Assessment of Hydrogeologic Conditions with Emphasis on Water Quality and Wastewater Injection, Southwest Sarasota and West Charlotte Counties, Florida

United States Geological Survey Water-Supply Paper 2371

Prepared in cooperation with the Southwest Florida Water Management District

U.S. DEPARTMENT OF THE INTERIOR
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Assessment of Hydrogeologic Conditions with Emphasis on Water Quality and Wastewater Injection, Southwest Sarasota and West Charlotte Counties, Florida

By C.B. HUTCHINSON

Prepared in cooperation with the Southwest
Florida Water Management District

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ABBREVIATIONS AND CONVERSION FACTORS

For readers who wish to convert measurements from inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
square foot per day (ft^2/d)	0.0929	square meter per day (m^2/d)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	0.0283	cubic meter (m^3)
cubic foot per day (ft^3/d)	0.0283	cubic meter per day (m^3/d)
square foot per pound (ft^2/lb)	1.007×10^{-6}	square meter per Newton (m^2/N)
gallon (gal)	3.785	liter (L)
gallon per minute (gal/min)	5.45	cubic meter per day (m^3/d)
gallon per day (gal/d)	3.785	liter per day (L/d)
gallon per minute (gal/min)	0.0631	liter per second (L/s)
million gallons per day (Mgal/d)	0.4381	cubic meter per second (m^3/s)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
pound per square foot (lb/ft^2)	0.0479	kilopascal (kPa)
pound per cubic foot (lb/ft^3)	0.0016	gram per cubic centimeter (g/cm^3)
foot per foot (ft/ft)	1.000	meter per meter (m/m)
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter [(m/d)/m]

ALTITUDE DATUM

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

ADDITIONAL ABBREVIATIONS

ROMP = Regional Observation and Monitor-Well Program
QWIP = Quality of Water Improvement Program
cP = centipoise
mg/L = milligrams per liter
pCi/L = picocuries per liter
Pt-Co = platinum-cobalt
FDER = Florida Department of Environmental Regulation
USGS = U.S. Geological Survey
HST3D = Heat and Solute Transport in Three Dimensions
FBG = Florida Bureau of Geology
SWFWMD = Southwest Florida Water Management District

Assessment of Hydrogeologic Conditions with Emphasis on Water Quality and Wastewater Injection, Southwest Sarasota and West Charlotte Counties, Florida

By C.B. Hutchinson

Abstract

The 250-square-mile area of southwest Sarasota and west Charlotte Counties is underlain by a complex hydrogeologic system having diverse ground-water quality. The surficial and intermediate aquifer systems and the Upper Floridan aquifer of the Floridan aquifer system contain six separate aquifers, or permeable zones, and have a total thickness of about 2,000 feet. Water in the clastic surficial aquifer system is potable and is tapped by hundreds of shallow, low-yielding supply wells. Water in the mixed clastic and carbonate intermediate aquifer system is potable in the upper part, but in the lower part, because of increasing salinity, it is used primarily for reverse-osmosis desalinization feed water and irrigation. Within the Upper Floridan aquifer, limestone and dolomite of the Suwannee permeable zone are tapped by irrigation and reverse-osmosis supply wells. The underlying, less permeable limestone of the Suwannee-Ocala semiconfining unit generally encompasses the transition zone between freshwater and very saline water. Interbedded limestone and dolomite of the Ocala-Avon Park moderately permeable zone and Avon Park highly permeable zone compose the deep, very saline injection zone.

Potential ground-water contamination problems include flooding by storm tides, upward movement of saline water toward pumping centers by natural and induced leakage or through improperly constructed and abandoned wells, and lateral and vertical movement of treated sewage and reverse-osmosis wastewater injected into deep zones. Effects of flooding are evident in coastal areas where vertical layering of fresh and saline waters is observed. Approximately 100 uncontrolled flowing artesian wells that have interaquifer flow rates as high as 350 gallons per minute have been located and scheduled for plugging by the Southwest Florida Water Management District in an attempt to improve ground-water quality of the shallow aquifers. Because each aquifer or permeable zone has unique head and water-quality characteristics, construction of single-zone wells would eliminate cross-contamination and borehole interflow. Such a program, when combined with the plugging of shallow-cased wells having long open-hole intervals connecting multiple zones, would safeguard ground-water resources in the study area.

The study area encompasses seven wastewater injection sites that have a projected capacity for injecting 29 million gallons per day into the zone 1,100 to 2,050 feet below land surface. There are six additional sites within 20 miles. The first well began injecting reverse-osmosis wastewater in 1984, and since then, other wells have been drilled and permitted for injection of treated sewage. A numerical model was used to evaluate injection-well design and potential for movement of injected wastewater within the hydrogeologic framework.

The numerical model was used to simulate injection through a representative well at a rate of 1 million gallons per day for 10 years. In this simulation, a convection cell developed around the injection well with the bouyant fresh injectant rising to form a lens within the injection zone below the lower Suwannee-Ocala semiconfining unit. Around an ideal, fully penetrating well cased 50 feet into the injection zone and open from a depth of 1,150 feet to 2,050 feet, simulations show that the injectant moves upward to a depth of 940 feet, forms a lens about 600 feet thick, and spreads radially outward to a distance of about 2,300 feet after 10 years. Comparison simulations of injection through wells having open depth intervals of 1,150 to 1,400 feet and 1,450 to 2,050 feet demonstrate that such changes in well construction have little effect on the areal spread of the injectant lens or the rate of upward movement. Simulations also indicate that reverse-osmosis wastewater injected beneath a supply well field, where water levels above the semiconfining unit are lowered 20 feet by pumping, would move upward after 10 years to a depth of 860 feet, or about 80 feet higher than at a site having no pumping stresses. Areal extrapolation of various pumping scenarios indicates that about 7 percent of the study area would be underlain by injected wastewater after 10 years of injection at the maximum projected capacity. Observation wells are needed in the upper part of the injection zone and within 2,000 feet of the injection well if the movement of the injectant within the first 10 years of operation is to be monitored.

INTRODUCTION

Coastal Sarasota and Charlotte Counties are being urbanized. The increased demands for potable water have produced a need for suitable methods of disposal of large volumes of wastewater. Because of the flat landscape and lack of suitable surface-water impoundment areas, ground water is the sole source of supply. No scarcity of supply exists; however, concentrations of sulfate and chloride in the ground water are undesirably high. In 1967, the city of Sarasota alleviated its water-quality problems by transporting water from a well field 15 mi east of the city. Problems of obtaining water supplies of acceptable quality persist in southwest Sarasota and west Charlotte Counties. This study focuses on that 250-mi^2 area (fig. 1).

Throughout this report, inferences are made concerning the chemical quality of water. The terminology used to describe water quality is modified slightly from a classification system used by Robingrove and others (1958, p. 3), as follows:

Class	Dissolved solids (mg/L)
Freshwater	0 to 500
Slightly saline	500 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 36,000
Briny	More than 36,000

The classification system considers freshwater to be that which meets the dissolved-solids concentration limit for potable water recommended by the Florida Department of Environmental Regulation (FDER). Slightly saline water is nonpotable, but it may be suitable for irrigation. Moderately saline water is suitable for desalinization. Very saline water is considered unusable, and the FDER allows injection of wastewater into some zones where very saline water is confined. Briny water does not occur in the study area, but it is classed as having a salinity greater than that of seawater.

The study area contains a complex hydrogeologic system. Water quality varies laterally and is stratified. Six water-bearing aquifers or permeable zones are recognized. Only the upper three aquifers contain potable water, although they too are contaminated by saline water in some areas. Contamination is caused primarily by inundation by storm tides and upward leakage of chloride- and sulfate-rich water from deep zones through semiconfining units or through uncased or improperly constructed wells that tap multiple zones.

Ten municipal water-supply systems in the study area provided about 11 Mgal/d of freshwater in 1985. The water is withdrawn from more than 200 wells, generally less than 200 ft deep, that have an average yield of less than 40 gal/min. Yields of most supply systems are inadequate to meet projected demands. Consequently, some communities have built reverse-osmosis water-treatment facilities to upgrade slightly saline ground water from deep aquifers to potable quality. This water supplements and is usually blended with fresh ground water from shallow aquifers.

Several communities have been issued permits by the FDER for testing the feasibility of injecting wastewater, including reverse-osmosis wastewater and treated sewage, into zones below those containing potable water. Suitable injection zones are poorly defined, and the effects of injection are not well understood. A potential exists for degrading the water quality in zones above the injection zone as a result of wastewater injection.

PURPOSE AND SCOPE

This report presents the results of a study to assess the hydrogeologic conditions and alternative water resources management measures that might be used to maintain or improve ground-water quality in southwest Sarasota and west Charlotte Counties. The study has three specific objectives:

1. Define the hydrogeologic framework,
2. Describe ground-water quality and assess the problem of uncontrolled flowing artesian wells, and
3. Demonstrate the usefulness of a solute-transport model as a tool for understanding the effects of wastewater injection on the hydrologic system.

The study was conducted from October 1983 through September 1988 in cooperation with the Southwest Florida Water Management District. The study area encompasses a strip 8 mi by 30 mi along the gulf coast of Sarasota and Charlotte Counties, including the towns of Venice and Englewood (fig. 1). Data were obtained from published and unpublished reports and from files of the U.S. Geological Survey (USGS). The Southwest Florida Water Management District provided data through its Regional Observation and Monitor-Well Program (ROMP) and Quality of Water Improvement Program (QWIP). Where data were lacking or incomplete, field tests were made to determine aquifer characteristics and water quality.

Aquifer hydraulic properties and water-quality were estimated by using existing information. These data were supplemented with data from tests at three ROMP sites that were constructed during the study period. Flow-meter tests and geophysical logs on 15 wells open to multiple water-bearing zones were interpreted to assess the effects of borehole interflow.

A conceptual model was developed to provide an understanding of underground injection and solute transport. The heat and solute-transport (HST3D) model was used to simulate a typical injection-well system described in the conceptual model. The model proved to be a helpful tool for understanding the radial and vertical movement of injected

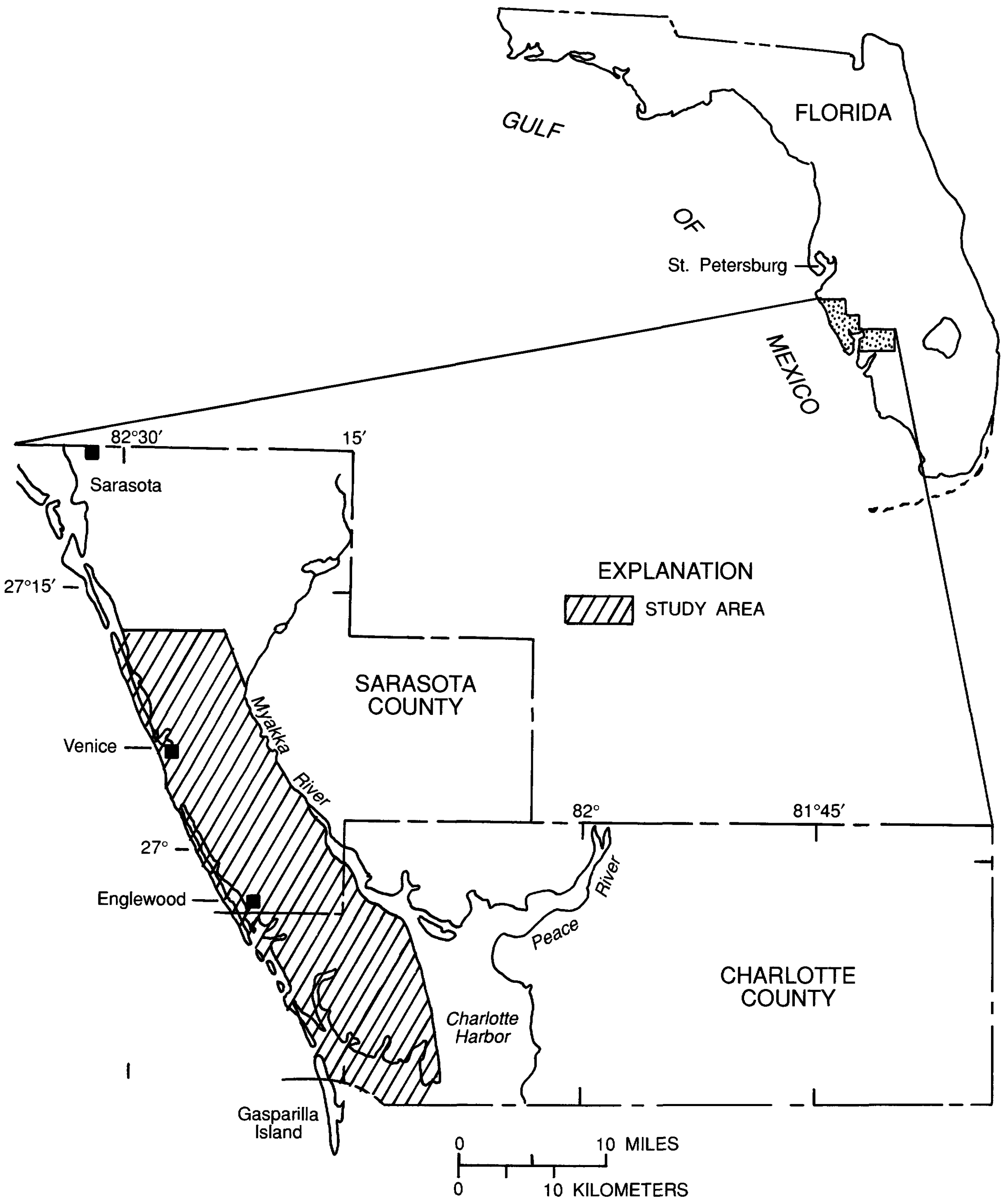


Figure 1. Location of the study area in west-central Florida.

sewage and reverse-osmosis wastewater around a single injection well that is representative of conditions in the study area. Predictive simulations provided insight for developing approaches to ground-water monitoring.

PREVIOUS INVESTIGATIONS

The first comprehensive studies of water resources in Sarasota County were performed by Stringfield (1933a,b). Those early reports warned of potential negative effects of developing additional water supplies in the county and documented flow rates of several artesian wells. Sutcliffe (1975, p. 51), in the first detailed appraisal of water resources in Charlotte County, recommended piping freshwater from the eastern part of the county to coastal urban areas. Joyner and Sutcliffe (1976) differentiated five artesian zones within the Myakka River basin. Wolansky (1983) lumped these zones into three aquifer units and mapped the head and water quality in each unit. Sutcliffe and Thompson (1983) tabulated water use for the Venice-Englewood area. Reports on test-injection wells described hydrogeologic conditions in central Sarasota County (Post, Buckley, Schuh, and Jernigan, Inc., 1984; 1989; Geraghty and Miller, Inc., 1985; Law Environmental, Inc., 1989), Englewood and North Port (CH2M Hill, Inc., 1986, 1988), and Gasparilla Island (Geraghty and Miller, Inc., 1986).

Other studies that aided this investigation include an evaluation of high transmissivity zones for liquid storage (Puri and Winston, 1974), a tabulation of uncontrolled flowing artesian wells in Florida (Healy, 1978), maps of zones widely used for subsurface injection (Miller, 1979; Wolansky and others, 1980), and aquifer properties that control movement of injected wastewater derived from studies in Pinellas County, 60 mi north of the study area (Hickey, 1982; GeoTrans, Inc., 1985). Supplementary data from the Southwest Florida Water Management District's ROMP and QWIP programs were provided through coordinator Kim Preedom.

DESCRIPTION OF THE STUDY AREA

Physiography and Drainage

Southwest Sarasota and west Charlotte Counties lie in the mid-Florida physiographic zone that includes the gulf coastal lowlands, gulf coastal lagoons, and gulf barrier chain subdivisions (White, 1970). The gulf coastal lowlands are a broad, gently sloping marine plain, and the gulf coastal lagoons and gulf barrier chain are erosional remnants of coastal prominences between estuaries. The lowlands are characterized by broad flatlands that have many sloughs, swampy areas, and creeks. Much of the area has been drained by canals and is platted for future development.

The study area is a nearly flat peninsula of land between the Myakka River and the Gulf of Mexico. The maximum tidal range unaffected by storms is about 3 ft at Venice on the gulf coast, 2.5 ft at the mouth of the Myakka River, and 2 ft at a gage 13 mi upstream. Land surface is less than 20 ft above sea level.

About 50 percent of the land has been mapped as flood prone on USGS 1:24,000 scale Flood Prone Area quadrangle maps. Figure 2 shows major areas that are statistically prone to inundation one time in 100 yr. The drainage canal system and excavation of the Intracoastal Waterway at Venice have increased the potential for saltwater intrusion (Clark, 1964). The potential for intrusion is greatest during hurricanes when tides may rise as high as 6 ft above normal, as shown by the hydrograph of the Myakka River at El Jobean, Fla., during Hurricane Elena in 1985 (fig. 2). Evidence of past inundation was observed during drilling and subsequent water-quality analyses at two coastal ROMP test-drilling sites where upper and lower zones of saline water "sandwich" a relatively fresh zone.

Water Budget

A water budget is a quantitative accounting of the water entering or leaving a hydrologic system for a specific time period. A generalized water budget for the Venice-Englewood area includes the following inputs and outputs:

Inputs	Outputs
Rainfall (R)	Evapotranspiration (ET)
Ground-water inflow (GI)	Ground-water outflow (GO)
Stream inflow (SI)	Stream outflow (SO)
Sewage inflow (SEW)	Pumpage (P)

When the hydrologic system is in equilibrium, inputs equal outputs with no change in ground-water storage. Wolansky (1983) developed the following general water budget for the Sarasota-Port Charlotte drainage area, with rates in inches per year.

$$R + GI + SI + SEW \simeq ET + GO + SO + P$$
$$51 + 1.2 + 0 + 0.3 \simeq 38 + 0.7 + 12.5 + 1.1$$

Pumpage, ground-water inflow, ground-water outflow, and sewage inflow are relatively small parts of the total water budget. Evapotranspiration and streamflow are major outflows of freshwater that are difficult to harness for man's use. Capture of some of the water taken up by evapotranspiration may be possible where the water table in the surficial aquifer is lowered by pumping from a network of many low-yielding wells. The flat landscape of the study area is not suitable for impoundment of streams or diversion of surface water.

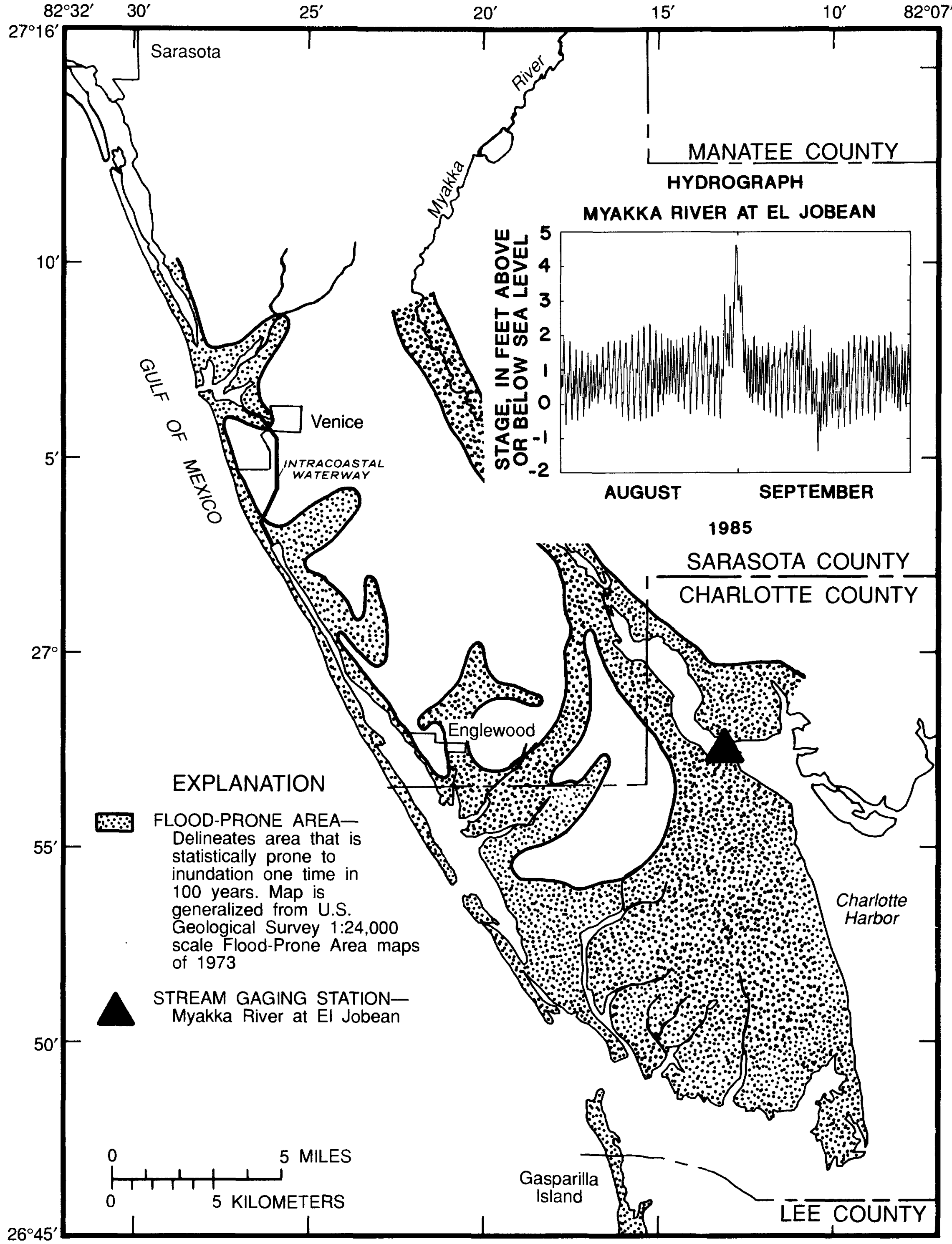


Figure 2. Flood-prone areas.

HISTORY OF WATER-RESOURCES DEVELOPMENT

Irrigation

Hundreds of wells have been drilled in the study area for a variety of purposes. During the period from 1900 to the early 1950's, many naturally flowing wells were drilled to obtain artesian (flowing) water for irrigation and stock watering. Stringfield (1933a, p. 148) reported that, in 1931, Venice Farms, a 6-mi^2 truck farm just east of Venice, had about 45 wells that were from 300 to 475 ft deep. Wells were usually cased to a depth of about 60 ft. Other major irrigation centers that had similarly constructed wells were on the east side of the Charlotte County peninsula near the mouth of the Myakka River. As urbanization replaced agriculture, many irrigation wells were simply abandoned rather than plugged.

Well-drilling regulations adopted by Sarasota County in the 1970's control the use of water and determine the aquifer from which water is to be withdrawn. The regulations require that (1) all wells that penetrate consolidated deposits must be cased with pipe having a minimum diameter of 3 in. and (2) all irrigation or industrial wells that yield more than 50 gal/min or have pumps greater than 1.5 horsepower must be cased to at least 300 ft below land surface. Such regulations help prevent contamination of the best quality water, which is within 200 ft of land surface, for domestic use and public water supply.

City of Venice

In 1931, the water supply of Venice was furnished by three shallow wells, all 135 ft deep, and the water had to be aerated to remove hydrogen sulfide (Stringfield, 1933a, p. 145). By 1963, 32 shallow wells had been installed. The quality of the raw water supply was marginal in that the average dissolved-solids concentration was 770 mg/L (Smally, Wellford, and Nalven, Inc., 1963, p. 52). To stay abreast of the rapidly increasing population, the city increased the number of wells to about 65 by 1975 and provided additional elevated storage of treated water (Sutcliffe and Thompson, 1983, p. 32). Increased pumping from closely spaced wells led to degradation of the quality of water, and supplies had to be augmented by low-pressure reverse-osmosis treatment of slightly saline ground water from a deeper source. By 1985, about 2 Mgal/d of raw water from five deep wells was being desalinated, and 1 Mgal/d of product water was being blended with 2.5 Mgal/d of shallow well water (James Hogan, City of Venice, oral commun., 1985). Specific capacities in approximately 30 shallow production wells declined during a short, relatively dry period in 1985; subsequently, the city drilled a sixth reverse-osmosis supply well.

The average dissolved-solids concentration of the composite inflow of well water to the reverse-osmosis plant increased from about 2,100 to 2,700 mg/L between 1984 and 1989, as shown in figure 3A. During the same period, the average concentration of composite water from the shallow supply wells increased from about 800 to 950 mg/L. The increasing salinity apparently is due to upconing of moderately saline water beneath the city's well fields.

City of Englewood

Englewood chronically has lacked a reliable supply of water of acceptable quality. Contamination is common, and historically, supplies have been drawn from very shallow wells that are vulnerable to pollution and seasonal water-level fluctuations. The first 20 supply wells, 40–80 ft deep, supplied a demand of 0.3 Mgal/d in 1964. By 1975, 43 production wells, clustered in 2 well fields, supplied an average of 1 Mgal/d and had a dissolved-solids concentration that fluctuated between 500 and 600 mg/L (Sutcliffe and Thompson, 1983). A third well field, 3 mi north of the city, began pumping about 1980. Shortly thereafter, concerns were raised over the potential for contamination of the new well field by water from nine abandoned flowing wells on adjoining property. The abandoned wells are scheduled to be plugged. By 1985, a high-pressure reverse-osmosis desalinization facility, nine supply wells that averaged 425 ft deep, and an 1,800-ft-deep injection well for disposal of reverse-osmosis wastewater were constructed. The wastewater is a very saline concentrate that has approximately double the dissolved-solids concentration of the influent well water. The reverse-osmosis plant has a design capacity of 3.6 Mgal/d of freshwater production. The injection well was installed to meet the FDER requirements for safe disposal of reverse-osmosis wastewater that contains high levels of radium.

Figure 3B illustrates trends in water quality at the Englewood injection site, which began operation in 1987. There has been a general rise in the dissolved-solids concentration of the reverse-osmosis wastewater from about 14,000 mg/L in 1987 to 19,000 mg/L in 1989. This indicates that there has also been an increase in the concentration of reverse-osmosis feed water pumped from the nine supply wells. This increase has been attributed to wells having progressively higher dissolved-solids concentrations coming online as demand for water increased (Michael Micheau, CH2M Hill, Inc., oral commun., 1989). Concentrations in reverse-osmosis supply well RO–1 and the monitor well MW–1 above the injection zone have not changed significantly.

Private Water-Supply Systems

In addition to the cities of Venice and Englewood, there are about 20 small developments that had private water-supply systems installed after about 1960 (table 1 and fig. 4). Daily capacities range from 500 to 1,152,000 gal. Freshwater-producing

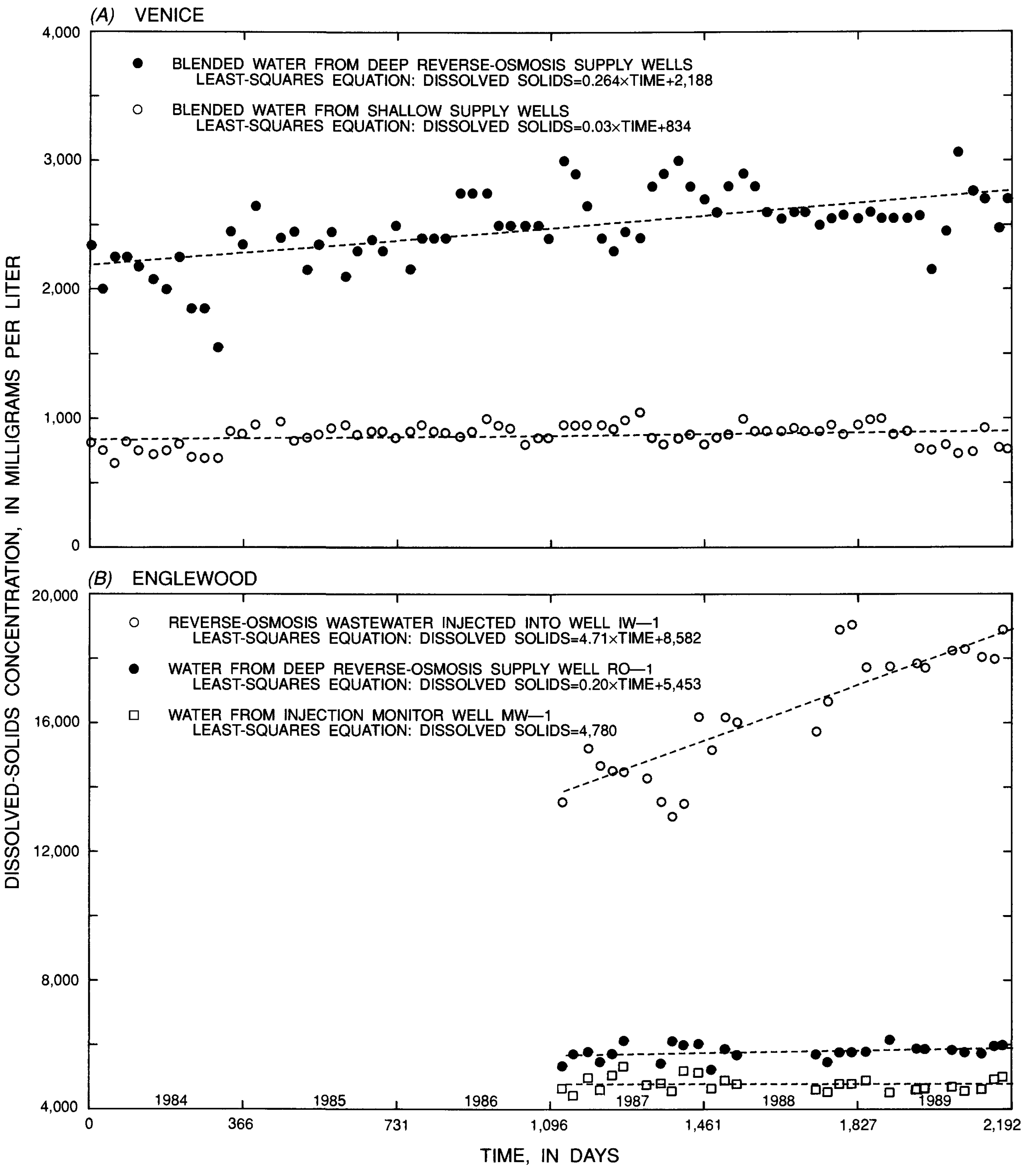


Figure 3. Trends in water quality at Venice (*A*) and Englewood (*B*).

