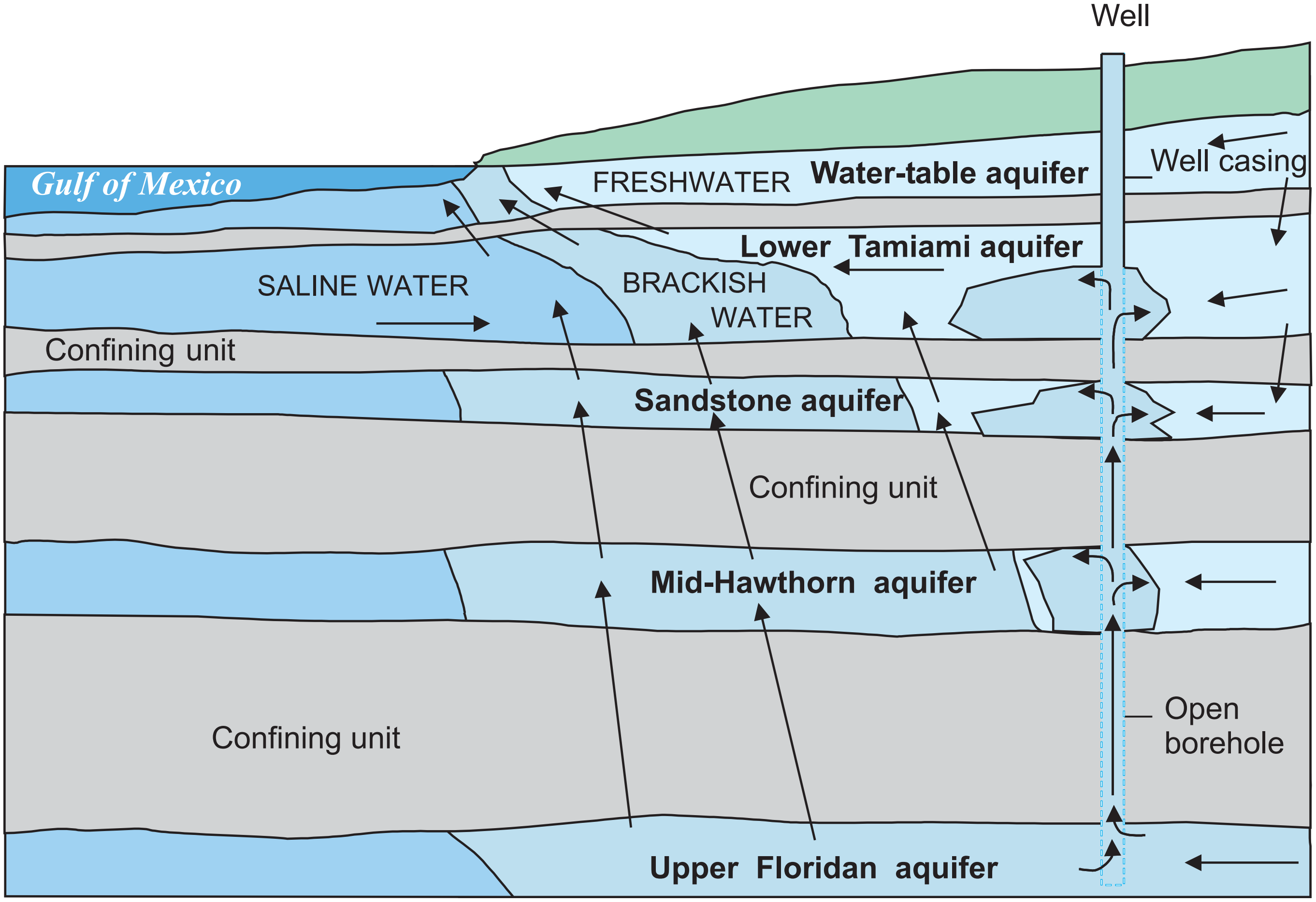
Distribution and Origin of Salinity in the Surficial and Intermediate Aquifer Systems, Southwestern Florida



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 01-4159

Prepared in cooperation with the
SOUTH FLORIDA WATER MANAGEMENT DISTRICT

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By David L. Schmerge

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Tallahassee, Florida
2001

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Sea level: In this report, ì sea levelî refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)ó a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

Chloride concentrations in the surficial and intermediate aquifer systems in southwestern Florida indicate a general trend of increasing salinity coastward and with depth. There are some notable exceptions to this trend. Brackish water is present in the sandstone and mid-Hawthorn aquifers in several inland areas in Lee County. In an area near the coast in Collier County, the lower Tamiami aquifer contains freshwater, with brackish water present farther inland. Saline water is present in the lower Tamiami aquifer along the coast in Collier County, but water is brackish in the underlying mid-Hawthorn and Upper Floridan aquifers.

The analyses of major ions, hydrogen and oxygen isotopes, and strontium isotopes indicate the primary sources of salinity are underlying aquifers and the Gulf of Mexico. Based on these data, much of the salinity is from upward leakage of brackish water from underlying aquifers. Discharge as diffuse upward leakage and artesian wells are two possible pathways of saltwater intrusion from underlying aquifers. Artesian wells open to multiple aquifers have been pathways of saltwater intrusion in the sandstone and mid-Hawthorn aquifers in much of Lee County. The source of brackish water in the lower Tamiami and mid-Hawthorn aquifers in Collier County may be natural diffuse leakage from underlying aquifers. The source of the saline water in the lower Tamiami aquifer in Collier County is apparently the Gulf of Mexico; it is unclear however, whether this saline water is residual water from former Pleistocene sea invasions or recent saltwater intrusion.

INTRODUCTION

Saltwater intrusion in the surficial and intermediate aquifer systems is a major threat to fresh ground-water supplies in southwestern Florida. The surficial and intermediate aquifer systems are the primary sources of freshwater in Lee and Collier Counties (Marella, 1999). Large withdrawals have caused substantial depressions in the potentiometric surface of both aquifer systems (Bengtsson and Radin, 2001), and ground-water levels in the region are expected to decrease in the future because of increasing demands for water. Saltwater intrusion in coastal aquifers is often attributed to long-term declines in ground-water levels; thus, further water-level declines may render the available water supplies nonpotable.

Prevention and successful remediation of saltwater intrusion are often dependent upon understanding the origin of salinity. Sources or processes other than the inland encroachment of seawater owing to ground-water declines can also cause saltwater intrusion (Bear and others, 1999). Previous research has shown that irrigation wells tapping multiple aquifers can be a pathway for saltwater intrusion in southwestern Florida (Sproul and others, 1972; Boggess and others, 1977; Fitzpatrick, 1986). These wells were commonly completed with only a short length of steel casing; brackish water flowed up the uncased (or corroded) wells and entered freshwater aquifers, resulting in saltwater intrusion. To abate this problem, the South Florida Water Management District (SFWMD) in 1979 began the Well Abandonment Project (Burns, 1983). An analysis of the effects of the well-plugging program on water quality indicated slight decreases in chloride concentrations on a local scale, but was inconclusive on a regional scale (La Rose, 1990).

The regional distribution of salinity and its origin are critical elements needed by water managers to ensure the protection of the fresh ground-water resources in Lee and Collier Counties. In 1998, the U.S. Geological Survey (USGS) began a cooperative study with the SFWMD to ascertain the extent of salinity and its sources in the surficial and intermediate aquifer systems of southwestern Florida.

Purpose and Scope

The purpose of this report is to determine the distribution and origin of salinity in the surficial and intermediate aquifer systems of Lee and western Collier Counties. Analyses of chloride concentrations in ground water and surface-geophysical data are used to map the distribution of salinity for the lower Tamiami, sandstone, and mid-Hawthorn aquifers. The chemical and isotopic (hydrogen, oxygen, and strontium) compositions of ground water from the lower Tamiami, sandstone, mid-Hawthorn, and Upper Floridan aquifers are described to identify the origin of salinity.

Description of Study Area

The study area encompasses about 1,400 mi^2 (square miles) in Lee and western Collier Counties (fig. 1) and is characterized by low topographic relief and a high water table. Land-surface elevations range from sea level along the coast to about 40 ft (feet). An extensive coastal swamp with numerous tidal streams, bays, and lagoons lies southeast of Naples with land-surface elevations typically less than 3 ft. The coast northward from Naples is generally higher and sandy without extensive coastal swamps. Major waterways include the Caloosahatchee, Estero, Imperial, and Cocohatchee Rivers. Numerous canals also have been constructed throughout the study area.

Hydrogeology

The hydrogeologic units of southwestern Florida are the surficial, intermediate, and Floridan aquifer systems that range in age from Paleocene to Holocene (fig. 2). The Paleocene to Oligocene sediments are several thousand feet thick, predominantly carbonate, and form the Floridan aquifer system consisting of the Upper Floridan aquifer, the middle confining unit, and the Lower Floridan aquifer (Reese, 2000). The Miocene to Holocene sediments are several hundred feet thick, predominately siliciclastic, and form the surficial and intermediate aquifer systems.

The surficial aquifer system is the permeable hydrogeologic unit bounded by land surface and the first occurrence of vertically persistent and laterally extensive beds of low permeability (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). In southwestern Florida, the surficial aquifer system consists of the water-table aquifer, confining beds, and the lower Tamiami aquifer (fig. 2). The thickness of the system ranges from about 200 ft in southwestern Collier County to less than 25 ft in northern Lee County. The water-table aquifer lies within undifferentiated deposits of Holocene to Pleistocene age and extends into the Tamiami Formation in northern Lee County where the confining beds are absent (Wedderburn and others, 1982; Knapp and others, 1986). The lower Tamiami aquifer, a major water-producing unit within much of the study area, generally lies within the lower part of the Tamiami Formation of Pliocene age and mainly consists of sandy, shelly limestone, and calcareous sandstone (Knapp and others, 1986). In some areas, the lower Tamiami aquifer extends down into unconsolidated quartz sand of late Miocene age (Knapp and others, 1986; Weedman and others, 1997; Edwards and others, 1998). Ground water within the surficial aquifer system generally flows coastward (Bengtsson and Radin, 2001). The surficial aquifer system is primarily recharged by precipitation, seepage from canals and other surface-water bodies, and upward leakage from the intermediate aquifer system.

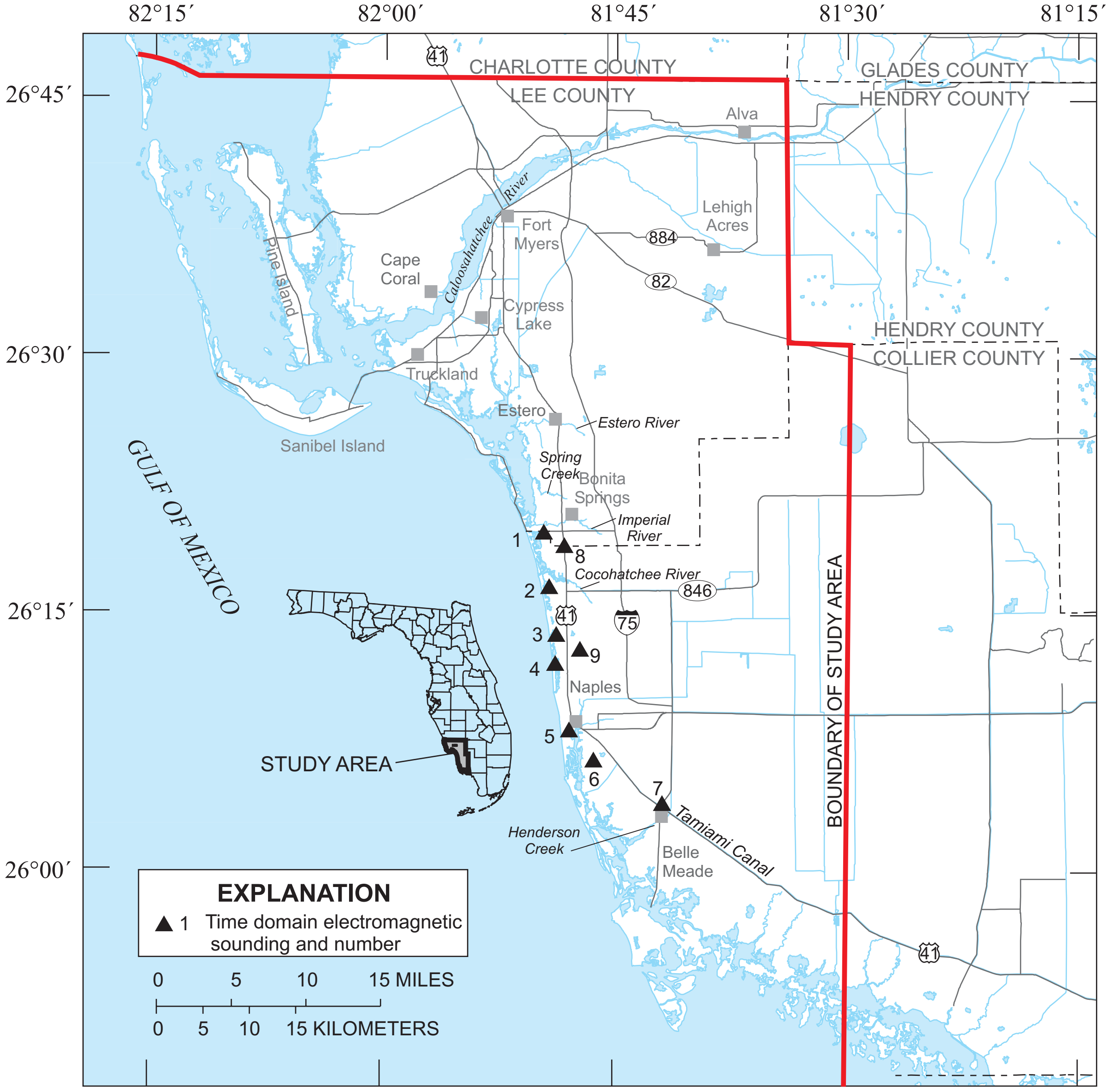

Figure 1. Location of study area in Lee and western Collier Counties, southwestern Florida.

The intermediate aquifer system consists of those units overlying and confining the Floridan aquifer system and underlying the surficial aquifer system (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). In southwestern Florida, the intermediate aquifer system consists of three relatively impermeable confining units and the sandstone and mid-Hawthorn aquifers and lies within the Hawthorn Group of Oligocene to Pliocene age (fig. 2). The sandstone aquifer consists of sandy limestone, sandstone, sandy dolomite, and calcareous sands and is thin or absent in the northwestern and southern parts of the study area (Wedderburn and others, 1982; Knapp and others, 1986). The mid-Hawthorn aquifer consists of sandy and phosphatic limestones and dolomites and is generally about 100 ft thick in the study area (Wedderburn and others, 1982; Knapp and others, 1986). Flow in the mid-Hawthorn aquifer is toward a large cone of depression near Cypress Lake, and flow in the sandstone aquifer is generally toward the coast, except for a cone of depression between Estero and Lehigh Acres (Bengtsson and Radin, 2001). Recharge to the intermediate aquifer system in the study area occurs through upward leakage from the Upper Floridan aquifer and through downward leakage from the surficial aquifer system (Bush and Johnston, 1988; Berndt and Katz, 1992).

Series		Geologic Unit		Approximate thickness (feet)	Lithology	Hydrogeologic unit		Approximate thickness (feet)
HOLOCENE TO PLEISTOCENE			UNDIFFERENTIATED	0-70	Quartz sand, silt, clay, and shell	SURFICIAL AQUIFER SYSTEM	WATER-TABLE AQUIFER	20 -100
PLIOCENE			TAMIAMI FORMATION	0-175	Silt, sandy clay, micritic limestone, sandy, shelly limestone, calcereous sandstone, and quartz sand		CONFINING BEDS	0-60
							LOWER TAMIAMI AQUIFER	0-160
MIOCENE		HAWTHORN GROUP	PEACE RIVER FORMATION	50-400	Interbedded sand, silt, gravel, clay, carbonate, and phosphatic sand	INTERMEDIATE AQUIFER SYSTEM	CONFINING UNIT	0-100
							SANDSTONE AQUIFER	0 -100
							CONFINING UNIT	10-250
			ARCADIA FORMATION	400-550	Sandy limestone, shell beds, dolomite, phosphatic sand and carbonate, sand, silt, and clay		MID-HAWTHORN AQUIFER	100
							CONFINING UNIT	100-400
OLIGOCENE			SUWANNEE LIMESTONE	0-600	Fossiliferous, calcarenitic limestone	FLORIDAN AQUIFER SYSTEM	UPPER FLORIDAN AQUIFER	700-1,200
EOCENE	LATE		OCALA LIMESTONE	0-400	Chalky to fossiliferous, calcarenitic limestone			
	MIDDLE		AVON PARK FORMATION	900-1,200	Fine-grained, micritic to fossiliferous limestone, dolomitic limestone, dense dolomite, and gypsum		CONFINING UNIT	500-800
	EARLY		? OLDSMAR FORMATION	? 800-1,400			LOWER FLORIDAN AQUIFER	1,400-1,800
PALEOCENE			CEDAR KEYS FORMATION	500-700	Dolomite and dolomitic limestone			
				1,200 ?	Massive anhydrite beds		CONFINING UNIT	1,200?

Figure 2. Generalized geology and hydrology of southwestern Florida. Modified from Reese (2000), based on data from Missimer (1997, 2001), Weedman and others (1997), and Edwards and others (1998).

METHODS AND DATA ANALYSIS

The distribution and origin of salinity in the surficial and intermediate aquifers were determined from water-quality data, geophysical logs, and time domain electromagnetic (TDEM) surface-geophysical data. Water-quality data were collected from 186 wells for this study. Most wells were sampled only for specific conductance and chloride concentration. Major ion and strontium isotope data were collected from 40 wells, and hydrogen and oxygen isotope data were collected from 49 wells. Historical chloride concentration data were used from 3 wells, and the chloride concentrations from 4 wells were estimated from geophysical logs. The TDEM data were used in areas of sparse well control in the lower Tamiami aquifer. Chloride concentrations were analyzed to determine the distribution of salinity in the water-table, lower Tamiami, sandstone, and mid-Hawthorn aquifers. The major ion and isotope data were analyzed to determine the origin of salinity in the lower Tamiami, sandstone, and mid-Hawthorn aquifers. No effort was made to determine the origin of salinity in the water-table aquifer because very little brackish or saline water was found.

Ground-Water Monitoring Well Network

Wells used in this regional salinity survey included monitoring wells and supply wells (municipal, irrigation, and domestic wells). The USGS Ground-Water Site Inventory (GWSI) and SFWMD saltwater intrusion monitoring (SALT) databases were searched for wells yielding water samples that could accurately represent the distribution of salinity of the regional hydrogeologic system. Well selection criteria were used to reduce the likelihood that characteristics of selected wells would bias results and possibly compromise the study objectives. The principal criteria included well location, well and casing depth, and hydrogeologic unit. The regional focus of this study was emphasized; some areas of elevated salinity were too limited in extent to map, and monitoring wells located within these areas were rejected. Because the study focused on saltwater intrusion, emphasis was given where possible to wells completed near the base of an aquifer.

Special consideration was given to the length of the screened or open interval of each well. Long screened or open intervals can induce mixing of waters of different quality because of vertical flow along the screened (or open) interval, which can cause bias in understanding the distribution of water quality in the aquifer and in interpreting the source(s) of the water. Where possible, wells completed with short, screened (or open) intervals were selected. Monitoring wells with long open intervals are common in the study area and were selected when nearby short interval wells were not available. Geophysical logs were obtained to ascertain whether the sampling intervals of some wells should be described as short or long. Well L-5727 is an example of a monitoring well with a long open interval in the lower Tamiami aquifer (fig. 3). Under ambient conditions, freshwater with a conductivity of about 1,000 µS/cm (microsiemens per centimeter) was flowing into the well near the bottom of the casing and moving downward, whereas brackish water with a conductivity of almost 5,000 µS/cm was flowing into the open interval near the bottom of the well and moving upward. The length of the interval of each well was considered in deciding how to collect a representative water sample from the aquifer.

Data for all wells used in this report are presented in appendix I and include USGS local well number, owner, USGS site identification number, aquifer, latitude, longitude, well depth, and casing depth. Data from all wells in this report are available in the GWSI database of the USGS.

Collection and Analysis of Data

A representative water sample from the respective aquifer was collected for each selected well. Purging methods varied depending upon the type of well. For monitoring wells with a short interval, a minimum of three well volumes of water were pumped prior to sampling while specific conductance was monitored. Supply wells had high-yielding pumps that were used routinely, and sampling began as soon as specific conductance stabilized.

