $f_A = (C_H - C_B) / (C_A - C_B)$ (4)

3. Solve for f_B: $f_B = 1.0 - f_A$

B. Establish f_A to f_B ratio by rearranging equation (2) in terms of f_B and substituting the result of equation (4) for f_A

$$f_A / f_B = f_A / (1.0 - f_A) \qquad (5)$$

C. Example using real values: C_A is the chloride concentration in sample A = 3.7 mg/L; C_B is the chloride concentration in sample B =10.8 mg/L; C_H is the chloride concentration in hypothetical sample = 6.1 mg/L

1. Substitute sample values for variables in equation (4): $(6.1 - 10.8) = (3.7 - 10.8)\, f_A$

2. Rearrange and solve for f_A: $f_A = -4.7 / -7.1$; thus $f_A = 0.66$

3. Solve for f_B: $1.0 = 0.66 + f_B$; Thus, $f_B = 0.34$

D. Establish f_A to f_B ratio by substituting f_A from C.2 and f_B from C.3 above into equation (5):

f_A to f_B is 0.66 / 0.34 or 1.94; thus, $f_A = 1.94 f_B$

III. Compute the fractions for the three end-member model using equations (1) and (2) by adding a third term representing sample C. C_C is chloride concentration for sample C = 2.6 mg/L; C_W is the chloride concentration for the water sample with unknown fractions of samples A, B, and C.

A. $C_w = C_A f_A + C_B f_B + C_C f_C$ (6)

B. Substitute f_A into equation (2) and equation (6) with the value from II.D above:

$$1.0 = 1.94 f_B + f_B + f_C \qquad (7)$$

$$C_w = C_A (1.94 f_B) + C_B f_B + C_C f_C$$

C. Substitute real values in equation (6): $5.3 = 3.7(1.94 f_B) + 10.8 f_B + 2.6 f_C$

D. Multiply equation (7) by −2.6, then subtract equation (7) from equation (6)

E. Simplify: $5.3 - 2.6 = 7.18 f_B + 10.8 f_B + 2.94 f_B$

F. Solve for f_B: $10.34 f_B = 2.70$; $f_B = 2.70 / 10.34 = 0.26$

Thus, $f_A = 1.94 f_B$ or 0.51, $f_B = 0.26$, and $f_C = 0.23$

Appendix B. Diagnostic and Residual Plots from Three Simple Linear Regression Analyses Predicting Nitrate as Nitrogen Concentration from Chloride Concentration in Selected Ground-Water Samples, Southwestern Albany Area, Georgia, September 1998 and March 1999