Table 1. Water-supply systems in southwest Sarasota and west Charlotte Counties

[gal/d, gallon per day; mg/L, milligrams per liter; RO, reverse osmosis; – –, no data]

Name	System capacity (gal/d)	Number of supply wells	Range casing/depth (ft)	Range in dissolved solids (mg/L)
Gasparilla Island	130,400	32	24/27–25/32	400–650
Bay Lake Estates	40,000	3RO	44/70–44/263	1,470–2,516
Circlewoods	240,000	4	57/130–77/130	406–639
Gulf View Estates	500	1	82/115	320
Fairwinds Condominium	144,000	2RO	– –	1,470–1,792
Florida Pines	2,000	1	46/133	595
Japanese Gardens	72,000	3	50/110–50/234	584–750
Kings Gate Club	30,000	2RO	40/208–40/215	1,718–2,040
Lake Village	75,000	2RO	90/93–93/96	1,672
Lyons Cove Condominium	6,000	1RO	– –	2,820
Myakka Trailer Park	17,000	1	– –	456
Palm and Pines Trailer Park	13,500	2RO	60/98	2,122
Plantation	1,152,000	2RO	245/380–247/380	– –
Sorrento Shores	300,000	4RO	– –	– –
Southbay Utility	205,000	4RO	– –/450	2,149
Spanish Lakes	200,000	3RO	65/95–70/160	636
Terra Cove	50,000	1RO	48/70	1,605
Venice Ranch	17,280	2RO	60/80–60/90	476–1,680
Venice	2,500,000	29	36/46–88/150	900
	5,500,000 (55 percent recovery)[1]	6RO	203/250–202/650	2,500
Venice Gardens	1,238,000	93	41/169–67.5/209	310–720
	2,500,000 (50 percent recovery)	3RO	240/380–240/500	1,140–1,260
Englewood	2,200,000	55	20/40–49/92	400
	2,000,000 70 percent recovery)	9RO	210/374–263/430	– –
Rotunda West	200,000	9	20/28	500
	500,000	2RO	60/140	9,000

[1] Of the water pumped for reverse-osmosis plant feed water, 55 percent is desalinated and pumped into the distribution system; 45 percent has increased salinity and is pumped to waste.

wells are generally less than 150 ft deep. Freshwater produced by many systems is blended with desalinated water from deeper reverse-osmosis supply wells.

Class I Injection Wells

Eight class I injection wells for disposal of wastewaer were in operation in 1989 in Sarasota, Charlotte, and Lee Counties, in and adjacent to the study area, and five more are proposed or under construction (fig. 5 and table 2). Class I wells are used for disposal of liquid wastes from sewage-treatment plants and reverse-osmosis desalination systems. Because of the cost of advanced wastewater treatment, the preferred alternative is deep-well injection, whereby secondary treated (aerated, filtered, and chlorinated) sewage and untreated radium-rich reverse-osmosis wastewater are injected into highly permeablesaltwater-bearing zones deep in the Floridan aquifer system. Because the FDER strictly monitors and controls injection-well systems, some site-specific hydrogeologic information is available for a regional assessment of water quality and aquifer properties.

The first injection well in the study area went online in 1984 at the Plantation residential development. Since then, wells at Venice Gardens, Englewood, and North Port became operational (fig. 5). Other proposed wells in the study area, or in adjacent Lee County that have potential for affecting the area, are listed in table 2. The estimated total capacity of the seven existing and proposed injection-well systems in the study area is about 29 Mgal/d. Six other proposed sites north, west, and south of the study area are close enough that injection at these sites may affect the study area. Injection rates are expected to increase substantially as growth continues along the gulf coast.

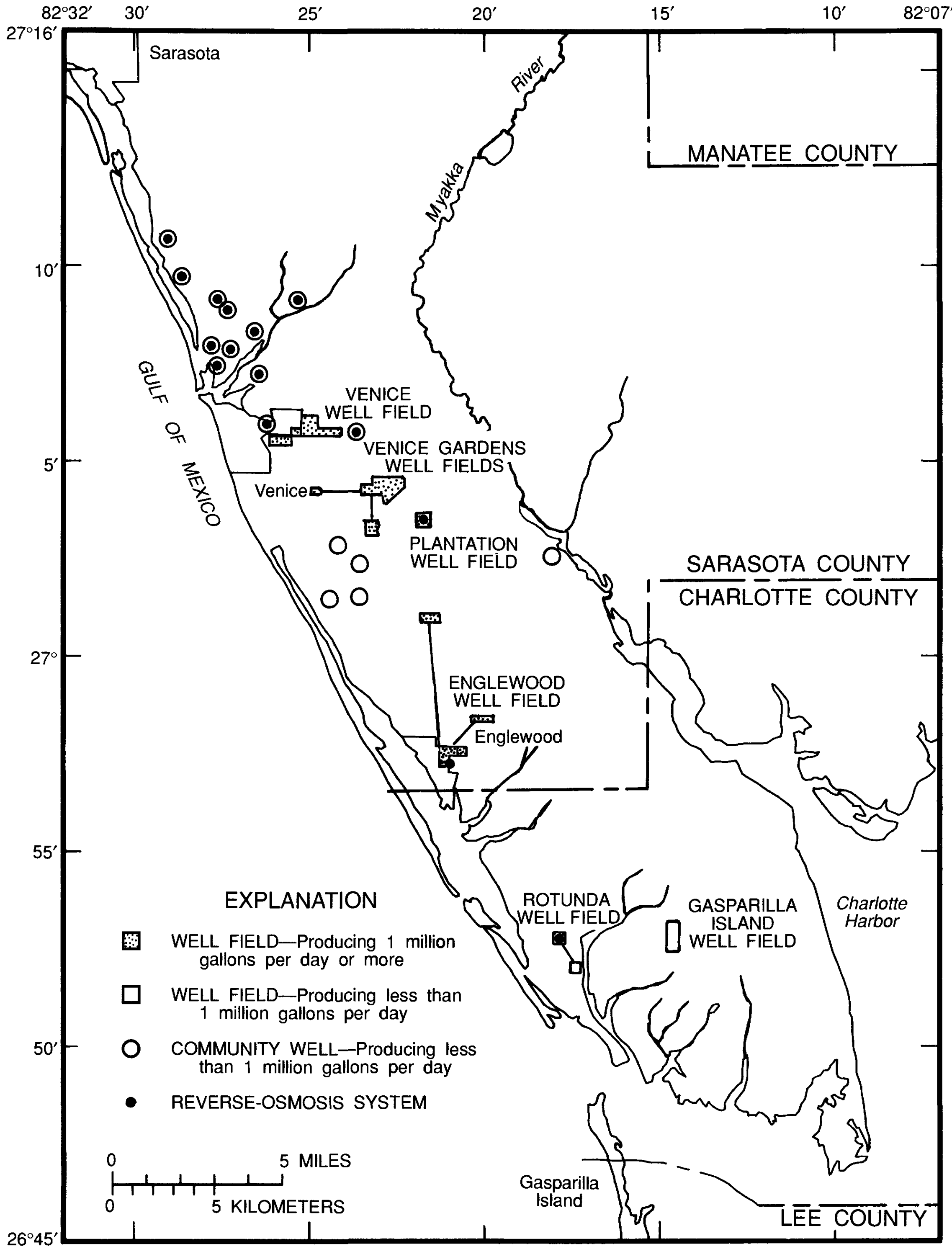


Figure 4. Community water systems.

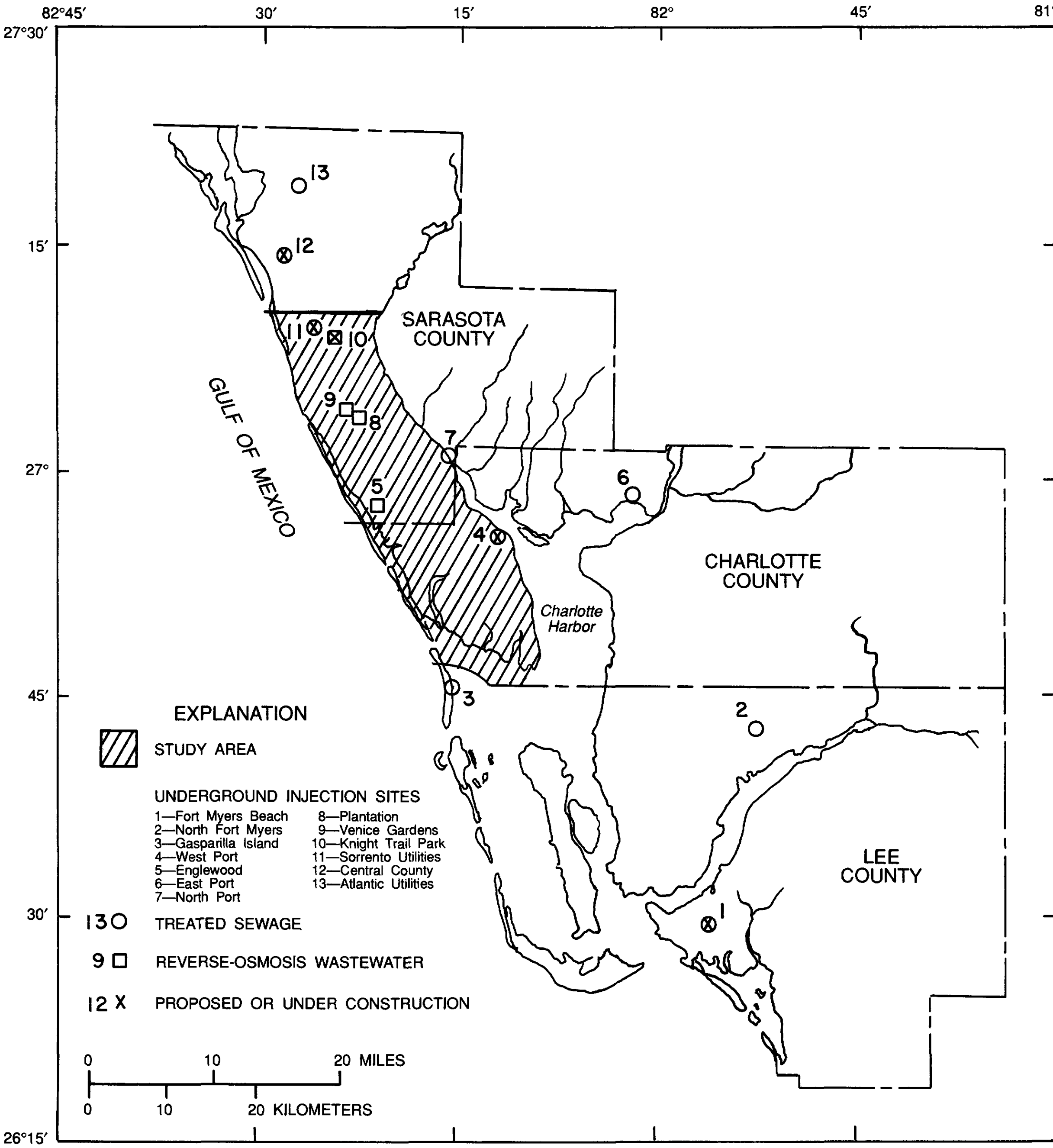


Figure 5. Class I injection-well sites in Sarasota, Charlotte, and Lee Counties.

Observation Wells

The observation-well network used in this study contains 135 wells (fig. 6 and table 3). Data from two springs were used to augment the well network data. Data from the network were used to prepare water-level maps, define the hydrogeologic framework, evaluate ground-water quality, and estimate hydraulic properties of the aquifer systems. Several sites contain well clusters of discrete-zone observation wells that provide information on the vertical distribution of head and water quality.

The first systematic drilling and testing program was undertaken by the USGS in 1962 (Sutcliffe and Joyner, 1968). Four test wells were drilled within the study area to collect hydrogeologic data, including:

1. Hydraulic head of each aquifer penetrated,
2. Chemical quality of water from each aquifer,
3. Materials penetrated during drilling,
4. Yield of each aquifer penetrated, and
5. Geophysical logs for each well at completed depths.

In the early 1980's, several test wells were drilled within the Englewood well field, and multizone observation

Table 2. Class I injection wells in Sarasota, Charlotte, and Lee Counties

[in., inch; Mgal/d, million gallons per day; RO, reverse osmosis; – –, no data]

Map no.[1]	Name	Casing Diameter (in.)	Casing Depth (ft)	Well depth (ft)	Capacity (Mgal/d) Current[2]	Capacity (Mgal/d) Projected	Injectant
1	Fort Myers Beach[3] (proposed).					9	Sewage.
2	North Fort Myers[3]	12	2,340	2,600	4	4	Sewage.
3	Gasparilla Island[3]	6	1,702	1,926	.3	.8	Sewage.
4	West Port (proposed)					14	Sewage.
5	Englewood	10.75	1,040	1,800	.5	1.6	RO reject.
6	East Port[3]	16	1,575	2,424	1	20.5	Sewage.
7	North Port	14	1,100	3,200	3.5	5	Sewage.
8	Plantation	8	1,102	1,605	.8	.8	RO reject.
9	Venice Gardens	8	1,388	1,705	1.8	1.8	RO reject.
10	Knight Trail Park (under construction 1989).	– –	– –	– –	– –	2.6	RO reject.
11	Sorrento Utilities (proposed).	– –	– –	– –	– –	3	Sewage.
12	Central County Utilities[3] (proposed).	– –	– –	– –	– –	8	Sewage.
13	Atlantic Utilities[3]	12	1,902	1,480	1.2	1.2	Sewage.
	Total				13.1	72.3	
	Total in study area				6.6	28.8	

[1]Map numbers are keyed to well locations in figure 5.

[2]1987.

[3]Outside study area, as defined in figures 1 and 5.

wells were installed at four ROMP sites by the Southwest Florida Water Management District. The USGS measures water levels in 33 wells within the study area. Figure 7 shows the observation wells at ROMP TR5–2. Towers were constructed about 25 ft above land surface that would allow the recording of the contained artesian head using conventional equipment. Complementing this network is at least one observation well that is open to an interval above the injection zone at each wastewater-injection site.

HYDROGEOLOGIC FRAMEWORK

Water-bearing formations in west-central Florida consist of Tertiary limestone and dolomite and Quaternary marine and nonmarine clastics. The hydrogeologic framework depicted in table 4 comprises the surficial, intermediate, and Floridan aquifer systems. Each system contains one or more permeable zones separated by low-permeability semiconfining units. Upper zones are utilized for production of freshwater for municipal supply and irrigation. Lower zones contain very saline water and are a repository for injected wastewaters, including treated sewage and reverse-osmosis wastewater.

Data from test wells and published reports (table 5 and fig. 8) were used to delineate hydrogeologic units in a wedge of deposits that total about 1,700 ft thick at the Atlantic Utilities injection test site in the northern part of the study area and 2,400 ft thick at the Gasparilla Island well in the southern part. Hydrogeologic units were identified by using geophysical and lithologic logs as follows:

1. Top of the surficial aquifer system is land surface.
2. Top of the intermediate aquifer system is based on the first observance of areally continuous clay or the shallowest large "kick" on a gamma-ray log.
3. Top of the Upper Floridan aquifer occurs where thick, relatively pure limestone is encountered and gamma-ray activity subsides.
4. Top of the Suwannee-Ocala semiconfining unit occurs below the base of a dolomitic limestone that is distinguished by high activity on gamma-ray logs.
5. Top of the Ocala-Avon Park moderately permeable zone is based on the presence of transmissive intervals identified in test injection wells.

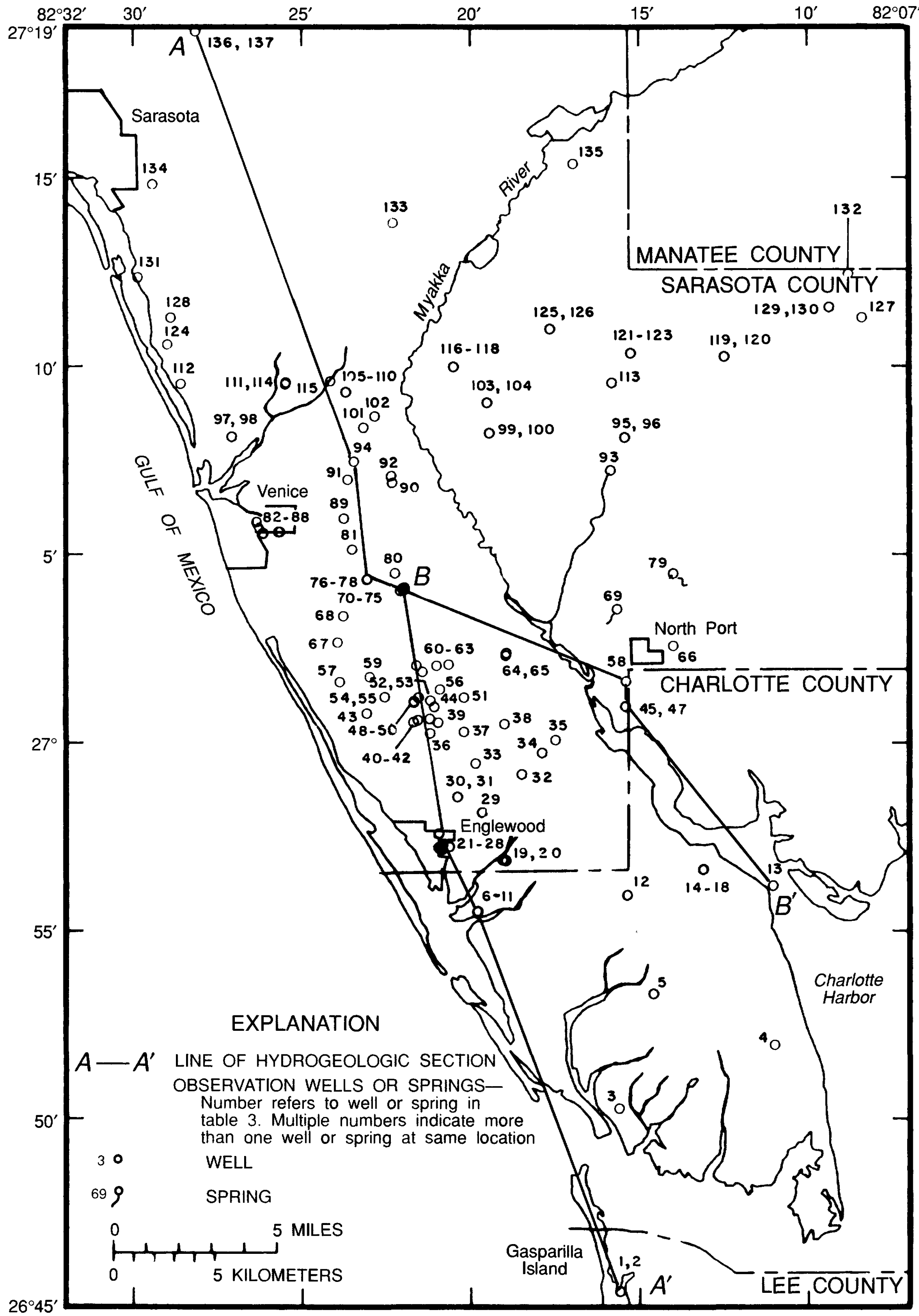


Figure 6. Locations of observation wells, springs, and hydrogeologic section lines *A–A'* and *B–B'*.

Table 3. Well records

[Data type: WL, water level; QW, quality of water; HG, hydrogeologic; AT, aquifer test; FS, flowmeter survey]

Index number	Latitude-longitude[1]	Casing/depth (ft)	Data type	Site name
1	264525082153501	1,702/1,926	WL,HG,QW,AT	Gasparilla Island injection well IW1.
2	264525082153502	340/360	WL,QW	Gasparilla Island injection monitor well.
3	265017082153701	346/413	WL,HG,QW	Placida well.
4	2651580821100	12,685	HG	Vanderbilt oil test.
5	2653200821435	<32	QW,AT	Gasparilla Island well field.
6	265531082194801	1,600/1,652	WL,HG,QW	ROMP TR3–3 Avon Park well.
7	265531082194802	1,080/1,120	WL,QW,FS	ROMP TR3–3 Ocala well.
8	265531082194803	680/900	WL,QW	ROMP TR3–3 Suwannee well.
9	265531082194804	370/410	WL,QW	ROMP TR3–3 Lower Hawthorn well.
10	265531082194805	155/175	WL,QW	ROMP TR3–3 Upper Hawthorn well.
11	265531082194806	10/30	WL	ROMP TR3–3 surficial well.
12	265557082152201	258/300	QW	USGS 19 San Cassa.
13	265612082110301	68/1,407	HG,QW	Cattledock Point well.
14	265638082130702	55/75	WL	ROMP TR3–1 Tamiami well.
15	265638082130703	140/160	WL,QW	ROMP TR3–1 Upper Hawthorn well.
16	265638082130704	250/270	WL	ROMP TR3–1 middle Hawthorn well.
17	265638082130705	380/400	WL,QW	ROMP TR3–1 lower Hawthorn well.
18	265638082130706	600/620	WL,HG,QW	ROMP TR3–1 Suwannee well.
19	265652082185801	/101	WL,QW	Englewood well 150.
20	265653082190301	175/320	WL,QW	Englewood reverse-osmosis test 1, RO–1.
21	265710082205101	152/310	WL,QW	Englewood reverse-osmosis test 2, RO–2.
22	265712082205701	51/110	WL,QW	Englewood well R–2.
23	265712082205702	7/17	WL	Englewood WP shallow well.
24	265714082203801	263/430	AT	Englewood production well RO–1.
25	265716082205101	1,040/1,800	WL,HG,QW,AT	Englewood injection well IW–1.
26	265716082205102	500/550	WL,QW	Englewood injection monitor well MW–1.
27	2657220822103	25/40	AT	Englewood production well 27.
28	265735082205701	49/55	AT	Englewood production well 9.
29	265809082194001	45/65	WL	Englewood well TH 6.
30	265834082202401	43.5/55	WL,QW	Englewood well 14.
31	265834082202402	10/20	WL,QW	Englewood well 14A.
32	2659100821830	/930	HG	Venetia 19.
33	265927082195201	56/110	QW	Englewood test well C–8.
34	265944082175401	28/101	QW	USGS 20 Plamore.
35	2700050821730	/996	HG	Venetia 9.
36	2700150822113	31/75	AT	Englewood production test well 2.
37	270018082201301	47/120	QW	Englewood test well C–7.
38	2700300821900	/840	HG,QW	Venetia 3A.
39	270032082205801	52/253	QW,FS	Venetia (Berry 8).
40	2700330822142	35/70	QW,AT	Englewood production test well 4.
41	270036082213401	41.5/70	WL,QW,AT	Englewood test well C–10.
42	2700380822113	35/70	QW,AT	Englewood production test well 5.
43	270047082230501	42/719	HG	Dolphin Bath & Racquet Club.
44	270057082210501	48/185	QW,FS	Venetia (Berry 7).
45	270058082152501	1,100/3,200	WL,HG,QW,AT	North Port deep injection well DIW.
46	270058082152502	730/750	WL,QW	North Port onsite monitor well.
47	270058082152503	560/600	WL,QW	North Port onsite monitor well.
48	2701040822141	42/70	QW,AT	Englewood production test well 3.
49	270106082214101	109/135	WL,QW	Englewood deep zone well 3.

Table 3. Well records—Continued

[Data type: WL, water level; QW, quality of water; HG, hydrogeologic; AT, aquifer test; FS, flowmeter survey]

Index number	Latitude-longitude[1]	Casing/depth (ft)	Data type	Site name
50	2701070822112	43/70	QW,AT	Englewood production test well 1.
51	270112082201201	65/120	QW	Englewood test well C–9.
52	270112082213301	58/70	WL,QW	Englewood production well 8.
53	270112082213302	20/25	WL	Englewood water-table well 8A.
54	270113082223302	40/70	WL,QW	Englewood production well 5.
55	270113082223303	10/15	WL	Englewood water-table well 5.
56	2701250822055	/830	HG	Venetia 15.
57	270137082235301	263/305	WL,QW	Manasota deep well 14.
58	270138082152401	1,100/1,150	WL,HG,QW	North Port satellite monitor well SMW.
59	2701450822300	/760	HG	Venetia 12A.
60	270153082212601	224/620	FS	Venetia 3 (Berry 9).
61	270203082210101	212/315	QW,FS	Venetia (Berry 3).
62	270203082213701	207/608	QW,FS	Venetia 2 (Berry 4).
63	270205082204001	290/472	FS	Venetia (Berry 5).
64	270219082185801	110/270	WL,QW,AT	Manatee Jr. College south well.
65	270223082185701	41/158	WL,QW	Manatee Jr. College middle well.
66	2702350821400	/916	HG	Frizell 1.
67	270240082235701	460/475	WL,HG,QW	ROMP TR4–2.
68	2703220822347	61/160	AT	Venice Gardens MWVG–1.
69	270333082154000		WL,QW	Warm Mineral Springs.
70	2704020822206	60/200	AT	Plantation well.
71	270403082220001	66/180	WL,QW	Plantation monitor well 1.
72	270404082215801	52/65	WL,QW	Plantation monitor well 2.
73	270406082215901	630/650	WL,QW	Plantation zone 4 monitor well.
74	270406082220101	1,102/1,605	WL,HG,QW,AT	Plantation deep injection test well DITW.
75	270407082215801	228/366	QW,AT	Plantation reverse-osmosis test well 2.
76	270420082230501	1,388/1,705	HG,QW,AT	Venice Gardens deep injection well DIW.
77	270421082230401	770/800	WL,QW	Venice Gardens injection monitor well 800.
78	270421082230402	200/400	WL,QW	Venice Gardens injection monitor well 400.
79	270430082140000		WL,QW	Little Salt Spring.
80	2704300822215	61/160	AT	Venice Gardens TP–49.
81	2705080822331	60/160	AT	Venice Gardens TPVG–1.
82	270533082261001	200/650	AT	Venice RO–5.
83	2705340822609	206/441	QW,AT	Venice RO–6.
84	2705360822539	77/140	QW,AT	Venice well 2.
85	2705360822542	42/59	AT	Venice well 9S.
86	270542082261801	86/163	WL,QW	Venice well 35.
87	270542082261802	/68	WL,QW	Venice well 36.
88	2705520822621	29/110	AT	Venice well 31.
89	270557082234601	47/390	FS	Venice Ranch Trailer Park (Ellis).
90	270654082222001	42/464	FS	Everglades Estates 1.
91	270659082233901	50/190	FS	Fox Lea Farms.
92	270705082222201	60/358	FS	Everglades Estates 2.
93	270714082155201	282/351	WL,QW	Test 18 Blackburn Ranch.
94	270728082232801	229/1,046	HG,QW	Wheelwright 1.
95	270807082152701	500/550	WL	MacArthur Tract 14FS.
96	270807082152702	275/300	WL	MacArthur Tract 14GS.
97	270808082270502	492/510	WL,QW	ROMP TR5–1 Suwannee well.
98	270808082270503	275/289	WL,QW	ROMP TR5–1 Hawthorn well.
99	270814082192701	500/554	WL	MacArthur Tract 3F.
100	270814082192702	65/230	WL	MacArthur Tract 3E.