Sampling methods also varied, depending upon the type of well and the depth to water. For monitoring wells with long open intervals, water samples were generally collected with a Kemmerer sampler positioned near the bottom of the unpurged well. This sampling method was only used to determine specific conductance and chloride concentration. For monitoring and observation wells with short intervals, a peristaltic pump was used to collect the sample when possible (water level within about 30 ft of land surface); a submersible pump was used if the depth to water was greater. Supply-well water samples were collected prior to entry into any holding tank and as close to the wellhead as possible.

Salinity Measurements

Common measures of salinity include chloride concentration, dissolved solids, and specific conductance. Chloride concentrations are used in this report to indicate salinity and were determined using the Mohr method (Fishman and Friedman, 1989). The concentration of dissolved solids is generally equivalent to the concentration of dissolved major ions. Chloride concentration relates to the concentration of total dissolved major ions of water samples collected during this study by the regression equation:

$$y = 0.571x - 260, (r^2 = 0.998, n = 40),$$

where y is the chloride concentration in milligrams per liter, x is the total dissolved major-ions concentration ranging from 320 to 25,000 mg/L (milligrams per liter), r^2 is the square of the correlation coefficient, and n is the number of observations. Fetter (1994) defined the concentration range of dissolved solids for freshwater as 0 to 1,000 mg/L, brackish water as 1,000 to 10,000 mg/L, and saline water as 10,000 to 100,000 mg/L. Thus, according to Fetterís definition, the chloride concentration range is 0 to 300 mg/L for freshwater, 300 to 5,000 mg/L for brackish water, and 5,000 to 60,000 mg/L for saline water. The chloride concentration of seawater is about 19,000 mg/L (Hem, 1989).

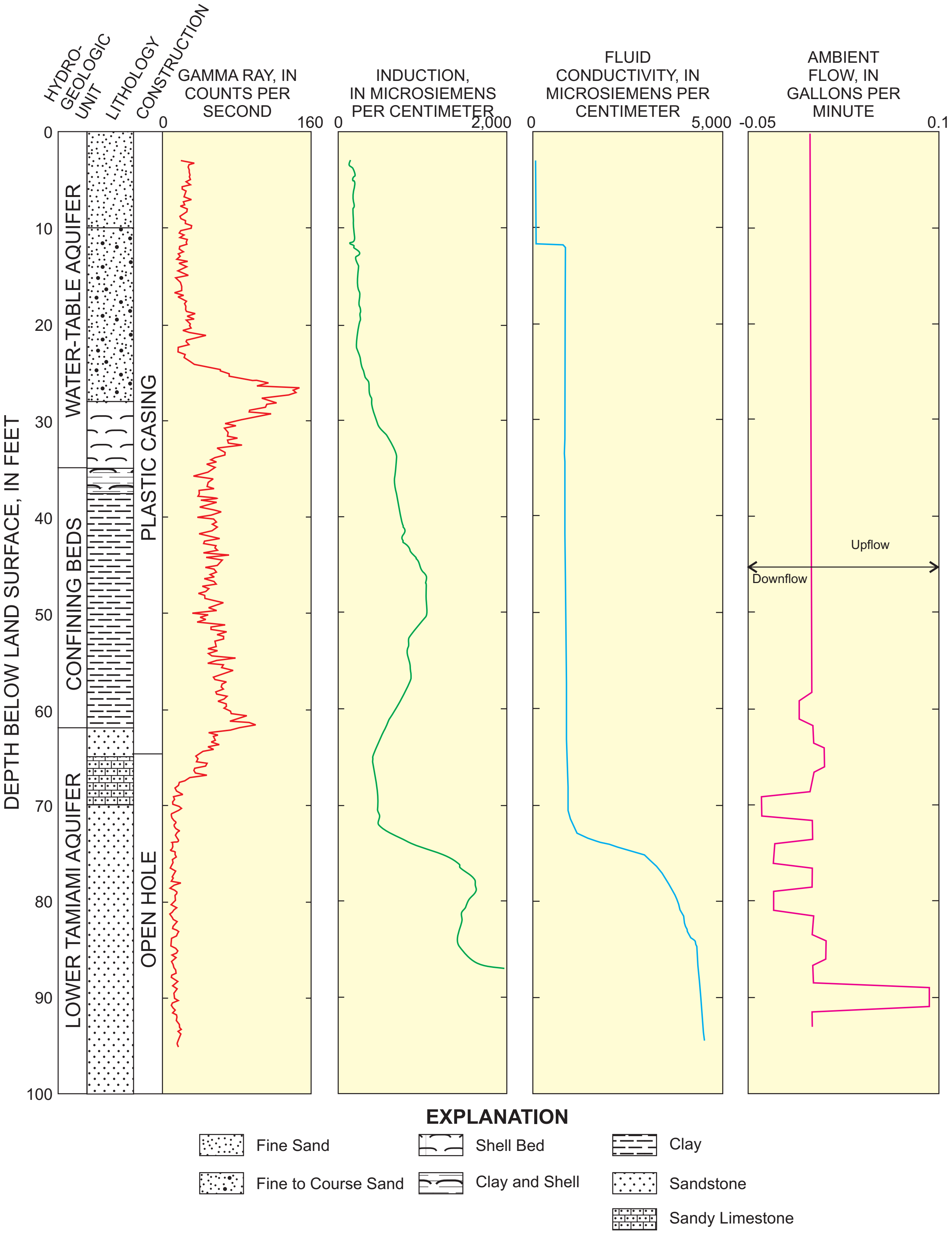

Figure 3. Geophysical logs, hydrogeology, lithology, and construction of monitoring well L-5727 in Lee County.

Specific conductance is a convenient way to measure salinity in the field. For water samples collected during this study, the chloride concentration (y) is related to specific conductance by the regression equation:

$$y = 0.389x - 270, (r^2 = 0.98, n = 178),$$

where x is the specific conductance ranging from 99 to 33,700 µS/cm. Water samples were unavailable for wells C-1113, C-1114, C-1118, and C-1119, but the specific conductance was estimated from geophysical logs (Weedman and others, 1997) and chloride concentrations were estimated from the specific conductance.

Time Domain Electromagnetic Soundings

The TDEM sounding method is a surface-geophysical technique that is well suited for ground-water exploration (Fitterman and Stewart, 1986). The TDEM soundings are made with a transmitter attached to a loop and a receiver attached to a coil. A constant current from the transmitter passes through the loop creating a primary magnetic field. The current is shut off, which induces electrical currents in the ground. The electrical conductivity of the ground controls the flow of these currents; zones of high conductivity allow the induced currents to flow relatively unimpeded compared to zones of low conductivity which impede the current flow. The induced currents in the ground produce a secondary magnetic field which induces a voltage in the receiver coil. The received signals are converted to an apparent resistivity, and the data are analyzed to create a layered-earth model of the formation conductivity.

TDEM soundings can be used to estimate the salinity of the pore water. Formation conductivity can be related to the properties of the formation and pore water by a function of the form (McNeill, 1990):

$$s = F^{-1}s_w + s_{clay},$$

where s is the formation conductivity, F is a formation factor related primarily to porosity, s_w is the pore-water conductivity, and s_{clay} is the conductivity of the clay. If the clay content is small, s_{clay} can be ignored and the pore-water conductivity can be estimated by multiplying the formation conductivity by the formation factor. In western Collier County, fluid conductivity in the lower Tamiami aquifer can be estimated from TDEM soundings by multiplying the interpreted formation conductivity by a formation factor of 2.4; however, the lower model layer in some instances provided only qualitative estimates, not quantitative (Paillet and others, 1999).

The TDEM soundings were used in this study to estimate the general water quality in the lower Tamiami aquifer between Bonita Springs and Belle Meade. Nine soundings were analyzed to create simple two- or three-layer models of formation conductivity (figs. 1 and 4). Site 8 in Bonita Springs is located next to monitoring well L-5727 (shown later in fig. 11). The induction log from L-5727 and the formation conductivity model are similar (figs. 3 and 4). The effect of clay content on formation conductivity is evident in the induction log of L-5727 where clay is present at a depth of 35 to 62 ft. For models 1 and 9, the formation conductivity of the bottom layer is probably primarily affected by clay; the depths to the bottom layer of these models are consistent with the base of the surficial aquifer system reported by Knapp and others (1986). The formation conductivities of all other model layers are assumed to be primarily a function of pore-water conductivity. Thus, the pore-water conductivity can be estimated by multiplying the formation conductivity by a formation factor of 2.4. The inferred salinity at the base of the lower Tamiami aquifer is fresh at site 9; brackish at sites 1, 2, 4, 7, and 8; and saline at sites 3, 5, and 6 (fig. 4).

Major Ions

Major ions were collected and analyzed for 40 water samples: 16 from the lower Tamiami aquifer, 6 from the sandstone aquifer, 14 from the mid-Hawthorn aquifer, and 4 from the Upper Floridan aquifer. Water samples collected for the analysis of major ions were passed through a 0.45-micron filter. Water samples for anion (chloride, sulfate, and bicarbonate) analysis were collected in untreated polyethylene bottles, and water samples for cation (sodium, calcium, magnesium, potassium, and strontium) analysis were collected in acid-washed polyethylene bottles and acidified with 1 mL (milliliter) of 70 percent nitric acid. Alkalinity (as bicarbonate) was determined in the field by titration with sulfuric acid. Quality-assurance measures included the use of equipment and field blanks. As an additional screening method for the accuracy of the major ion analysis, any water sample with a charge-balance error that exceeded ±10 percent was not used for this study.

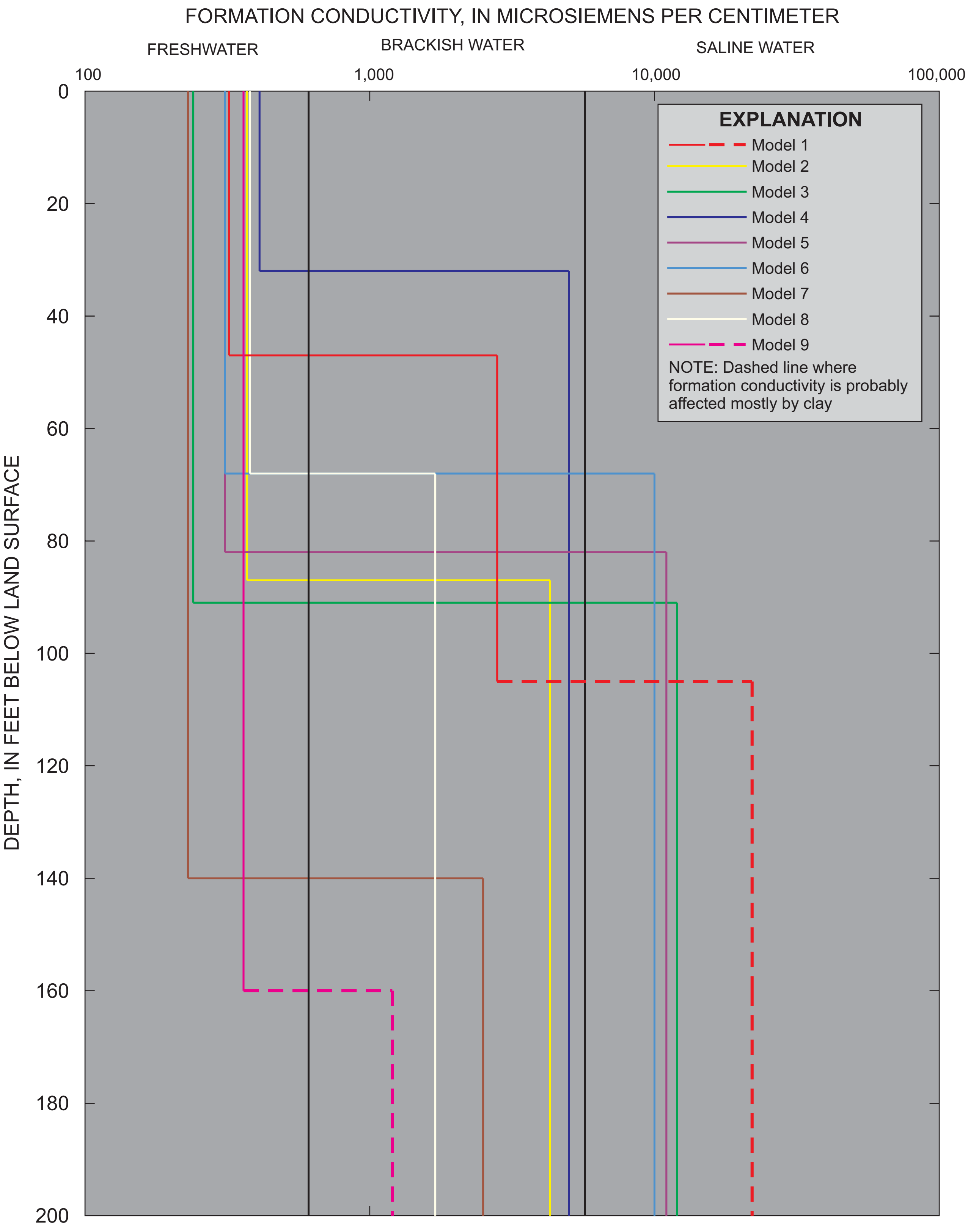

Figure 4. Interpreted formation conductivity models for time domain electromagnetic soundings, southwestern Florida.

The chemical composition of waters has a linear trend when plotted on a trilinear diagram for the lower Tamiami, sandstone, and mid-Hawthorn aquifers (fig. 5). Linear trends suggest that simple mixing between two end members is controlling the water chemistry of each aquifer. In the lower Tamiami aquifer, a fresh calcium-bicarbonate water is mixing with a brackish sodium-chloride water. The water in the sandstone aquifer plots along a similar mixing line as the lower Tamiami aquifer, but the freshwater end member is calcium-sodium-bicarbonate-chloride. Magnesium is present in larger amounts in the mid-Hawthorn aquifer, and the water composition suggests simple mixing between a mixed water type and a sodium-chloride water type. The water type of the Upper Floridan aquifer is sodium-chloride.

High strontium concentrations in waters collected for this study are generally associated with high chloride concentrations (fig. 6). Solute concentrations in ground water can be affected by saltwater mixing and reactions with aquifer minerals. Chloride is assumed conservative and, therefore, an indicator of saltwater mixing. For waters from the lower Tamiami aquifer, strontium increases with chloride; most of the waters plot along a linear trend near the saltwater mixing line

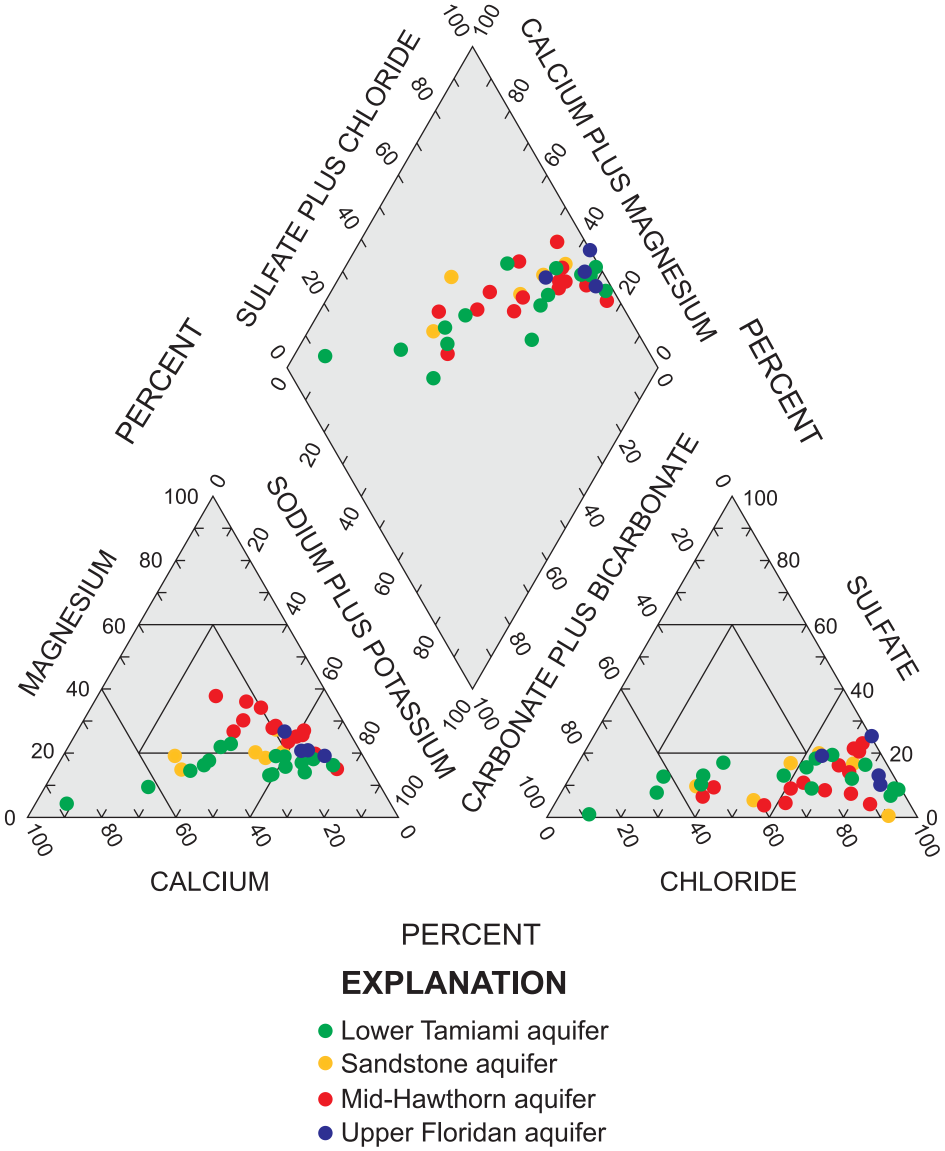

Figure 5. Chemical composition of ground water within the study area, southwestern Florida.

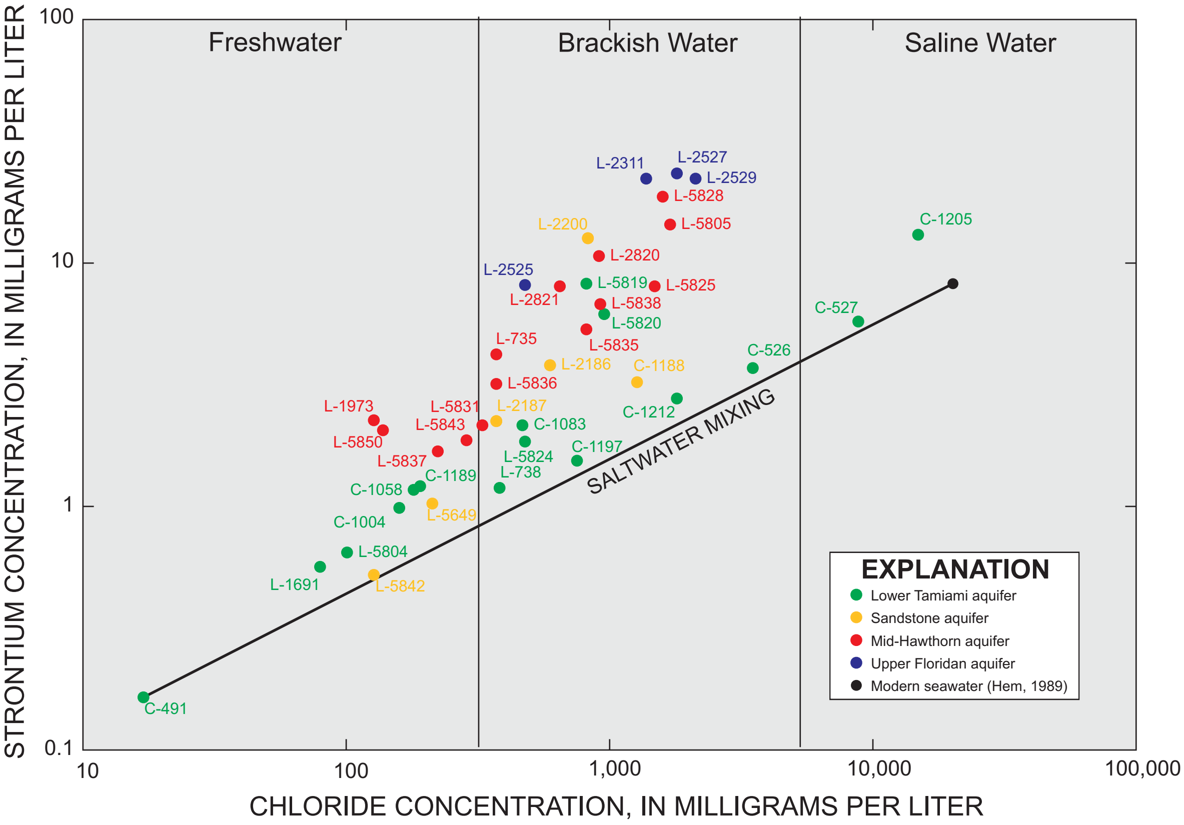

Figure 6. Relation between strontium and chloride concentrations in ground water within the study area, southwestern Florida.

determined from freshwater (well C-491) and modern seawater (Hem, 1989). Strontium increases with chloride for waters from the mid-Hawthorn aquifer, but strontium concentrations are elevated over saltwater mixing, indicating mineral dissolution. For the sandstone aquifer, strontium also generally increases with chloride. Strontium isotopes can be used to determine the origin of dissolved strontium in the water and, because high strontium concentrations are associated with high chloride concentrations, strontium isotopes can be used to determine the origin of salinity.