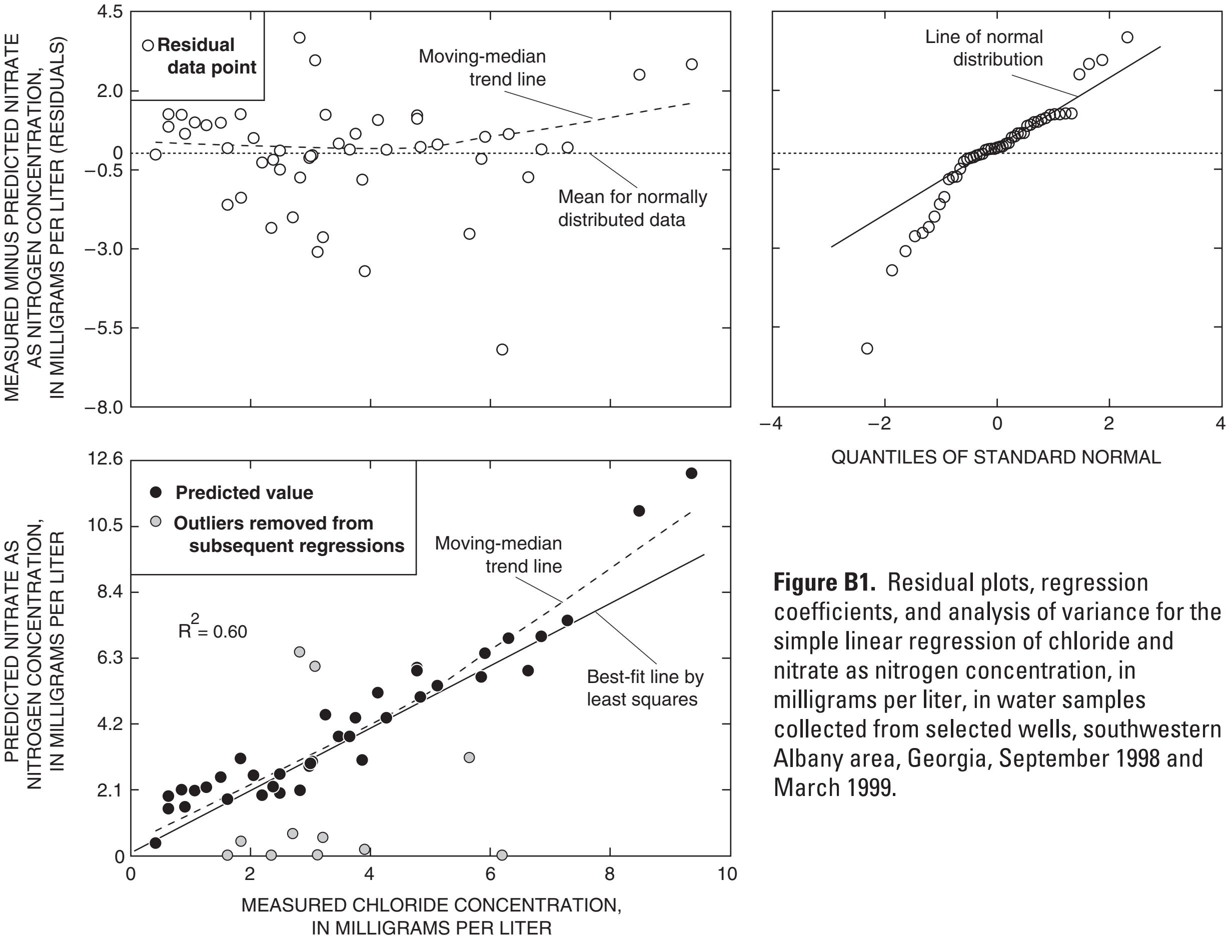

Figure B1. Residual plots, regression coefficients, and analysis of variance for the simple linear regression of chloride and nitrate as nitrogen concentration, in milligrams per liter, in water samples collected from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999.

Linear regression coefficients

[<, less than]

Parameter	Value	Standard error	t-value	p-value
Intercept	−2.4243	0.7560	−3.2066	0.0024
Chloride	1.0912	0.1307	8.3498	<0.001

Analysis of variance

[<, less than]

Parameter	Degrees of freedom	Sum of squares	Mean square error	F-value	p-value
Chloride	1	213.21	213.21	69.72	<0.001
Residuals	47	143.73	3.06		

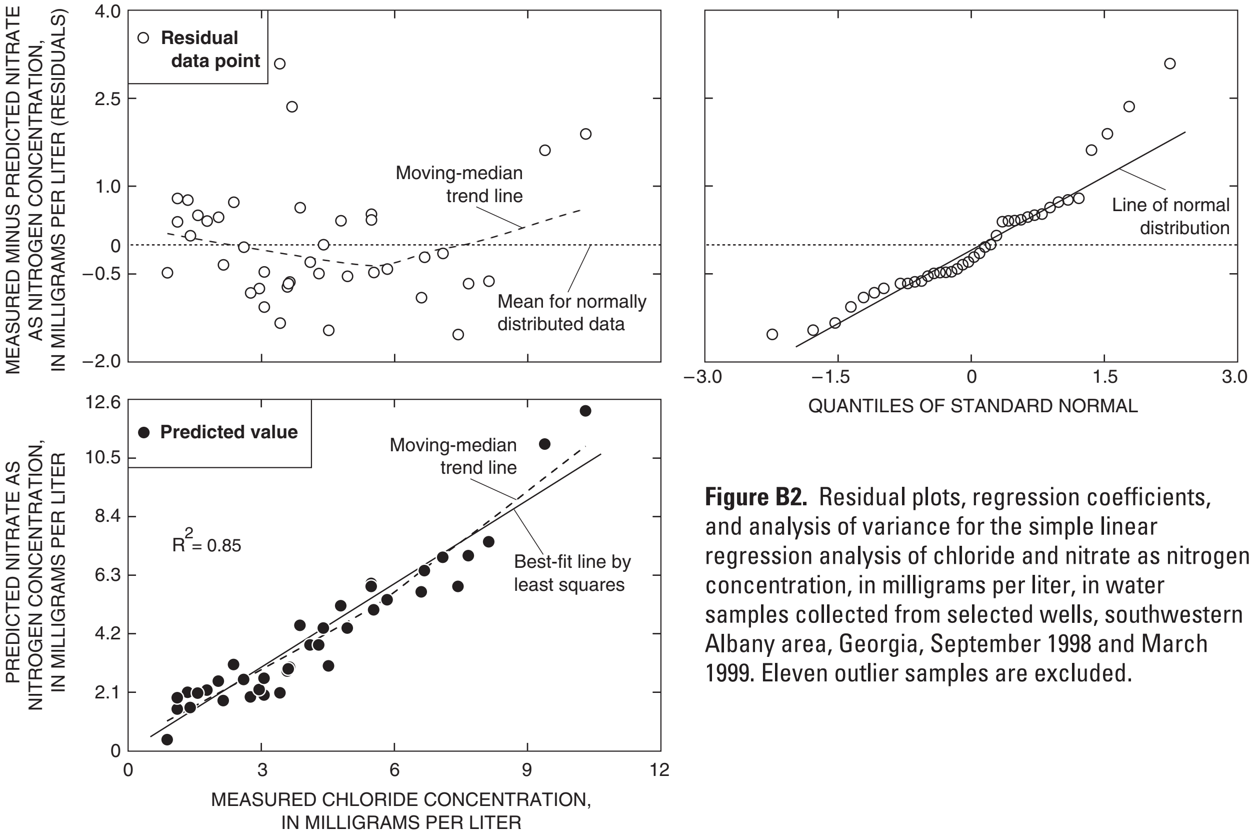

Figure B2. Residual plots, regression coefficients, and analysis of variance for the simple linear regression analysis of chloride and nitrate as nitrogen concentration, in milligrams per liter, in water samples collected from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999. Eleven outlier samples are excluded.