Table 3. Well records—Continued

[Data type: WL, water level; QW, quality of water; HG, hydrogeologic; AT, aquifer test; FS, flowmeter survey]

Index number	Latitude-longitude[1]	Casing/depth (ft)	Data type	Site name
101	270822082231101	40/286	WL,QW	Henry Ranch 1.
102	270840082225101	/78	WL,QW	Henry Ranch 3.
103	270902082193108	699/1,000	WL	RMR Cluster 21 Floridan well.
104	270902082193109	/240	WL	RMR Cluster 21 Hawthorn well.
105	270919082234201	8/13	WL	ROMP TR5–2 surficial well.
106	270919082234202	100/120	WL,QW,AT	ROMP TR5–2 upper Hawthorn well.
107	270919082234203	245/265	WL,QW	ROMP TR5–2 lower Hawthorn well.
108	270919082234204	360/400	WL,QW,AT,FS	ROMP TR5–2 Tampa well.
109	270919082234205	510/700	WL,QW,AT	ROMP TR5–2 Suwannee well.
110	270919082234206	850/890	WL,HG,QW	ROMP TR5–2 Ocala well.
111	270931082252901	44/256	WL,QW,FS	Ewing Ranch (Holland).
112	270932082283501	308/669	FS	Sorrento Shores well.
113	270933082154901	500/550	WL	MacArthur Tract 14FN.
114	270934082252801	/100	WL,QW	Myakka River Nursery.
115	2709360822409	1,599/1,915	WL,HG,AT,QW	Knight Trail Park exploratory/monitor well.
116	270959082203001	410/425	WL,HG	ROMP 19 WLAM.
117	270959082203002	87/205	WL	ROMP 19 WUAM.
118	270959082203003	32/67	WL,QW	ROMP 19 WS.
119	271015082122901	500/629	WL	MacArthur Tract 20F.
120	271015082122902	101/253.5	WL	MacArthur Tract 20C.
121	271021082151601	410/419	WL,HG	ROMP 19 ELAM.
122	271021082151602	80/121	WL	ROMP 19 EUAM.
123	271021082151603	14.5/34.5	WL	ROMP 19 ES.
124	271035082285901	/710	WL,QW	Southbay Utilities deep well.
125	271059082173901	50/551	WL	MacArthur Tract 6F.
126	271059082173902	60/240	WL	MacArthur Tract 6E.
127	271118082082401	62/301	WL	Mabry Carlton 16.
128	271118082285301	157/255	WL,QW	Osprey well 9.
129	271134082092201	78/100	WL	Big Slough deep well.
130	271134082092202	19/25	WL	Big Slough shallow well.
131	271222082295201	41/224	WL,QW	Sarasota County Historical Society.
132	271227082084801	311/369	WL	Mabry Carlton 6.
133	271348082221801	/182	WL	Buck Hawkins Bermuda Patch.
134	271450082292601	/1,200	WL,QW	Mann Golf Course well.
135	271522082165801	72/360	WL	Old Palmer well.
136	271853082280901	1,480/1,902	WL,HG,QW,AT	Atlantic Utilities test/injection well.
137	271853082280902	1,130/1,240	QW	Atlantic Utilities deep monitor well.

[1]The latitude-longitude well number 264525082153501 represents a well in the 1-second quadrangle bounded by latitude 26°45′25" on the south and longitude 82°15′35" on the east. The suffix 01 indicates that the well is the first well inventoried in the quadrangle. A missing suffix indicates that the location of the well was approximated from township-range-section information.

6. Top of the Avon Park highly permeable zone is the occurrence of a vertically persistent dolomite section that commonly is fractured and provides geophysical signatures of high resistivity on the dual-induction log and cycle skipping (cyclic high-amplitude velocity measurements) on the sonic log.
7. Top of the middle confining unit of the Floridan aquifer system is marked by the occurrence of dolomite that contains inclusions of anhydrite and gypsum. This stratum is considered to be impermeable.

Many aquifer tests have been conducted in the study area, including five during this study. Table 6 lists the findings of each test, which are keyed by index number to the location map in figure 6. The following sections present detailed analyses of tests of the injection zone.

Surficial Aquifer System

The surficial aquifer system consists primarily of Pliocene to Holocene age intermixed sand, clay, shell, and phosphate gravel having stringers of limestone and marl. The 50-ft-thick aquifer system is unconfined; however, lenses of sand, marl, and limestone contain water under

Figure 7. Observation wells having casings as high as 23 ft above land surface to retain artesian head. (Photograph by L.D. Windom.)

confined conditions in some areas. It is tapped for public supply where more permeable underlying aquifers contain saline water. The Gasparilla Island well field (fig. 4) is typical of development of the surficial aquifer system with 32 supply wells that are 27 to 32 ft deep and that are finished with 3 to 7 ft of well screen (table 1). Yield is restricted to about 20 gal/min for each well to prevent upconing of saline water.

Depth to the water table is generally less than 5 ft. In areas of low topographic relief and near the coast and Myakka River, the water table is virtually at land surface. Fluctuations of the water table vary in response to rainfall and range over about 5 ft. Figure 9 shows several hydrographs including that of the water level in a 25-ft-deep observation well within one of Englewood's well fields. Water levels between 1980 and 1988 ranged from about –5 to 14 ft, with respect to sea level. The water table is affected by seasonal variations in rainfall and by pumping from nearby production wells that tap the underlying intermediate aquifer.

Recharge to the surficial aquifer system occurs as rainfall, upward leakage through semiconfining beds where the altitude of the potentiometric surface of the intermediate aquifer system is higher than the water table, infiltration of irrigation water, and upward flow from deep aquifers through improperly cased wells or abandoned flowing wells. Discharge from the surficial aquifer system is by evapotranspiration, upward seepage into streams and along the coast, pumpage from wells, and downward leakage where the water table is higher than the potentiometric surface of the intermediate aquifer system.

Hydraulic properties of the surficial aquifer system vary over short distances, primarily due to heterogeneity of lithologic units. Clark (1964, p. 32) reported a transmissivity of 1,100 ft2/d for the "first artesian aquifer" at Venice, based on a pumping test of a well cased to 42 ft and open to 59 ft below land surface. This test was categorized by Wolansky (1983, p. 17) and Duerr and Wolansky (1986, p. 10) as a test of the surficial aquifer system because the deposits comprise the Bone Valley Formation and upper part of the Tamiami Formation. Sutcliffe (1975, p. 34) reported transmissivity of the surficial aquifer system to range from 1,340 to 1,870 ft2/d at the Gasparilla Island well field in Charlotte County.

Wells at the Venice, Englewood, Rotunda, and Gasparilla Island well fields tap the surficial aquifer system. Elsewhere, hundreds of small-diameter wells tap the aquifer for domestic supply, lawn irrigation, and watering livestock. Through 1986, the Englewood Water District, which supplies Englewood and nearby communities, received 726 shallow-well permit applications. In 1986, there were 77 applications for small-diameter, private wells.

Intermediate Aquifer System

The intermediate aquifer system includes all rocks that lie between and collectively retard the exchange of water between the overlying surficial aquifer system and the underlying Floridan aquifer system. The system consists of Miocene and younger fine-grained clastic deposits that are interlayered with carbonate rocks. Discontinuous confining units, consisting of sandy clay, clay, and marl at the top, middle, and bottom of the system, separate it into two aquifer units known as the Tamiami-upper Hawthorn aquifer and the lower Hawthorn-upper Tampa aquifer.

The intermediate aquifer system thickens from north to south from less than 400 ft north and east of Venice to more than 600 ft at Gasparilla Island (fig. 10). Fine-grained sediments separate the Tamiami-upper Hawthorn and lower Hawthorn-upper Tampa aquifers within the system and are not clearly delineated by gamma-ray logs due to naturally occurring high gamma activity of the phosphorite in the carbonate rocks. Lithologic and flowmeter logs indicate multiple zones of high and low permeability that appear to be discontinuous. Transmissivity is generally less than 10,000 ft^2/d, and the system exhibits storage characteristics of a confined aquifer (table 6).

Table 4. Hydrogeologic framework

System	Series	Stratigraphic unit	Hydrogeologic unit			Depth below land surface (feet)	Use of zone
Quaternary	Holocene Pleistocene	Terrace deposits Caloosahatchee Marl	Surficial aquifer system		Surficial aquifer	0–50	Source of domestic and municipal supplies.
Tertiary	Pliocene	Tamiami Formation	Intermediate aquifer system[1]		Semiconfining unit	50–60	
					Tamiami-upper Hawthorn aquifer[2]	60–100	
	Miocene	Hawthorn Formation			Semiconfining unit	100–240	
		Tampa Limestone			Lower Hawthorn-Upper Tampa aquifer[2]	240–410	Source of reverse-osmosis feed and irrigation supplies.
					Lower Tampa semiconfining unit	410–500	
	Oligocene	Suwannee Limestone	Floridan aquifer system[3]	Upper Floridan aquifer[3]	Suwannee permeable zone	500–750	
	Eocene	Ocala Limestone			Lower Suwannee-Ocala semiconfining unit	750–1,100	
					Ocala-Avon Park moderately permeable zone	1,100–1,400	Injection zone for sewage and reverse-osmosis wastewater.
		Avon Park Formation[2]			Avon Park highly permeable zone	1,400–2,075	
					Middle confining unit[3]	2,075–2,400	
	Paleocene	Oldsmar and Cedar Keys Formations			Lower Floridan aquifer[3]	2,400–?	Unused.

[1]Based on nomenclature of Southeastern Geological Society (1986).
[2]Based on nomenclature of Wolansky (1983).
[3]Based on nomenclature of Miller (1986).

Water-level hydrographs in figure 9 show that head increases with depth throughout the study area. Levels rise in the rainy summer in response to reductions in pumpage and upgradient recharge east of the study area, and they fall in the dry spring when ground-water outflow and pumpage exceed recharge. Relatively large head differences (10–25 ft) between shallow and deep zones within the intermediate aquifer system indicate appreciable hydraulic separation of aquifer units; however, water-level trends are parallel, implying that the aquifers are interconnected or affected by the same stresses. Interconnection of aquifer systems through uncased, fully penetrating wells is a problem in the study area that will be addressed separately.

The USGS measures water levels in the intermediate and Floridan aquifer systems each May and September to portray annual low and high conditions, respectively. Figures 11 and 12 show the May 1987 potentiometric surface of the Tamiami-upper Hawthorn aquifer and the composite or average potentiometric surface of all water-bearing units within the intermediate aquifer system. Flow in both units is from east to west and heads are above sea level at the coast, which indicates that recharge occurs somewhere east of the Myakka River and discharge is

Table 5. Hydrogeologic data from selected test wells

[SWFWMD, Southwest Florida Water Management District; FBG, Florida Bureau of Geology; – –, no data]

Index no.	Latitude-longitude	Section-township-range	Well identification[1]	Altitude of land surface (ft)	Depth of hole (ft)	Altitude of top of hydrogeologic unit (ft): Intermediate aquifer	Suwannee permeable zone	Lower Suwannee-Ocala semiconfining unit	Ocala-Avon Park moderately permeable zone	Avon Park highly permeable zone	Middle confining unit	Data source
1	2645250821535	4–43S–20E	Gasparilla Island injection well IWI.	8	1,926	–52	–732	–1,020	–1,452	–1,730	– –	Geraghty and Miller, Inc. (1986).
3	2650170821537	12–42S–20E	Placida #8	3	413	–52	– –	– –	– –	– –	– –	Sutcliffe and Joyner (1968).
4	2651580821100	35–41S–21E	Vanderbilt Oil test well	4	12,685	– –	–669	–1,029	–1,279	–1,679	–2,384	Puri and Winston (1974) FBG W–3214.
6	2655310821948	8–41S–20E	ROMP TR3–3 Avon Park test hole.	6	1,700	–29	–680	–940	–1,420	–1,630		SWFWMD.
13	2656120821103	2–41S–21E	Cattledock Point well	3	1,407	–40	–660	–970	– –	– –	– –	Lithologic and geophysical logs.
18	2656380821307	4–41S–21E	ROMP TR3–1 Suwannee test hole.	7	650	–13	–590	– –	– –	– –	– –	SWFWMD.
25	2657160822051	31–40S–20E	Englewood injection well IW–1.	10	1,800	–40	–640	–910	–1,050	–1,570	– –	CH2M Hill, Inc. (1986).
32	2659100821830	21–40S–20E	Venetia 19	11	930	–29	–720	– –	– –	– –	– –	FBG log W–10218.
35	2700050821730	15–40S–20E	Venetia 9	11	996	–69	–705	– –	– –	– –	– –	FBG log W–9860.
38	2700300821900	9–40S–20E	Venetia 3A	14	840	–66	–645	– –	– –	– –	– –	FBG log W–9883.
43	2700470822305	11–40S–19E	Dolphin Bath & Racquet Club.	5	719	–20	–590	– –	– –	– –	– –	Geophysical logs.
45	2700580821525	12–40S–20E	North Port deep injection well DIW.	5	3,200	–65	–550	–815	–1,095	–1,495	–2,005	CH2M Hill,Inc. (1987a).
56	2701250822055	6–40S–20E	Venetia 15	15	830	–60	–530	–755	– –	– –	– –	FBG log W–9882.
58	2701380821524	1–40S–20E	North Port satellite monitor well SMW.	4	1,150	–60	–715	–900	– –	– –	– –	CH2M Hill, Inc. (1987a).
59	2701450822300	3–40S–19E	Venetia 12A	15	760	–65	–535	–735	– –	– –	– –	FBG log W–9890.
66	2702350821400	32–39S–21E	Frizell 1	13	916	–87	–462	–767	– –	– –	– –	FBG log W–9884.
67	2702400822357	34–39S–19E	ROMP TR4–2 test hole	15	607	–62	–525	– –	– –	– –	– –	SWFWMD.
74	2704060822201	24–39S–19E	Plantation deep injection test well DITW.	12	1,605	–44	–640	–850	–1,090	–1,460	– –	Post, Buckley, Schuh, and Jernigan, Inc. (1984).
76	2704200822305	22–39S–19E	Venice Gardens deep injection well DIW.	12	1,705	–33	–598	–800	–1,300	–1,424		Geraghty and Miller, Inc. (1985).
94	2707280822328	34–38S–19E	Wheelwright 1	14	1,046	–26	–485	–772	– –	– –	– –	FBG log W–7398.
97	2708080822705	36–38S–18E	ROMP TR5–1 Suwannee test hole.	10	654	–15	–478	– –	– –	– –	– –	SWFWMD.
110	2709190822342	22–38S–19E	ROMP TR5–2 Ocala test hole.	15	906	–35	–485	–735	– –	– –	– –	Hutchinson and Trommer (in press).
115	2709360822409	21–38S–19E	Knight Trail Park exploratory/monitor well.	15	2,156	–15	–505	–850	–1,100	–1,435	–1,895	Law Environmental, Inc. (1989).
116	2709590822030	18–38S–20E	ROMP 19 WLAM	20	425	–30	–375	– –	– –	– –	– –	SWFWMD.
121	2710210821516	13–38S–20E	ROMP 19 ELAM	31	419	–19	–367	– –	– –	– –	– –	SWFWMD.
136	2718530822809	35–36S–18E	Atlantic Utilities test/injection well.	17	1,902	– 3	–440	–760	–1,000	–1,420	–1,780	Post, Buckley, Schuh, and Jernigan, Inc. (1986).

[1]Wells identified as test holes may have a drilled depth that does not necessarily coincide with the well depth listed in table 3.

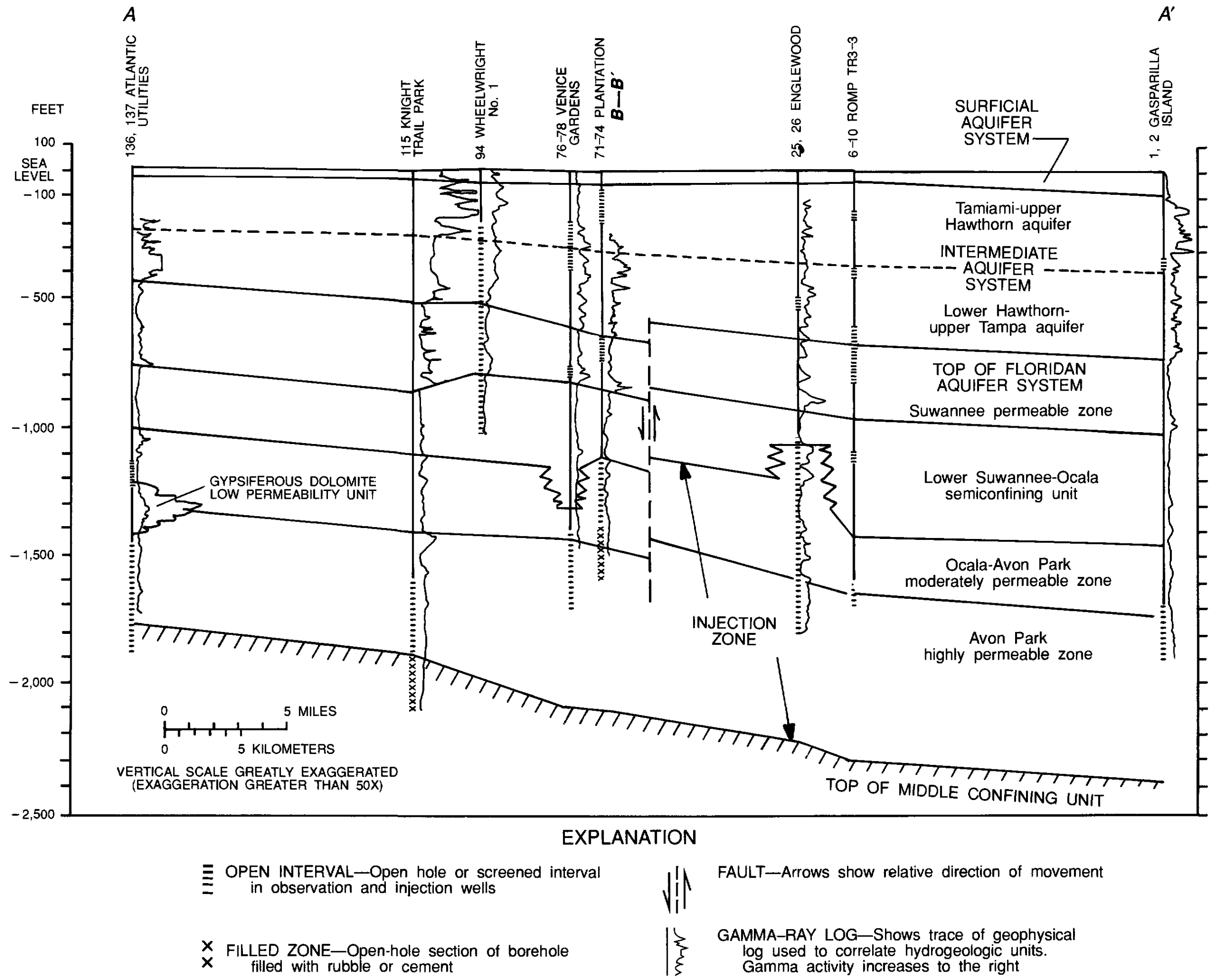


Figure 8. Hydrogeologic section *A–A′* showing well completion details and gamma-ray geophysical logs. (Location of section is shown in fig. 6.)

upward to the surficial aquifer and west and south to the Gulf of Mexico and Charlotte Harbor. Depressions in the potentiometric surfaces occur at well fields between Venice and Englewood and east of the Myakka River at Warm Mineral Springs and Little Salt Springs. At Warm Mineral Springs, divers reached a depth of 230 ft (Royal, 1978, p. 216), which corresponds to the middle of the intermediate aquifer system.

Floridan Aquifer System

The Floridan aquifer system consists of a thick sequence of carbonate rocks that generally have been referred to in the past as the Floridan aquifer. The Floridan aquifer system, as defined by Miller (1986, p. B45), comprises:

> ...a vertically continuous sequence of carbonate rocks of generally high permeability that are mostly of middle and late Tertiary age, that are hydraulically connected in varying degrees, and whose permeability is, in general, an order to several orders of magnitude greater than that of those rocks that bound the system above and below.
> ... (in west-central Florida), less-permeable carbonate units of subregional extent separate the system into two aquifers, ... called the Upper and Lower Floridan aquifer....

In the study area, the permeable part of the Floridan aquifer system is the Upper Floridan aquifer. Deep test holes at Sarasota (Sutcliffe, 1979) and at the North Port injection site (CH2M Hill, Inc., 1988) have demonstrated that, once intergranular evaporites of the middle confining unit (table 4) are encountered in drilling, there is relatively little or no permeability down to the bedded evaporites that form the base of the Floridan aquifer system. The Lower Floridan aquifer apparently does not exist in southwest Sarasota and west Charlotte Counties.

Within the study area, the Upper Floridan aquifer has not been widely exploited for water supplies because of its generally poor water quality. Until recently, it was tapped only by a few deep irrigation wells with shallow casings (less than 100 ft) for high yield of relatively poor quality water. With the development of reverse-osmosis and large sewage-treatment plants, the aquifer has become an important source of slightly saline to moderately saline water as well as a receptacle for injected wastewater.

Data from geologic logs and hydraulic testing at injection-well sites have revealed much about local hydrogeologic conditions that can be extrapolated beyond the study area. Regional hydrogeologic units within the Upper Floridan aquifer are defined herein in descending order:

Table 6. Summary of aquifer tests

[ft^2/d, square feet per day; (ft/d)/ft, feet per day per foot; – –, no data]

Index no.	Latitude-longitude	Hydro-geologic unit[1] or open interval	Depth interval (ft)	Trans-missivity (ft^2/d)	Leakance coefficient [(ft/d)/ft]	Storage coefficient	Reference
1	2645250821535	AP	1,702–1,926	64,000	– –	– –	Geraghty and Miller, Inc. (1986).
5	2653200821435	S	<32	1,340–1,850	– –	0.02	Sutcliffe (1975, p. 34).
24	2657140822038	LH–UT	260–425	8,200	– –	.000085	CH2M Hill, Inc. (1980).
25	2657160822051	O–AP	1,040–1,600	48,000	– –	– –	CH2M Hill, Inc. (1986).
		O–AP	1,040–1,800	80,000	– –	– –	CH2M Hill, Inc.(1986).
27	2657220822103	T	25–40	7,800	– –	.00005	Wolansky (1983).
28	2657350822057	T	49–55	5,500	0.0007	.00011	Wolansky (1983).
36	2700150822113	T	31–75	1,260	.12	.00087	CH2MHill, Inc. (1978).
40	2700330822142	T	35–70	3,320	.000036	.000016	CH2M Hill, Inc. (1978).
41	2700360822134	T	41.5–70	3,800	.00024	.00017	Wolansky (1983).
42	2700380822113	T	35–70	1,525	.005	.000058	CH2M Hill, Inc. (1978).
45	2700580821525	SUW–O	560–1,100	8,900	– –	– –	CH2M Hill, Inc. (1988).
		SUW–AP	560–1,600	72,000	– –	– –	CH2M Hill, Inc. (1988).
		AP	1,100–2,000	150,000	– –	– –	CH2M Hill, Inc. (1988).
		AP–OLD	1,100–3,200	140,000–370,000	– –	– –	CH2M Hill, Inc. (1988).
48	2701040822141	T	42–70	1,608	– –	– –	CH2M Hill, Inc. (1978).
50	2701070822112	T	43–70	2,970	.013	.00065	CH2M Hill, Inc. (1978).
64	2702190821858	T–UH	110–270	200	– –	.00002	USGS test, 1984.
68	2703220822347	T–UH	61–160	650	.00022	.0003	Geraghty and Miller, Inc. (1980).
70	2704020822206	T–UH	60–200	300	– –	– –	Post, Buckley, Schuh, and Jernigan, Inc. (1981).
74	2704060822201	O–AP	1,102–1,605	67,000	– –	– –	Post, Buckley, Schuh, and Jernigan, Inc. (1984).
75	2704070822158	LH–UT	228–366	5,600	.00026	.00033	Post, Buckley, Schuh, and Jernigan, Inc. (1982b).
76	2704200822305	AP	1,388–1,705	24,000	– –	– –	Geraghty and Miller, Inc. (1985).
80	2704300822215	T–UH	61–160	400	– –	– –	Geraghty and Miller, Inc. (1980).
81	2705080822331	T–UH	60–160	650	– –	– –	Geraghty and Miller, Inc. (1980).
82	2705330822610	LH–SUW	200–650	17,900	.0001	.00013	Wolansky (1983).
83	2705340822609	LH–UT	206–441	15,400	– –	.00064	Post, Buckley, Schuh, and Jernigan, Inc. (1982a).
84	2705360822539	T–UH	77–140	550	.0005	.000042	Post, Buckley, Schuh, and Jernigan, Inc. (1982a).
85	2705360822542	T	42–59	1,100	.0001	.00013	Clark (1964).
88	2705520822621	T–UH	29–110	800	.00018	.00011	Clark (1964).
[2]106	2709190822342	T–UH	60–100	5,000	– –	– –	USGS test, 1986.
[2]108	2709190822342	LH–UT	240–410	10,000	– –	– –	USGS test, 1986.
109	2709190822342	SUW	510–700	13,000	– –	– –	Hutchinson and Trommer (in press).
115	2709360822409	AP	1,599–1,915	300,000	– –	– –	Law Environmental, Inc. (1989).
136	2718530822809		1,480–1,902	5,000	– –	– –	Post, Buckley, Schuh, and Jernigan, Inc. (1989).

[1]Test wells tap a single hydrogeologic unit or open interval of permeable and semiconfining zones as follows:

S = Surficial aquifer system
T = Tamiami open interval
T-UH = Tamiami-upper Hawthorn aquifer
LH-UT = Lower Hawthorn-upper Tampa aquifer
LH-SUW = Lower Hawthorn-Suwannee open interval
SUW = Suwannee permeable zone
SUW-O = Suwannee-Ocala open interval
SUW-AP = Suwannee-Avon Park open interval
O-AP = Ocala-Avon Park open interval
AP = Avon Park highly permeable zone
AP-OLD = Avon Park- Oldsmar open interval

[2]Test at the ROMP TR5–2 site consisted of pumping a well open from 60 to 410 ft and making generalizations about depth intervals of permeable units based on flowmeter surveys. The test hole was subsequently cased at multiple intervals as indicated in table 3.

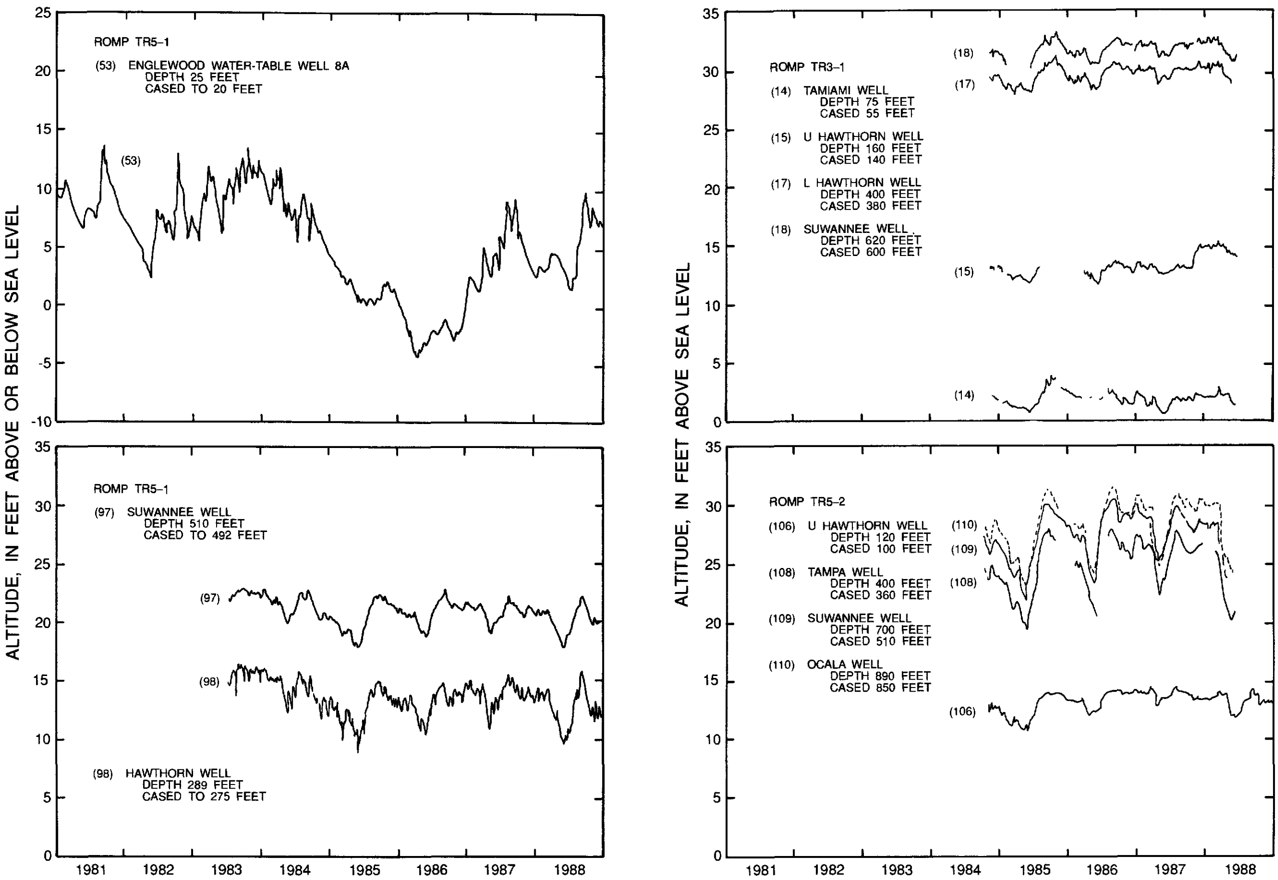


Figure 9. Daily maximum water levels in selected observation wells. (Site numbers in parentheses are indexed to table 3 and fig. 6.)

(1) the Suwannee permeable zone, (2) the lower Suwannee-Ocala semiconfining unit, (3) the Ocala-Avon Park moderately permeable zone, and (4) the Avon Park highly permeable zone.