Strontium Isotopes

Strontium isotopes have proven to be a useful tracer for ground-water movement and the origin of salinity (Clark and Fritz, 1997). The strontium-87 to strontium-86 ratio ($^{87}Sr/^{86}Sr$) has varied substantially in seawater over geologic time. Most carbonate rocks in southern Florida are marine in origin, so strontium contained within the rock originated from seawater during the time of deposition. The strontium isotope ratio of carbonate rocks has been measured throughout the Phanerozoic Eonothem, and its strong variation during the late Cenozoic Erathem has provided a high-resolution dating tool (Elderfield, 1986; Howarth and McArthur, 1997). The $^{87}Sr/^{86}Sr$ of the rock will be reflected in the $^{87}Sr/^{86}Sr$ of ground water with which it has equilibrated (the time length of this equilibration process is uncertain). Therefore, waters that have geochemically evolved in marine deposits of differing age will have contrasting strontium isotope ratios. This phenomenon has been useful in determining the origin of solutes in ground water. For example, Sacks and Tihansky (1996) used strontium isotopes to demonstrate that the Upper Floridan aquifer is a source of sulfate for the intermediate aquifer system in southwestern Florida.

Strontium isotope ratios were collected and analyzed using solid-source mass spectrometry for 40 water samples: 16 from the lower Tamiami aquifer, 6 from the sandstone aquifer, 14 from the mid-Hawthorn aquifer, and 4 from the Upper Floridan aquifer. Results are reported as the absolute ratio of the radiogenic isotope ^{87}Sr to the stable isotope ^{86}Sr in appendix II. The ratio of unfractionated strontium-88 (^{88}Sr) to ^{86}Sr, assumed to be 8.37521, is used as an internal standard to correct for stable isotope fractionation, and uncertainties are 2 x 10^{-5} (T. Bullen, U.S. Geological Survey, written commun., 2000). The ^{87}Sr/^{86}Sr is plotted as a function of the inverse of strontium concentration (fig. 7). The inverse is used so that waters, which are mixtures of two end members, will plot along a straight line. The ranges of the ^{87}Sr/^{86}Sr in seawater from the Eocene to Pliocene Epochs are shown for reference.

Hydrogen and Oxygen Stable Isotopes

The stable isotopes of hydrogen and oxygen in water are affected by meteorological processes and can be helpful in understanding the origin of the water. The isotopic ratios of hydrogen (^{2}H/^{1}H) and oxygen (^{18}O/^{16}O) are commonly expressed using the delta (δ) notation, delta deuterium (δ^{2}H) and delta oxygen (δ^{18}O) respectively, in parts per thousand or per mil. δ^{2}H and δ^{18}O in freshwater are linearly correlated on a global scale, and the relation is known as the ì global meteoric water lineî (Craig, 1961). Waters from cold climates are generally isotopically lighter than waters from warm climates, and this partitioning can be helpful in characterizing environments of ground-water recharge (Clark and Fritz, 1997). The residual of evaporated surface water is isotopically heavier than the initial water, resulting in a linear correlation; this evaporative line has a lesser slope than the meteoric water line (Clark and Fritz, 1997). Linear correlations of δ^{2}H and δ^{18}O are also expected from mixing of seawater with ground water (Bear and others, 1999).

Hydrogen and oxygen isotopes were collected and analyzed for 49 water samples: 16 from the lower Tamiami aquifer, 6 from the sandstone aquifer, 15 from the mid-Hawthorn aquifer, and 12 from the Upper Floridan aquifer. Hydrogen isotope analyses were performed (at 30 degrees Celsius) using a hydrogen equilibration technique which measures deuterium activity (Coplen and others, 1991). Oxygen isotope analyses were performed using the carbon dioxide (CO_2) equilibration technique (at 25 degrees Celsius) of Epstein and Mayeda (1953).

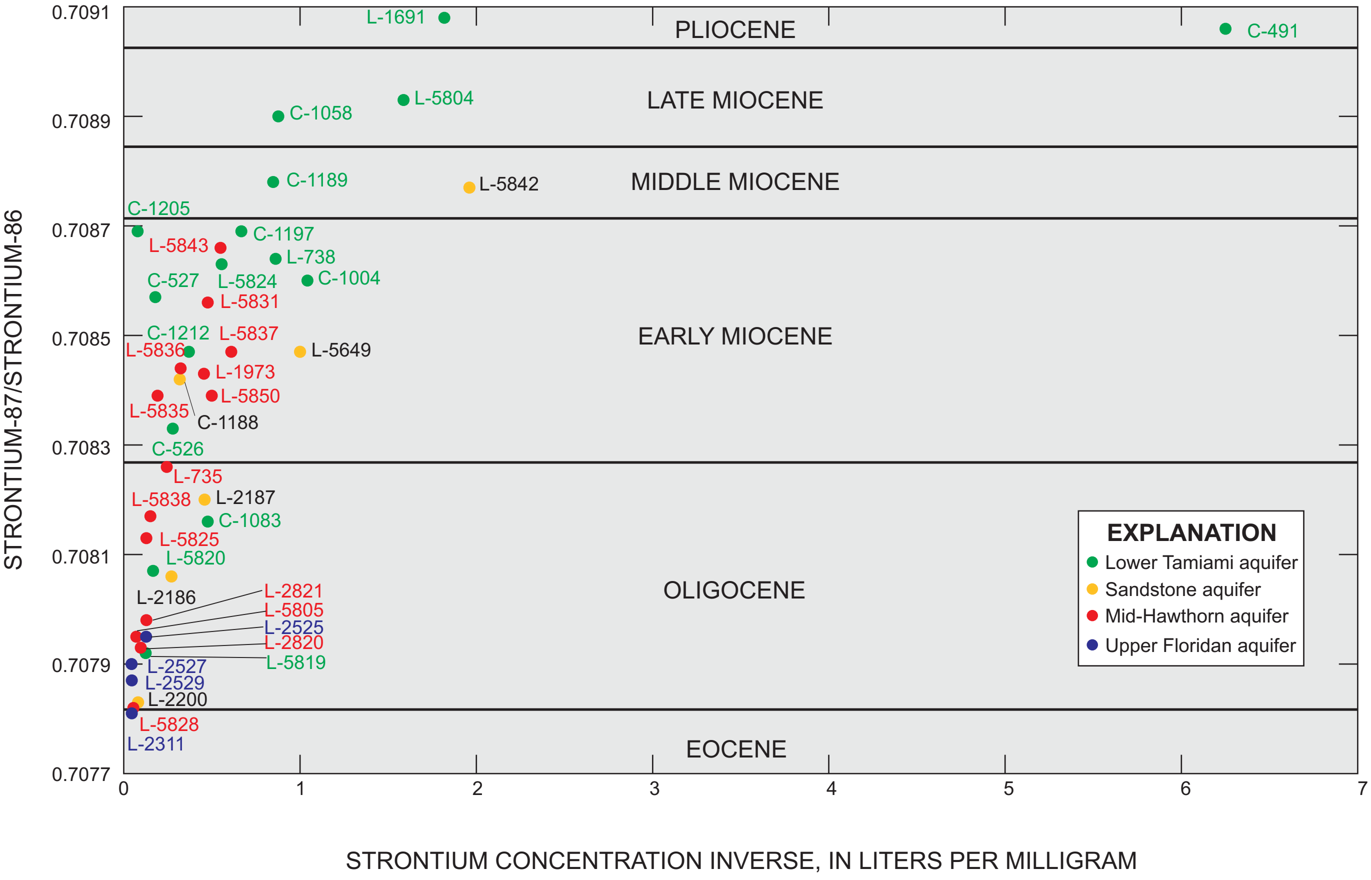

Figure 7. Relation between the ratio of strontium-87 to strontium-86 and the inverse of strontium concentration in ground water within the study area, southwestern Florida.

Stable isotope ratios of hydrogen are reported relative to Vienna standard mean ocean water (VSMOW), as δ^2H shown in per mil, on a scale normalized such that $\delta^2H = -428$ per mil for standard light Antarctic precipitation (SLAP). Stable isotope ratios of oxygen are reported relative to VSMOW, as $\delta^{18}O$ shown in per mil, on a scale normalized such that $\delta^{18}O = -55.5$ per mil for SLAP. The uncertainty of hydrogen and oxygen isotopic analyses are 2 and 0.2 per mil, respectively.

Sources of recharge, water that has undergone evaporation, and mixing of waters from different sources can be identified for ground water within the study area by plotting δ^2H as a function of $\delta^{18}O$ (fig. 8). The global meteoric water line is shown as a line of reference; precipitation in Florida generally plots along the global meteoric water line (Swart and others, 1989; Katz and others, 1995; Krulikas and Giese, 1995; Swancar and Hutchinson, 1995). Waters from the Upper Floridan and mid-Hawthorn aquifers plot in a cluster near, but below, the global meteoric water line (δ^2H about -5 per mil and $\delta^{18}O$ about -1.5 per mil). Some waters from the sandstone and lower Tamiami aquifers plot within this group. Other waters from the sandstone and lower Tamiami aquifers plot below this cluster and the global meteoric water line along a linear trend with a positive slope.

Evaporation and mixing between two distinct ground waters are two processes that plot along a linear trend and can be distinguished by plotting δ^2H as a function of chloride concentration (fig. 9). Water from wells C-491, C-526, C-527, and C-1205 in the lower Tamiami aquifer plot near a saltwater mixing line following the relation:

$$\delta^2H = 0.00143(\pm0.00007)x \text{ ñ } 15.71(\pm0.55),$$
$$(r^2 = 0.996, n = 4),$$

where x is the chloride concentration in milligrams per liter. As a function of $\delta^{18}O$, this saltwater mixing relation (fig. 8) is:

$$\delta^2H = 6.43(\pm0.67)\delta^{18}O + 3.50(\pm1.31), (r^2 = 0.98, n = 4).$$

Water samples from the lower Tamiami and sandstone aquifers with chloride concentrations less than 300 mg/L were used to infer an evaporation line (fig. 8) following the relation:

$$\delta^2H = 5.54(\pm0.55)\delta^{18}O + 1.66(\pm0.76), (r^2 = 0.94, n = 8).$$

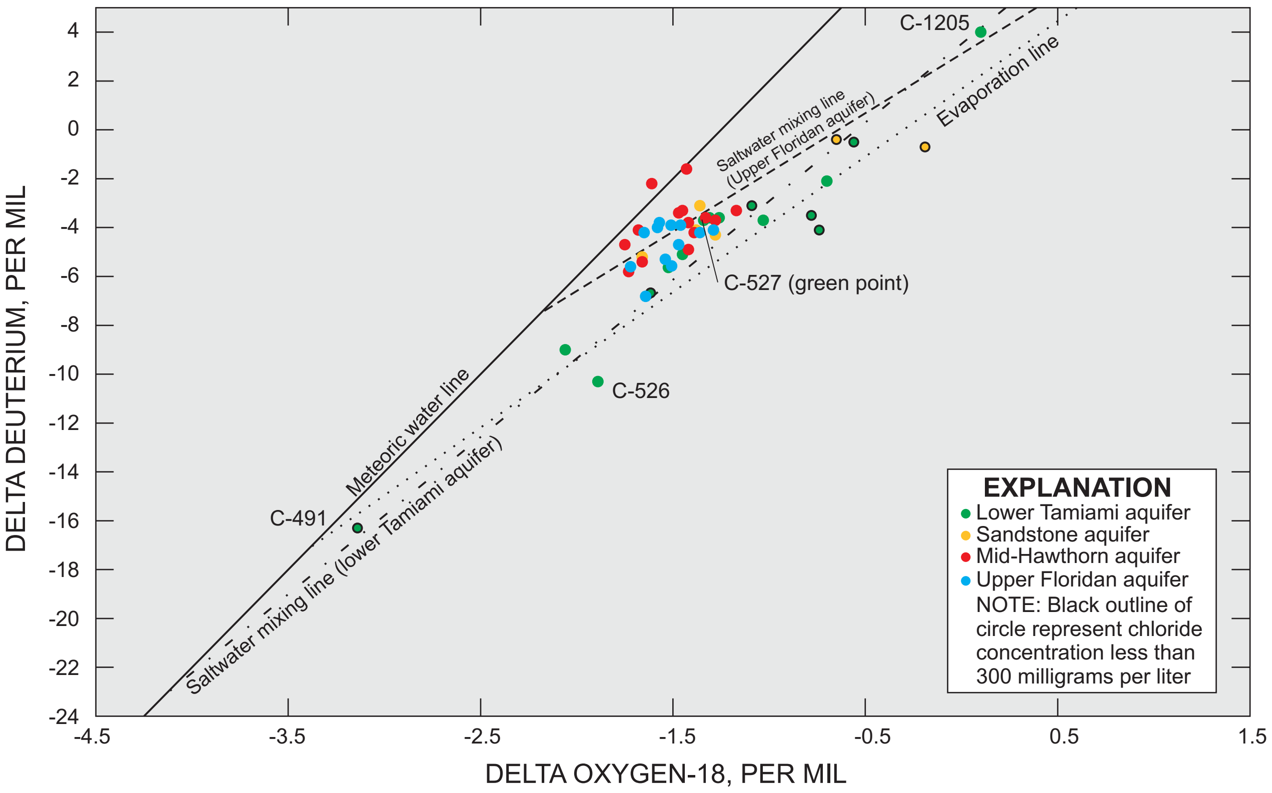

Figure 8. Relation between delta deuterium and delta oxygen-18 in ground water within the study area, southwestern Florida.

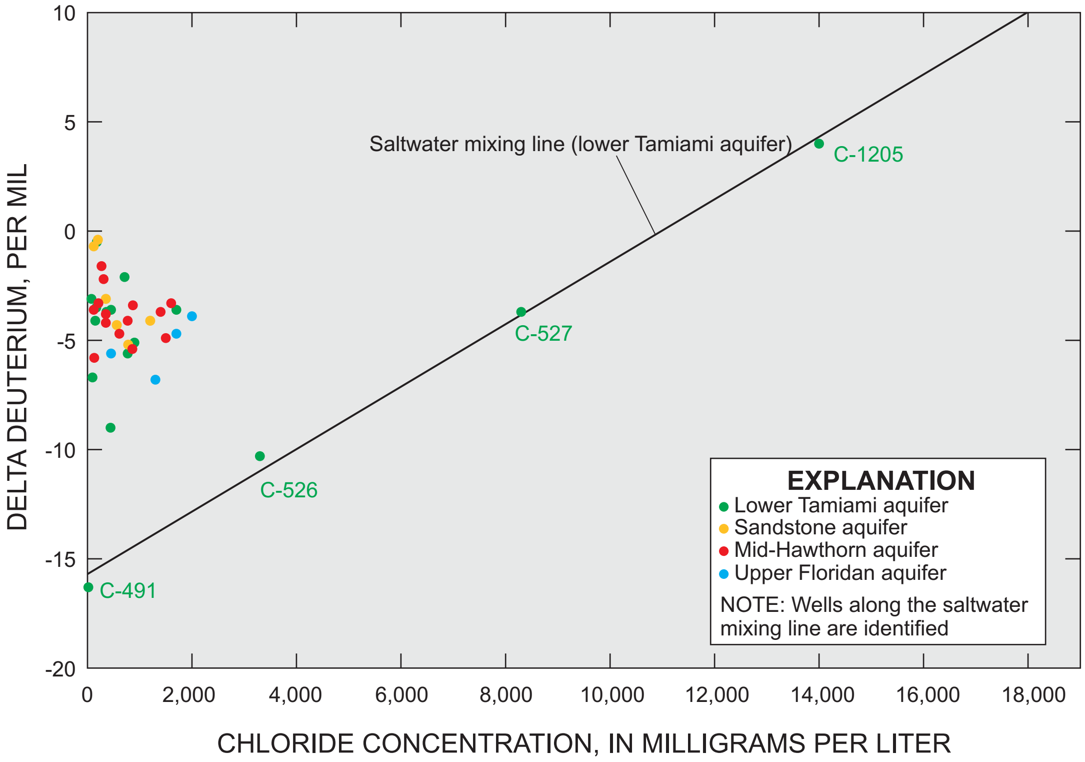

Figure 9. Relation between delta deuterium and chloride concentration in ground water within the study area, southwestern Florida.

DISTRIBUTION OF SALINITY

The distribution of salinity in the surficial and intermediate aquifer systems and well control points are shown in a series of maps (figs. 10-16). Salinity variations are delineated by lines of equal chloride concentration shown for 100, 300, 1,000, and 5,000 mg/L. Chloride data are presented in appendix II, with concentrations ranging from 10 to 14,000 mg/L.

Water-Table Aquifer

The salinity of the water-table aquifer in the study area was generally fresh; chloride concentrations ranged from 10 to 530 mg/L and brackish water was found only at wells L-1456, L-3205, and L-5867 (app. II). Water-quality data were collected from 41 wells (fig. 10). Most chloride concentrations were less than 100 mg/L, although chloride concentrations often exceeded 100 mg/L in the vicinity of tidal rivers and canals, and on barrier islands. Tidal rivers where chloride concentrations exceeded 100 mg/L include: Spring Creek, Imperial River, Cocohatchee River, and Henderson Creek (fig. 1). Chloride concentrations also exceeded 100 mg/L on Sanibel Island, Pine Island, and near tidal canals in Cape Coral (fig. 1).

Lower Tamiami Aquifer

The regional distribution of salinity in the lower Tamiami aquifer was determined from water-quality data collected from 58 wells (figs. 11 and 12). Chloride concentrations ranged from 15 mg/L at well C-490 to 14,000 mg/L at well C-1205 (app. II). Salinity generally increased coastward. Near Bonita Springs, water was generally brackish and chloride concentrations exceeded 1,000 mg/L at wells L-5725, L-5727, and L-5847. Near the coastline of Collier County from Naples northward, chloride concentrations were 3,300 mg/L (C-526) and 8,300 mg/L (C-527); and TDEM models 2 to 5 suggest the presence of the saltwater interface at depths of about 87, 91, 32, and 82 ft, respectively (fig. 4). In the area of extensive coastal swamp southeast of Naples, saline water was found in the lower Tamiami aquifer as far inland as U.S. Highway 41. An area about 1 mi inland from the Naples coastline, about 10 mi long and 2 mi wide, had chloride concentrations less than 100 mg/L.