Linear regression coefficients

[<, less than]

Parameter	Value	Standard error	t-value	p-value
Intercept	−2.1112	0.4607	−4.5826	<0.001
Chloride	1.11501	0.0788	14.5920	<0.001

Analysis of variance

[<, less than]

Parameter	Degrees of freedom	Sum of squares	Mean square error	F-value	p-value
Chloride	1	213.89	213.89	212.93	<0.001
Residuals	38	38.17	1.00		

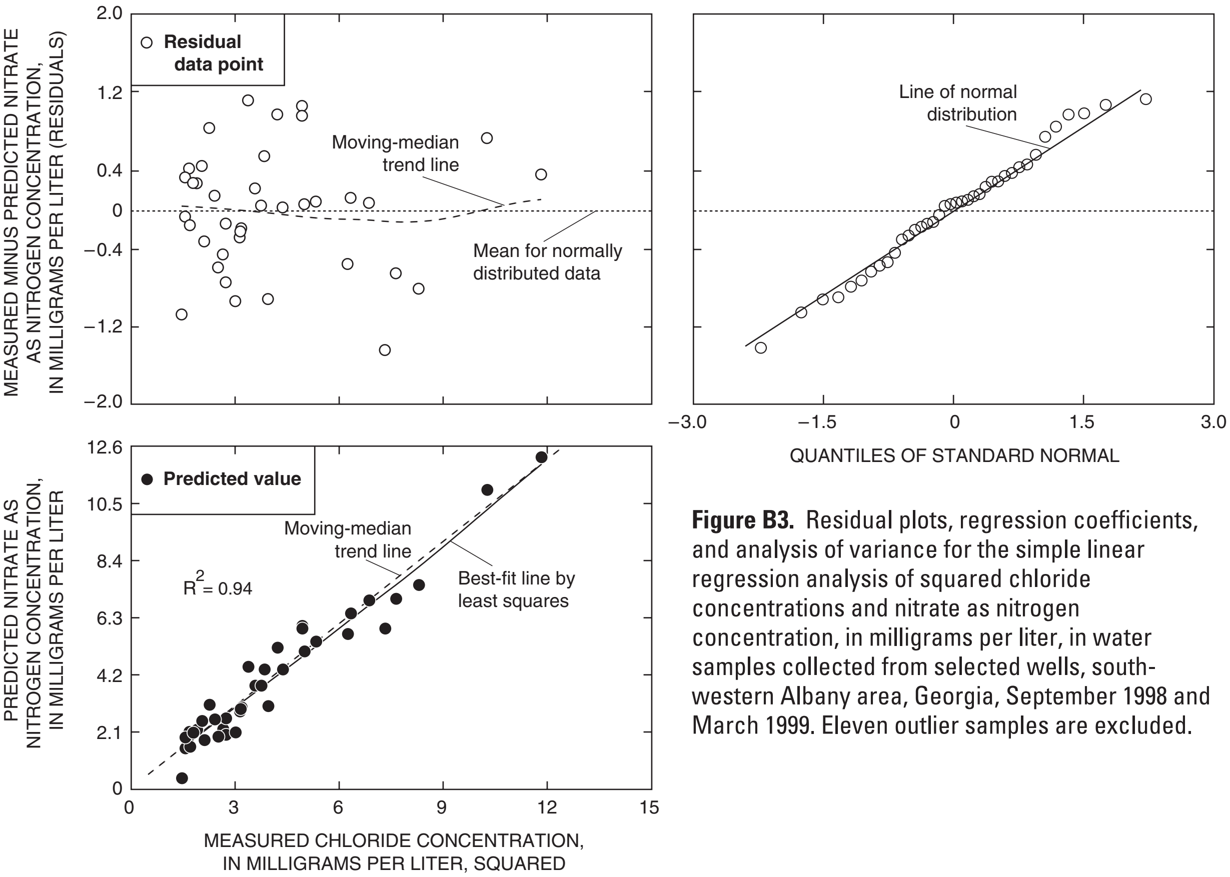

Figure B3. Residual plots, regression coefficients, and analysis of variance for the simple linear regression analysis of squared chloride concentrations and nitrate as nitrogen concentration, in milligrams per liter, in water samples collected from selected wells, southwestern Albany area, Georgia, September 1998 and March 1999. Eleven outlier samples are excluded.

Linear regression coefficients

[<, less than]

Parameter	Value	Standard error	t-value	p-value
Intercept	0.8183	0.1706	4.7961	<0.001
Chloride^2	.0944	.0039	23.9755	<0.001

Analysis of variance

[<, less than]

Parameter	Degrees of freedom	Sum of squares	Mean square error	F-value	p-value
Chloride^2	1	228.62	228.62	574.82	<0.001
Residuals	36	14.32	.40		

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