Suwannee Permeable Zone

The Suwannee permeable zone is the uppermost permeable unit within the Upper Floridan aquifer. The zone was defined by using lithologic and geophysical logs of wells listed in table 5. The 300-ft-thick zone is confined above by clayey carbonate rocks within the intermediate aquifer system and below by low-permebility limestones at the base of the Suwannee or upper part of the Ocala Limestone. The top of the zone lies between 500 and 750 ft below land surface and slopes from 485 ft below sea level at ROMP TR5–2 southward to 732 ft below sea level at Gasparilla Island (index numbers 110 and 1, respectively, in fig. 6 and table 5). The zone is characterized by moderate transmissivity as determined in tests at ROMP TR5–2 (13,000 ft^2/d, index number 109, table 6) and North Port (8,900 ft^2/d, index number 45, table 6).

The lithology of the Suwannee permeable zone is characterized by porous limestone in the upper 200 ft and interbedded limestone and dolomite in the lower 100 ft. The zone yields water from several discrete intervals (CH2M Hill, Inc., 1988, p. 3–11). Based on tests at the North Port well, which taps the full thickness of the zone, producing intervals are in the limestone and comprise about one-third of the total thickness of the zone. The dolomitic interval (760–810 ft) within the Suwannee permeable zone does not appear to yield significant quantities of water.

A fault was discovered through geophysical log correlation of the dolomitic limestone interval near the base of the Suwannee permeable zone. The dolomitic limestone interval is identified by a gamma-ray correlation marker of increased radiation activity. A 100-ft offset of the interval is interpreted from gamma-ray logs of wells 4,000 ft apart at the North Port injection site. The marker on logs of the satellite monitor and injection wells occurs at 800 to 900 ft and 700 to 800 ft, respectively (fig. 13). Displacement appears to occur above the gamma-ray correlation marker and possibly below the marker between the lower part of the intermediate aquifer system and extending below the base of the Ocala-Avon Park moderately permeable zone. The fault was traced areally in figure 14 by mapping the configuration of the top of the dolomitic limestone interval on gamma-ray and lithologic logs of wells listed in table 5. The fault strikes approximately east-west.

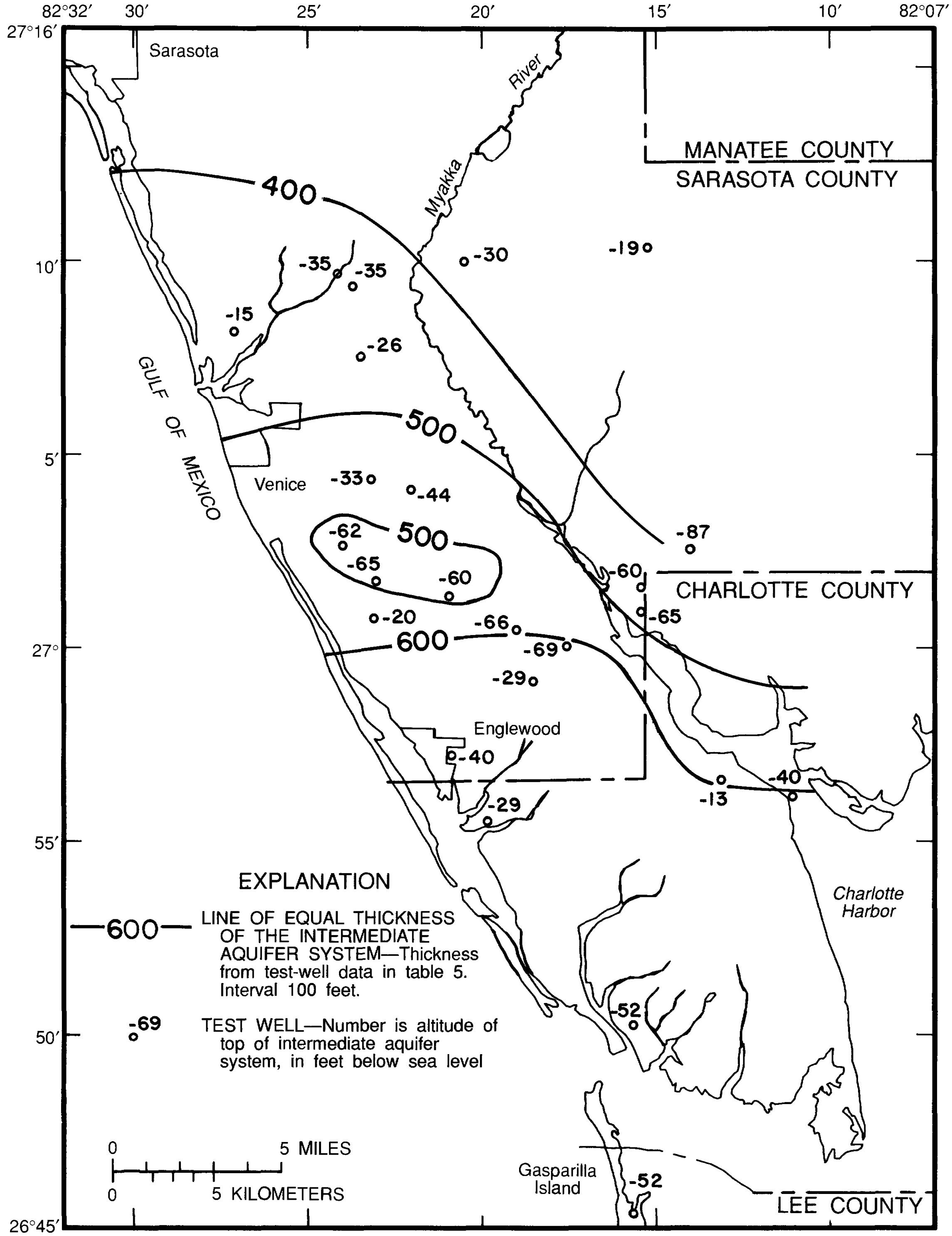


Figure 10. Altitude of the top and thickness of the intermediate aquifer system.

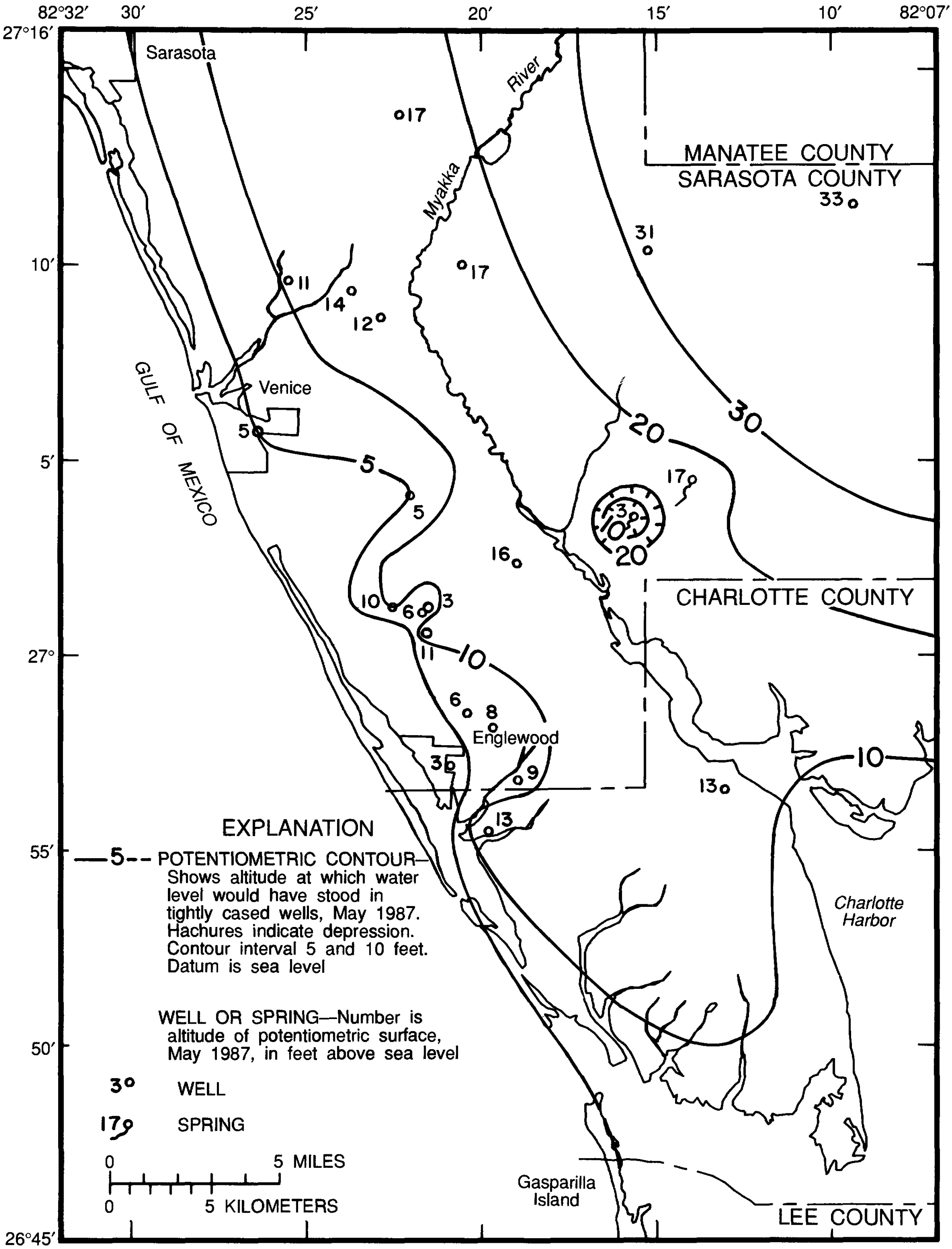


Figure 11. Potentiometric surface of the Tamiami-upper Hawthorn aquifer, May 1987. (Modified from Lewelling, 1987a.)

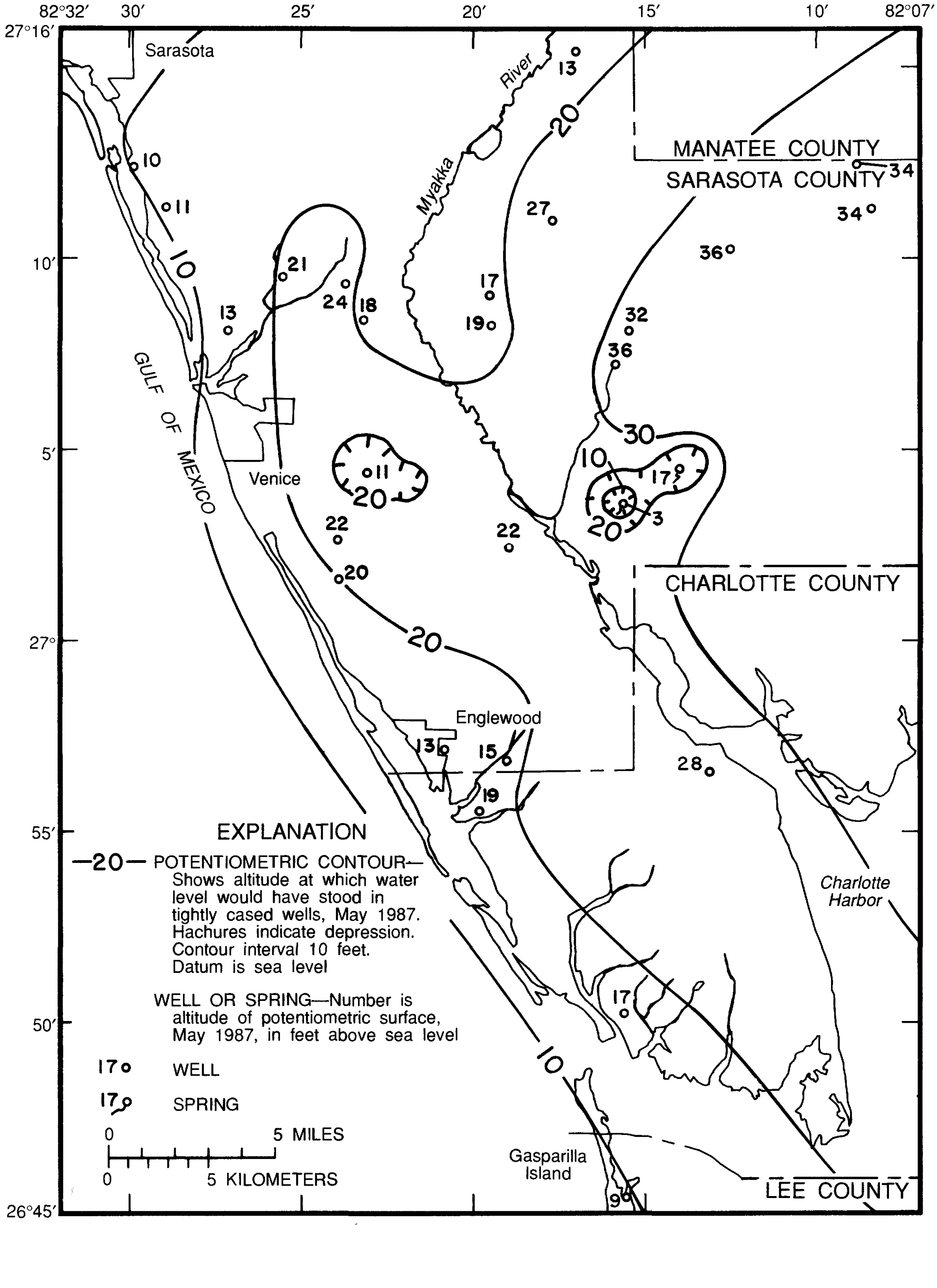


Figure 12. Composite potentiometric surface of water-bearing units within the intermediate aquifer system, May 1987. (Modified from Lewelling, 1987a.)

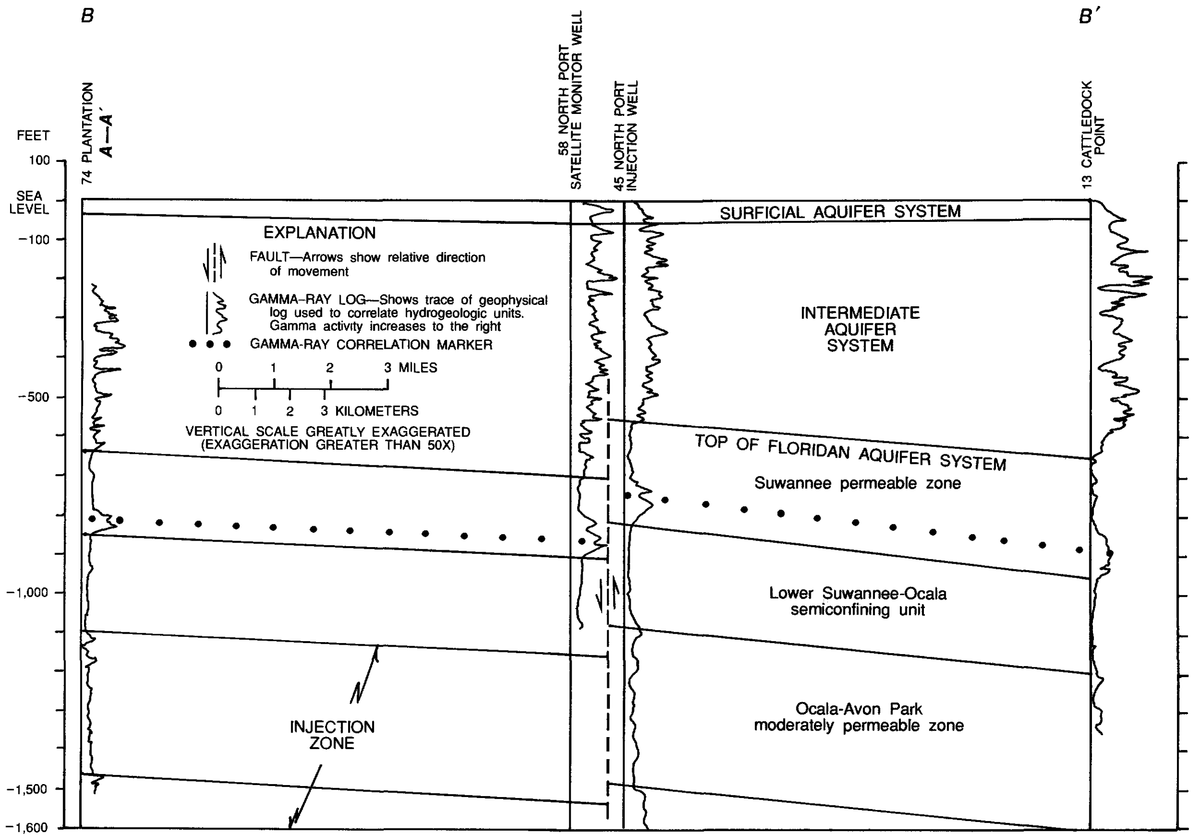


Figure 13. Hydrogeologic section *B–B′* showing fault based on interpretations of gamma-ray logs. (Location of section is shown in figs. 6 and 14.)

Other evidence, which points to the offset as a fault as opposed to a stratigraphic or erosional feature, is:

1. If the offset is stratigraphically controlled, a reversal of the north-south regional dip of formations would have had to occur, which is not likely in a marine depositional environment.
2. If diagenetic dolomitization had occurred along an isolated erosional or solution feature, the offset would likely correspond to a local anomaly within the regional framework. It is not likely that such a feature could be mapped regionally.
3. The fault aligns with a 100-ft offset in the Suwannee Limestone approximately 20 mi east of the North Port injection site, as delineated in a geologic section by Gilboy (1985).
4. The fault is approximately parallel to similar faults within the Suwannee Limestone near Cape Coral, 40 mi south-southeast of North Port, as mapped by Sproul and others (1972), which indicates response to the same tectonism at both sites.
5. Warm Mineral and Little Salt Springs are from 2 to 3 mi north of the fault. As their names suggest, warm saline water flows from the springs, indicating a deep source such as upwelling along a fault or fault zone.
6. Although the top of the Ocala Limestone is an erosional surface, evidence for the offset does not support an erosional feature, such as a river channel. The gamma-ray correlation marker slopes constantly through wells 13, 58, and 74, which implies that the marker at well 45 is high relative to the regional slope (fig. 13). The Suwannee permeable zone is slightly thicker in well 45 than it is in well 58. This is the opposite of what would be expected if Suwannee sediments had been deposited over an irregular Ocala surface.

A section of the May 1987 potentiometric-surface map that encompasses the southwest Sarasota and west Charlotte Counties study area is shown in figure 15 (Lewelling, 1987b). The map represents water levels in the freshwater-bearing part of the Upper Floridan aquifer, which correspond to the heads in the Suwannee permeable zone. Artesian heads are above land surface, and the gradient is from east to west from 30 ft above sea level at the Myakka River to about 20 ft above sea level at the gulf coast. Depressions were drawn around Warm Mineral and Little Salt Springs because the chemical and physical properties of the discharge suggest a deep source, possibly the Upper Floridan aquifer. Annual fluctuations of the surface between May low and September high levels are about 5 ft at ROMP sites TR5–1 and TR5–2 and about 2 ft at ROMP TR3–1 (fig. 9).

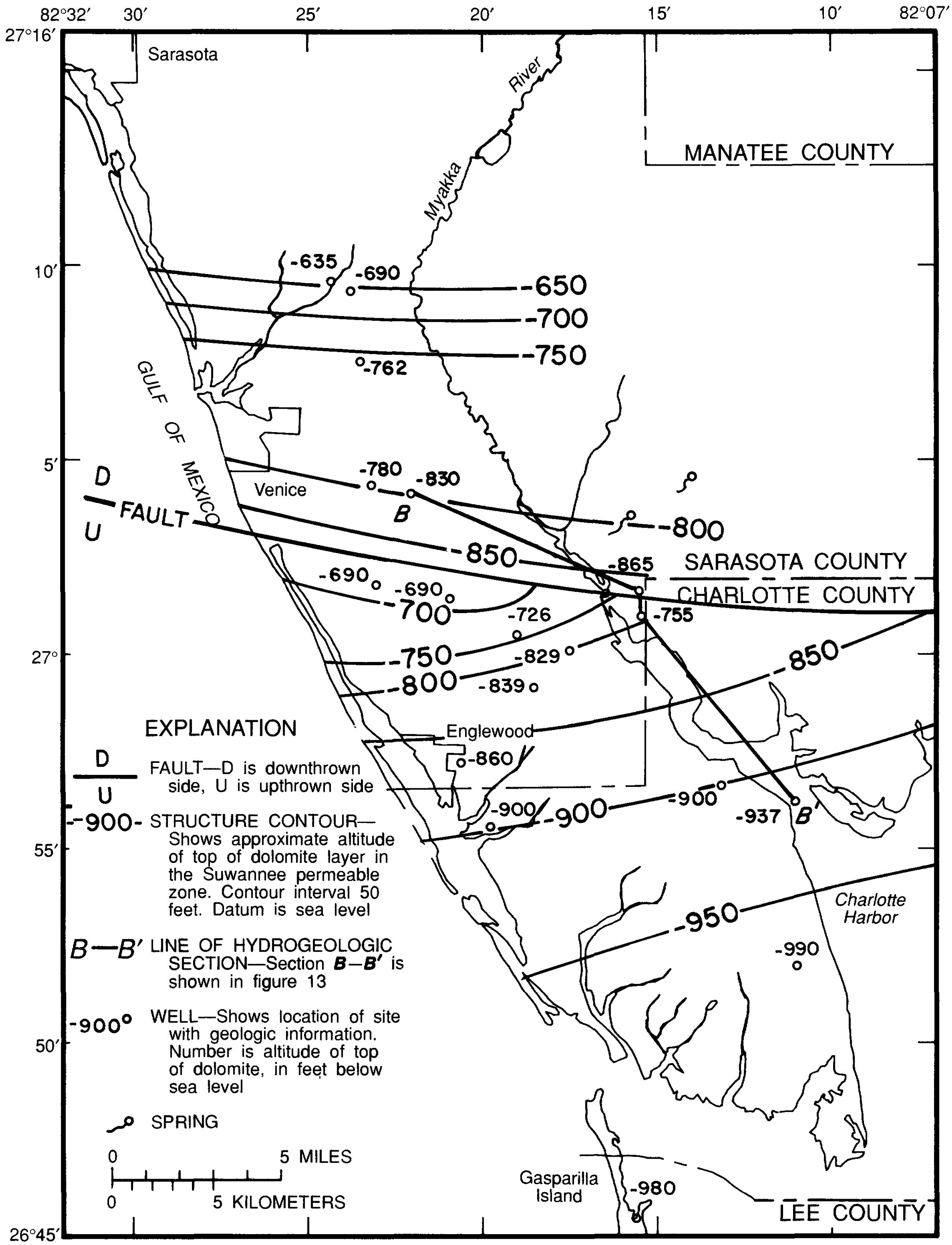


Figure 14. Configuration of the top of the dolomite layer of the Suwannee permeable zone within the Upper Floridan aquifer.

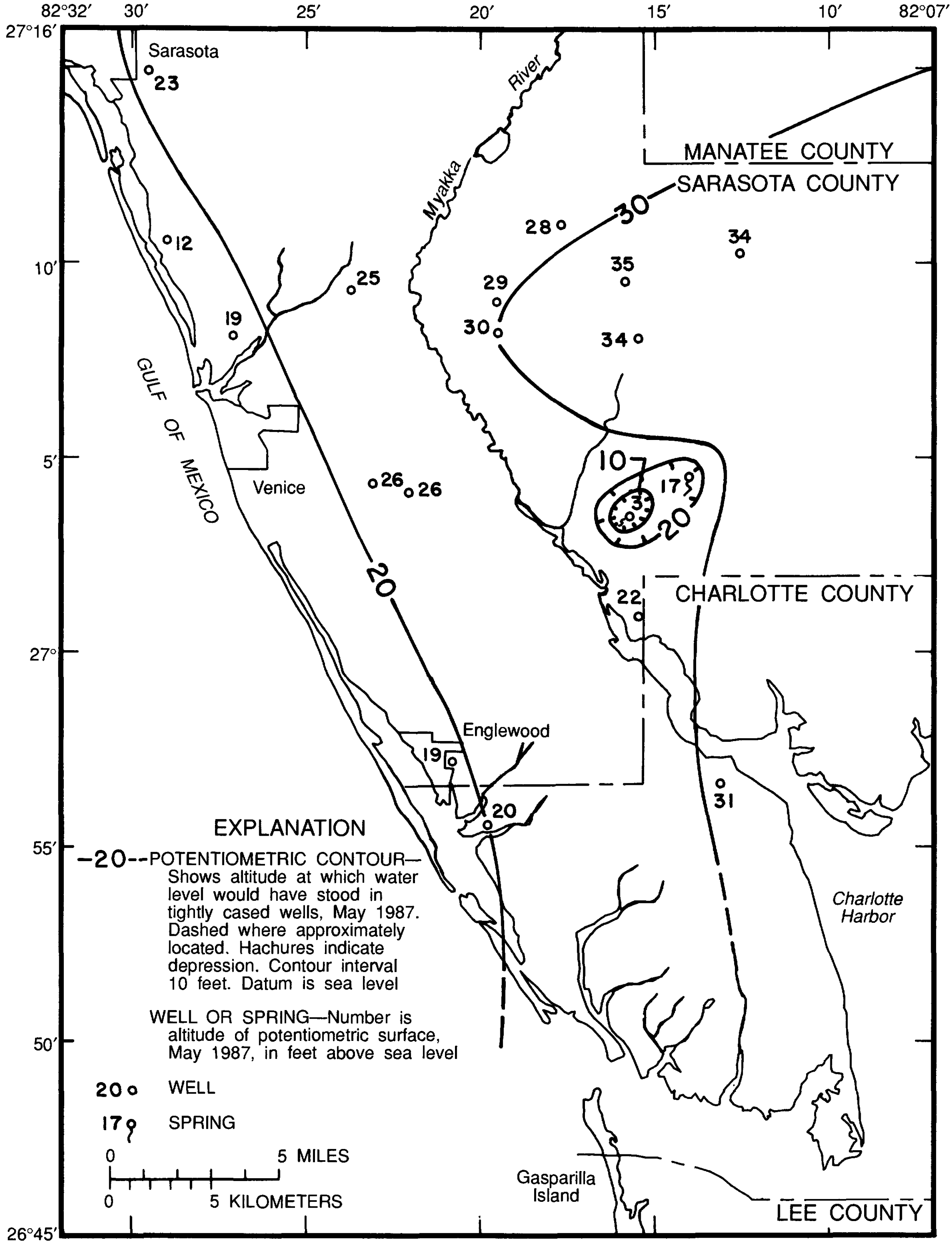


Figure 15. Potentiometric surface of the Upper Floridan aquifer, May 1987. (Modified from Lewelling, 1987b.)

Lower Suwannee-Ocala Semiconfining Unit

Chapter 17–28.21 of the Florida Department of Environmental Regulation (1982b) rules for underground injection control states:

> ...At least one confining zone above the injection zone is required. The applicant must demonstrate that the confining zone has sufficient areal extent, thickness, lithologic and hydraulic characteristics to prevent injected fluid migration and that it insures protection of underground sources of drinking water....

In the study area, the lower Suwannee-Ocala semiconfining unit is the principal hydrogeologic unit that satisfies the FDER requirement. The unit is a fine-grained, soft to partially indurated, micritic limestone containing abundant miliolid remains and scattered large foraminifera. In the 1980's, the unit was identified over a wide area of southwest Florida through drilling and testing at injection-well sites. Prior to injection-site testing, the unit was considered to have permeability comparable to the rest of the Upper Floridan aquifer, although it was tapped by only a few irrigation wells over 800 ft deep.

The Suwannee-Ocala semiconfining unit was delineated by interpreting gamma-ray logs. The unit exhibits low gamma radiation and is characteristic of pure limestone. It occurs immediately below the dolomitic limestone marker bed. The top of the Suwannee-Ocala semiconfining unit occurs above the base of the Suwannee Limestone in several geologic logs of test wells in the study area. The bottom of the unit is highly irregular and corresponds to the top of the injection zone within the Ocala Limestone at sites 25, 45, and 74 and was estimated to coincide with the top of the Avon Park Formation at other test wells for which hydrogeologic data are available (table 5).

Hydraulic properties of the semiconfining unit were estimated from an aquifer test at ROMP TR5–2 and measured core permeabilities and packer tests at the injection sites. As part of this study, a radial flow model was used to simulate drawdown in a lower Suwannee-Ocala semiconfining unit observation well in response to pumping from the overlying Suwannee permeable zone (Hutchinson and Trommer, in press). Vertical hydraulic conductivity estimated through computer simulation is 0.1 ft/d, which falls within a range of 0.1 to 0.25 ft/d for vertical and horizontal conductivities measured in cores and packer tests (table 7). Hydraulic conductivity of the unit is low compared to that of the overlying Suwannee permeable zone (65 ft/d) and the underlying injection zone (100 ft/d).