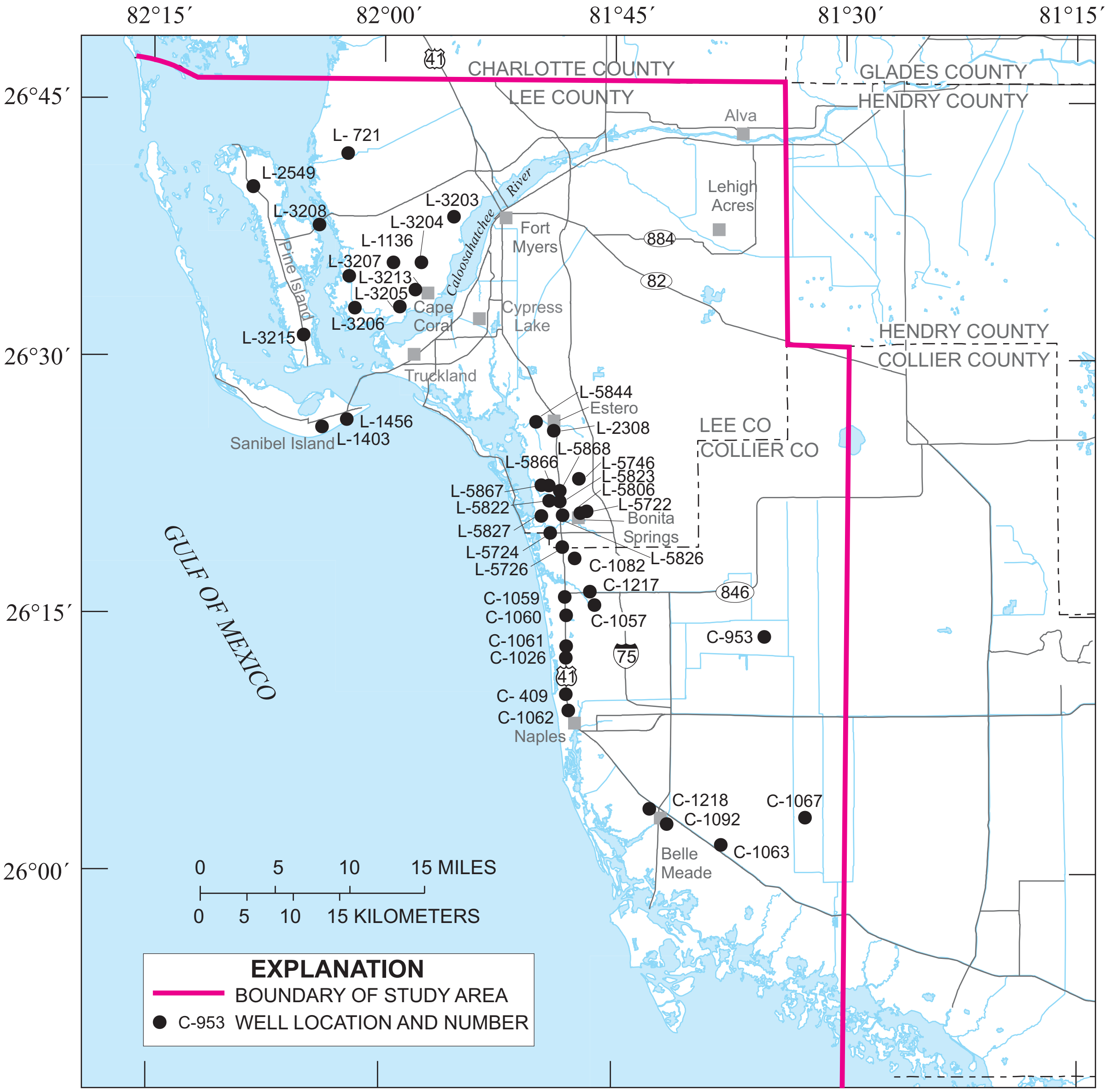

Figure 10. Location of wells completed in the water-table aquifer, southwestern Florida.

Water-quality data, geophysical logs from four wells (C-1113, C-1114, C-1118, and C-1119) (Weedman and others, 1997) and TDEM soundings (Hite, 1997) along a transect near the eastern boundary of the study area (fig. 11) suggest water generally is brackish throughout much of the aquifer in Collier County between U.S. Highway 41 and Interstate 75 (fig. 12).

The major salinity features evident in the lower Tamiami aquifer have been previously reported. Knapp and others (1986) reported similar results in the areas of fresh and brackish water (the saline water was not mapped owing to no well control points). Klein (1954) reported that the shallow water-table and lower Tamiami aquifers contained salty or brackish water over much of the area south of U.S. Highway 41. Sherwood and Klein (1963) mapped the extent of this saline water and an inland area of brackish water from Estero to Belle Meade (fig. 12); in the area that they referred to as brackish, chloride concentrations are often less than 300 mg/L, but most chloride concentrations are greater than 100 mg/L.

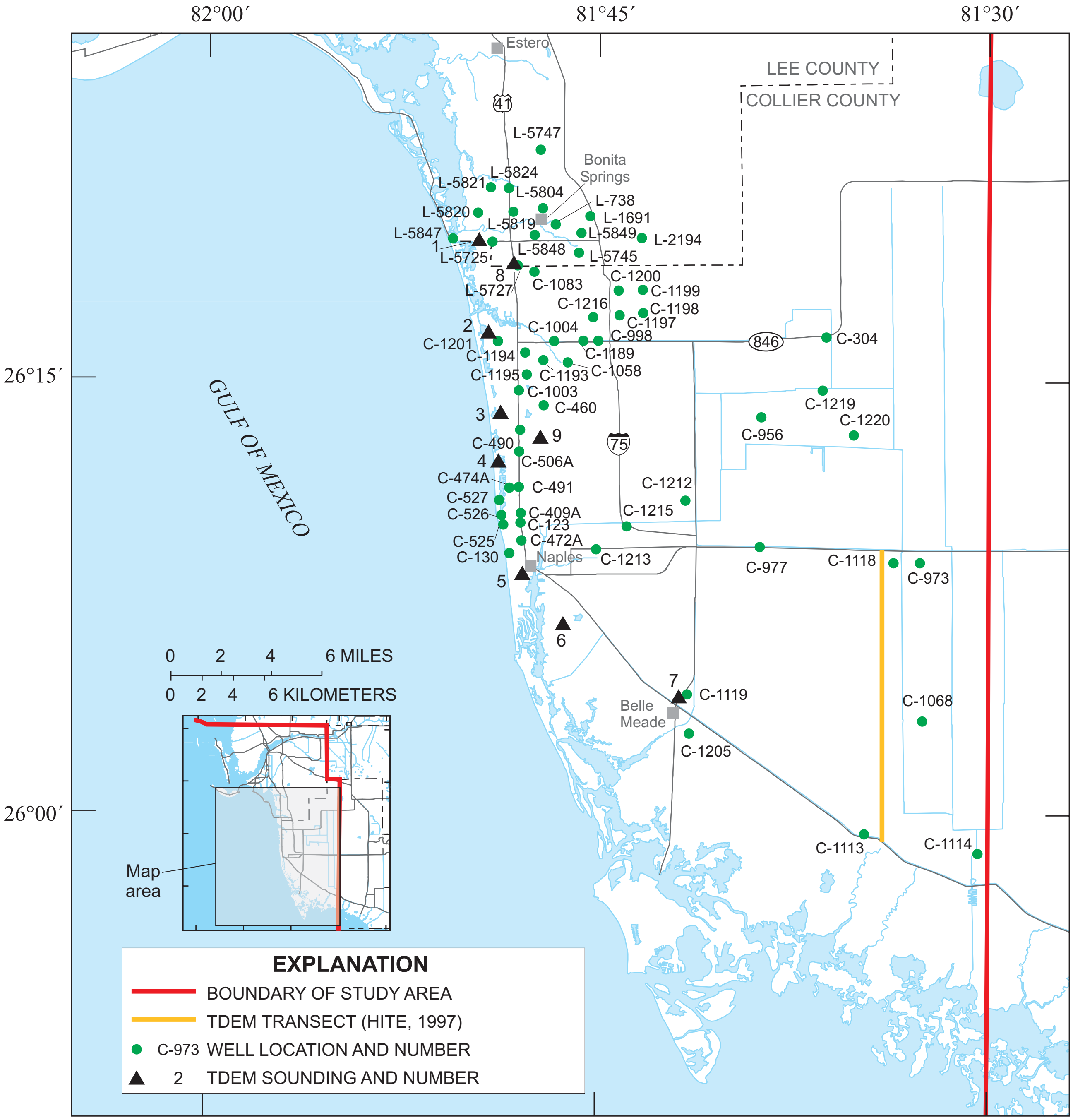

Figure 11. Location of wells completed in the lower Tamiami aquifer and time domain electromagnetic (TDEM) surveys, southwestern Florida.

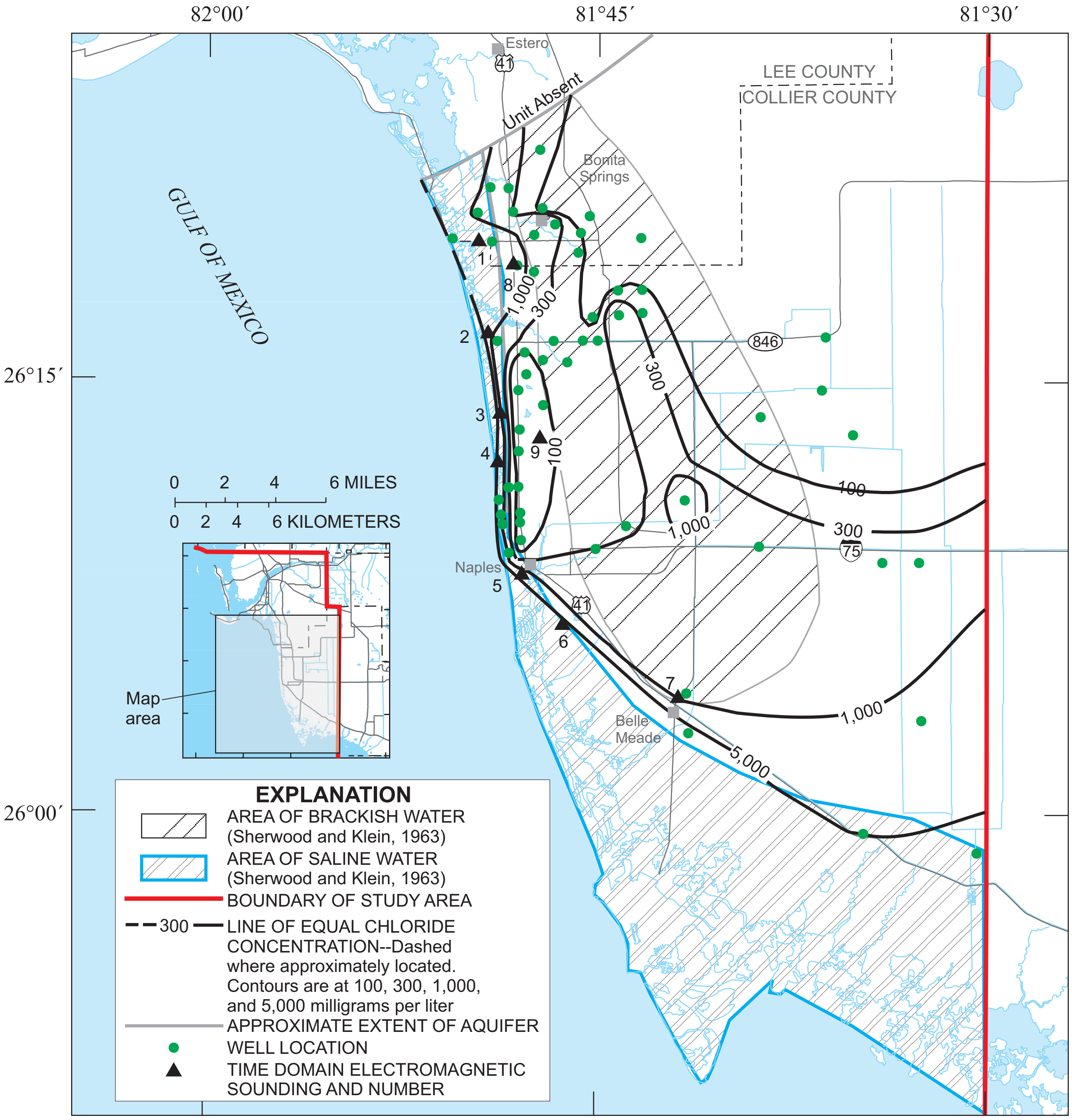

Figure 12. Lines of equal chloride concentration in ground water from the lower Tamiami aquifer, southwestern Florida. Areas of brackish and saline water from Sherwood and Klein (1961).

Sandstone Aquifer

The regional distribution of salinity in the sandstone aquifer was determined from water-quality data collected from 22 wells (figs. 13 and 14). Chloride concentrations ranged from 35 mg/L (L-2193 and L-5664) in southeastern Lee County to 1,200 mg/L (C-1188) in northwestern Collier County. In addition to northwestern Collier County, brackish water was also found east of Estero and in northeastern Lee County. These three areas of brackish water also were indicated by salinity data collected between 1974 and 1977 (Wedderburn and others, 1982).

Mid-Hawthorn Aquifer

The regional distribution of salinity in the mid-Hawthorn aquifer was delineated from water-quality data collected from 60 wells (figs. 15 and 16). Most of the wells are located in western Lee County. No wells were available for sampling in northeastern Lee County or near the coast in Collier County. Owing to sparse well control in Collier County, historic chloride concentration data were used for wells C-115 in Naples and C-1204 in Belle Meade. The chloride concentrations were about 2,200 mg/L at well C-115 (Klein, 1954) and 2,500 mg/L at well C-1204 (Missimer & Associates, 1993).

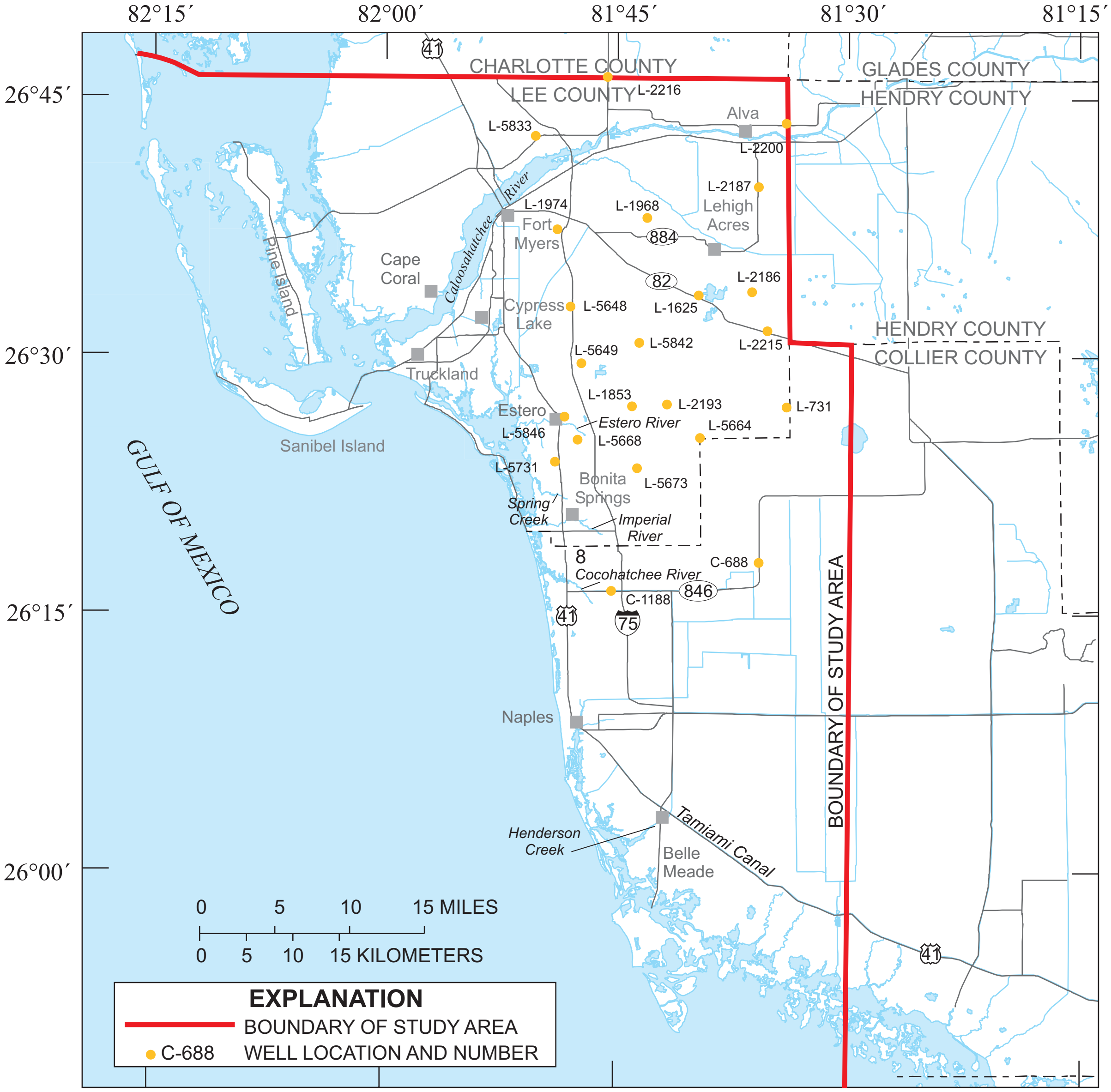

Figure 13. Location of wells completed in the sandstone aquifer, southwestern Florida.

Salinity generally increased to the south and toward the coast with chloride concentrations in the mid-Hawthorn aquifer ranging from 26 to 2,500 mg/L (app. II). Brackish water was found along the entire coast of the study area. In the area west of the Caloosahatchee River, brackish water was previously observed during 1974-79 by Wedderburn and others (1982), and a comparison of the extent of brackish water between 1974-79 and 1999-2000 suggests that little change in the position of the brackish water has occurred over the last 26 years. On the southern side of the Caloosahatchee River, brackish water from artesian irrigation wells open to the Upper Floridan aquifer has been previously reported (Sproul and others, 1972; Boggess and others, 1977; and La Rose, 1990) and may be present in the mid-Hawthorn aquifer all along the southern side of the Caloosahatchee River and in Lehigh Acres. The extent of the brackish water is less certain in Collier County, owing to the limited amount of data.

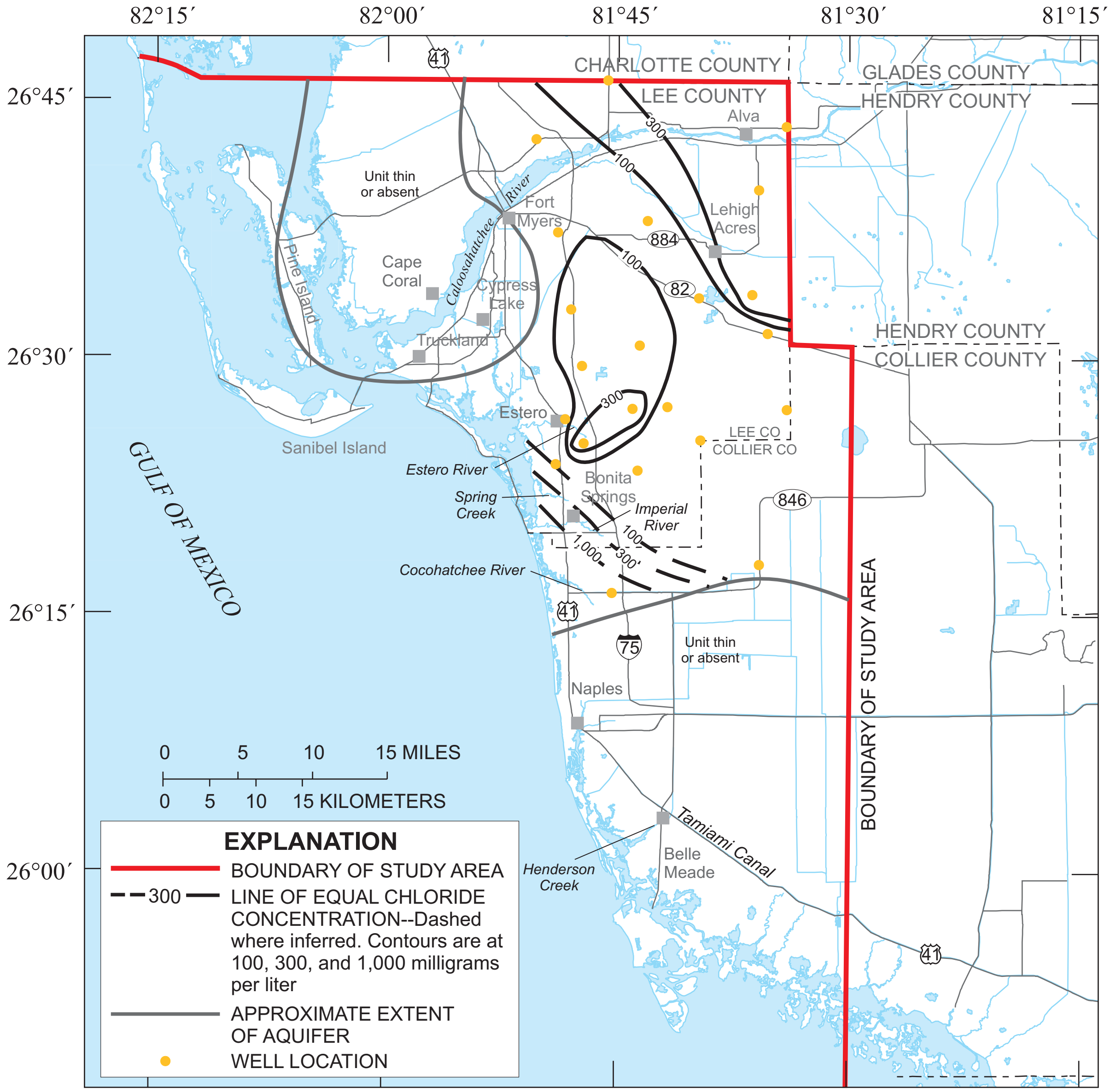

Figure 14. Lines of equal chloride concentration in ground water from the sandstone aquifer, southwestern Florida.