Injection Zone

The injection zone comprises about 1,000 ft of permeable rocks of the Upper Floridan aquifer below the lower Suwannee-Ocala semiconfining unit and above the middle confining unit of the Floridan aquifer system (table 4). Two permeable units within the zone have been identified through drilling and testing at injection-well sites (fig. 5). The upper unit, herein named the Ocala-Avon Park moderately permeable zone, consists of about 300 ft of interbedded, porous limestone and dolomite. The lower unit, the Avon Park highly permeable zone, consists of up to 700 ft of massive, hard, dark-brown dolomite that contains large solution channels that have developed along fractures (Wolansky and others, 1980). This highly fractured lower unit is recognized by cycle skipping on sonic logs and high resistivity on induction logs. Test-injection wells commonly are cased to the uppermost permeable unit within the injection zone. This depth is highly variable, as demonstrated by 1,040 ft and 1,702 ft of casing in the Englewood and Gasparilla Island test-injection wells, respectively (index nos. 25 and 1 in fig. 6).

Transmissivity of the injection zone was estimated mostly from single-well tests that are required by the FDER as part of the injection site permitting process (table 6). The tests were usually conducted on partially penetrating wells and are summarized in the following text to provide insight as to the variability of this important regional unit.

1. Gasparilla Island.—A transmissivity of approximately 64,000 ft^2/d was estimated in an unspecified procedure by using data from a 560-gal/min, 8-h injection test (Geraghty and Miller, Inc., 1986). The well has a 224-ft open-hole interval from 1,702 to 1,926 ft below land surface in the upper part of the Avon Park highly permeable zone. Interpretations of geophysical logs, lithologic logs, and packer tests were used to conclude that the Ocala-Avon Park moderately permeable zone had an insignificant injection capacity; therefore, it was cased off.
2. Englewood.—A transmissivity of approximately 80,000 ft^2/d was estimated from a log-log time-drawdown plot for a 1,000-gal/min, 480-min withdrawal test (CH2M Hill, Inc., 1986). The well has a 760-ft open-hole interval from 1,040 to 1,800 ft below land surface in the upper part of the injection zone. A previous test, with a 1,150-ft open-hole interval from 450 to 1,600 ft deep and just into the top of the Avon Park highly permeable zone, yielded a transmissivity of 48,000 ft^2/d, estimated by the above procedure, for a 962-gal/min, 395-min test.
3. North Port.—A transmissivity between 140,000 and 370,000 ft^2/d was estimated by using various analytical techniques for a 2,200-gal/min, 24-h test (CH2M Hill, Inc., 1988). The well is 3,200 ft deep and has a 2,100-ft open-hole interval that fully penetrates the 910-ft-thick injection zone and taps underlying units. The lower transmissivity value was based on analysis of data from the pumped well. The higher value was derived from analysis of data from a partially penetrating satellite monitor well 4,000 ft north of the pumped well. A fault may lie between the two wells, thereby complicating analysis of the test. Earlier tests, conducted as the well was being drilled, produced transmissivity estimates of 8,900 and 72,000 ft^2/d for open-hole intervals of 560 to 1,100 ft and 560 to 1,600 ft, respectively.

By subtraction, transmissivity is approximately 63,000 ft^2/d for the interval from 1,100 to 1,600 ft that taps the Ocala-Avon Park moderately permeable zone and the upper 100 ft of the Avon Park highly permeable zone. A subsequent analysis of a 200-minute test of the interval from 1,100 to 2,000 ft produced a transmissivity estimate of 150,000 ft^2/d for the total thickness of the injection zone. Comparison of test results indicates that the lower 400 ft of the injection zone is more permeable than the upper 500 ft, and permeability is low in formations below 2,000 ft.

4. Plantation.—A transmissivity of approximately 67,000 ft^2/d was estimated by using various procedures to analyze plots of drawdown and recovery for a 650-gal/min, 5-d injection test (Post, Buckley, Schuh, and Jernigan, Inc., 1984). The well was reported to have a 503-ft open-hole depth interval from 1,102 to 1,605 ft at the top of the injection zone, but when logged, the bottom 256 ft of hole had filled in. If only the upper 247 ft were tested, it could be considered a representative test of the Ocala-Avon Park moderately permeable zone, and results are similar to the 80,000-ft^2/d value estimated from the North Port injection site.
5. Venice Gardens.—A transmissivity of approximately 24,000 ft^2/d was calculated from a 37-min recovery period following a 1,400-gal/min, 24-h injection test (Geraghty and Miller, Inc., 1985). The well has a 317-ft open-hole interval from depths of 1,388 to 1,705 ft in the upper part of the Avon Park highly permeable zone. Geophysical log interpretations were used to conclude that the Ocala-Avon Park moderately permeable zone would not accept significant quantities of injectant; therefore, this zone was cased off in the completed injection well.
6. Knight Trail Park.—A transmissivity of approximately 300,000 ft^2/d was estimated by using semilogarithmic plots of drawdown and recovery for a 747-gal/min, 3-h test (Law Environmental, Inc., 1989, p. 3–38). The well has a 272-ft open-hole interval that taps the lower part of the Avon Park highly permeable zone. The first significant hydraulic conductivity was encountered at a depth of about 1,600 ft, which is about 150 ft below the top of the dark-brown dolomite that comprises the Avon Park highly permeable zone. Although the 150-ft interval appears to have a low hydraulic conductivity, it may be just coincidental that no fractures were encountered by the borehole. The dolomitic injection zone correlates stratigraphically with that in St. Petersburg as

Table 7. Porosity and hydraulic conductivity of the lower Suwannee-Ocala semiconfining unit

[ft/d, feet per day; – –, no data]

Index number[1]	Depth (ft)	Porosity	Hydraulic conductivity: Vertical (ft/d)	Hydraulic conductivity: Horizontal (ft/d)	Method	Source
25	922	0.37	0.01	0.03	Lab	CH2M Hill, Inc. (1986).
	926	.40	.01	.03	Lab	
	931	.45	.09	.11	Lab	
	916–926	– –	– –	.25	Packer	
45	862	.37	.57	.57	Lab	CH2M Hill, Inc. (1988).
	913	.37	2.27	1.13	Lab	
	916	.37	.28	.57	Lab	
	947	.31	.09	.14	Lab	
	1,020	.24	.06	.09	Lab	
	1,029	.22	.06	.06	Lab	
	1,072	.22	.03	.06	Lab	
	1,074	.22	.02	.02	Lab	
	1,105	.27	.01	.01	Lab	
	1,020–1,032	– –	– –	.19	Packer	
	1,054–1,066	– –	– –	.52	Packer	
74	842	.09	– –	– –	Lab	Post, Buckley, Schuh, and Jernigan, Inc. (1982b).
	854	.43	– –	– –	Lab	
	913	.03	– –	.23	Lab	
76	1,217	.28	– –	– –	Lab	Geraghty and Miller, Inc. (1985).
	1,262	.24	– –	– –	Lab	
	1,328	.28	– –	– –	Lab	
110	750–1,100	– –	.1	.1	Model	Hutchinson and Trommer (in press).
115	1,053	.22	.01	.08	Lab	Law Environmental, Inc. (1989).
	1,152	.25	.005	.007	Lab	
	1,043–1,068	– –	– –	2.2–7.3	Packer	

[1]Index numbers correspond to those in table 3 and figure 6.

described by Hickey (1982, p. 15) who reported it as having variable hydraulic conductivity in the upper part. He originally hypothesized that a confining unit existed between the producing intervals in the upper and lower parts of the zone (much like what is observed at Knight Trail Park). Subsequent data from injection tests at St. Petersburg proved that the permeable intervals are interconnected. This interconnection was attributed by Hickey to fractures at some distance from the well that were not encountered by the borehole. It is likely that the Knight Trail Park injection-monitor well was not open to fractures in the upper part of the injection zone; therefore, it was cased off.

7. Atlantic Utilities.—A transmissivity of approximately 5,000 ft^2/d was estimated by using a logarithmic plot of drawdown for a 1,390-gal/min, 24-h test (Post, Buckley, Schuh, and Jernigan, Inc., 1989, p. 8–15). The well has a 422-ft open-hole interval in the Avon Park highly permeable zone. Although the site is about 10 mi north of the study area (fig. 5), test data may be extrapolated to the boundary. The low transmissivity may be attributed to an anomalous relatively impermeable gypsiferous dolomite section above the injection zone that correlates with the upper part of the Avon Park highly permeable zone at other injection sites.

Although there was little uniformity in how the aquifer tests were conducted and analyzed, it is apparent from test results that the transmissivity, hence the hydraulic conductivity, of the upper part of the injection zone is quite variable, whereas the lower part has fairly uniform transmissivity. Of the seven test-injection sites, three had significant injection capacity in the upper part (Ocala-Avon Park moderately permeable zone), as well as in the underlying Avon Park highly permeable zone.

The Avon Park highly permeable zone is the primary zone targeted for injection because of its ability to receive large volumes of wastewater having relatively low injection pressure. Wolansky and others (1980) produced a regional map of west-central Florida showing the configuration of the top of the zone based on hydrogeologic data from two test wells within southwest Sarasota and west Charlotte Counties. The estimated top of this zone has now been revised (fig. 16) by using additional data from deep injection and ROMP test holes. The surface slopes uniformly under a gradient of 15 ft/mi from north to south from about 1,400 ft below sea level at Venice to 1,700 ft below sea level at Gasparilla Island. The revised map may be useful for estimating depths of proposed injection wells.

The potentiometric surface of the injection zone was mapped by using water levels measured in two observation wells and six injection wells prior to injection of wastewater (fig. 17). The zone contains very saline water of constant density having dissolved-solids concentrations varying between about 25,000 and 35,000 mg/L. Some water-level measurements were several years apart and do not represent a "snapshot" of the potentiometric surface. The map depicts the potential for ground-water movement to the coast with an environmental head gradient of about 1 ft/mi between the North Port and Englewood injection wells where water-level measurements are accurate. Head measurements at the Plantation and Gasparilla Island injection wells were estimated from historical records of pumping tests. These two wells were drilled by using a closed-circulation method, which precluded accurate measurements of head in the injection zone.

WATER QUALITY

Native Ground Water

The quality of ground water is controlled by contact time with and composition of rocks and soil through which it moves. Thus, the chemical quality of water from an aquifer depends upon lithology of the aquifer. Quartz sand, the principal mineral of the surficial aquifer system, is relatively insoluble. The sandy and clayey limestone and dolomite of the intermediate aquifer system are more soluble than the quartz sand, but because they contain silicate minerals, they are probably less soluble than the relatively pure carbonates of the Upper Floridan aquifer. In addition to the dissolution of the rock matrix, solute is added in deep zones where ancient seawater is slowly being flushed from the system and in shallow zones where intrusion is occurring. The above conceptual system should result in water that has increasing salinity with depth and proximity to the gulf coast.

The principal chemical constituents in ground water within the study area that affect potability are chloride, sulfate, dissolved solids, fluoride, and radium. Iron and color often affect the potability of water for esthetic rather than health reasons. Recommended or permitted maximum concentrations for these constituents in public water supplies are as follows:

Constituent	Florida Department of Environmental Regulation Standard for public drinking water systems[1]
Chloride (mg/L)	250
Color (Pt-Co units)	15
Dissolved solids (mg/L)	500
Fluoride (mg/L)	1.6[2]
Iron (mg/L)	.3
Radium 226 + 228 (pCi/L)	5
Sulfate (mg/L)	250

[1]Florida Department of Environmental Regulation, 1982a.
[2]Based on mean air temperature of study area, 73 °F.

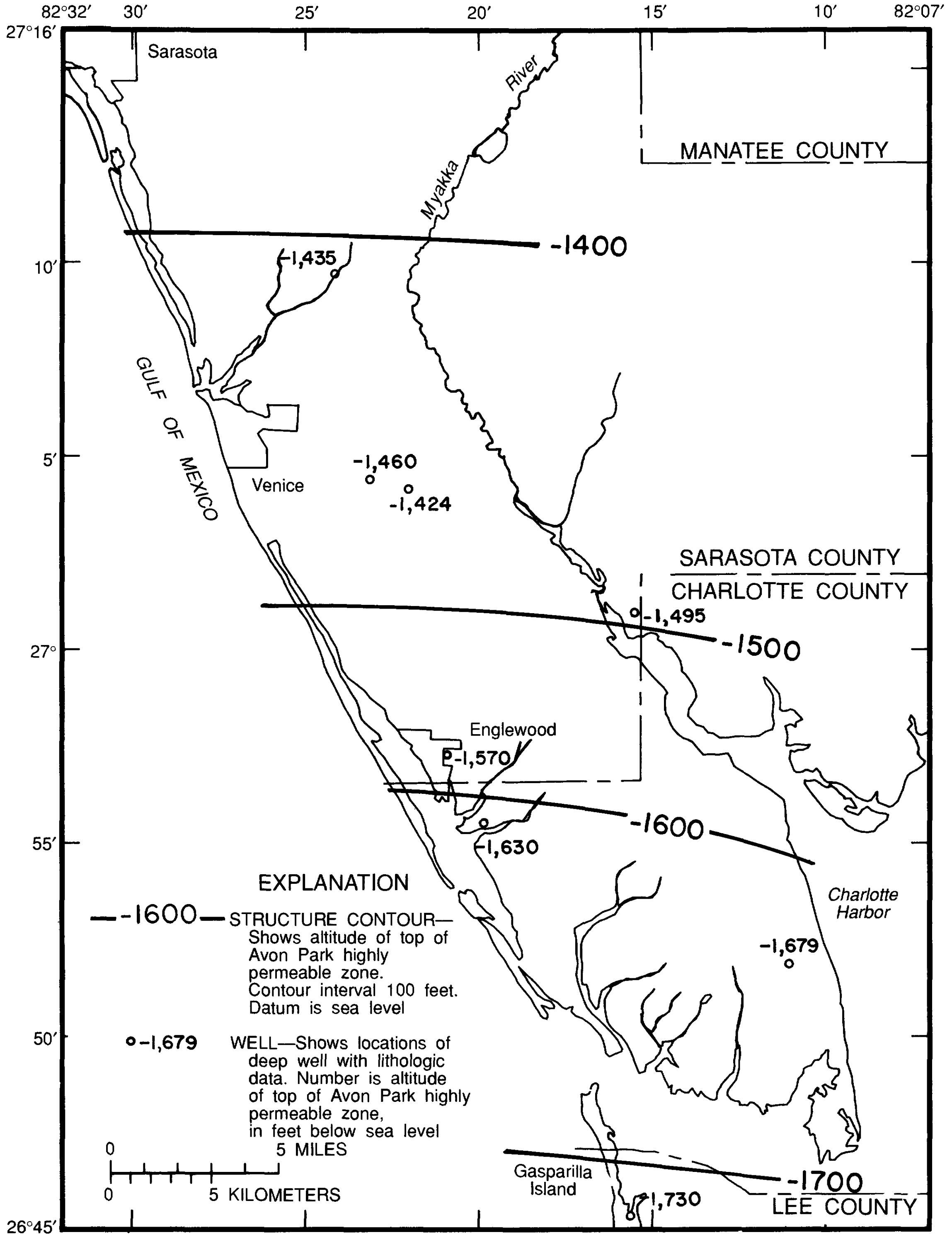


Figure 16. Configuration of the top of the Avon Park highly permeable zone within the Upper Floridan aquifer. (Modified from Wolansky and others, 1980.)

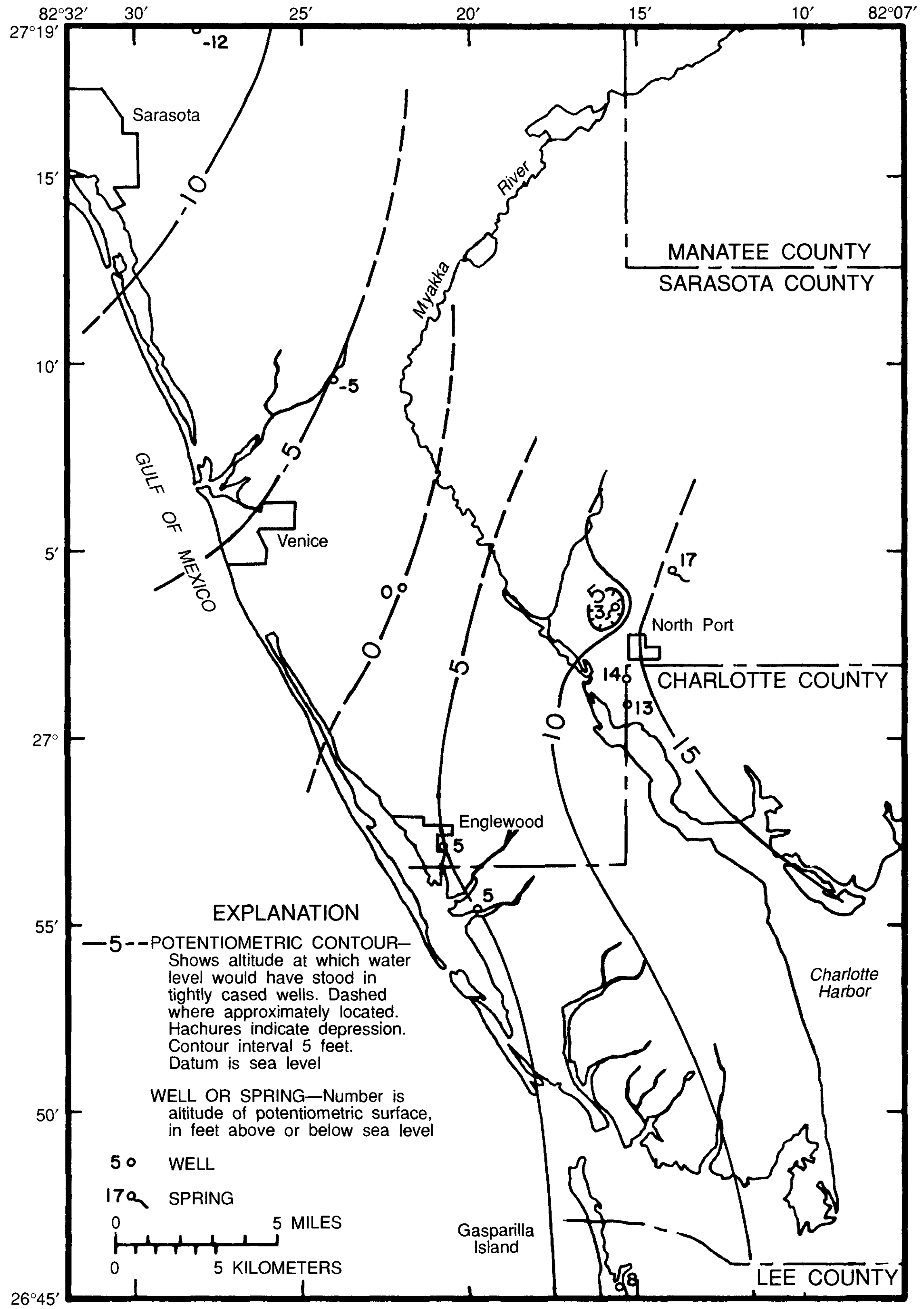


Figure 17. Potentiometric surface of the very saline injection zone within the Upper Floridan aquifer.

Dissolved-solids concentration is the major concern for ground-water management in the study area. Critical concentrations for various uses of an aquifer are as follows:

Dissolved-solids range (mg/L)	Use of aquifer
<500	Potable water source.
500–8,000 (approximate)	Source of water for irrigation supplies and low-pressure reverse-osmosis treatment process.
>10,000	Potential receiving zone for treated sewage or source for high-pressure reverse-osmosis treatment process.

The study area is in a coastal pensinsular setting where a shallow, potable water lens grades downward and coastward to seawater. Transition zones from freshwater to very saline water do not conform to hydrogeologic boundaries; however, permeability may control the position of the interface.

Figure 6 shows the locations of wells and springs for which chemical analyses are listed in table 8. Figures 18 through 21 illustrate the areal distributions of dissolved-solids concentrations within four important water-bearing zones: shallow Tamiami-upper Hawthorn aquifer, composite intermediate aquifer system, Suwannee permeable zone, and the deep injection zone. Superimposed on the maps are Stiff diagrams that show relative concentrations of major constituents that constitute the dissolved solids. Conclusions drawn from table 8 and the maps are:

1. Raw ground water generally does not meet drinking-water standards. Only 13 wells produced water that had a dissolved-solids concentration less than the 500-mg/L limit for potable supply. Two of these wells are 30 ft deep or less and tap the surficial aquifer, nine are between 65 and 180 ft deep and tap the Tamiami-upper Hawthorn aquifer, and two are more than 250 ft deep. Nineteen other wells between 55 and 185 ft deep that tap the Tamiami-upper Hawthorn aquifer produced water that contained at least 500 mg/L of dissolved solids (17 wells diagrammed in fig. 18 and wells 52 and 87 in table 8).
2. Salinity of ground water generally increases with depth. Median dissolved-solids concentrations for the sampled zones are as follows:

Hydrogeologic unit	Number of samples	Median dissolved solids (mg/L)	Class
Surficial aquifer system	2	<500	Fresh.
Tamiami-upper Hawthorn aquifer (fig. 18).	25	660	Slightly saline.
Composite intermediate aquifer system (fig. 19).	23	2,170	Slightly saline.
Suwannee permeable zone (fig. 20).	12	3,210	Moderately saline.
Injection zone (fig. 21).	9	32,800	Very saline.

Coastal areas do not conform to this general water-quality model, as indicated by analyses in table 8 from isolated depth intervals at ROMP sites TR3–1 and TR3–3 and from the Cattledock Point well as it was being drilled. At each site, water with a high chloride concentration was observed at depths of less than 200 ft. Salinity decreases considerably between about 200 and 600 ft, but eventually the water becomes very saline with depth. Very saline water near the surface can probably be attributed to past tidal inundation because the sites are low-lying and near the coast.

3. Salinity changes from north to south. In the upper three hydrogeologic units, water is less saline in the north than in the south. Water type grades from calcium sulfate in the north to sodium chloride in the south where there is probably residual seawater in the system. Water in the injection zone is very saline and is similar in composition to seawater.
4. Little Salt and Warm Mineral Springs derive water from deep sources. Little Salt (site 79) and Warm Mineral Springs (site 69) may be fed from multiple zones between land surface and the injection zone. Stiff diagrams of spring-water quality are included in figures 18 through 21 to facilitate comparison with water quality from discrete permeable zones that possibly contribute to spring flow. Little Salt Spring discharges water with a dissolved-solids concentration of 3,000 mg/L, which is similar in composition to water from wells that tap the Suwannee permeable zone (median dissolved solids of 3,210 mg/L). Water from Warm Mineral Springs, having a dissolved-solids concentration range between 18,000 and 21,000 mg/L, is very saline and resembles water collected from an interval between 68 and 1,407 ft in the Cattledock Point well (dissolved-solids concentration of 18,000 mg/L). This implies that the spring taps the injection zone and, therefore, may provide a conduit for upward movement of injected wastewater. The dissolved-solids concentration, temperature, and individual ionic constituents indicate that the spring flow sampled at a depth of 230 ft contains about 60 percent seawater. Likely avenues for the spring's discharge are upward along unmapped faults similar to the fault discovered 2–4 mi to the south.

Figure 22 shows hydrogeologic section A–A′ (line of section is shown in fig. 6) with superimposed dissolved-solids concentrations derived from packer-test and well-water analyses. The 10,000-mg/L line of dissolved solids, which is the minimum concentration acceptable for injection, is about 1,200 ft deep at the Atlantic Utilities injection site (136) in the north about 3 mi inland and less than 300 ft deep at the Gasparilla Island site (1, 2), which is actually off the Florida peninsula. In the northern part of the study area, the lower Suwannee-Ocala semiconfining unit contains or is underlain by moderately saline water that is unacceptable for injection, as exemplified at the Atlantic Utilities and Plantation sites (136 and 71–74). In the southern part, the thick semiconfining unit separates usable water from injected wastewater.

Table 8. Ground-water quality

[Bicarbonate was calculated by multiplying measured alkalinity by 1.2194. Dissolved-solids residue is reported if the analysis was made; otherwise, dissolved solids represents the calculated sum of ionic constituents. mg/L, milligrams per liter; – –, no data]

Index no.	Latitude-longitude	Casing/depth (ft)	Date	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L HCO_3)	Sulfate (mg/L)	Chloride (mg/L)	Dissolved solids (mg/L)	Site name
1	264525082153501	1,702/1,926	1–29–85	– –	– –	9,464	– –	– –	– –	18,982	36,100	Gasparilla Island injection well IW1 .
2	264525082153502	340/360	11–18–66	753	989	10,600	418	140	2,660	18,800	32,800	Gasparilla Island injection monitor well.
3	265017082153701	346/413	1–13–66	300	440	3,700	100	– –	470	7,100	12,000	Placida #8.
5	2653200821435	<32	11–18–69	120	6	42	0	354	0	74	421	Gasparilla Island well field.
6	265531082194801	1,600/1,652	9–03–86	700	1,100	11,000	460	139	2,800	19,000	35,200	ROMP TR3–3 Avon Park well.
7	265531082194802	1,080/1,120	9-03–86	750	1,000	9,500	380	146	2,300	17,000	31,000	ROMP TR3–3 Ocala well.
8	265531082194803	680/900	5–28–87	400	500	4,200	120	177	1,100	8,000	14,000	ROMP TR3–3 Suwannee well.
9	265531082194804	370/410	9–04–86	110	100	330	20	175	280	760	1,700	ROMP TR3–3 lower Hawthorn well.
10	265531082194805	155/175	9–03–86	110	200	1,500	56	141	470	3,100	5,500	ROMP TR3–3 upper Hawthorn well.
12	265557082152201	258/300	5–13–66	230	180	970	26	180	450	2,000	4,000	USGS 19 San Cassa.
13	265612082110301	68/85	0–00–66	300	470	3,400	120	196	500	7,000	24,500	Cattledock Point well.
		68/189	0–00–66	130	90	230	15	194	17	760	2,130	
		68/410	0–00–66	240	180	1,200	32	148	520	2,300	5,320	
		68/743	3–21–66	244	170	1,050	28	154	512	2,100	4,904	
		68/1,031	3–25–66	299	269	1,880	60	148	718	3,640	8,040	
		68/1,407	3–25–66	464	666	5,190	186	134	1,500	9,870	18,000	
15	265638082130703	140/160	5–06–86	110	80	380	14	183	17	920	2,040	ROMP TR3–1 upper Hawthorn well.
17	265638082130705	380/400	5–06–86	130	84	360	20	175	500	610	1,910	ROMP TR3–1 lower Hawthorn well.
18	265638082130706	600/620	2–02–86	110	79	270	17	217	470	410	1,500	ROMP TR3–1 Suwannee well.
19	265652082185801	– –/101	9-15–87	– –	– –	– –	– –	– –	25	2,500	[1]4,700	Englewood well 150.
20	265653082190301	175/320	12-17–75	130	120	490	17	159	150	1,200	2,200	Englewood RO 1.
21	265710082205101	152/310	1–06–76	210	110	540	19	165	160	1,400	2,600	Englewood RO 2.
22	265712082205701	51/110	5–22–74	95	6	19	1	244	29	40	330	Englewood well R–2.
25	265716082205101	1,040/1,800	1–23–86	594	[2]680	9,990	[2]290	146	2,550	19,050	33,300	Englewood injection well IW–1.
26	265716082205102	500/550	2–04–86	173	[2]500	926	[2]130	100	264	2,400	4,490	Englewood injection monitor well MW–1.
30	265834082202401	43.5/55	9–22–87	– –	– –	– –	– –	– –	44	320	[1]980	Englewood well 14.
31	265834082202402	10/20	2–08–79	24	2	– –	– –	64	28	6	[1]140	Englewood well 14A.
33	265927082195201	56/110	4–09–81	130	60	230	8	184	13	670	1,630	Englewood test well C–8.
34	265944082175401	28/101	8–04–66	170	110	680	14	190	130	1,500	3,240	USGS 20 Plamore.
37	270018082201301	47/120	4–09–81	74	28	84	6	178	16	250	590	Englewood test well C–7.
39	270032082205801	52/253	4–10–81	170	100	380	12	200	430	830	2,170	Venetia (Berry 8).
40	2700330822142	35/70	0–00–78	295	38	73	– –	304	0	72	484	Englewood production test well 4.
41	270036082213401	41.5/70	1–19–76	110	7	36	1	362	0	60	423	Englewood test well C–10.
42	2700380822113	35/70	0–00–78	300	10	8	– –	308	4	36	406	Englewood production test well 5.
44	270057082210501	48/185	4–09–81	90	48	2	7	195	210	190	791	Venetia (Berry 7).

Table 8. Ground-water quality—Continued

[Bicarbonate was calculated by multiplying measured alkalinity by 1.2194. Dissolved-solids residue is reported if the analysis was made; otherwise, dissolved solids represents the calculated sum of ionic constituents. mg/L, milligrams per liter; – –, no data]

Index no.	Latitude-longitude	Casing/depth (ft)	Date	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L HCO3)	Sulfate (mg/L)	Chloride (mg/L)	Dissolved solids (mg/L)	Site name
45	270058082152501	1,100/3,200	11–13–87	1,520	720	8,700	315	134	3,060	16,600	32,800	North Port deep injection well DIW.
46	270058082152502	730/750	11–13–87	920	720	3,500	126	122	1,450	7,910	15,000	North Port onsite monitor well.
47	270058082152503	560/600	11–13–87	1,000	72	2,500	68	124	975	5,400	10,900	North Port onsite monitor well.
48	2701040822141	42/70	0–00–78	282	32	77	– –	304	0	62	458	Englewood production test well 3.
49	270106082214101	109/135	9–15–87	– –	– –	– –	– –	– –	14	70	[1]360	Englewood deep zone well 3 .
50	2701070822112	43/70	0–00–78	302	18	59	– –	317	0	44	546	Englewood production test well 1.
51	270112082201201	65/120	4–09–81	82	32	92	7	213	16	270	756	Englewood test well C–9.
52	270112082213301	58/70	1–14–80	– –	9	– –	– –	378	0	110	531	Englewood production well 8.
54	270113082223302	40/70	8–05–86	140	15	75	2	376	26	180	650	Englewood production well 5.
57	270137082235301	263/305	8–25–66	12	19	55	7	180	1	56	250	Manasota deep well 14.
58	270138082152401	1,100/1,150	11–27–87	1,360	456	6,800	230	139	1,960	13,000	25,200	North Port satellite monitor well SMW.
61	270203082210101	212/315	1–31–84	– –	– –	– –	– –	– –	600	380	[1]1,200	Venetia (Berry 3).
62	270203082213701	207/608	2–01–84	– –	– –	– –	– –	– –	730	460	[1]1,500	Venetia 2 (Berry 4).
63	270205082204001	290/472	1–30–84	– –	– –	– –	– –	– –	850	680	[1]1,700	Venetia (Berry 5).
64	270219082185801	102/274	3–21–84	– –	– –	– –	– –	– –	840	1,100	[1]2,900	Manatee Jr. College south well.
65	270223082185701	41/158	3–21–84	– –	– –	– –	– –	– –	30	170	[1]500	Manatee Jr. College middle well.
67	270240082235701	460/475	5–19–82	210	110	120	7	162	720	260	1,600	ROMP TR4–2.
69	270333082154000		4–24–72	500	580	5,200	250	159	1,700	9,500	18,000	Warm Mineral Springs top.
			7–31–73	520	730	7,300	210	159	1,700	11,400	21,000	Warm Mineral Springs 230-ft depth.
71	280403082220001	66/180	3–11–87	– –	– –	– –	– –	– –	53	69	326	Plantation monitor well 1
72	270404082215801	52/65	3–11–87	– –	– –	– –	– –	– –	198	29	228	Plantation monitor well 2.
73	270406082215901	630/650	3–11–87	– –	– –	– –	– –	– –	1,250	892	3,520	Plantation zone 4 monitor well.
74	270406082220101	1,102/1,605	8–08–83	850	982	5,546	546	130	2,540	18,900	34,090	Plantation deep injection test well DITW.
75	270407082215801	228/366	5–16–82	243	139	154	19	150	972	358	2,058	Plantation RO test well 2.
76	270420082230501	1,388/1,705	6–10–85	– –	– –	10,947	– –	– –	2,530	17,745	32,100	Venice Gardens deep injection well DIW.
77	270420082230502	770/800	6–10–85	– –	– –	613	– –	– –	1,320	1,116	3,780	Venice Gardens injection monitor well 800.
78	270420082230503	200/400	6–10–85	– –	– –	423	– –	– –	1,320	642	2,930	Venice Gardens injection monitor well 400.
79	270430082140000		10–30–72	180	130	750	19	171	510	1,300	3,000	Little Salt Spring.
83	2705340822609	206/441	6–13–82	310	143	138	18	134	1,200	300	2,750	Venice RO 6.
84	2705360822539	77/140	6–05–82	120	45	101	29	97	415	130	1,240	Venice well 2.
86	270542082261801	86/163	11–20–87	– –	– –	– –	– –	– –	270	110	[1]660	Venice well 35.
87	270542082261802	– –/68	9–21–87	– –	– –	– –	– –	– –	150	110	[1]620	Venice well 36.
93	270714082155201	282/351	4–22–66	100	80	63	5	170	410	120	890	Test 18 Blackburn Ranch.
94	270728082232801	229/1,046	9–09–65	430	160	32	5	140	1,500	60	2,300	Wheelwright 1.
97	270808082270502	492/510	11–23–87	– –	– –	– –	– –	– –	1,400	54	[1]1,600	ROMP TR5–1 Suwannee well.
98	270808082270502	275/289	11–23–87	– –	– –	– –	– –	– –	1,200	33	[1]1,400	ROMP TR5–1 Hawthorn well.
101	270822082231101	40/286	4–01–81	330	130	26	5	137	1,300	30	1,900	Henry Ranch 1.
102	270840082225101	– –/78	4–03–81	340	120	35	5	178	1,200	60	1,900	Henry Ranch 3.

Table 8. Ground-water quality—Continued

[Bicarbonate was calculated by multiplying measured alkalinity by 1.2194. Dissolved-solids residue is reported if the analysis was made; otherwise, dissolved solids represents the calculated sum of ionic constituents. mg/L, milligrams per liter; – –, no data]

Index no.	Latitude-longitude	Casing/depth (ft)	Date	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L HCO_3)	Sulfate (mg/L)	Chloride (mg/L)	Dissolved solids (mg/L)	Site name
106 . . .	270919082234202	100/120	5–06–86	220	76	40	5	173	730	54	1,300	ROMP TR5–2 upper Hawthorn well.
107 . . .	270919082234203	245/265	5–06–86	300	120	32	5	157	1,100	36	1,700	ROMP TR5–2 lower Hawthorn well.
108 . . .	270919082234204	360/400	5–06–86	450	150	23	4	146	1,500	38	2,300	ROMP TR5–2 Tampa well.
109 . . .	270919082234205	510/700	5–07–86	520	150	22	4	149	1,700	41	2,500	ROMP TR5–2 Suwannee well.
110 . . .	270919082234206	850/890	5–06–86	450	160	16	5	135	1,600	20	2,400	ROMP TR5–2 Ocala well.
111 . . .	270931082252901	44/256	7–09–86	400	150	29	5	141	1,500	40	2,200	Ewing Ranch (Holland).
114 . . .	270934082252801	– –/100	9–17–87	– –	– –	– –	– –	– –	1,000	50	[1]1,200	Myakka River Nursery.
115 . . .	2709360822409	1,599/1,915	3–09–89	792	1,120	10,200	397	171	1,600	18,900	37,570	Knight Trail Park.
118 . . .	270959082203003	32/67	2–18–82	92	11	40	2	348	0	56	390	ROMP 19 WS.
124 . . .	271035082285901	– –/710	8–19–80	460	170	130	6	170	1,700	260	2,900	Southbay Utilities deep well.
128 . . .	271118082285301	157/255	2–18–66	78	23	29	3	190	82	78	420	Osprey well 9.
131 . . .	271222082295201	41/224	2–08–82	260	160	40	7	180	1,100	36	1,700	Sarasota County Historical Society.
134 . . .	271450082292601	– –/1,200	9–17–87	– –	– –	– –	– –	– –	1,400	280	[1]1,800	Mann Golf Course well.
136 . . .	271853082280901	1,480/1,902	11–29–88	19	1,400	12,500	303	– –	3,700	24,000	36,100	Atlantic Utilities test/injection well.
. . .	271853082280902	1,130/1,240	5–19–88	343	118	42	4	155	1,040	117	1,800	
									250	250	500	Drinking water standards.
				410	1,350	10,500	390	142	2,700	19,000	35,000	Seawater.

[1]Dissolved–solids concentration estimated from specific conductance (Hem, 1985, p. 57).

[2]Magnesium and potassium estimated as the residual of dissolved solids-measured constituents, then allocated in proportion to ratios observed in equivalent hydrogeologic units at ROMP TR3–3.

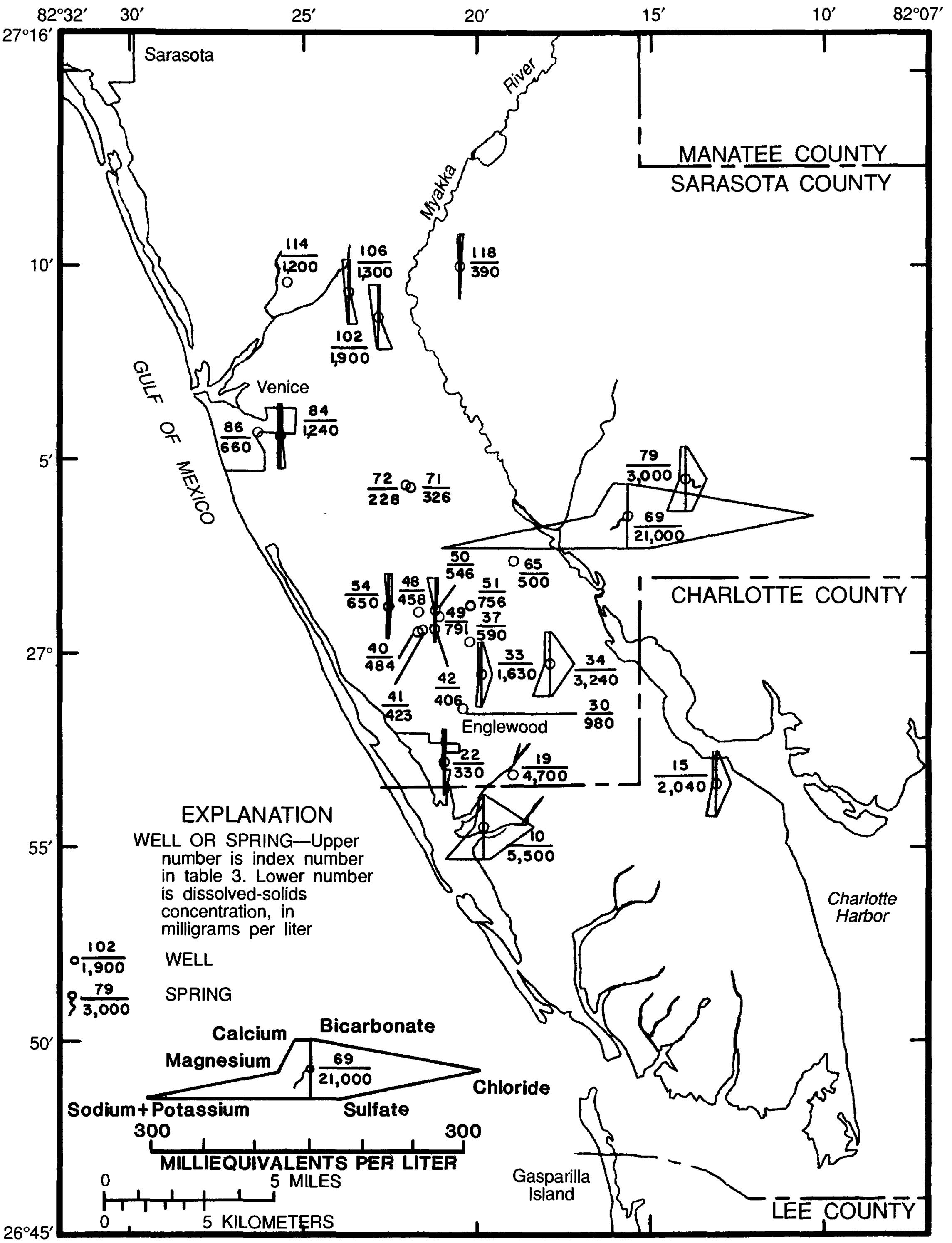


Figure 18. Dissolved-solids concentrations and Stiff diagrams depicting quality of water from springs and from wells that tap the Tamiami-upper Hawthorn aquifer.

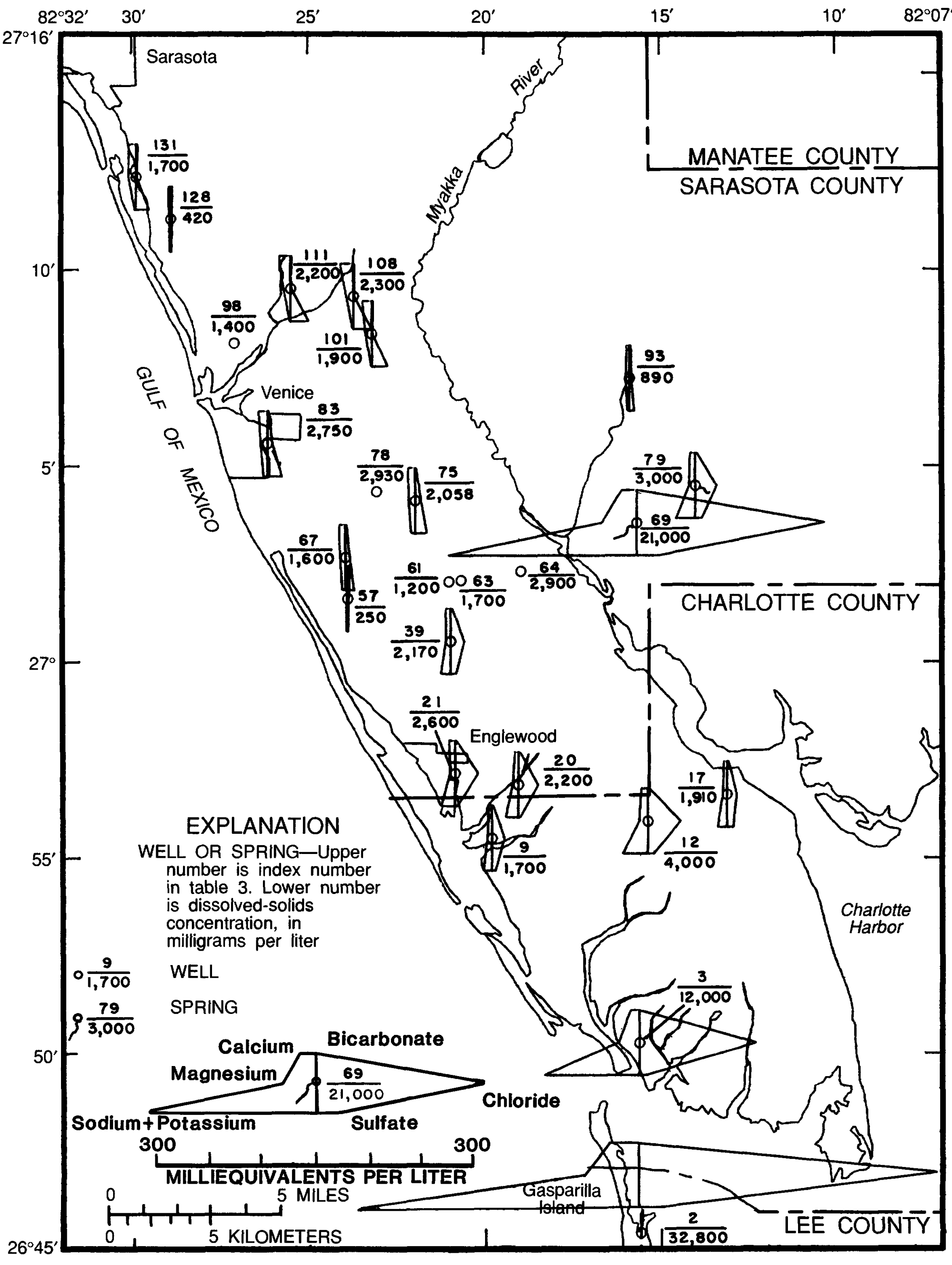


Figure 19. Dissolved-solids concentrations and Stiff diagrams depicting quality of water from springs and from wells that tap the lowermost or multiple zones within the intermediate aquifer system.

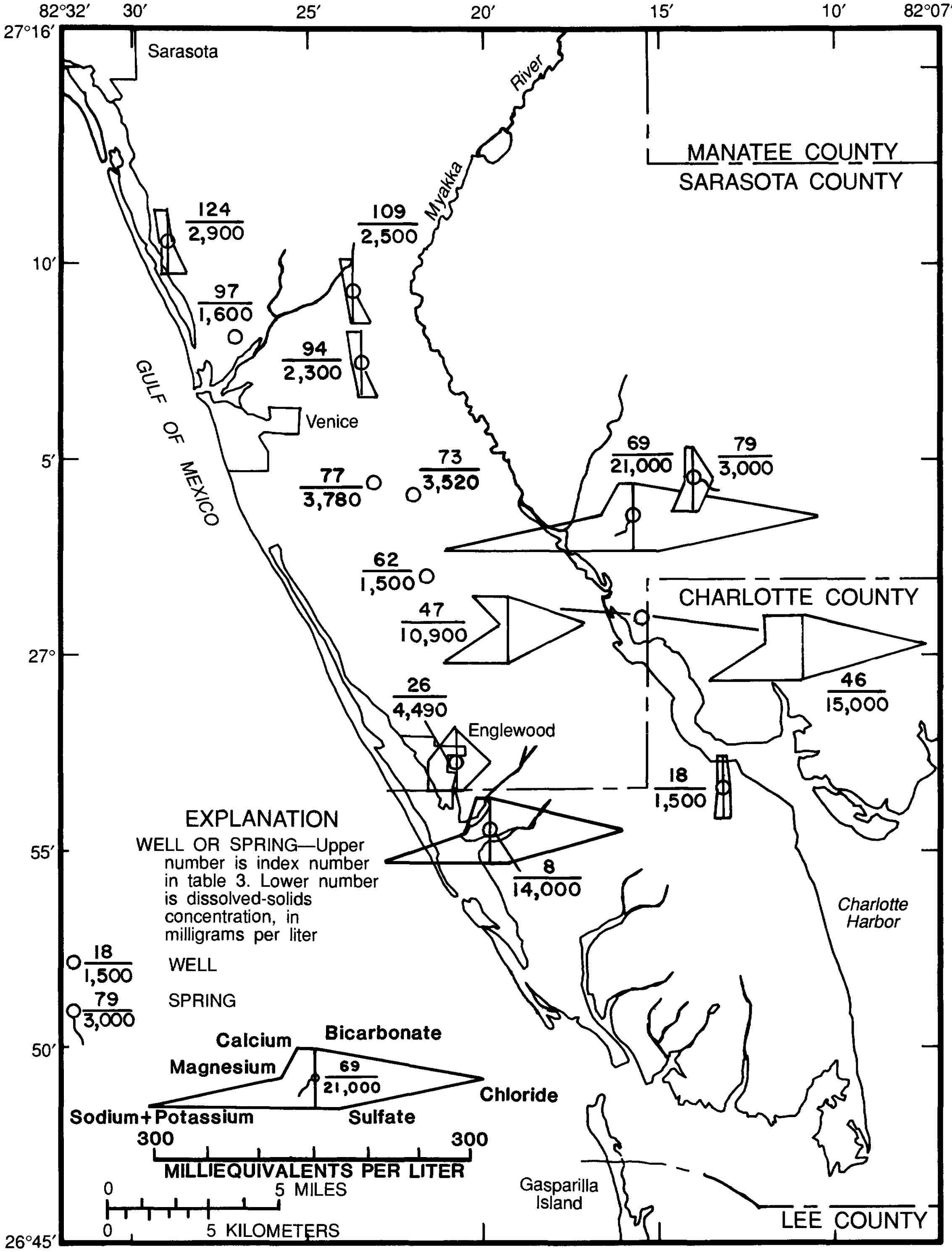


Figure 20. Dissolved-solids concentrations and Stiff diagrams depicting quality of water from springs and from wells that tap the Suwannee permeable zone.

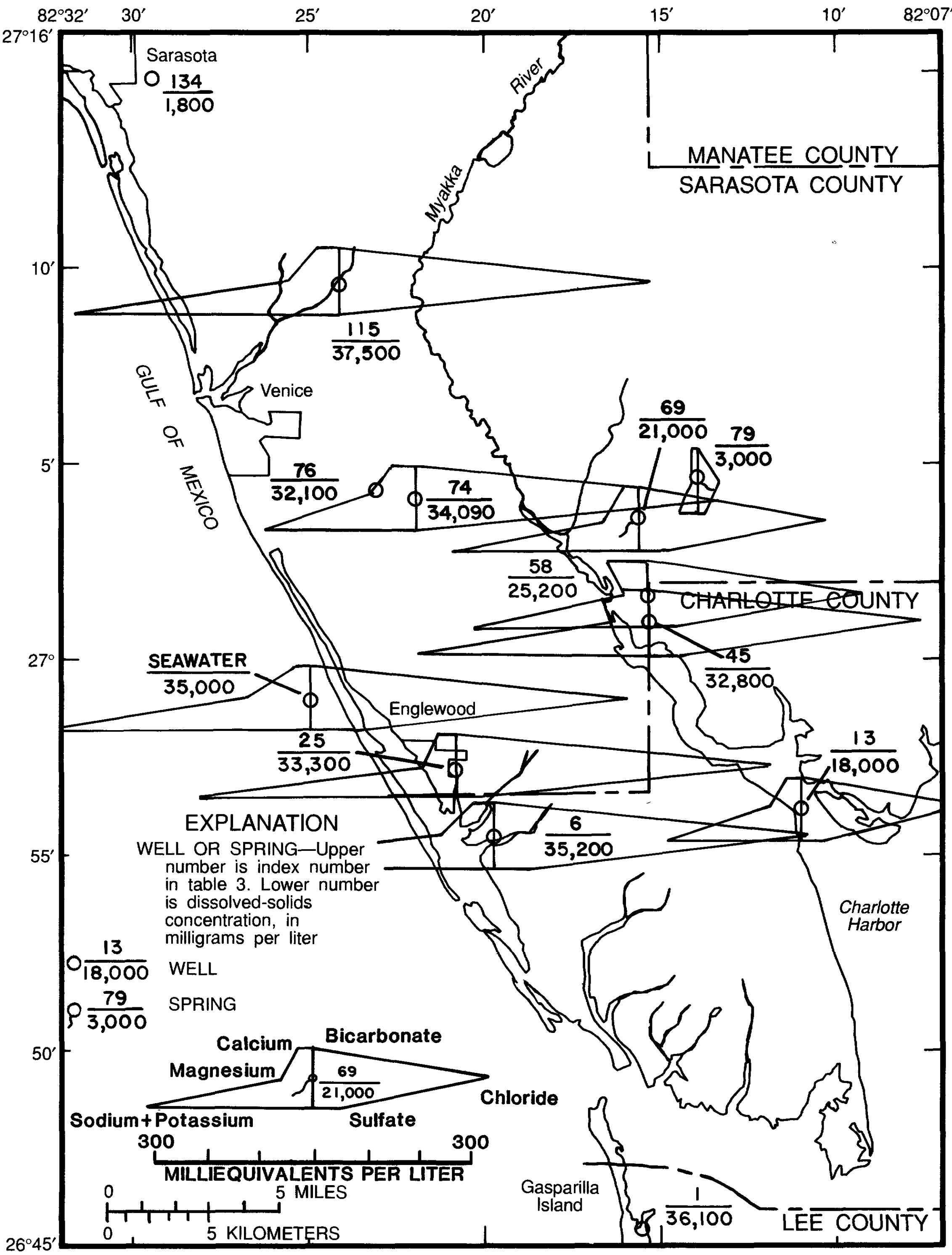


Figure 21. Dissolved-solids concentrations and Stiff diagrams depicting quality of water from springs and from wells that tap the injection zone.

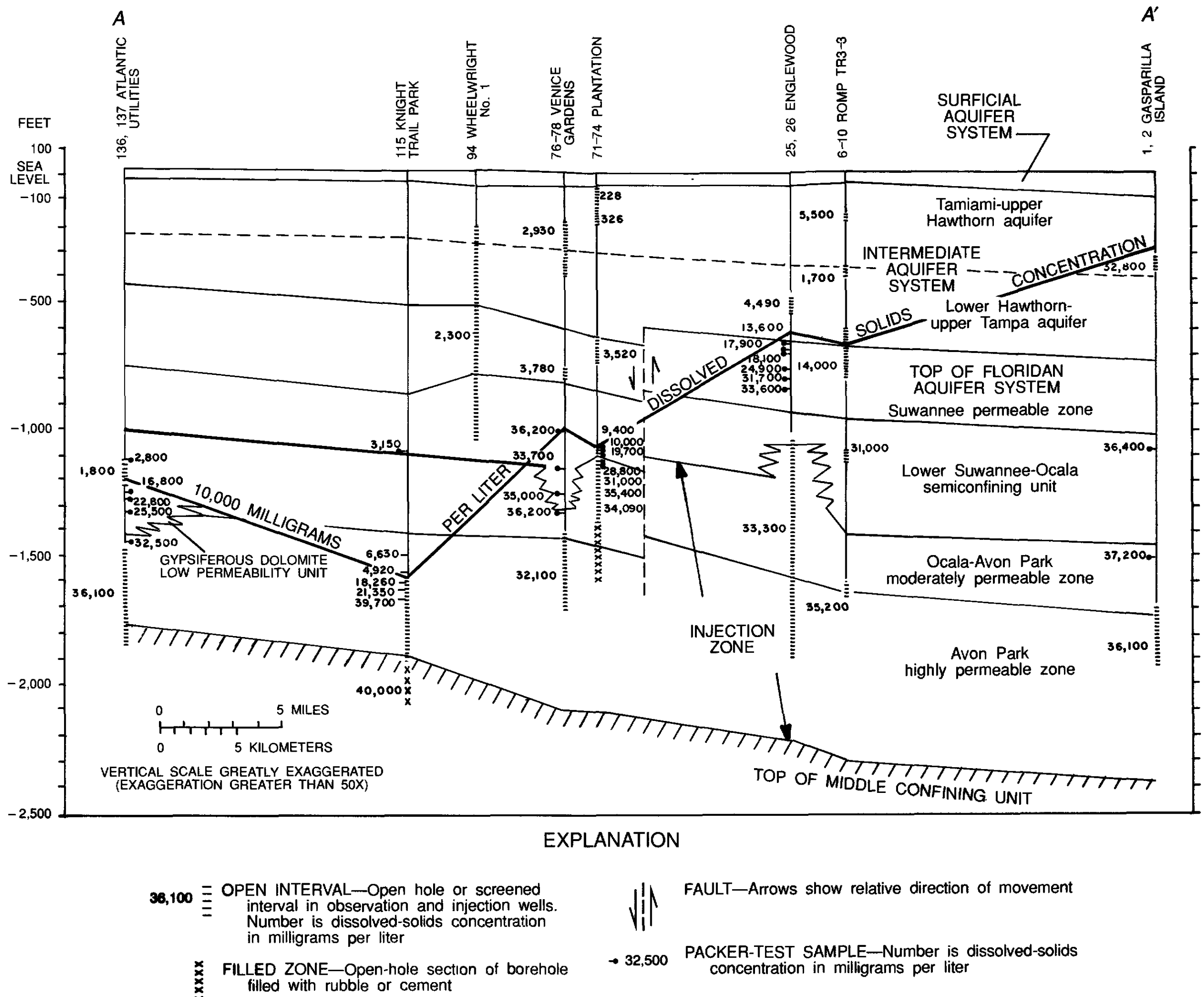


Figure 22. Hydrogeologic section with 10,000-mg/L dissolved-solids concentration delineated from packer-test and well-water analyses. (Wells are indexed to lists of data in tables 3 and 8.)

The altitude of the 10,000-mg/L dissolved-solids interface was mapped by using water-quality information from injection sites (fig. 23). The highest interface altitude is about 500 ft below sea level along the gulf coast. The interface dips inland to the north and northeast under a gradient of 50 ft/mi. Comparison with figure 22 indicates that the 10,000-mg/L interface is below the top of the potential injection zone in the northern third of the study area. At the Atlantic Utilities injection site (site 13, figs. 5 and 23), 10 mi north of the study area, the interface lies 1,200 ft below sea level. This altitude is 200 ft below the top of the Ocala-Avon Park moderately permeable zone, which coincides with the top of the injection zone defined within the study area.

Injected Wastewater

Two classes of wastewater are injected through deep wells in the study area: treated sewage and reverse-osmosis wastewater. The sewage is largely residential and commercial in nature and does not contain hazardous or industrial wastes. The injectant is characteristically aerated, filtered, and chlorinated secondary effluent having about 5 mg/L of suspended solids, a pH of about 8.0, and a dissolved-solids concentration of less than 500 mg/L. The reverse-osmosis wastewater is a concentrated solution that contains about twice the dissolved-solids concentration as in the feed water pumped from wells. Reverse-osmosis processes in use in the study area include spiral-wound membrane and hollow-fiber low-pressure systems, which operate at approximately 200 lb/in^2. Englewood uses a high-pressure system, which operates at approximately 600 lb/in^2. The dissolved-solids concentration of the wastewater is about 5,000 mg/L at Venice, 7,000 mg/L at Plantation, and 15,000 mg/L at Englewood. The reason for injection as opposed to discharge to bays and estuaries is that the waters have dissolved radium-226 concentrations above 5 pCi/L.