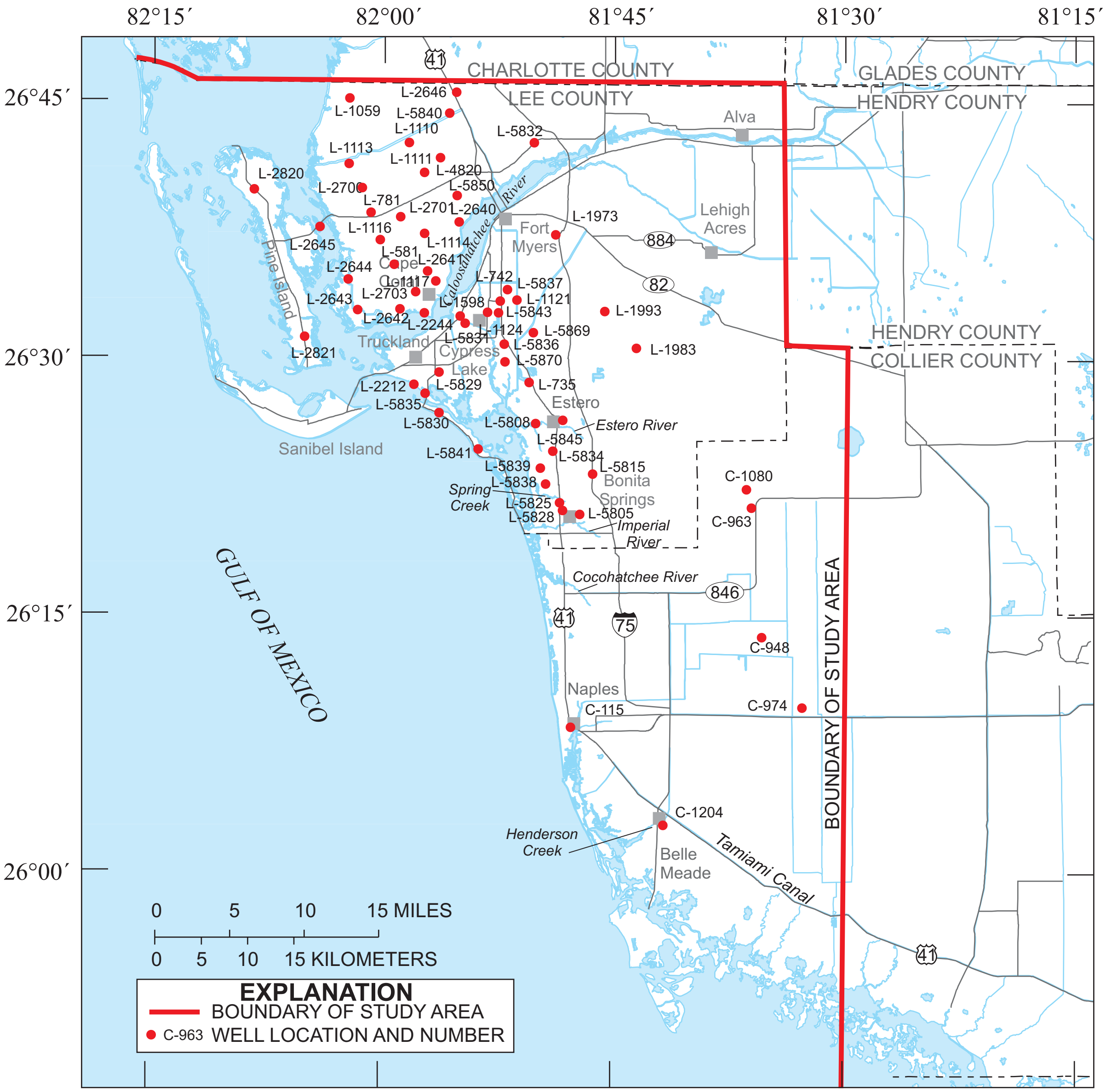

Figure 15. Location of wells completed in the mid-Hawthorn aquifer, southwestern Florida.

ORIGIN OF SALINITY

The chemistry of the surficial and intermediate aquifer systems in southwestern Florida is strongly affected by seawater mixing and interaquifer leakage. Upward leakage from underlying aquifers, downward leakage from overlying aquifers, and saltwater intrusion from the Gulf of Mexico are discussed as sources of salinity in the study area.

Upward Leakage from Underlying Aquifers

Flowing artesian wells open to multiple aquifers have been pathways for saltwater intrusion in southwestern Florida. In 1978, about 15,000 flowing artesian wells throughout the State were discharging mineralized water, and about 1,850 were located in Lee County; of 350 wells surveyed in Lee County in the SFWMD deep-well plugging program, 91 percent of the wells

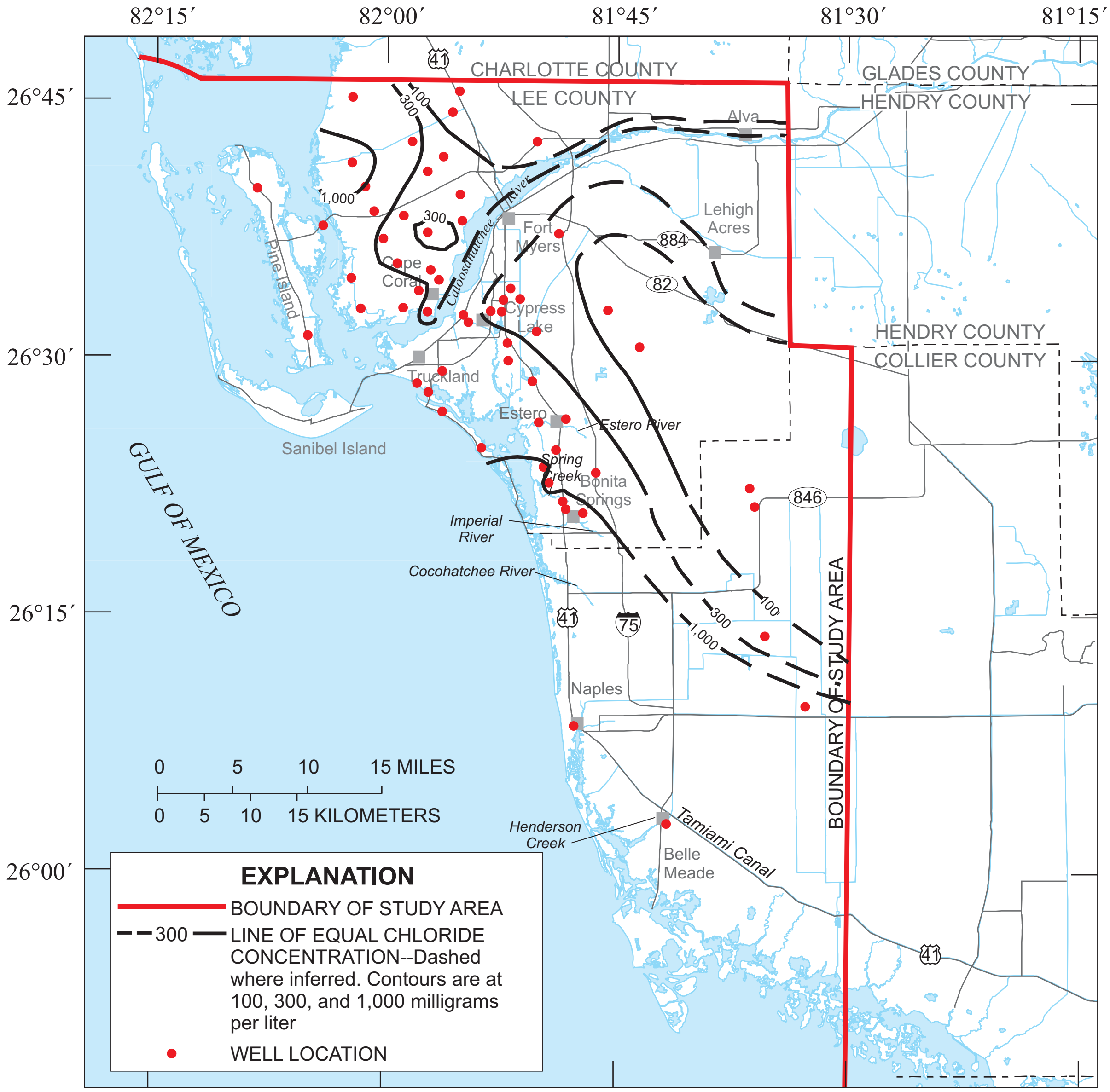

Figure 16. Lines of equal chloride concentration in ground water from the mid-Hawthorn aquifer, southwestern Florida.

were open to both the Upper Floridan and mid-Hawthorn aquifers and 12 percent of the wells were also open to the sandstone aquifer (Burns, 1983). Many of the wells were located along the southern side of the Caloosahatchee River and in Cape Coral, Lehigh Acres, Estero, and Bonita Springs. Brackish water from the Upper Floridan aquifer flowed up these wells and into exposed overlying aquifers, causing saltwater intrusion (figs. 17 and 18). Artesian irrigation wells apparently are less common in Collier County, and saltwater intrusion from leaking wells has not been reported.

The principal means of natural discharge from underlying aquifers in the study area is probably diffuse upward leakage. For the Upper Floridan aquifer, natural discharge occurs almost exclusively as diffuse upward leakage in southern Florida at a rate below 0.5 in/yr (inches per year) according to Bush and Johnston (1988). Buried faults have been reported as possible flow paths allowing saltwater intrusion into the Upper Floridan aquifer (Sproul and others, 1972; Burns, 1983), but have not been reported as a possible mechanism for saltwater to intrude the surficial or intermediate aquifer systems.

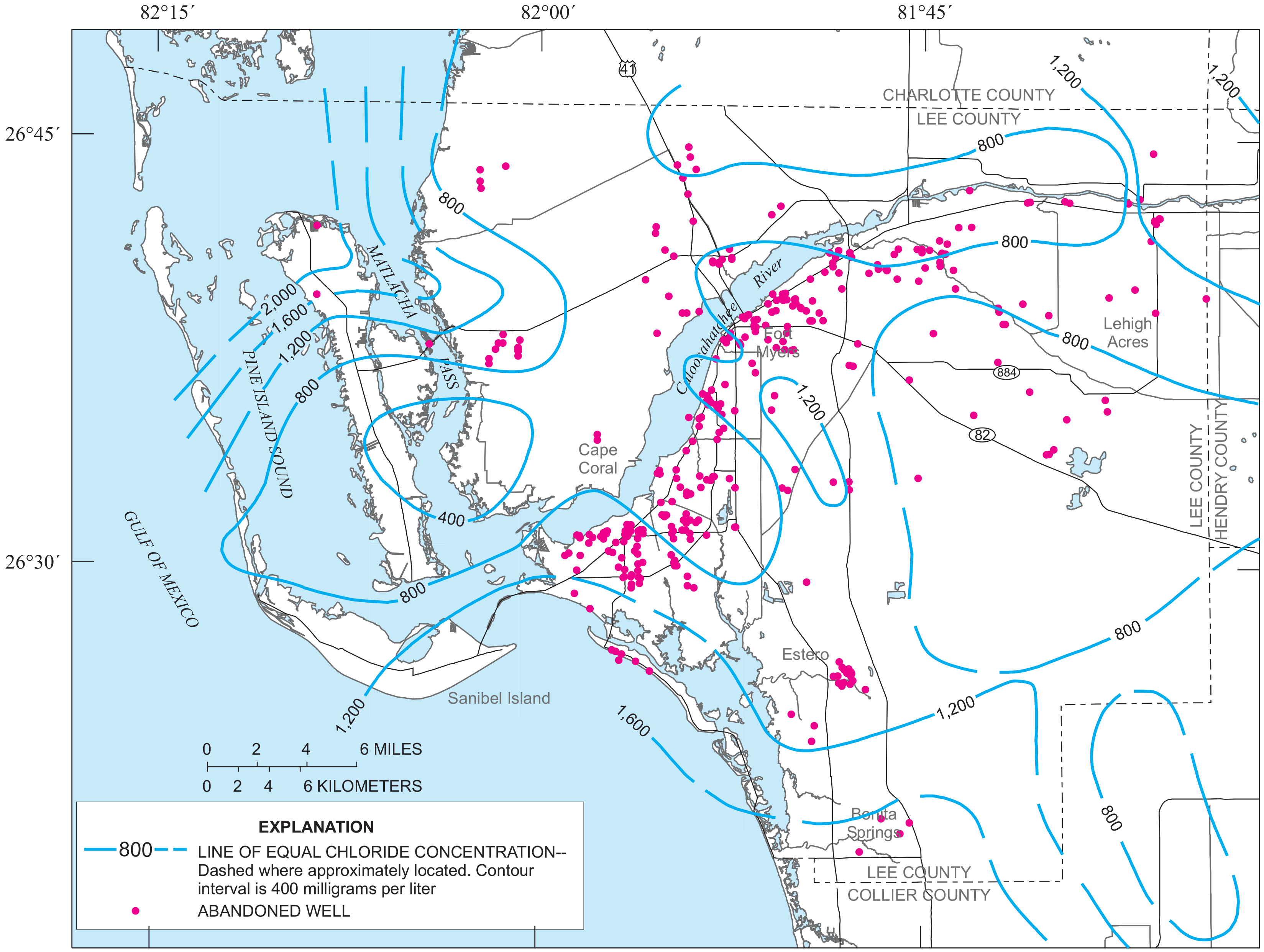

Figure 17. Lines of equal chloride concentration in ground water from the Upper Floridan aquifer (from Reese, 2000) and location of wells surveyed in the South Florida Water Management District deep-well plugging program (from Burns, 1983), southwestern Florida.

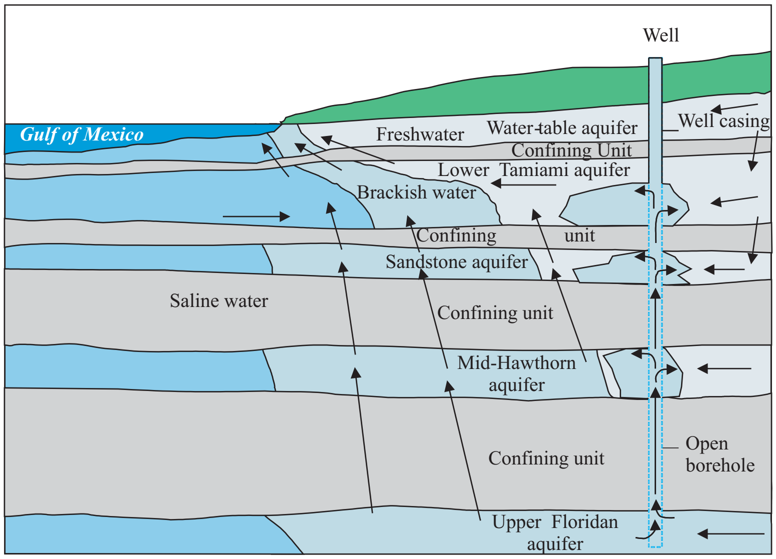

Figure 18. Generalized flow patterns, southwestern Florida. Brackish water in the well from the Upper Floridan aquifer is moving into freshwater zones of the mid-Hawthorn, sandstone, and lower Tamiami aquifers.

Onshore springs have not been detected in the study area; the ì pseudo springî at the Shangri-la Motel Health Resort in Bonita Springs, identified by the public as a spring, is an artesian well (Rosenau and others, 1977). The ì mud holeî is a submarine spring about 12 mi (miles) offshore from the southwestern coast of Florida (Kohout and others, 1981).

Mid-Hawthorn Aquifer

Waters from the mid-Hawthorn aquifer have hydrogen and oxygen isotope compositions similar to waters from the Upper Floridan aquifer (fig. 8), indicating the source of recharge may be the same for both aquifers. Water in the Upper Floridan aquifer in the study area is perhaps greater than 100,000 years old (Meyer, 1989) and presumably recharged in the present-day recharge area in central Florida. Recharge of paleowater in the Floridan aquifer system has been reported to be isotopically heavier than present-day recharge, owing to climatic conditions in the southeastern United States differing from that of the present (Plummer, 1993; Sacks and Tihansky, 1996). Waters from the Upper Floridan and mid-Hawthorn aquifers plot on the saltwater mixing line for the Upper Floridan aquifer (fig. 8) previously reported by Sacks and Tihansky (1996). The freshwater end member (paleowater recharge) of the Upper Floridan aquifer saltwater mixing line is isotopically heavier than the freshwater end member (recent recharge) of the lower Tamiami saltwater mixing line (fig. 8). The hydrogen and oxygen isotope data suggest that the Upper Floridan aquifer is the source of the brackish water in the mid-Hawthorn aquifer.

The chemical compositions of waters from the mid-Hawthorn aquifer are consistent with the interpretation that the Upper Floridan aquifer is the source of salinity. Chloride concentrations range from 26 to 2,500 mg/L in the mid-Hawthorn aquifer (app. II) and from 400 to 4,000 mg/L in the Upper Floridan aquifer (Reese, 2000). Waters from the mid-Hawthorn aquifer have a linear trend on a trilinear diagram (fig. 5); a plot relating strontium concentration to chloride concentration (fig. 6) strongly suggests that the water compositions are controlled by simple mixing of two end members. Freshwater in the mid-Hawthorn aquifer apparently is mixing with a brackish sodium-chloride water type (the water type of the Upper Floridan aquifer).

The strontium data also are consistent with the interpretation that the source of brackish water in the mid-Hawthorn aquifer is the Upper Floridan aquifer. Waters from the Upper Floridan aquifer have $^{87}Sr/^{86}Sr$ that range from 0.70781 to 0.70795, corresponding to a late Eocene to early Oligocene age (fig. 7). This age range corresponds to the Ocala Limestone and Suwanee Limestone units within the Upper Floridan aquifer (fig. 2). Waters from the mid-Hawthorn aquifer have strontium isotope ratios ranging from 0.70782 to 0.70866 and have a linear trend (fig. 7), suggesting mixing of two water types. The mid-Hawthorn aquifer lies within the upper Arcadia Formation of Miocene age. In order to have $^{87}Sr/^{86}Sr$ ratios less than 0.70827 (the strontium ratio of the Oligocene/Miocene boundary), water from a Miocene unit must receive substantial inflow from the Floridan aquifer system. For the mid-Hawthorn aquifer, the strontium data suggest simple mixing between two end members: brackish water from the Upper Floridan aquifer and freshwater from the mid-Hawthorn aquifer (figs. 6 and 7).

Saltwater intrusion caused by numerous artesian wells open to both the Upper Floridan and mid-Hawthorn aquifers has been reported in the vicinity of Cypress Lake in Lee County (Sproul and others, 1972; Boggess and others, 1977; La Rose, 1990). Boggess and others (1977) reported four of these wells, located near the mid-Hawthorn monitoring well L-1598 (fig. 15), contained water with chloride concentrations ranging from 1,100 to 1,420 mg/L. The four wells were subsequently plugged between 1970 and 1973. Water from well L-1598 was first sampled on July 10, 1972, with a chloride concentration of 800 mg/L. Recently, the chloride concentration in water from this well was 460 mg/L (app. II). The decrease in salinity at well L-1598 suggests that these four wells have been successfully plugged.

Areas of brackish water in the mid-Hawthorn aquifer in Cape Coral also have resulted from saltwater intrusion through upward leaking wells. Fitzpatrick (1986) reported chloride concentrations greater than 800 mg/L in mid-Hawthorn domestic supply wells near mid-Hawthorn monitoring well L-1114 (fig. 15) during 1979-81, which suggested the salinity was caused by saltwater intrusion from a well open to both the mid-Hawthorn and Upper Floridan aquifers. The well serving as the source of the saltwater intrusion was not identified and perhaps was never plugged. The chloride concentration in water from well L-1114 was 210 mg/L on August 10, 1970 (the earliest data on record) and 510 mg/L on May 21, 1981. Water from well L-1114 had a chloride concentration of 640 mg/L on November 17, 1999 (app II). The data from this well suggest saltwater intrusion may be continuing in the area. Well L-2703 (fig. 15) is in another area of brackish water in Cape Coral that is probably caused by upward leakage from a well (Fitzpatrick, 1986). The chloride concentration in water has been nearly constant at this site over the last 20 years, and it is uncertain whether the leaking well was ever plugged.

Saltwater intrusion in the mid-Hawthorn aquifer has probably occurred by upward leaking wells in much of Lee County, owing to the large number of wells estimated to have been open to both the mid-Hawthorn and Upper Floridan aquifers. Few monitoring wells were available for this study along the southern part of the Caloosahatchee River, but the abundance of old irrigation wells from Truckland to Alva and Lehigh Acres suggests that much of the water in the mid-Hawthorn aquifer in this area may be brackish (figs. 16 and 17). Artesian wells open to both the mid-Hawthorn and Upper Floridan aquifers have also been reported along the coast west of Cape Coral and from Truckland to Bonita Springs (Smith and others, 1982; Burns, 1983, and South Florida Water Management District, 1990); these wells may have been the source of much of the brackish water in the mid-Hawthorn aquifer along the coast in Lee County. Fewer artesian wells have been reported in Collier County, and the extent of saltwater intrusion in the mid-Hawthorn aquifer from upward leaking wells is uncertain.