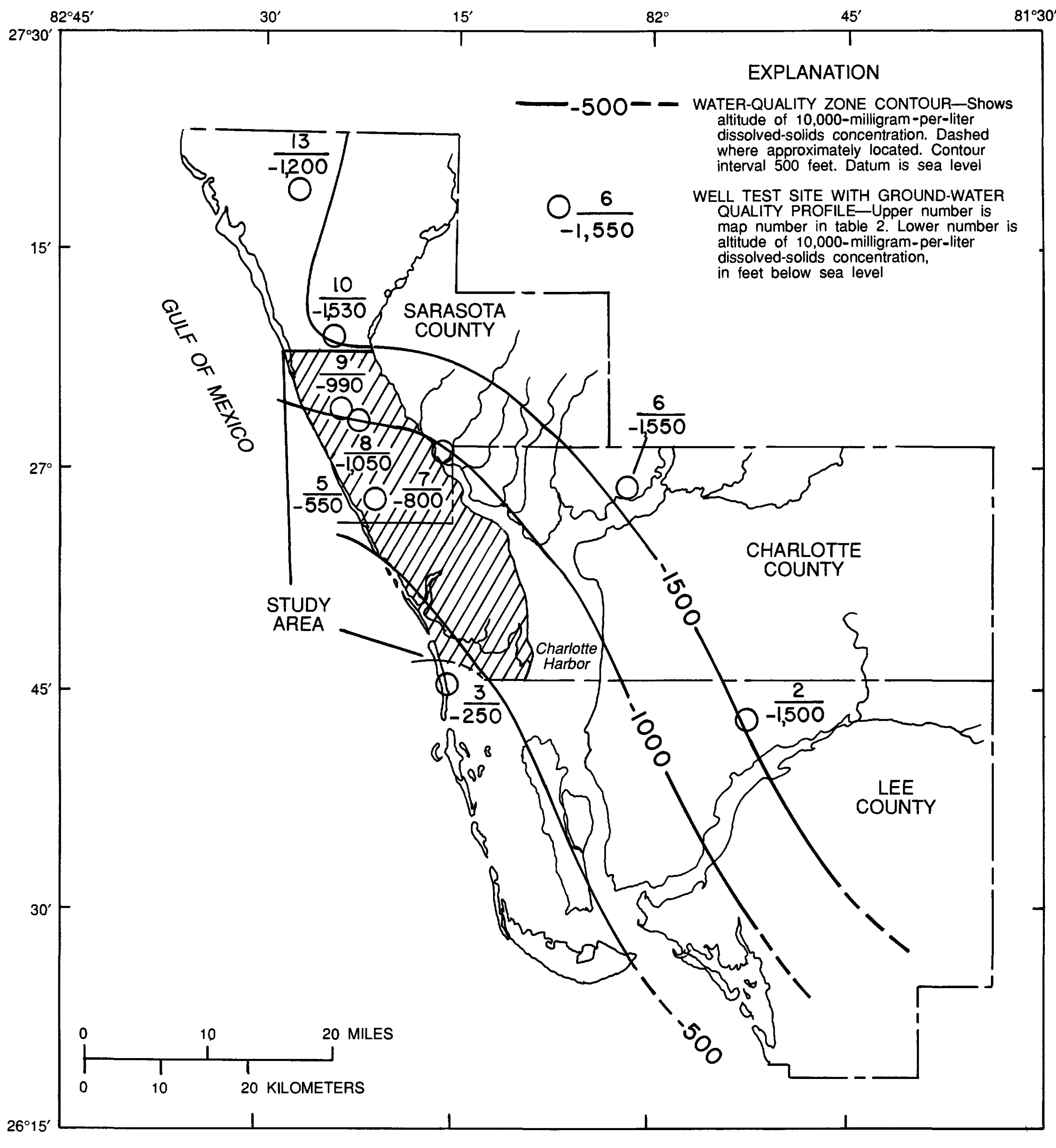


Figure 23. Altitude of the 10,000-mg/L dissolved-solids concentration in ground water.

UNCONTROLLED FLOWING ARTESIAN WELLS

Sarasota and Charlotte Counties lie within the principal problem area identified by Healy (1978, p.2) in an appraisal of uncontrolled flowing artesian wells. Healy defined such wells as:

> ...artesian well(s) either without a mechanism for controlling discharge or a well that is allowed to flow continuously at the land surface as well as those wells that only flow internally below land surface through corroded or leaky casings or from improperly cased or otherwise poorly constructed wells....

Figure 24 is a schematic diagram that compares a properly constructed well in a single artesian aquifer with two uncontrolled flowing artesian wells. The uncontrolled wells have corroded or shallow casings and cross connect permeable zones, thereby allowing upward flow of more saline water from the deep zone into less saline shallow zones. The typical uncontrolled flowing well is a 300- to 500-ft-deep irrigation well with 50 ft of corroded and leaky casing that was drilled in the 1950's. As housing developments replaced farmland, many wells were capped and forgotten. Figure 25 shows locations of approximately 100

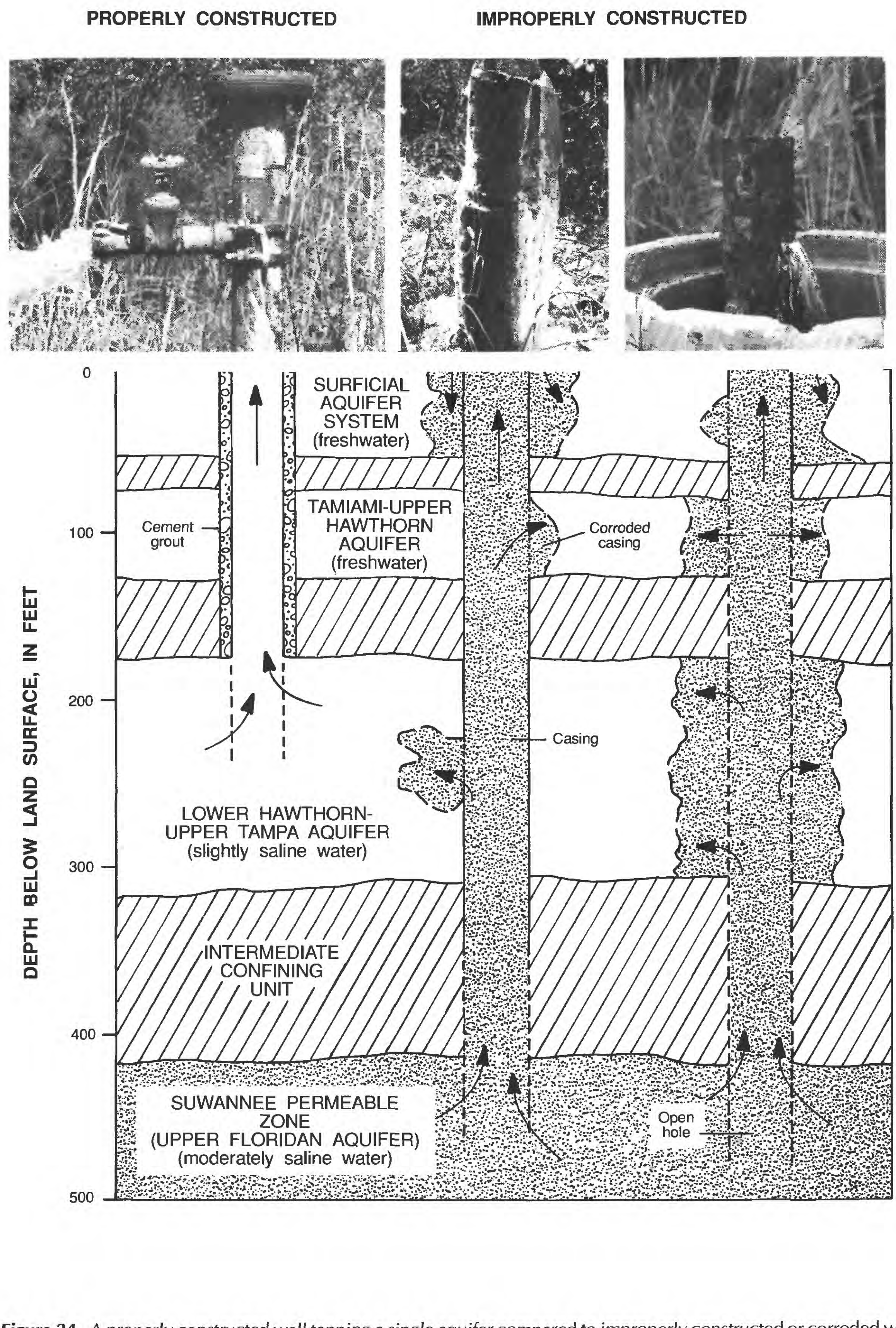


Figure 24. A properly constructed well tapping a single aquifer compared to improperly constructed or corroded wells that may allow cross contamination of aquifers with saline water.

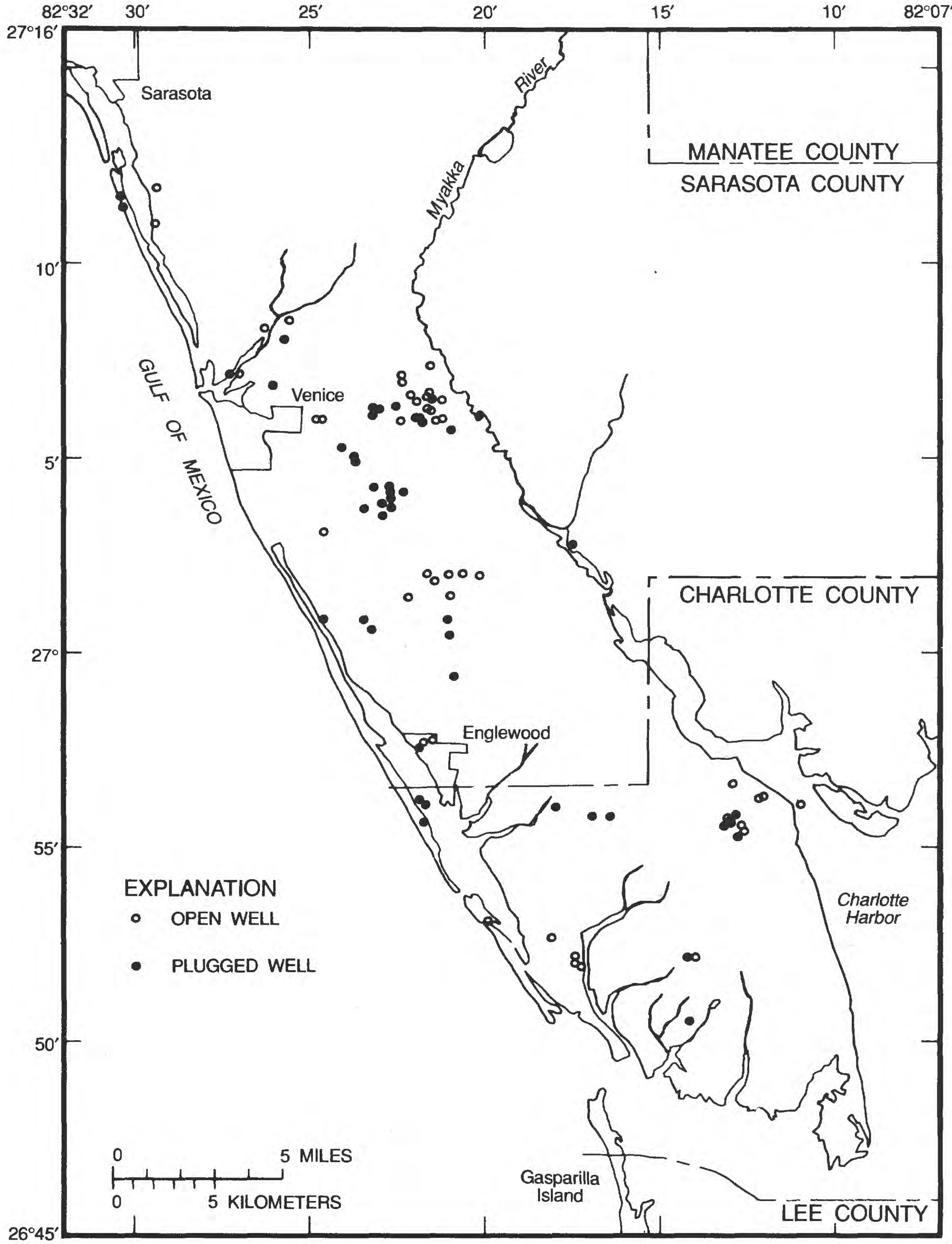


Figure 25. Locations of plugged wells and uncontrolled flowing artesian wells scheduled to be plugged by the Southwest Florida Water Management District and other agencies.

uncontrolled flowing wells identified in the study area (Preedom, 1984). By 1986, about half of the wells had been plugged by the Southwest Florida Water Management District and public utilities agencies.

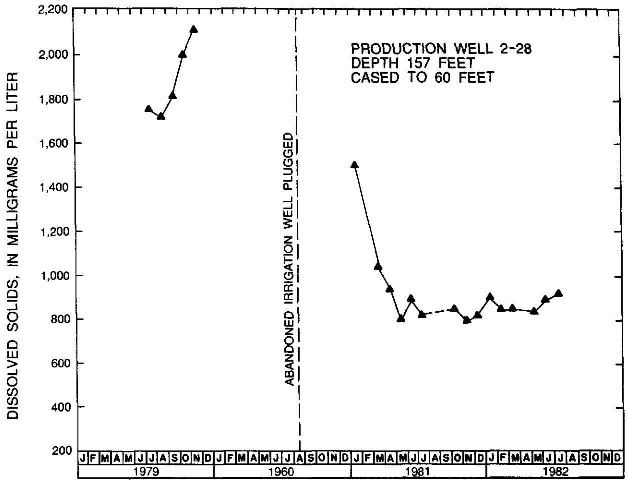


Figure 26. Dissolved solids in water from a Venice Gardens Utilities production well before and after plugging of nearby uncontrolled flowing artesian well. (Peter Palmer, Geraghty and Miller, Inc., written commun., 1986.)

A well-plugging program conducted by Venice Gardens Utilities has proved successful at the Venice Gardens well-field area (fig. 4). Thirteen wells within 1 mi of well-field number 2 were plugged under the program (Peter Palmer, Geraghty and Miller, Inc., written commun., 1986). Figure 26 dramatically illustrates a 50-percent reduction in dissolved solids in water from a supply well after plugging of a nearby uncontrolled flowing artesian well. The dissolved-solids concentration of blended raw water from 38 wells in the field was reduced from about 750 to 600 mg/L after plugging the 13 wells.

Borehole geophysical surveys were conducted to assess the problem of internal flow in deep wells that are open to multiple permeable zones. Procedures consisted of running caliper and flowmeter logs while each well was shut in (no flow at land surface). Internal flow was quantified on the basis of relations between cross-sectional area and measured borehole velocity. Figure 27 illustrates an example survey in a 190-ft-deep well (index no. 91, table 3) where internal flow was measured at 73 gal/min. Most of the flow enters the borehole between 100 and 120 ft, as evidenced by the flowmeter and fluid-conductance logs. The logger operator explained that the "kick" in the fluid conductance log is not caused by a change in water quality but by rapid flow over the sensitive logging tool. All flow reenters the formation at the bottom of the 60-ft well casing. The caliper log indicates an obstruction in the well at a depth of 37 ft.

Figure 28 shows results of spinner flowmeter surveys in 14 wells throughout the study area. The wells range in depth from 185 to 1,066 ft. Internal flow rates, measured between 0 and 350 gal/min, with a median rate of 10 gal/min, are relatively high in the Venice area and highest at ROMP site TR5–2 (site 108, fig. 28). There, a 480-ft-deep well had been constructed with 60 ft of casing and was open for about 1 yr prior to conversion to a cluster well containing two small-diameter wells. Flow in that well entered the borehole at 350 ft and left the borehole at 330 ft. Seven other wells having open depth intervals approximately between 300 and 400 ft did not have nearly as much internal flow as that measured in the ROMP TR5–2 well.

Water-level and water-quality investigations have shown that each aquifer or permeable zone has unique head and chemical characteristics. Construction of single-zone wells would safeguard ground-water resources by preventing cross-contamination and borehole interflow.

MODEL SIMULATION OF WASTEWATER INJECTION

The hydrogeologic system in southwest Sarasota and west Charlotte Counties is conceptualized as containing multiple permeable zones separated by leaky semiconfining units. Ground-water salinity increases with depth and proximity to the gulf coast, and there is upwelling of ground water in this coastal zone of natural discharge. Superimposed on this simplified 2,000-ft-thick system is a projected 29 Mgal/d of treated sewage and reverse-osmosis wastewater injected into the bottom 1,000 ft. An assessment of the likely fate of the injected fluids using a model as a numerical simulation tool is an objective of this study. Questions to be answered are:

1. How will the wastewater spread radially from a representative well?
2. What is the rate of vertical movement of wastewater from the injection zone through the overlying semiconfining unit?
3. Does well construction control the distribution of wastewater in the injection zone?
4. Does pumping from a reverse-osmosis supply well field above the injection zone speed circulation of the injected wastewater upward into the supply zone?
5. What is the long-term areal impact of injecting at projected rates?

A model of ground-water flow and solute transport was used to improve the understanding of the hydrologic system and answer questions concerning the effects of injecting reverse-osmosis wastewater and treated sewage. The model uses a numerical solution that involves integrated finite-difference methods to solve partial-differential equations of ground-water flow and solute transport. The model, HST3D (Heat and Solute Transport in Three Dimensions; Kipp,

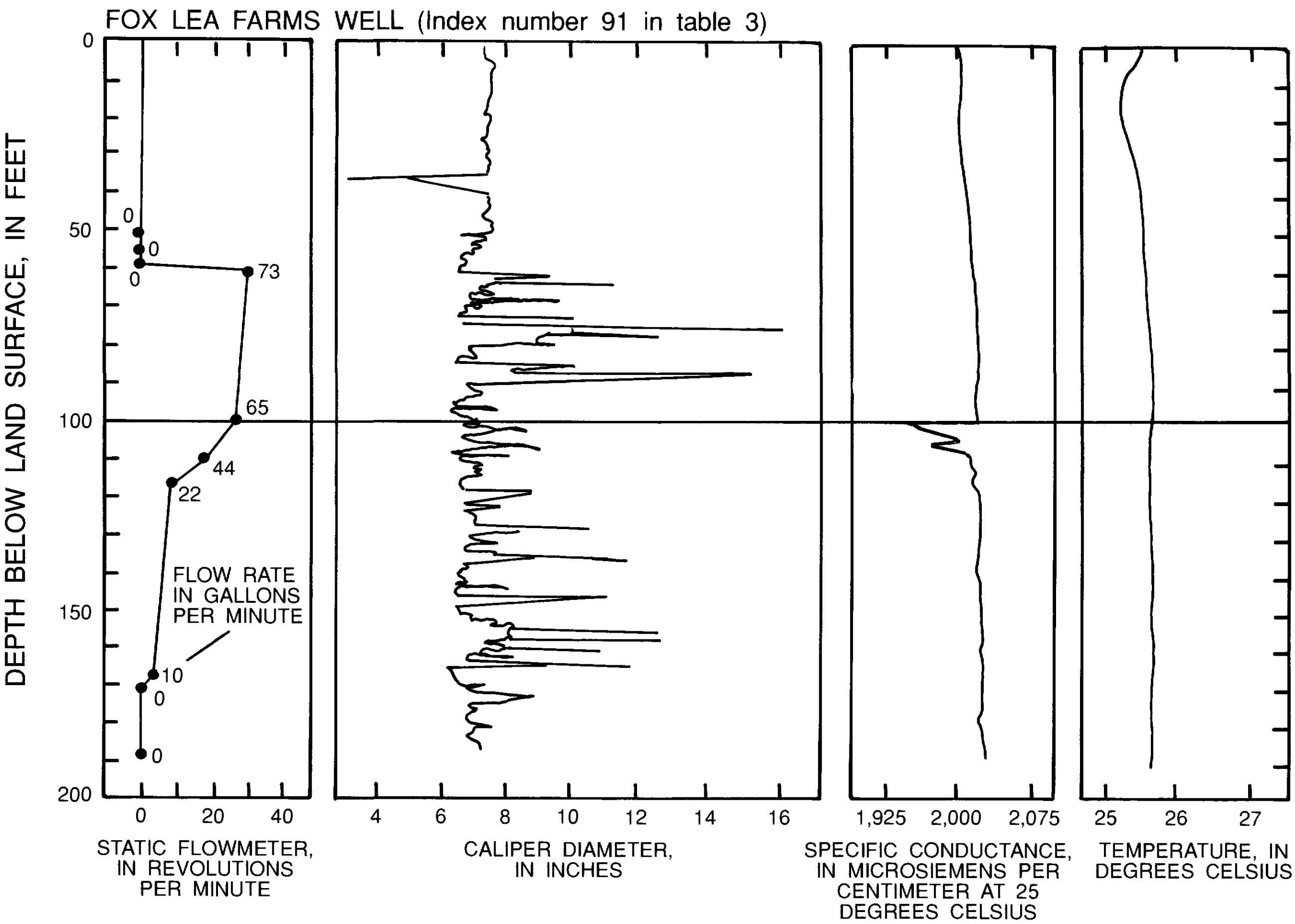


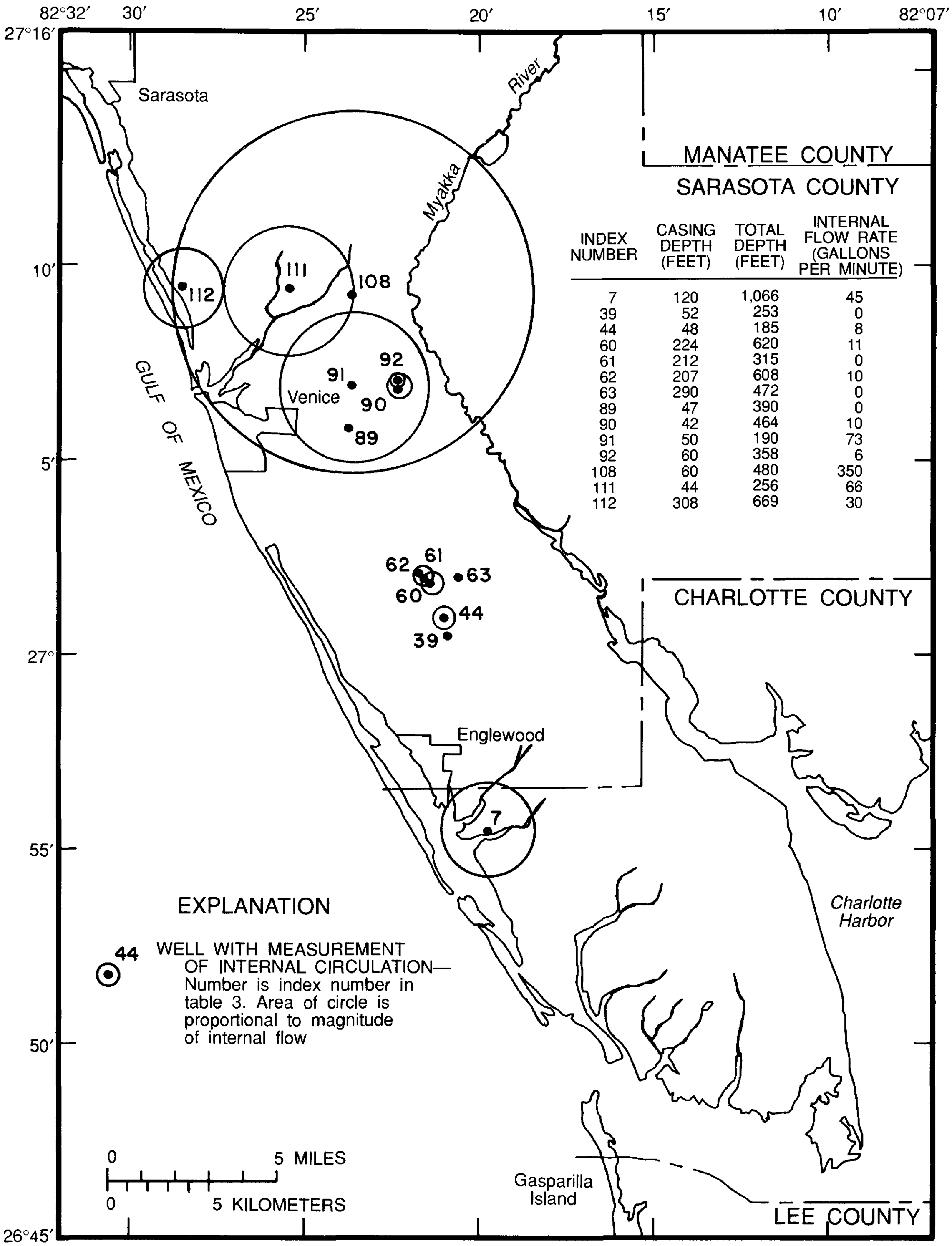
Figure 27. Borehole geophysical logs used to assess internal circulation in an uncontrolled flowing artesian well.

1986a), can simulate variable-density ground-water flow and liquid-waste disposal into deep saline aquifers. It represents the latest generation of a program developed by INTERCOMP Resource Development and Engineering, Inc. (1976), and revised by INTERA Environmental Consultants, Inc. (1979). The parent code, known as the Subsurface Waste Injection Program (SWIP), has been completely rewritten with many modifications, improvements, and corrections. The reader is referred to Kipp's (1986a) report for a complete discussion of the model code and numerical methods. The model is used as a tool in this study to analyze the mechanics of wastewater injection through a representative well.

Ideally, a three-dimensional model that incorporates all layers and variations in hydraulic properties and injection rates is desirable. Considering the lack of a detailed regional hydrogeologic framework and the limitations of modern computer facilities, injection is simulated by using an alternative two-dimensional model of flow and transport radially around a single prototype well representative of those constructed in the study area. Conclusions drawn from simulation of the single-well injection case are used to assess regional impacts.

Modeling procedures and their application to the study are diagrammed in figure 29. The hydrogeologic region representative of the study area was formulated around a hypothetical ideal well cased through the lower Suwannee-Ocala semiconfining unit and fully penetrating the Ocala-Avon Park injection zone. The region was subdivided into discrete areas defined by cylindrical coordinates, boundary conditions were established, and hydraulic and transport properties were estimated for each element in the point-distributed grid. Model-input values of selected physical parameters, including viscosity, temperature, and density, were held constant in all model simulations. Other input parameters and time and space subdivisions were adjusted by trial and error within limits to establish a "best-estimate" model of injection through an ideal, fully penetrating well.

Three simulation phases were employed in modeling injection and solute transport. In the first phase, finite-differencing options available in the model were tested to evaluate numerical dispersion and stability, and a comparison check was made with results of the saturated-unsaturated transport (SUTRA) finite-element model. The second phase included testing the sensitivity of the "best-estimate model" by varying input parameters over plausible ranges of values.



INDEX NUMBER	CASING DEPTH (FEET)	TOTAL DEPTH (FEET)	INTERNAL FLOW RATE (GALLONS PER MINUTE)
7	120	1,066	45
39	52	253	0
44	48	185	8
60	224	620	11
61	212	315	0
62	207	608	10
63	290	472	0
89	47	390	0
90	42	464	10
91	50	190	73
92	60	358	6
108	60	480	350
111	44	256	66
112	308	669	30

Figure 28. Internal circulation measured in uncontrolled flowing artesian wells.

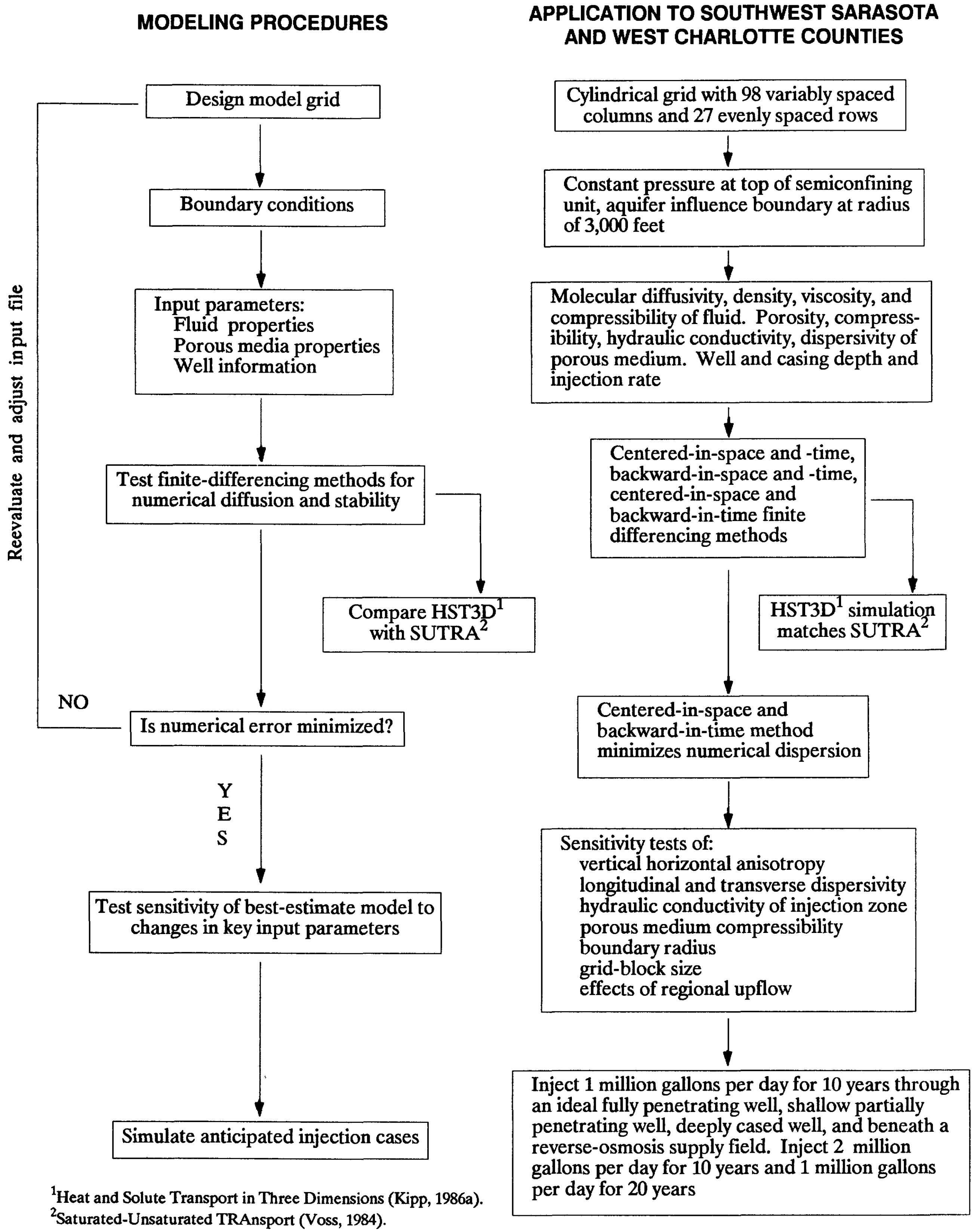


Figure 29. Modeling procedures.