Sandstone Aquifer

The source of salinity in the sandstone aquifer in northeastern Lee County is probably the Upper Floridan aquifer. Water samples from sandstone monitoring wells L-2186, L-2187, and L-2200 (fig. 13) have $^{87}Sr/^{86}Sr$ in the range of Oligocene seawater (fig. 7). This suggests the sandstone aquifer in this area is receiving substantial inflow from the Floridan aquifer system (fig. 2). The hydrogen and oxygen isotope data support this conclusion because these three waters plot within the cluster of waters from the Upper Floridan aquifer (fig. 8). Chloride concentrations in the Upper Floridan aquifer in this area range from about 500 to 1,400 mg/L, and the sulfate concentration is about 300 mg/L (Reese, 2000). Water from wells L-2186, L-2187, and L-2200 had chloride concentrations of 560, 350, and 780 mg/L, respectively. Sulfate concentrations were 240, 140, and 240 mg/L, respectively, and were higher in water from these three wells than from the other sampled sandstone wells (app. II).

The brackish water in the sandstone aquifer in northeastern Lee County and a small region about 1 mi east of Estero may have been caused by artesian wells open to both the sandstone aquifer and one or more underlying aquifers (figs. 14 and 17). At least 14 wells near Lehigh Acres and 9 wells near Estero were open to both the sandstone aquifer and underlying aquifers prior to plugging (Burns, 1983). The data are consistent with the interpretation that artesian wells provided the pathway for saltwater intrusion. However, the well plugging had no apparent affect on the salinity of the sandstone aquifer near wells L-1853 and L-2187. The chloride concentration in water from well L-1853 was 330 mg/L on March 12, 1975, and 320 mg/L on January 3, 2000. The chloride concentration in water from well L-2187 was 340 mg/L on April 22, 1983, and 350 mg/L on March 7, 2000.

Lower Tamiami Aquifer

Upward leakage from underlying aquifers was detected in 12 of 16 waters sampled in the lower Tamiami aquifer. These waters had $^{87}Sr/^{86}Sr$ less than the strontium ratio of the middle/late Miocene boundary (fig. 7), but the lower Tamiami aquifer lies within late Miocene to Pliocene sediments (fig. 2). The lower Tamiami aquifer, therefore, likely receives inflow from the intermediate or Floridan aquifer system. Of the 12 waters with $^{87}Sr/^{86}Sr$ less than the strontium ratio of the middle/late Miocene boundary, 10 had chloride concentrations exceeding 300 mg/L. The 4 waters with $^{87}Sr/^{86}Sr$ greater than the strontium ratio of the middle/late Miocene boundary had chloride concentrations less than 300 mg/L. The strontium isotope data, therefore, suggest that underlying aquifers are a source of salinity in the lower Tamiami aquifer. In the Bonita Springs area, three wells (C-1083, L-5819, and L-5820) contained brackish water with $^{87}Sr/^{86}Sr$ in the range of Oligocene seawater (fig. 7) and, therefore, likely receive inflow from the Floridan aquifer system (fig. 2). The extensive area of brackish water in the lower Tamiami aquifer (fig. 12), previously reported by Sherwood and Klein (1963), was interpreted as residual water from former Pleistocene sea invasions. The strontium isotope data collected from wells C-1197 and C-1212 (figs. 7 and 11), however, indicate an alternate interpretation; much of the brackish water is due to upward leakage from underlying aquifers.

Well L-2310 (not shown) in Bonita Springs tapped the Upper Floridan aquifer and may have been a pathway for upward leakage into the lower Tamiami aquifer. The chloride concentration of water from nearby well L-738 gradually increased from 110 to 395 mg/L between 1968 and 2000 (fig. 19). The strontium isotope data from well L-738 indicate the source of the brackish water is an underlying aquifer. Well L-2310 was drilled in 1976, corresponding closely to the time in which the chloride concentration in water at well L-738 began increasing. The poorly sealed annulus of well L-2310 may have provided a pathway for saltwater intrusion into the lower Tamiami aquifer. Well L-2310 was damaged in 1998 and plugged in 1999. The chloride concentration in water from well L-738 was 305 mg/L on April 23, 2001, the lowest observed value in 5 years. Owing to the plugging of well L-2310, it is hypothesized that water from well L-738 will be fresh within 1 or 2 years.

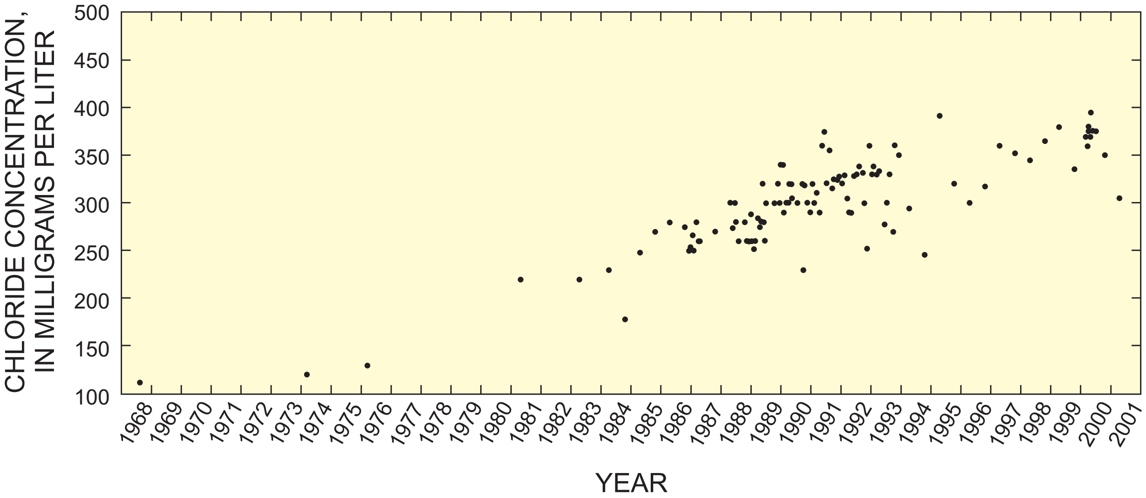

Figure 19. Chloride concentration trend at well L-738 in Lee County, 1968-2001.

Downward Leakage from Overlying Aquifers

Saltwater intrusion from overlying aquifers can occur only in areas where high salinity water is found in an overlying aquifer, head gradients permit downward flow into underlying aquifers, and a flow path is available. Cape Coral is one location where all these conditions may be present. The Caloosahatchee River and tidal canals permit seawater to move inland, causing seepage of saline water into the water-table aquifer. Water levels in the mid-Hawthorn aquifer were more than 40 ft below sea level in some areas of Cape Coral due to pumpage. Old, steel-cased, abandoned wells in the mid-Hawthorn aquifer (more than 1,000 were plugged) are abundant in Cape Coral (Burns, 1983); and the casings of these wells can corrode prior to plugging, creating a flow path for downward leakage.

Saltwater intrusion from the downward movement of saline water through corroded metal casings of wells occurred in Cape Coral (Boggess and others 1977; Fitzpatrick, 1986). Well L-952 (not shown), cased with galvanized iron pipe, was drilled to the mid-Hawthorn aquifer in 1961 and used for irrigation. Use of the well was discontinued in 1967 when the water became saline. A 1969 study indicated that the well contained water with a chloride concentration of 26,400 mg/L, which came from a zone of saline water in the water-table aquifer at a depth of about 50 to 60 ft (Boggess and others, 1977). The casing had corroded and developed holes, and the well was plugged in September 1969. A nearby mid-Hawthorn monitoring well (L-2244) contained water with a chloride concentration of 390 mg/L on April 26, 1978 (the earliest data on record). Brackish water from the well was last observed on April 12, 1984, and on April 19, 2000, the chloride concentration was 100 mg/L (app. II).

Chloride data suggest a downward leaking well may be the source of a small area of brackish water in the mid-Hawthorn aquifer in Cape Coral. This area of saltwater intrusion appears to be smalló perhaps 1,000 ft in diameteró and is not shown on the map of the distribution of salinity for the mid-Hawthorn aquifer. Chloride concentrations in water from several domestic self-supply wells completed in the mid-Hawthorn aquifer have increased from about 300 to about 5,000 mg/L (Michael Cason, City of Cape Coral, written commun., 2000). The chloride concentrations are too high for the water to be from the Upper Floridan aquifer (fig. 17), and there is a lake with access to the Gulf of Mexico about 300 ft to the west with chloride concentrations exceeding 10,000 mg/L. It is hypothesized that the metal casing of a well near the access lake has corroded, and saline water is moving down the well and into the mid-Hawthorn aquifer. On a regional scale, no evidence of saltwater intrusion by downward leakage from overlying aquifers was found.

Saltwater from the Gulf of Mexico

The Gulf of Mexico is probably the source of the saline water along the coast in the lower Tamiami aquifer (fig. 12); the gulf is the only known body of water in the study area with salinity high enough to account for the saline water found in the lower Tamiami aquifer. Chloride concentrations in water from wells C-526, C-527, and C-1205 were 3,300, 8,300, and 14,000 mg/L, respectively. Water from these wells plot along a saltwater mixing line showing the relation between δ^2H and chloride concentration, and results are clearly different from the other waters sampled (fig. 9). The strontium isotope data for the same wells however, indicated some upward leakage from an underlying aquifer is occurring; but the chloride concentration in water from the Upper Floridan aquifer was only about 4,000 mg/L in this area (Reese, 2000) and probably about 2,200 to 2,500 mg/L in the mid-Hawthorn aquifer (Klein, 1954; Missimer & Associates, 1993). The geochemical, hydrogen and oxygen isotope, and strontium isotope data suggest mixing between freshwater recharge, brackish upward leakage, and saline water from the Gulf of Mexico.

The age of the saline water in the lower Tamiami aquifer is uncertain; the saline water may be recent saltwater intrusion, or it may be residual water from former Pleistocene sea invasions. Klein (1954) reported recent saltwater intrusion in the lower Tamiami aquifer in Naples. Sherwood and Klein (1963) stated, ìRecent seawater encroachment has occurred along the coast where the natural balance between the fresh ground water and seawater has been altered by man. Major areas of seawater encroachment extend from around the southern sections of the Everglades National Park to the Naples area on the west coast.î The saline water, however, does not have the strontium isotope signature of modern seawater, but of early Miocene seawater; the strontium data might be explained by old seawater mixing with brackish water from an underlying aquifer.

SUMMARY

The surficial and intermediate aquifer systems are the primary sources of ground-water supply in southwestern Florida. Saltwater intrusion is a threat because of ground-water level declines and projected increasing demands. Salinization in coastal aquifers is commonly attributed to the inland encroachment of seawater, but other sources can also cause an increase in salinity. A better understanding of the distribution of salinity and its origin is critical for water managers to ensure the protection of these freshwater resources.

Maps of the salinity distribution of four aquifers (mid-Hawthorn, sandstone, lower Tamiami, and water-table aquifers) indicate a general trend of increasing chloride concentrations toward the coast and with depth. Notable exceptions to this trend are the inland areas of brackish water in the mid-Hawthorn and sandstone aquifers in Lee County. Another exception is the lower Tamiami aquifer in southern Collier County where salinity is substantially higher than in underlying aquifers.

The analysis of major ions, hydrogen and oxygen isotopes, and strontium isotopes indicate that underlying brackish aquifers and the Gulf of Mexico are the primary sources of salinity in the study area. Evidence of upward leakage of brackish water from underlying aquifers was found in the mid-Hawthorn, sandstone, and lower Tamiami aquifers. The source of saline water in the lower Tamiami aquifer in coastal Collier County is apparently the Gulf of Mexico; it is unclear however, whether this saline water is residual water from former Pleistocene sea invasions or recent saltwater intrusion.

Mechanisms responsible for upward leakage are difficult to determine, but two likely pathways are artesian wells and diffuse upward discharge. The available data suggest that artesian wells have contributed substantially to saltwater intrusion in the mid-Hawthorn and sandstone aquifers in Lee County. Upward leakage from underlying aquifers was detected in the lower Tamiami aquifer in Bonita Springs, and artesian wells may, at least in part, account for the saltwater intrusion observed there. Apparently, few artesian wells were drilled in western Collier County, so the extent of saltwater intrusion from leaking wells is uncertain. Much of the brackish water observed in the lower Tamiami and mid-Hawthorn wells in western Collier County may be from natural upward discharge by diffuse leakage from underlying aquifers.

REFERENCES CITED

Bear, Jacob, Cheng, A.H.D, Sorek, Shaul, and others, eds., 1999, Seawater intrusion in coastal aquifersó Concepts, methods and practices: Dordrecht, Netherlands, Kluwer Academic Publishers, 625 p.

Bengtsson, T., and Radin, H., 2001, Water level elevation maps of the primary aquifers in the lower west coast of Florida, *in* Geology and hydrology of Lee County, Florida: Durward H. Boggess memorial symposium, Florida Geological Survey Special Publication 49, p. 139-149.

Berndt, M.P., and Katz, B.G., 1992, Hydrochemistry of the surficial and intermediate aquifer systems in Florida: U.S. Geological Survey Water-Resources Investigations Report 91-4186, 24 p.

Boggess, D.H., Missimer, T.M., and OíDonnell, T.H., 1977, Saline-water intrusion related to well construction in Lee County, Florida: U.S. Geological Survey Water-Resources Investigations Report 77-33, 29 p.

Burns, W.S., 1983, Well plugging applications to the inter-aquifer migration of saline groundwater in Lee County, Florida: West Palm Beach, South Florida Water Management District Technical Publication 83-8, 77 p.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-C, 80 p., 17 pls.

Clark, I.D., and Fritz, Peter, 1997, Environmental isotopes in hydrogeology: Boca Raton, Fla., Lewis Publishers, 328 p.

Coplen, T.B., Wildman, J.D., and Chen, J., 1991, Improvements in the gaseous hydrogen-water equilibration technique for hydrogen isotope ratio analysis: Analytical Chemistry, v. 63, p. 910-912.

Craig, Harmon, 1961, Standard for reporting concentrations of deuterium and oxygen-18 in natural water: Science, v. 133, p. 1833-1834.

Edwards, L.E., Weedman, S.D., Simmons, K.R., and others, 1998, Lithostratigraphy, petrography, biostratigraphy, and strontium-isotope stratigraphy of the surficial aquifer system of western Collier County, Florida: U.S. Geological Survey Open-File Report 98-205, 79 p.

Elderfield, H., 1986, Strontium isotope stratigraphy: Palaeogeography, palaeoclimatology, palaeoecology, v. 57, p. 71-90.

Epstein, S., and Mayeda, T., 1953, Variations of the $^{18}O/^{16}O$ ratio in natural waters: Geochimica et Cosmochimica Acta, v. 4, p. 213-224.

Fetter, C.W., 1994, Applied hydrogeology (3d ed.): Upper Saddle River, New Jersey, Prentice Hall, 691 p.

Fishman, M.J., and Friedman, L.J. eds., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Fitterman, D.V., and Stewart, M.T., 1986, Transient electromagnetic sounding for groundwater: Geophysics, v. 51, p. 995-1005.

Fitzpatrick, D.J., 1986, Hydrogeologic conditions and saline-water intrusion, Cape Coral, Florida, 1979-81: U.S. Geological Survey Water-Resources Investigations Report 85-4231, 31 p.

Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Hite, L.R., 1997, Aquifer delineation in southwest Florida using time-domain electromagnetics: Dayton, Ohio, M.S. Thesis, Wright State University, 77 p.

Howarth, R.J., and McArthur, J.M., 1997, Statistics for strontium isotope stratigraphy: A robust LOWESS fit to the marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age: Journal of Geology, v. 105, p. 441-456.

Katz, B.G., Lee, T.M., Plummer, L.N., and Busenberg, E., 1995, Chemical evolution of groundwater near a sinkhole lake, northern Florida, 1. Flow patterns, age of groundwater, and influence of lake water leakage: Water Resources Research, v. 31, p. 1549-1564.

Klein, Howard, 1954, Ground-water resources of the Naples area, Collier County, Florida: Florida Geological Survey Report of Investigations 11, 64 p.

Knapp, M.S., Burns, W.S., and Sharp, T.S., 1986, Preliminary assessment of the groundwater resources of western Collier County, Florida: West Palm Beach, South Florida Water Management District Technical Publication 86-1, 106 p.

Kohout, F.A., Munson, R.C., Turner, R.M., and Royal, W.R., 1981, Satellite observations of a geothermal submarine spring off Florida west coast, *in* Satellite hydrology: William T. Pecora memorial symposium on remote sensing, Sioux Falls, S.D., 1979: American Water Resources Association, Technical Publication TPS81-1, p. 570-578.

Krulikas, R.K., and Giese, G.L., 1995, Recharge to the surficial aquifer system in Lee and Hendry Counties, Florida: U.S. Geological Survey Water-Resources Investigations Report 95-4003, 21 p.

La Rose, H.R., 1990, Geohydrologic framework and an analysis of a well-plugging program, Lee County, Florida: U.S. Geological Survey Water-Resources Investigations Report 90-4063, 26 p.

Marella, R.L., 1999, Water withdrawals, use, discharge, and trends in Florida, 1995: U.S. Geological Survey Water-Resources Investigations Report 99-4002, 90 p.

McNeill, J.D., 1990. Use of electromagnetic methods for groundwater studies, *in* W.H. Ward, ed., Geotechnical and Environmental Geophysics: Tulsa, Okla., Society of Exploratory Geophysicists, p. 191-218.

Meyer, F.W., 1989, Hydrogeology, ground-water movement, and subsurface storage in the Floridan aquifer system in southern Florida: U.S. Geological Survey Professional Paper 1403-G, 59 p.

Missimer, T.M., 1997, Late Oligocene to Pliocene evolution of the central portion of the South Florida Platform: Mixing of siliciclastic and carbonate sediments: Ph.D. Dissertation, University of Miami, 2 Volumes, 993 p.

ó ñó 2001, Late Paleogene and Neogene chronostratigraphy of Lee County, Florida, *in* Geology and hydrology of Lee County, Florida: Durward H. Boggess memorial symposium, Florida Geological Survey Special Publication 49, p. 67-90.

Missimer & Associates, 1993, Phase II Collier County aquifer storage and recovery project preliminary report: 47 p.

Paillet, F., Hite, L., and Carlson, M., 1999, Integrating surface and borehole geophysics in ground water studiesñ An example using electromagnetic soundings in south Florida: Journal of Environmental and Engineering Geophysics, v. 4, p. 45-55.

Plummer, L.N., 1993, Stable isotope enrichment in paleowaters of the southeast Atlantic Coastal Plain, United States: Science, v. 262, p. 2016-2020.

Reese, R.S., 2000, Hydrogeology and the distribution of salinity in the Floridan aquifer system, southwestern Florida: U.S. Geological Survey Water-Resources Investigations Report 98-4253, 86 p.

Rosenau, J.C., Faulkner, G.L., Hendry, C.W., Jr., and Hull, R.W., 1977, Springs of Florida: Florida Geological Survey Geological Bulletin 31, revised, 461 p.

Sacks, L.A., and Tihansky, A.B., 1996, Geochemical and isotopic composition of ground water, with emphasis on sources of sulfate, in the Upper Floridan aquifer and intermediate aquifer system in southwest Florida: U.S. Geological Survey Water-Resources Investigations Report 96-4146.

Sherwood, C.B., and Klein, Howard, 1963, Ground-water resources of northwestern Collier County, Florida: Florida Geological Survey Information Circular 29, 44 p.

Smith, C.A., Lidz, L., and Meyer, F.W., 1982, Data on selected deep wells in south Florida: U.S. Geological Survey Open-File Report 82-348, 144 p.

South Florida Water Management District, 1990, Abandoned artesian well plugging work plan: West Palm Beach, South Florida Water Management District, 12 p., app. A-G.

Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986, Hydrogeological units of Florida: Florida Department of Natural Resources, Bureau of Geology, Special Publication 28, 9 p.

Sproul, C.R., Boggess, D.H., and Woodard, H.J., 1972, Saline water intrusion from deep artesian sources in the McGregor Isles area of Lee County, Florida: Florida Bureau of Geology Information Circular 75, 30 p.

Swancar, Amy, and Hutchinson, C.B., 1995, Chemical and isotopic composition and potential for contamination of water in the Upper Floridan aquifer, west-central Florida, 1986-89: U.S. Geological Survey Water-Supply Paper 2409, 70 p.

Swart, P.K., Sternberg, L., Steinen, R., and Harrison, S.A., 1989, Controls on the oxygen and hydrogen isotopic composition of the water of Florida Bay, U.S.A.: Chemical Geology, v. 79, p. 113-123.

Wedderburn, L.A., Knapp, M.S., Waltz, D.P., and Burns, W.S., 1982, Hydrogeologic reconnaissance of Lee County, Florida: West Palm Beach, South Florida Water Management District Technical Publication 82-1, 192 p.

Weedman, S.D. Paillet, F.L., Means, G.H., and Scott, T.M., 1997, Lithology and geophysics of the surficial aquifer system in western Collier County, Florida: U.S. Geological Survey Open-File Report 97-436, 167 p.

Appendix I

Inventory of Wells

Appendix I. Inventory of wells used in this study

[Owner: USGS, U.S. Geological Survey; PBID, Pelican Bay Improvement District; QCCC, Quail Creek Country Club; FCWC, Florida Cities Water Company; SFWMD, South Florida Water Management District. Aquifer: SAS, surficial aquifer system; WT, water-table aquifer; LT, lower Tamiami aquifer; SS, sandstone aquifer; MH, mid-Hawthorn aquifer; UF, upper Floridan aquifer]

Local well number	Other well identifier	Owner	USGS site identification number	Aquifer	Lati-tude	Longi-tude	Well depth	Bottom of casing
C-115	--	City of Naples	260830081474301	MH	260830	814743	540	300
C-123	--	USGS	261003081475801	LT	261004	814759	157	97
C-130	--	USGS	260902081480401	LT	260902	814823	72	69
C-304	--	USGS	261630081360001	LT	261637	813615	130	125
C-409	--	USGS	261024081480102	WT	261026	814800	16	14
C-409A	--	USGS	261024081480101	LT	261024	814757	73	63
C-460	--	USGS	261405081465501	LT	261407	814706	66	64
C-472A	--	USGS	260925081475201	LT	260926	814754	70	66
C-474A	--	USGS	261114081482301	LT	261117	814824	72	63
C-490	--	USGS	261243081480301	LT	261314	814801	71	70
C-491	--	USGS	261117081480101	LT	261118	814802	71	70
C-506A	--	USGS	261233081480201	LT	261232	814802	71	62
C-525	--	USGS	261002081483701	LT	261000	814836	83	63
C-526	--	USGS	261018081484101	LT	261020	814842	68	63
C-527	--	USGS	261048081484801	LT	261051	814847	72	63
C-575	--	USGS	261438081481001	UF	261319	814804	652	352
C-688	--	USGS	261802081354801	SS	261804	813546	242	220
C-948	--	USGS	261347081351701	MH	261348	813517	420	370
C-953	--	USGS	261347081351201	WT	261348	813513	40	12
C-956	--	USGS	261343081384802	LT	261346	813844	260	60
C-963	--	USGS	262121081355502	MH	262123	813559	340	310
C-973	--	USGS	260843081324201	LT	260844	813238	150	90
C-974	--	USGS	260941081324201	MH	260941	813239	460	400
C-977	--	USGS	260915081385902	LT	260916	813846	140	75
C-998	--	USGS	261620081450201	LT	261623	814501	62	52
C-1003	--	USGS	261436081480301	LT	261439	814803	61	51
C-1004	--	USGS	261620081464401	LT	261622	814643	60	52
C-1026	--	USGS	261233081480202	WT	261233	814800	38	28
C-1057	--	USGS	261537081461201	WT	261537	814612	20	8
C-1058	--	USGS	261537081461202	LT	261538	814611	80	62
C-1059	--	USGS	261604081480901	WT	261606	814809	25	10
C-1060	--	USGS	261459081480401	WT	261500	814803	25	10
C-1061	--	USGS	261311081480101	WT	261312	814801	25	10
C-1062	--	USGS	260925081475101	WT	260927	814751	24	10
C-1063	--	USGS	260137081375901	WT	260140	813757	55	30
C-1067	--	USGS	260314081323101	WT	260316	813231	65	30
C-1068	--	USGS	260314081323102	LT	260316	813231	200	120
C-1080	--	USGS	262228081361902	MH	262228	813619	309	238
C-1082	--	USGS	261805081473301	WT	261820	814730	20	10
C-1083	--	USGS	261805081473302	LT	261820	814730	74	58
C-1092	--	USGS	260251081412801	WT	260252	814128	19	14
C-1113	--	USGS	255920081344301	SAS	255920	813443	207	--

Appendix I. Inventory of wells used in this study (Continued)

[Owner: USGS, U.S. Geological Survey; PBID, Pelican Bay Improvement District; QCCC, Quail Creek Country Club; FCWC, Florida Cities Water Company; SFWMD, South Florida Water Management District. Aquifer: SAS, surficial aquifer system; WT, water-table aquifer; LT, lower Tamiami aquifer; SS, sandstone aquifer; MH, mid-Hawthorn aquifer; UF, upper Floridan aquifer]

Local well number	Other well identifier	Owner	USGS site identification number	Aquifer	Latitude	Longitude	Well depth	Bottom of casing
C-1114	--	USGS	255840081302201	SAS	255840	813022	196	--
C-1118	--	USGS	260834081334501	SAS	260834	813345	201	--
C-1119	--	USGS	260404081414201	SAS	260404	814142	210	--
C-1188	CO-21	PBID	261624081451301	SS	261624	814513	225	170
C-1189	CO-22	PBID	261623081453501	LT	261623	814535	75	61
C-1193	MW-2	Stonebridge Country Club	261542081470701	LT	261542	814707	75	45
C-1194	MW-1	Pelican Marsh	261558081474901	LT	261558	814749	80	50
C-1195	MW-2	Pelican Marsh	261512081474501	LT	261512	814745	68	48
C-1197	CO-112	QCCC	261716081441201	LT	261716	814412	85	80
C-1198	CO-98	QCCC	261721081431801	LT	261721	814318	90	85
C-1199	CO-108	QCCC	261809081431901	LT	261809	814319	92	88
C-1200	CO-110	QCCC	261808081441501	LT	261808	814415	70	65
C-1201	--	Naples Memorial Gardens	261621081485201	LT	261621	814852	60	20
C-1204	Manatee Road ASR MW-C	Collier County Utilities	260247081414103	MH	260248	814142	520	465
C-1205	Manatee Road ASR MW-D	Collier County Utilities	260247081414104	LT	260247	814126	150	110
C-1212	Golden Gate MW-D	FCWC	261052081413801	LT	261052	814138	101	98
C-1213	--	Foxfire Community Association	260910081450201	LT	260910	814502	84	40
C-1215	MW-PP1	Partridge Point	260958081435301	LT	260958	814353	87	73
C-1216	CO-18	PBID	261712081451301	LT	261712	814513	90	51
C-1217	Well 1	Piper's Pointe	261624081463001	WT	261624	814630	29	23
C-1218	CO-596	Eagle Creek Country Club	260344081423401	WT	260344	814234	11	6
C-1219	Production well 16	Collier County Utilities	261442081362301	LT	261442	813623	150	92
C-1220	Production well 20	Collier County Utilities	261309081351101	LT	261309	813511	131	83
L-581	--	USGS	263532081592201	MH	263533	815921	177	110
L-721	--	USGS	264153082022301	WT	264154	820222	18	9
L-731	--	USGS	262703081340201	SS	262704	813401	243	165
L-735	--	USGS	262839081503100	MH	262840	815030	270	223
L-738	--	USGS	262022081464201	LT	262024	814641	75	61
L-742	--	USGS	263323081522401	MH	263326	815225	225	138
L-781	--	USGS	263834082005301	MH	263835	820053	290	82
L-1059	--	USGS	264517082022101	MH	264516	820219	189	156
L-1110	--	USGS	264241081582401	MH	264241	815825	238	147
L-1111	--	USGS	264147081562701	MH	264149	815623	165	137
L-1113	--	USGS	264120082022101	MH	264126	820220	230	126
L-1114	--	USGS	263720081573101	MH	263722	815723	172	124
L-1116	--	USGS	263633082002701	MH	263659	820016	205	106
L-1117	--	USGS	263438081563201	MH	263436	815638	248	126
L-1121	--	USGS	263327081512001	MH	263330	815120	220	147
L-1124	--	USGS	263246081531501	MH	263247	815314	230	126

Appendix I. Inventory of wells used in this study (Continued)

[Owner: USGS, U.S. Geological Survey; PBID, Pelican Bay Improvement District; QCCC, Quail Creek Country Club; FCWC, Florida Cities Water Company; SFWMD, South Florida Water Management District. Aquifer: SAS, surficial aquifer system; WT, water-table aquifer; LT, lower Tamiami aquifer; SS, sandstone aquifer; MH, mid-Hawthorn aquifer; UF, upper Floridan aquifer]

Local well number	Other well identifier	Owner	USGS site identification number	Aquifer	Lati-tude	Longi-tude	Well depth	Bottom of casing
L-1136	--	USGS	263532081592202	WT	263533	815921	20	15
L-1403	--	USGS	262549082035301	WT	262555	820355	12	3
L-1456	--	USGS	262622082022001	WT	262622	820220	33	32
L-1598	--	USGS	263233081550301	MH	263233	815501	176	137
L-1625	--	USGS	263329081394302	SS	263332	813942	218	162
L-1691	--	USGS	262042081455001	LT	262042	814521	69	58
L-1853	--	USGS	262706081435401	SS	262706	814358	210	130
L-1968	--	USGS	263807081430301	SS	263801	814303	165	70
L-1973	--	USGS	263718081485001	MH	263720	814850	225	172
L-1974	--	USGS	263718081485002	SS	263720	814850	135	85
L-1983	--	USGS	263041081433101	MH	263043	814332	345	321
L-1993	--	USGS	263251081452801	MH	263252	814536	242	190
L-2186	--	USGS	263344081361703	SS	263345	813616	160	133
L-2187	--	USGS	263950081355401	SS	263950	813552	154	136
L-2193	--	USGS	262713081414401	SS	262713	814142	292	220
L-2194	--	USGS	261957281432201	LT	262000	814322	137	81
L-2200	--	USGS	264329081340401	SS	264331	813406	163	122
L-2212	--	USGS	262831081575901	MH	262832	815800	236	135
L-2215	--	USGS	263127081351602	SS	263129	813516	149	99
L-2216	--	USGS	264608081454101	SS	264610	814539	150	130
L-2244	--	USGS	263242081572101	MH	263243	815721	207	150
L-2292	--	USGS	263718081485003	UF	263721	814850	616	302
L-2295	--	USGS	262552081485702	UF	262552	814854	610	300
L-2308	--	USGS	262552081485703	WT	262546	814854	14	12
L-2311	--	USGS	263344081361704	UF	263346	813616	625	300
L-2328	--	USGS	264608081454103	UF	264610	814539	600	300
L-2435	--	USGS	263307081555901	UF	263407	815600	704	352
L-2525	--	USGS	263117082051001	UF	263118	820508	645	405
L-2526	--	USGS	264517082022102	UF	264516	820219	605	300
L-2527	--	USGS	263955082083101	UF	263954	820830	605	360
L-2528	--	USGS	263907081592701	UF	263908	815926	625	420
L-2529	--	USGS	262944081560801	UF	262915	815625	545	304
L-2531	--	USGS	264427081362601	UF	264433	813626	605	345
L-2549	--	USGS	263955082083103	WT	263954	820830	80	58
L-2640	--	USGS	263813081552801	MH	263814	815528	180	128
L-2641	--	USGS	263533081573401	MH	263535	815734	170	118
L-2642	--	USGS	263257081585701	MH	263259	815857	160	108
L-2643	--	USGS	263253082014201	MH	263257	820152	200	141
L-2644	--	USGS	263440082022001	MH	263444	820215	180	128
L-2645	--	USGS	263743082041201	MH	263744	820412	210	160
L-2646	--	USGS	264537081552202	MH	264539	815521	220	170
L-2700	--	USGS	264002082012801	MH	264002	820128	205	165
L-2701	--	USGS	263819081585801	MH	263820	815857	206	175

Appendix I. Inventory of wells used in this study (Continued)

[Owner: USGS, U.S. Geological Survey; PBID, Pelican Bay Improvement District; QCCC, Quail Creek Country Club; FCWC, Florida Cities Water Company; SFWMD, South Florida Water Management District. Aquifer: SAS, surficial aquifer system; WT, water-table aquifer; LT, lower Tamiami aquifer; SS, sandstone aquifer; MH, mid-Hawthorn aquifer; UF, upper Floridan aquifer]

Local well number	Other well identifier	Owner	USGS site identification number	Aquifer	Lati-tude	Longi-tude	Well depth	Bottom of casing
L-2703	--	USGS	263357081575602	MH	263400	815756	160	120
L-2820	--	USGS	263955082083102	MH	263954	820830	241	192
L-2821	--	USGS	263117082051002	MH	263118	820509	340	290
L-3203	--	USGS	263813081552802	WT	263814	815528	18	8
L-3204	--	USGS	263533081573402	WT	263535	815734	18	8
L-3205	--	USGS	263257081585702	WT	263259	815857	18	8
L-3206	--	USGS	263253082014202	WT	263253	820152	18	8
L-3207	--	USGS	263440082022002	WT	263444	820215	18	8
L-3208	--	USGS	263743082041202	WT	263744	820412	18	8
L-3213	--	USGS	263357081575603	WT	263400	815756	18	8
L-3215	--	USGS	263117082051003	WT	263118	820509	18	8
L-4820	--	USGS	264053081572501	MH	264057	815725	190	128
L-5648	--	USGS	263249081474401	SS	263251	814757	123	118
L-5649	--	USGS	262934081495801	SS	262935	814714	128	118
L-5664	--	USGS	262514081393402	SS	262516	813935	300	180
L-5668	--	USGS	262513081471802	SS	262513	814718	155	106
L-5673	--	USGS	262331082383202	SS	262331	814337	135	130
L-5722	--	USGS	262102081464401	WT	262104	814645	21	8
L-5724	--	USGS	261946081490301	WT	261948	814905	35	25
L-5725	--	USGS	261946081490302	LT	261948	814905	128	65
L-5726	--	USGS	261859081481901	WT	261900	814817	32	22
L-5727	--	USGS	261859081481902	LT	261859	814729	100	65
L-5731	--	Bonita Bay	262351081485402	SS	262352	814854	120	90
L-5745	--	USGS	261900081454602	LT	261927	814545	105	57
L-5746	--	USGS	262258081471801	WT	262300	814717	15	10
L-5747	--	USGS	262258081471802	LT	262300	814717	105	59
L-5801	--	USGS	263115081483502	UF	263114	814834	635	450
L-5804	--	SFWMD	262058081471201	LT	262058	814710	75	65
L-5805	--	SFWMD	262058081471202	MH	262058	814710	298	276
L-5806	--	SFWMD	262057081471101	WT	262058	814710	18	8
L-5808	--	SFWMD	262630081484802	MH	262617	815004	208	192
L-5815	San Carlos Estates ASR SMW-1	Bonita Springs Utilities	262318081462004	MH	262319	814622	321	234
L-5819	LM-1644	Bonita Bay	262050081481801	LT	262050	814818	86	75
L-5820	LM-1645	Bonita Bay	262048081494001	LT	262048	814940	104	97
L-5821	LM-1646	Bonita Bay	262141081491101	LT	262141	814911	128	120
L-5822	LM-1647	Bonita Bay	262141081491102	WT	262141	814911	23	18
L-5823	LM-1648	Bonita Bay	262138081482901	WT	262138	814829	23	18
L-5824	LM-1649	Bonita Bay	262138081482902	LT	262138	814829	100	78
L-5825	LM-1675	Bonita Bay	262138081482903	MH	262138	814829	220	19
L-5826	LM-1650	Bonita Bay	262051081481801	WT	262051	814818	25	20
L-5827	LM-1651	Bonita Bay	262048081494002	WT	262048	814940	24	19
L-5828	LM-3554	Bonita Bay	262112081481701	MH	262112	814817	271	238

Appendix I. Inventory of wells used in this study (Continued)

[Owner: USGS, U.S. Geological Survey; PBID, Pelican Bay Improvement District; QCCC, Quail Creek Country Club; FCWC, Florida Cities Water Company; SFWMD, South Florida Water Management District. Aquifer: SAS, surficial aquifer system; WT, water-table aquifer; LT, lower Tamiami aquifer; SS, sandstone aquifer; MH, mid-Hawthorn aquifer; UF, upper Floridan aquifer]

Local well number	Other well identifier	Owner	USGS site identification number	Aquifer	Lati-tude	Longi-tude	Well depth	Bottom of casing
L-5829	--	Bayside Estates	262915081562201	MH	262915	815622	185	145
L-5830	--	Beach United Methodist Church	262653081562101	MH	262653	815621	220	190
L-5831	Well 5	Brandywine Condominiums	263208081544201	MH	263208	815442	220	160
L-5832	North Fort Myers emergency well 1	Lee County Utilities	264244081501601	MH	264244	815016	198	138
L-5833	North Fort Myers emergency well 2	Lee County Utilities	264244081501602	SS	264244	815016	105	64
L-5834	Well 2	Fountain Lakes	262440081485601	MH	262440	814856	260	245
L-5835	--	David Green	262801081571601	MH	262801	815716	220	200
L-5836	--	Kelley's Gardens	263055081520801	MH	263055	815208	195	165
L-5837	--	Leisure Estates	263407081515701	MH	263407	815158	200	135
L-5838	LM-2017	Pelican Nest	262244081492301	MH	262244	814923	300	235
L-5839	LM-4979	Pelican Nest	262340081494401	MH	262340	814944	285	215
L-5840	LM-2214	Lake Fairways	264426081554801	MH	264426	815548	180	150
L-5841	--	Royal Pelican Condominiums	262446081534801	MH	262446	815348	220	200
L-5842	Green Meadows production well 1	FCWC	263047081433101	SS	263047	814331	180	170
L-5843	College Parkway production well 2	FCWC	263246081523401	MH	263245	815232	230	126
L-5844	--	SFWMD	262630081484801	WT	262617	815004	35	25
L-5845	--	SFWMD	262628081482002	MH	262629	814818	178	165
L-5846	--	SFWMD	262628081482001	SS	262628	814818	120	100
L-5847	--	Beach and Tennis Club	261954081503701	LT	261954	815037	90	82
L-5848	MW-1	Bonita Springs Utilities	262002081472901	LT	262002	814729	80	75
L-5849	MW-2	Bonita Springs Utilities	262007081454101	LT	262007	814541	100	81
L-5850	Waterway Estates production well 15	FCWC	263936081551601	MH	263936	815516	208	160
L-5866	LM-3663	Pelican Nest	262234081491301	WT	262234	814913	20	10
L-5867	LM-3664	Pelican Nest	262235081494201	WT	262235	814942	20	10
L-5868	LM-4014	Spring Creek at Pelican Landing	262216081483001	WT	262216	814830	21	11
L-5869	--	Eagle Ridge Golf and Tennis Club	263136081501501	MH	263136	815015	200	177
L-5870	Bobcat well	Forest Country Club	262953081520501	MH	262953	815205	250	180

Appendix II

Water-Quality Data

Appendix II. Water-quality data

[μS/cm, microsiemens per centimeter; mg/L, milligrams per liter; δ²H, delta deuterium; δ¹⁸O, delta oxygen-18; ⁸⁷Sr/⁸⁶Sr, ratio of strontium-87 to strontium-86; e, estimated value; --, no data]

Well number	Date	Specific conductance (μS/cm)	Chloride (mg/L)	Sulfate (mg/L)	Bicarbonate (mg/L)	Sodium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Strontium (mg/L)	δ^2H (per mill)	$\delta^{18}O$ (per mill)	$^{87}Sr/^{86}Sr$
C-115	03-24-52	--	2,200	--	--	--	--	--	--	--	--	--	--
C-123	05-25-99	417	24	--	--	--	--	--	--	--	--	--	--
C-130	05-01-99	830	74	--	--	--	--	--	--	--	--	--	--
C-304	04-19-00	640	46	--	--	--	--	--	--	--	--	--	--
C-409	05-01-99	709	39	--	--	--	--	--	--	--	--	--	--
C-409A	05-01-99	449	25	--	--	--	--	--	--	--	--	--	--
C-460	04-24-00	433	34	--	--	--	--	--	--	--	--	--	--
C-472A	05-16-00	752	65	--	--	--	--	--	--	--	--	--	--
C-474A	05-01-99	765	120	--	--	--	--	--	--	--	--	--	--
C-490	04-30-99	363	15	--	--	--	--	--	--	--	--	--	--
C-491	06-08-00	417	16	2.1	220	7.9	74	2.3	0.50	0.16	-16.3	-3.14	0.70906
C-506A	05-01-99	444	23	--	--	--	--	--	--	--	--	--	--
C-525	04-24-00	2,870	700	--	--	--	--	--	--	--	--	--	--
C-526	06-09-00	9,660	3,300	350	240	1,300	310	148	37	3.6	-10.3	-1.89	0.70833
C-527	05-31-00	23,200	8,300	1,100	330	4,200	480	503	120	5.6	-3.7	-1.34	0.70857
C-575	12-12-00	5,000	1,200	--	--	--	--	--	--	--	--	--	--
C-688	04-19-00	711	48	--	--	--	--	--	--	--	--	--	--
C-948	11-16-99	1,700	180	--	--	--	--	--	--	--	--	--	--
C-953	04-17-00	607	22	--	--	--	--	--	--	--	--	--	--
C-956	04-20-93	811	54	--	--	--	--	--	--	--	--	--	--
C-963	04-19-00	407	30	--	--	--	--	--	--	--	--	--	--
C-973	05-31-00	2,610	600	--	--	--	--	--	--	--	--	--	--
C-974	11-10-99	6,850	2,000	--	--	--	--	--	--	--	--	--	--
C-977	04-19-00	3,310	880	--	--	--	--	--	--	--	--	--	--
C-998	04-30-99	1,180	140	--	--	--	--	--	--	--	--	--	--
C-1003	04-30-99	480	28	--	--	--	--	--	--	--	--	--	--
C-1004	04-06-00	1,100	150	90	290	94	90	23	7.1	0.96	-4.1	-0.74	0.70860
C-1026	04-30-99	751	65	--	--	--	--	--	--	--	--	--	--
C-1057	05-26-99	656	43	--	--	--	--	--	--	--	--	--	--
C-1058	04-06-00	1,270	170	84	420	100	120	22	4.9	1.14	-3.5	-0.78	0.70890
C-1059	04-24-00	843	100	--	--	--	--	--	--	--	--	--	--
C-1060	05-26-99	535	48	--	--	--	--	--	--	--	--	--	--
C-1061	04-24-00	375	74	--	--	--	--	--	--	--	--	--	--

Appendix II. Water-quality data (Continued)

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; δ^{2}H, delta deuterium; δ^{18}O, delta oxygen-18; ^{87}Sr/^{86}Sr, ratio of strontium-87 to strontium-86; e, estimated value; --, no data]

Well number	Date	Specific conductance (µS/cm)	Chloride (mg/L)	Sulfate (mg/L)	Bicarbonate (mg/L)	Sodium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Strontium (mg/L)	δ^{2}H (per mill)	δ^{18}O (per mill)	^{87}Sr/^{86}Sr
C-1062	05-25-99	830	91	--	--	--	--	--	--	--	--	--	--
C-1063	04-17-00	558	30	--	--	--	--	--	--	--	--	--	--
C-1067	06-01-00	1,050	86	--	--	--	--	--	--	--	--	--	--
C-1068	06-01-00	5,410	1,600	--	--	--	--	--	--	--	--	--	--
C-1080	04-19-00	607	26	--	--	--	--	--	--	--	--	--	--
C-1082	04-30-99	99	10	--	--	--	--	--	--	--	--	--	--
C-1083	04-05-00	1,980	440	150	270	260	110	32	8.8	2.1	-9.0	-2.06	0.70816
C-1092	05-19-00	638	35	--	--	--	--	--	--	--	--	--	--
C-1113	--	14,000e	5,000e	--	--	--	--	--	--	--	--	--	--
C-1114	--	25,000e	9,000e	--	--	--	--	--	--	--	--	--	--
C-1118	--	3,000e	800e	--	--	--	--	--	--	--	--	--	--
C-1119	--	2,000e	500e	--	--	--	--	--	--	--	--	--	--
C-1188	03-22-00	3,720	1,200	8.4	170	410	140	121	58	3.15	-4.1	-1.38	0.70842
C-1189	04-06-00	1,340	180	70	450	120	120	27	6.6	1.18	-0.5	-0.56	0.70878
C-1193	10-22-99	1,340	230	--	--	--	--	--	--	--	--	--	--
C-1194	10-22-99	782	100	--	--	--	--	--	--	--	--	--	--
C-1195	10-22-99	565	40	--	--	--	--	--	--	--	--	--	--
C-1197	04-27-00	3,080	710	280	350	420	170	52	12	1.5	-2.1	-0.70	0.70869
C-1198	04-27-00	1,470	220	--	--	--	--	--	--	--	--	--	--
C-1199	05-25-00	969	110	--	--	--	--	--	--	--	--	--	--
C-1200	05-25-00	1,000	100	--	--	--	--	--	--	--	--	--	--
C-1201	04-27-00	3,450	860	--	--	--	--	--	--	--	--	--	--
C-1204	--	7,000e	2,500e	--	--	--	--	--	--	--	--	--	--
C-1205	06-28-00	33,700	14,000	1,800	300	6,600	1,200	940	60	12.7	4.0	0.10	0.70869
C-1212	06-16-00	5,350	1,700	490	220	930	220	131	23	2.7	-3.6	-1.31	0.70847
C-1213	05-18-00	1,770	300	--	--	--	--	--	--	--	--	--	--
C-1215	05-16-00	1,080	150	--	--	--	--	--	--	--	--	--	--
C-1216	05-30-00	924	80	--	--	--	--	--	--	--	--	--	--
C-1217	05-17-00	962	140	--	--	--	--	--	--	--	--	--	--
C-1218	05-30-00	1,780	290	--	--	--	--	--	--	--	--	--	--
C-1219	06-02-00	720	58	--	--	--	--	--	--	--	--	--	--
C-1220	06-02-00	--	36	--	--	--	--	--	--	--	--	--	--
L-581	06-26-00	820	210	--	--	--	--	--	--	--	--	--	--
L-721	04-29-99	441	17	--	--	--	--	--	--	--	--	--	--

Appendix II. Water-quality data (Continued)

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; δ^{2}H, delta deuterium; δ^{18}O, delta oxygen-18; ^{87}Sr/^{86}Sr, ratio of strontium-87 to strontium-86; e, estimated value; --, no data]

Well number	Date	Specific conductance (µS/cm)	Chloride (mg/L)	Sulfate (mg/L)	Bicarbonate (mg/L)	Sodium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Strontium (mg/L)	δ^{2}H (per mill)	δ^{18}O (per mill)	^{87}Sr/^{86}Sr
L-731	03-10-00	588	40	--	--	--	--	--	--	--	--	--	--
L-735	03-24-00	1,470	350	57	150	140	56	58	13	4.1	-3.8	-1.42	0.70826
L-738	04-05-00	1,720	360	110	320	230	76	32	13	1.16	-3.7	-1.03	0.70864
L-742	06-04-00	541	72	--	--	--	--	--	--	--	--	--	--
L-781	04-03-00	2,050	480	--	--	--	--	--	--	--	--	--	--
L-1059	04-19-00	1,720	440	--	--	--	--	--	--	--	--	--	--
L-1110	04-17-00	2,090	500	--	--	--	--	--	--	--	--	--	--
L-1111	05-30-99	1,120	200	--	--	--	--	--	--	--	--	--	--
L-1113	11-09-99	3,550	1,100	--	--	--	--	--	--	--	--	--	--
L-1114	11-17-99	2,070	640	--	--	--	--	--	--	--	--	--	--
L-1116	01-04-00	20,000	180	--	--	--	--	--	--	--	--	--	--
L-1117	11-17-99	790	150	--	--	--	--	--	--	--	--	--	--
L-1121	01-05-00	1,350	280	--	--	--	--	--	--	--	--	--	--
L-1124	01-05-00	911	180	--	--	--	--	--	--	--	--	--	--
L-1136	04-29-99	666	68	--	--	--	--	--	--	--	--	--	--
L-1403	04-28-99	1,110	180	--	--	--	--	--	--	--	--	--	--
L-1456	04-28-99	2,500	460	--	--	--	--	--	--	--	--	--	--
L-1598	10-27-99	1,880	460	--	--	--	--	--	--	--	--	--	--
L-1625	03-08-00	806	82	--	--	--	--	--	--	--	--	--	--
L-1691	04-26-00	775	75	52	320	73	60	22	7.2	0.55	-3.1	-1.09	0.70908
L-1853	01-03-00	1,450	320	--	--	--	--	--	--	--	--	--	--
L-1968	03-08-00	646	56	--	--	--	--	--	--	--	--	--	--
L-1973	06-30-00	781	120	28	290	73	39	37	11	2.2	-3.6	-1.33	0.70843
L-1974	05-01-00	648	90	--	--	--	--	--	--	--	--	--	--
L-1983	01-27-00	743	39	--	--	--	--	--	--	--	--	--	--
L-1993	01-25-00	650	89	--	--	--	--	--	--	--	--	--	--
L-2186	03-07-00	2,470	560	240	250	300	130	55	9.5	--	-4.3	-1.28	--
	07-17-00	--	--	--	--	--	--	--	--	3.7	--	--	0.70806
L-2187	03-07-00	1,760	350	140	270	190	94	41	10	--	-3.1	-1.36	--
	06-09-00	--	--	--	--	--	--	--	--	2.18	--	--	0.70820
L-2193	01-26-00	692	35	--	--	--	--	--	--	--	--	--	--
L-2194	05-28-99	924	79	--	--	--	--	--	--	--	--	--	--
L-2200	03-07-00	2,990	780	240	160	380	120	71	14	--	-5.2	-1.66	--
	06-13-00	--	--	--	--	--	--	--	--	12.3	--	--	0.70783

Appendix II. Water-quality data (Continued)

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; δ^{2}H, delta deuterium; δ^{18}O, delta oxygen-18; ^{87}Sr/^{86}Sr, ratio of strontium-87 to strontium-86; e, estimated value; --, no data]

Well number	Date	Specific conductance (µS/cm)	Chloride (mg/L)	Sulfate (mg/L)	Bicarbonate (mg/L)	Sodium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Strontium (mg/L)	δ^{2}H (per mill)	δ^{18}O (per mill)	^{87}Sr/^{86}Sr
L-2212	11-09-99	2,030	490	--	--	--	--	--	--	--	--	--	--
L-2215	03-09-00	742	46	--	--	--	--	--	--	--	--	--	--
L-2216	01-27-00	1,120	240	--	--	--	--	--	--	--	--	--	--
L-2244	04-19-00	695	100	--	--	--	--	--	--	--	--	--	--
L-2292	02-24-00	3,440	--	--	--	--	--	--	--	--	-5.6	-1.51	--
L-2295	02-26-00	2,390	--	--	--	--	--	--	--	--	-4.1	-1.29	--
L-2308	04-30-99	575	20	--	--	--	--	--	--	--	--	--	--
L-2311	02-24-00	--	--	--	--	--	--	--	--	--	-6.8	-1.64	--
	06-14-00	3,930	1,300	590	150	680	150	120	20	21.6	--	--	0.70781
L-2328	02-24-00	3,970	--	--	--	--	--	--	--	--	-3.8	-1.57	--
L-2435	02-25-00	10,700	--	--	--	--	--	--	--	--	-4.2	-1.36	--
L-2525	02-22-00	--	--	--	--	--	--	--	--	--	-5.6	-1.72	--
	05-26-00	1,880	450	180	160	230	66	61	19	7.9	--	--	0.70795
L-2526	02-23-00	2,500	--	--	--	--	--	--	--	--	-4.0	-1.58	--
L-2527	02-23-00	--	--	--	--	--	--	--	--	--	-4.7	-1.47	--
	05-26-00	5,800	1,700	280	140	850	160	146	27	22.7	--	--	0.70790
L-2528	02-23-00	3,780	--	--	--	--	--	--	--	--	-5.3	-1.54	--
L-2529	02-26-00	--	--	--	--	--	--	--	--	--	-3.9	-1.46	--
	07-18-00	5,940	2,000	430	170	1,100	140	162	38	21.6			0.70787
L-2531	02-25-00	3,080	--	--	--	--	--	--	--	--	-4.2	-1.65	--
L-2549	05-25-00	758	70	--	--	--	--	--	--	--	--	--	--
L-2640	04-19-00	1,060	210	--	--	--	--	--	--	--	--	--	--
L-2641	04-17-00	951	160	--	--	--	--	--	--	--	--	--	--
L-2642	04-19-00	1,460	340	--	--	--	--	--	--	--	--	--	--
L-2643	04-19-00	3,700	980	--	--	--	--	--	--	--	--	--	--
L-2644	04-19-00	3,720	960	--	--	--	--	--	--	--	--	--	--
L-2645	02-22-00	--	--	--	--	--	--	--	--	--	-6.0	-1.49	--
	04-17-00	2,490	660	--	--	--	--	--	--	--	--	--	--
L-2646	11-17-99	613	72	--	--	--	--	--	--	--	--	--	--
L-2700	11-09-99	3,390	1,000	--	--	--	--	--	--	--	--	--	--
L-2701	04-19-00	578	66	--	--	--	--	--	--	--	--	--	--
L-2703	04-17-00	1,670	360	--	--	--	--	--	--	--	--	--	--
L-2820	02-23-00	--	--	--	--	--	--	--	--	--	-5.4	-1.66	--
	06-30-00	2,450	860	58	180	360	100	79	22	10.4	--	--	0.70793

Appendix II. Water-quality data (Continued)

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; δ^2H, delta deuterium; δ^{18}O, delta oxygen-18; ^{87}Sr/^{86}Sr, ratio of strontium-87 to strontium-86; e, estimated value; --, no data]

Well number	Date	Specific conductance (µS/cm)	Chloride (mg/L)	Sulfate (mg/L)	Bicarbonate (mg/L)	Sodium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Strontium (mg/L)	δ^2H (per mill)	δ^{18}O (per mill)	^{87}Sr/^{86}Sr
L-2821	02-23-00	--	--	--	--	--	--	--	--	--	-4.7	-1.75	--
	05-26-00	2,350	610	190	160	320	72	74	19	7.8	--	--	0.70798
L-3203	04-29-99	636	48	--	--	--	--	--	--	--	--	--	--
L-3204	04-29-99	585	11	--	--	--	--	--	--	--	--	--	--
L-3205	04-29-99	2,130	530	--	--	--	--	--	--	--	--	--	--
L-3206	04-29-99	826	83	--	--	--	--	--	--	--	--	--	--
L-3207	04-29-99	1,020	45	--	--	--	--	--	--	--	--	--	--
L-3208	04-29-99	1,150	90	--	--	--	--	--	--	--	--	--	--
L-3213	04-29-99	948	120	--	--	--	--	--	--	--	--	--	--
L-3215	04-29-99	1,160	230	--	--	--	--	--	--	--	--	--	--
L-4820	04-17-00	1,010	180	--	--	--	--	--	--	--	--	--	--
L-5648	10-27-99	1,040	180	--	--	--	--	--	--	--	--	--	--
L-5649	06-29-00	976	200	27	270	66	100	23	4.4	1	-0.4	-0.65	0.70847
L-5664	03-08-00	629	35	--	--	--	--	--	--	--	--	--	--
L-5668	04-29-99	2,230	540	--	--	--	--	--	--	--	--	--	--
L-5673	01-26-00	631	64	--	--	--	--	--	--	--	--	--	--
L-5722	04-30-99	966	100	--	--	--	--	--	--	--	--	--	--
L-5724	04-30-99	1,480	290	--	--	--	--	--	--	--	--	--	--
L-5725	04-24-00	4,910	1,200	--	--	--	--	--	--	--	--	--	--
L-5726	04-30-99	750	74	--	--	--	--	--	--	--	--	--	--
L-5727	05-26-99	6,940	1,900	--	--	--	--	--	--	--	--	--	--
L-5731	04-26-00	836	100	--	--	--	--	--	--	--	--	--	--
L-5745	04-19-00	1,070	140	--	--	--	--	--	--	--	--	--	--
L-5746	04-30-99	585	28	--	--	--	--	--	--	--	--	--	--
L-5747	04-18-00	900	120	--	--	--	--	--	--	--	--	--	--
L-5801	02-26-00	4,340	--	--	--	--	--	--	--	--	-3.9	-1.51	--
L-5804	05-11-00	950	95	39	420	64	130	12	4.6	0.63	-6.7	-1.62	0.70893
L-5805	03-23-00	6,220	1,600	680	120	1,000	110	110	87	14	-3.3	-1.17	0.70795
L-5806	04-25-00	821	90	--	--	--	--	--	--	--	--	--	--
L-5808	03-21-00	1,580	380	--	--	--	--	--	--	--	--	--	--
L-5815	08-02-99	1,700	340	--	--	--	--	--	--	--	--	--	--
L-5819	04-04-00	2,880	770	300	260	410	130	71	17	8	-5.6	-1.52	0.70792
L-5820	04-05-00	3,160	900	190	240	410	150	75	17	6	-5.1	-1.45	0.70807
L-5821	05-03-00	3,730	1,000	--	--	--	--	--	--	--	--	--	--

Appendix II. Water-quality data (Continued)

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; δ^{2}H, delta deuterium; δ^{18}O, delta oxygen-18; ^{87}Sr/^{86}Sr, ratio of strontium-87 to strontium-86; e, estimated value; --, no data]

Well number	Date	Specific conductance (µS/cm)	Chloride (mg/L)	Sulfate (mg/L)	Bicarbonate (mg/L)	Sodium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Strontium (mg/L)	δ^{2}H (per mill)	δ^{18}O (per mill)	^{87}Sr/^{86}Sr
L-5822	05-05-00	1,170	180	--	--	--	--	--	--	--	--	--	--
L-5823	04-04-00	1,210	220	--	--	--	--	--	--	--	--	--	--
L-5824	04-04-00	1,820	450	82	280	170	120	49	10	1.8	-3.6	-1.26	0.70863
L-5825	03-20-00	4,700	1,400	560	210	790	130	124	33	7.8	-3.7	-1.28	0.70813
L-5826	04-27-00	745	140	--	--	--	--	--	--	--	--	--	--
L-5827	04-05-00	1,390	200	--	--	--	--	--	--	--	--	--	--
L-5828	03-21-00	5,700	1,500	570	190	840	150	133	37	18.2	-4.9	-1.42	0.70782
L-5829	01-05-00	1,460	360	--	--	--	--	--	--	--	--	--	--
L-5830	01-06-00	2,780	880	--	--	--	--	--	--	--	--	--	--
L-5831	03-23-00	1,400	310	61	260	160	55	47	12	2.1	-2.2	-1.61	0.70856
L-5832	01-04-00	800	62	--	--	--	--	--	--	--	--	--	--
L-5833	01-04-00	800	88	--	--	--	--	--	--	--	--	--	--
L-5834	01-06-00	1,140	240	--	--	--	--	--	--	--	--	--	--
L-5835	03-24-00	2,650	770	100	240	370	66	90	22	5.2	-4.1	-1.68	0.70839
L-5836	03-23-00	1,520	350	81	240	170	56	51	14	3.1	-4.2	-1.39	0.70844
L-5837	03-24-00	1,070	210	18	250	95	63	33	5.5	1.64	-3.3	-1.45	0.70847
L-5838	03-22-00	3,250	870	220	230	430	82	97	26	6.6	-3.4	-1.47	0.70817
L-5839	04-20-99	4,160	1,200	--	--	--	--	--	--	--	--	--	--
L-5840	07-17-00	460	46	--	--	--	--	--	--	--	--	--	--
L-5841	12-15-99	2,680	820	--	--	--	--	--	--	--	--	--	--
L-5842	05-10-00	937	120	44	320	70	94	17	2.4	0.51	-0.7	-0.19	0.70877
L-5843	03-20-00	1,260	270	27	250	110	63	43	10	1.82	-1.6	-1.43	0.70866
L-5844	03-21-00	624	55	--	--	--	--	--	--	--	--	--	--
L-5845	03-20-00	3,610	1,000	--	--	--	--	--	--	--	--	--	--
L-5846	05-09-00	810	95	--	--	--	--	--	--	--	--	--	--
L-5847	04-25-00	4,300	1,300	--	--	--	--	--	--	--	--	--	--
L-5848	04-26-00	2,970	700	--	--	--	--	--	--	--	--	--	--
L-5849	04-26-00	859	100	--	--	--	--	--	--	--	--	--	--
L-5850	05-18-00	862	130	40	280	62	53	40	3.8	2	-5.8	-1.73	0.70839
L-5866	04-25-00	822	110	--	--	--	--	--	--	--	--	--	--
L-5867	04-25-00	1,650	410	--	--	--	--	--	--	--	--	--	--
L-5868	05-05-00	1,080	80	--	--	--	--	--	--	--	--	--	--
L-5869	10-28-99	632	110	--	--	--	--	--	--	--	--	--	--
L-5870	05-31-00	3,200	840	--	--	--	--	--	--	--	--	--	--