In the third phase, the model was used to simulate the probable response of the hydrologic system to various injection scenarios.

Subdivision in Space and Time

The continuous aquifer region was subdivided spatially by using a cylindrical-coordinate system with a grid mesh (fig. 30). The primary subdivision is the cell, which is the volume over which flow and solute balances are made to give the nodal finite-difference equations. The second subdivision is the element, bounded by four corner nodes, which is the minimum volume with uniform porous-medium properties. A third subdivision is the subdomain, which is the common volume of an element with a cell. A cell may have as many as four subdomains if it is an interior cell, or as few as one subdomain if it is a corner cell. The finite-difference equations are assembled by adding the contributions of each subdomain in turn to the equation for a given cell. Because wells are usually open over the more permeable zones of the formation, the open-hole intervals are specified by sets of elements rather than by cells. The upper and lower parts of the open-hole interval are one-half the cell thickness in length, unless the cell in question forms an upper or lower boundary, in which case, the cell is already a half cell. In a well bore segment that terminates at a half cell, flow (and solute) is spread over the whole cell at half the whole cell rate. To help overcome this limitation, injection casing was set one node below the top of the injection zone (1,150 ft) rather than at the top.

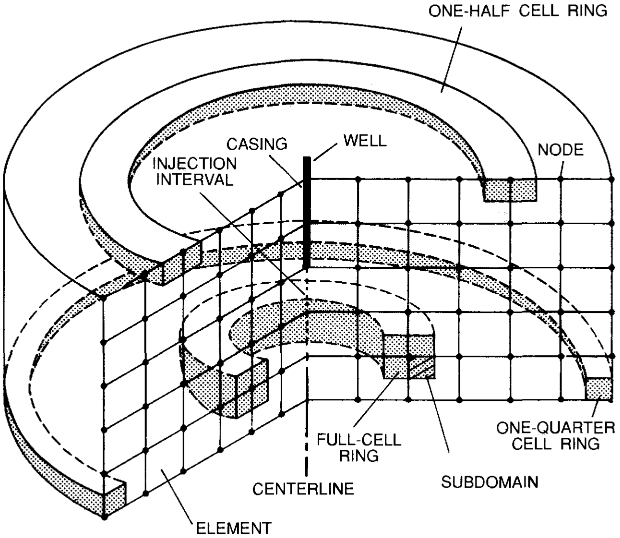


Figure 30. Finite-difference grid for a cylindrical-coordinate system. (Modified from Kipp, 1986a.)

The nodal grid of 27 evenly spaced horizontal rows and 98 variably spaced vertical columns extends radially outward 3,000 ft from the injection well (fig. 31). Vertical 50-ft spacing was assigned within the depth interval 750 to 2,050 ft, which encompasses the lower Suwannee-Ocala semiconfining unit, Ocala-Avon Park moderately permeable zone, and Avon Park highly permeable zone. Radial spacing expands logarithmically from the well, where spacing between columns 1 and 2 is 0.14 ft, out to 350 ft (column 45), where spacing then becomes a uniform 50 ft to the perimeter at 3,000 ft. Spatial subdivision empirical guidelines for stability in central-in-space finite-difference equations (Voss, 1984, p. 232) suggest that the largest radial dimension should not exceed 4 times the longitudial dispersivity (which was set at 20 ft), and the largest vertical dimension should be less than 10 times the transverse dispersivity (which was set at 5 ft). Tests of the effectiveness of the grid spacing are evaluated in the "Sensitivity Analysis" section.

Time increments used to step through the model computations are expanded automatically by the model. As the simulation progresses, an empirical algorithm tends to increase the time step such that the maximum specified change in pressure or solute scaled concentration is achieved. Simulations that were made to observe effects of spatial and temporal subdivision by using various finite-difference weighting are described in the "Numerical Dispersion and Stability" section.

Boundary Conditions

The major criterion used to define hypothetical boundaries for the model was to determine the area that might be affected by a fully penetrating well that injects 1 Mgal/d for 10 yr. The model encompasses the injection zone from 1,100 to 2,050 ft deep and the overlying lower Suwannee-Ocala semiconfining unit from 750 to 1,100 ft deep. The bottom coincides with the impermeable middle confining unit of the Floridan aquifer system (Miller, 1986) and is considered a no-flow boundary. The top is a constant-pressure boundary equivalent to a 750-ft column of freshwater, presumed to exist in overlying formations. The injection well forms the left boundary and is cased from 750 to 1,150 ft and has an open interval from 1,150 to 2,050 ft. The right boundary is defined by a transient flow, aquifer-influence function, which utilizes the Carter-Tracy approximation as adapted by Kipp (1986b) to compute flow rates between the inner gridded aquifer region and an infinite outer region where aquifer properties are known only in a general sense. Use of the Carter-Tracy approximation eliminates the need for spatial subdividing of the outer region, which is beyond the zone of transport.

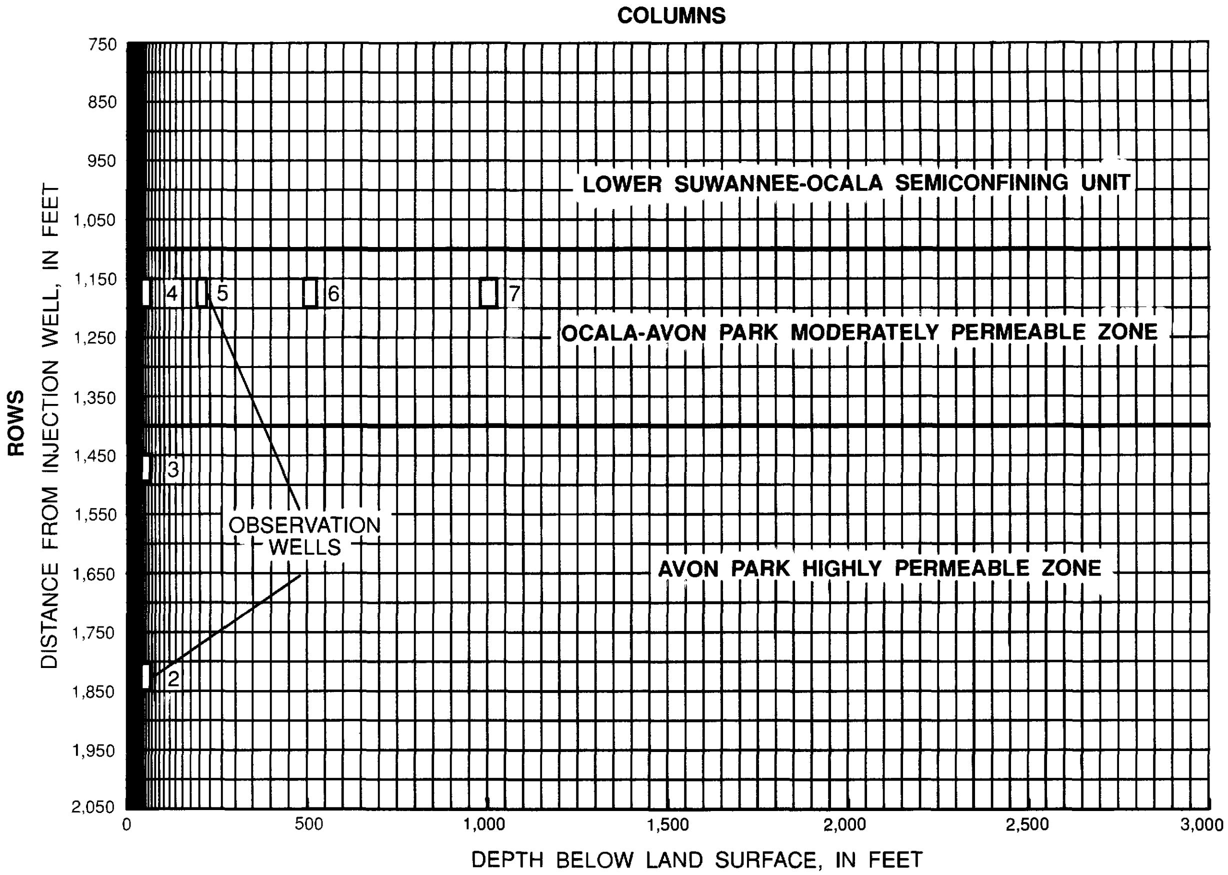


Figure 31. Model grid of 27 rows and 98 columns showing locations of six observation wells within grid.

The primary benefit of using the aquifer-influence function boundary condition is the reduction in size of the simulation region, resulting in less computer storage requirements and a savings in execution time. The radius of the inner region was set at 3,000 ft. The outer region is modeled as an infinite cylinder with a height of 1,300 ft. Tests conducted to evaluate the aquifer-influence boundary condition are described in the "Sensitivity Analysis" section.

Input Parameters

Model-input parameters were derived from aquifer tests, laboratory tests of rock cores, and published standards as follows:

1. Fluid properties.—Density, viscosity, and compressibility of the injectant and native waters were either measured or estimated. Measured values at 25 °C are:

Water sample	Density g/cm^3	Density lb/ft^3	Viscosity, centipoise	Specific conductance, µS/cm at 25 °C
Englewood reverse-osmosis wastewater.	1.0095	63.01	0.9289	23,000
Gasparilla Island treated sewage.	.9992	62.37	.9039	3,500
ROMP TR3–3 (1,050–1,700 ft deep).	1.0232	63.87	.9500	41,000

The physical properties of these three waters were represented in the model as reverse-osmosis injectant, treated sewage injectant, and native formation water, with the exception that native water density was set at 64.0 lb/ft^3.

The order-magnitude range in specific conductance is an indicator of the contrast in water quality between the injectant and native formation water. In addition to these properties, compressibility of water was held constant at 3.3×10^{-6} ft^2/lb (4.4×10^{-10} m^2/n) (Freeze and Cherry, 1979, p. 52), and molecular diffusivity of the solute in the porous media was set at 8.75×10^{-7} ft^2/d (9×10^{-6} m^2/d) (Kimbler and others, 1975).

2. Porous media properties.—Three porous zones were modeled that correspond with hydrogeologic units: (1) lower Suwannee-Ocala semiconfining unit, (2) Ocala-Avon Park moderately permeable zone, and (3) Avon Park highly permeable zone. Values assigned to these zones include:

	Zone		
	(1)	(2)	(3)
Hydraulic conductivity (ft/d)	0.1	25	100
Porosity	.25	.15	.15
Matrix compressibility (ft^2/lb)	1.5×10^{-5}	6.2×10^{-6}	5.5×10^{-7}
Longitudinal dispersivity (ft)	20	20	20
Transverse dispersivity (ft)	5	5	5

Modeled hydraulic conductivity and compressibility values were based on aquifer tests described in this report, packer tests, laboratory measurements (table 7), and values derived from a separate model analysis of an aquifer test described by Hutchinson and Trommer (in press).

Estimates of the porosity of the lower Suwannee-Ocala semiconfining unit were based on laboratory measurements of limestone cores from test-injection wells (table 7). Except for the values at North Port, it is unclear whether the porosities reported by the laboratory are "total" or "effective." Effective porosity, which accounts for interconnected pore space, was measured at North Port (CH2M Hill, Inc., 1988). Porosity was set at 0.25 in the semiconfining unit and 0.15 in the injection zone, where fracture porosity is presumed predominant in the dolomites. Hickey (1989) derived a fracture porosity of 0.10 for the dolomitic injection zone in Pinellas County and successfully simulated injection and solute transport under the assumption of diffuse flow through a porous medium.

Longitudinal and transverse dispersivities of the system were set at 20 ft and 5 ft, respectively. These values meet gridding stability criteria recommended in Voss (1984, p. 232), where longitudinal and transverse dispersivities are greater than one-fourth and one-tenth of the radial and vertical grid spacings, respectively. The validity of the porous media properties were evaluated by means of sensitivity tests.

3. Well characteristics.—The injection-well surface occurs at the first column of nodes. A depth interval of 1,150 to 2,050 ft is specified as the length of well bore that communicates with the injection zone. The model allocates injection flow of 1 Mgal/d (694 gal/min) over rows 1 through 19 by mobility factors that are based on cell position, relative hydraulic conductivity, and an element completion factor. An element completion factor of zero means the well is cased off from the aquifer in that element. A reduced permeability around the well bore can be approximately represented by specifying a completion factor less than one. Injection rate was lowest in the half cell at the bottom of the casing (6 gal/min) and highest through whole cells within the Avon Park highly permeable zone (49 gal/min). In addition to the injection well, six observation wells that have 50-ft completion intervals were included (fig. 31). Graphs of scaled solute concentration and hydraulic pressure in the observation wells were used to test the stability of the model simulation.

Numerical Dispersion and Stability

An inherent problem in mathematical models is the difficulty in applying finite-difference methods to problems of convective transport. It is well known that the type of finite-difference method used can introduce numerical dispersion caused by truncation error that is virtually indistinguishable from physical dispersion (Lantz, 1970; INTERCOMP Resource Development and Engineering, Inc., 1976; and Kipp, 1986a). Compounding this problem are spatial and temporal instabilities, represented by oscillations in the flow and concentration fields, which may persist without growth or decay.

Numerical dispersion and stability can be controlled through judicious selection of finite-difference approximation methods and adherence to spatial and temporal subdivision criteria. Under selected methods, the magnitude of the truncation error is a function of the Darcian velocity, size of time step, and element size. Stability is a function of the pore velocity, size of time step, element size, and dispersivity. Stability in the radial injection model requires small elements near the well and small time steps early in the simulation to adequately portray rapidly changing pressures and concentrations. As the simulation progresses, a constant-velocity flow field is established and the solute front is distributed over a much larger cylindrical face. Velocity and concentration changes reduce as the simulation progresses; hence, the time step may be increased as the simulation progresses, and element size may be enlarged in proportion to the radial distance from the injection well.

Guidelines for selecting various combinations of finite-difference approximation methods are summarized by INTERCOMP Resource Development and Engineering, Inc. (1976, p. 5.5). The centered-in-space (CIS) and centered-in-time (CIT) combination is desirable in that there is no truncation error and, therefore, no numerical dispersion. Stability problems in the solution may arise if the ratio of time step to element size becomes too large at a specific pore velocity. The backward-in-space (BIS) and backward-in-time (BIT) combination always produces a stable solution; however, numerical dispersion may produce severe errors due to truncation of the time and space derivatives. Use of a CIS-BIT combination removes spatial but not temporal truncation error and can be unstable if spatial guidelines for dispersivity are not met. Using the BIS-CIT combination removes temporal (but not spatial) truncation error and can be unstable if the ratio of time step to block size is too large.

Model runs were made to test how different combinations of finite-difference approximation methods would control numerical dispersion and stability of the model solution. Initially, a CIS-CIT combination was employed under the assumption that numerical dispersion would be eliminated and a stable solution would be obtained. After many runs, it was determined that, regardless of the time and spatial subdivisions used, a stable solution could not be achieved. When time steps were too large, divergent oscillations in the pressure and solute-concentration fields were apparent, and the model would exceed the specified maximum iterations allowed for a cycle at a given time plane. When time steps were very small (0.000001 to 0.0001 d), oscillations did not expand; however, the model computations would take several days of computer time to simulate several hours of injection. Apparently, the small elements near the well bore limit the time step. Results of simulations that demonstrate these instabilities are shown in figures 32 and 33.

When CIS-CIT, CIS-BIT, and BIS-BIT simulation results in figure 32 are compared, significant differences are evident. BIS-BIT (fig. 32*C*) produces a smooth, nonoscillatory flow field with a maximum radius of intrusion of about 2,300 ft, but the severity of truncation error, which affects the distribution of solute, is unknown. CIS-CIT (fig. 32*A*) produces a mildly oscillating flow field with a maximum radius of intrusion of about 2,700 ft. Instability denoted by the flow field is severe in both permeable units of the injection zone between radii of 200 and 700 ft where grid spacing ranges from 29 to 50 ft. The instability under CIT

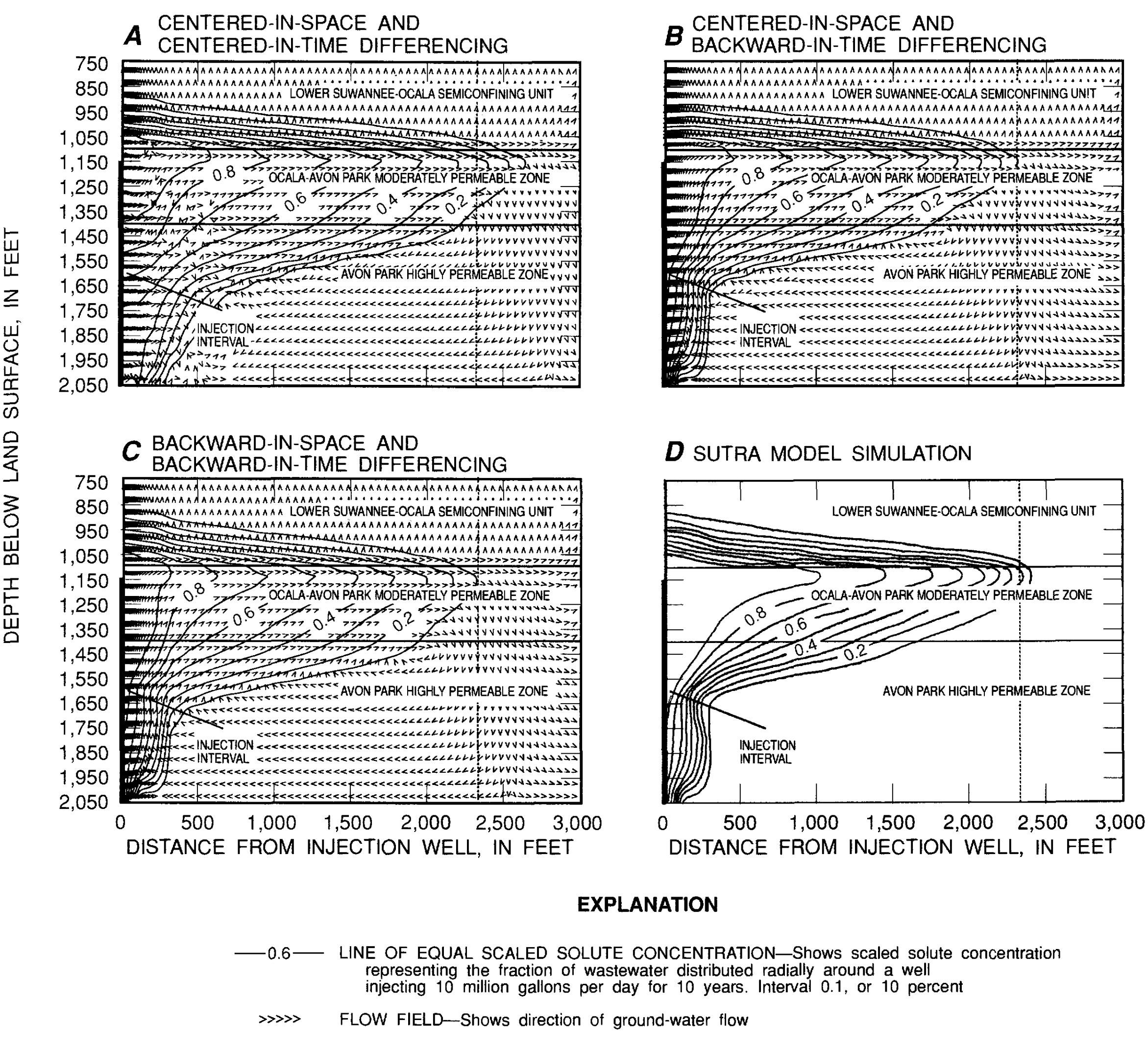


Figure 32. Radial sections showing the flow field and scaled solute concentration using various finite-difference methods.

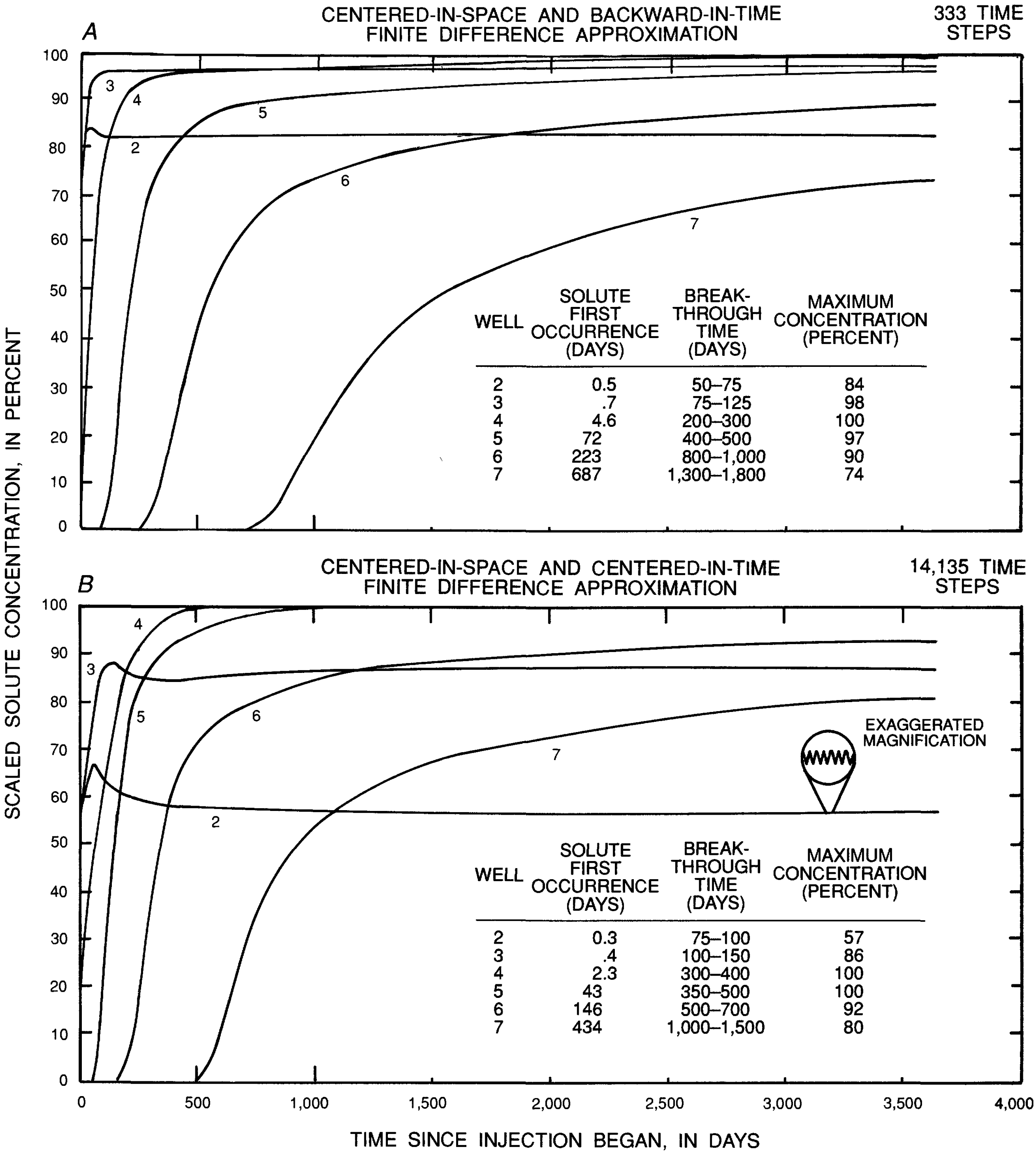


Figure 33. Simulated scaled solute concentrations in six observation wells—a comparison of finite-difference methods. (See fig. 31 for locations of wells within model grid.)

apparently produces more dispersion of the solute distribution than does truncation error under BIT. CIS-BIT (fig. 32*B*) produces a thinner lens of injectant when compared to BIS-BIT, which indicates that some improvement is achieved by eliminating spatial truncation error. INTERCOMP Resource Development and Engineering, Inc. (1976, p. 4.43), suggests that the density influence may be so dominant that truncation error is overshadowed by convection.

Figure 33 shows how concentrations vary with time at six points (simulated wells) within flow fields simulated by using CIS-BIT and CIS-CIT combinations of finite-difference approximation methods. The curves all show first occurrences of solute, rapid rises in concentration to some breakthrough region, and maximum scaled solute concentrations. First occurrence times under the CIS-CIT method are sightly more than half those simulated under the CIS-BIT method. The largest difference in the first occurrence time is 253 d at well 7. The arrival time is 434 d when the CIS-CIT method (fig. 33B) is used, compared to 687 d for the CIS-BIT method (fig. 33A). Breakthrough curves also appear to be influenced by the CIS-CIT oscillating flow field in that breaks in slope are not as sharp as in the CIS-BIT uniform flow field. Breakthrough occurs earlier under the CIS-BIT method close to the injection well and earlier under the CIS-CIT method beyond about 350 ft, which indicates that the zone of severest oscillation retards breakthrough near the well and accelerates breakthrough in distant regions. Maximum concentrations for wells 2, 5, 6, and 7 are within 10 percent under each finite-difference method, and at well 4, the CIS-CIT and CIS-BIT concentrations peak after about 50 to 75 days at 57 and 84 percent, respectively. During early time, concentrations at well 2 increase steadily and then peak as bouyancy operates to truncate the rise and eventually dilute the initial slug of injectant. Although it cannot be seen on the graphs in figure 33, the CIS-BIT plots (fig. 33A) are smooth curves through 333 points, whereas the CIS-CIT plots (fig. 33B) are sawtoothed (oscillatory) curves through 14,135 points. The numbers of points represent time steps required for the simulation. The scale of oscillations is on the order of one-hundredth of 1 percent. The instability percentage is small, but when it is multiplied through thousands of time steps, the additive smearing of the solute distribution may be large.

The distributions of scaled solute concentrations simulated under the various finite-difference approximation methods do not vary greatly, indicating that each combination of methods produces an acceptable solution. The time that it takes to complete a 10-yr, 1-Mgal/d injection simulation, however, is an important modeling consideration. Following is a comparison of the number of time steps and central processing time of the various finite-difference approximation methods operated on a PRIME 9955 computer system.

Finite-difference approximation method	Range of time steps (d)	Number of time steps required for solution	Central processing unit time (min)
CIS-CIT	0.00001–1	14,135	5,500
BIS-BIT	.0001–20	327	130
CIS-BIT	.0001–36	244	83
BIS-CIT	.00001–.01	about 3,000 (abort)	927

For the specified finite-difference grid, the CIS-BIT method minimized numerical dispersion and oscillation and required fewer time steps and, thus, less computer time than other methods. The BIS-CIT method always produced a divergent solution, which resulted in abnormal termination of model runs before one-half day of simulation had been completed.

A separate model run was made by using SUTRA to see if HST3D produced unreasonably severe error caused by oscillatory instabilities using CIS-CIT or numerical dispersion using CIS-BIT. SUTRA employs a hybrid finite-element and integrated finite-difference approximation method that utilizes "upstream weighting," or backward-in-space differencing (Voss, 1984). If through the use of different numerical methods the two models produce similar results, then numerical errors are probably small, and confidence would be gained in the HST3D simulation. This emperical relation was devised in light of difficulties perceived with the rigorous mathematical analysis of numerical error. The distributions of scaled solute concentrations simulated in the CIS-BIT and SUTRA runs are similar (fig. 32*B* and *D*). The main difference is that the SUTRA simulation produced a sharper front (delineated by more closely spaced contours) than that simulated by using CIS-BIT. Under SUTRA and CIS-BIT simulations, the zone of dispersion between the 0.1 and 0.9 scaled solute concentrations at the top of the injection zone ranged over radial distances of 1,400 and 1,800 ft, respectively. The similarity of results produced by the separate models supports the credibility of the HST3D simulations. Sensitivity analyses and predictive simulations in the following sections of the report are based on CIS-BIT methods because processing time is minimized.

Sensitivity Analysis

Tests were made of the model's sensitivity to changes of physical and hydraulic properties by varying one input parameter at a time over a reasonable range and then simulating 10 yr of injecting 1 Mgal/d. A sensitivity test of the model, therefore, is used as a tool for demonstrating which properties or characteristics have the most effect on the movement of injectants. Properties that greatly affect the simulated distribution of solute should be measured as accurately as possible in data-collection programs.

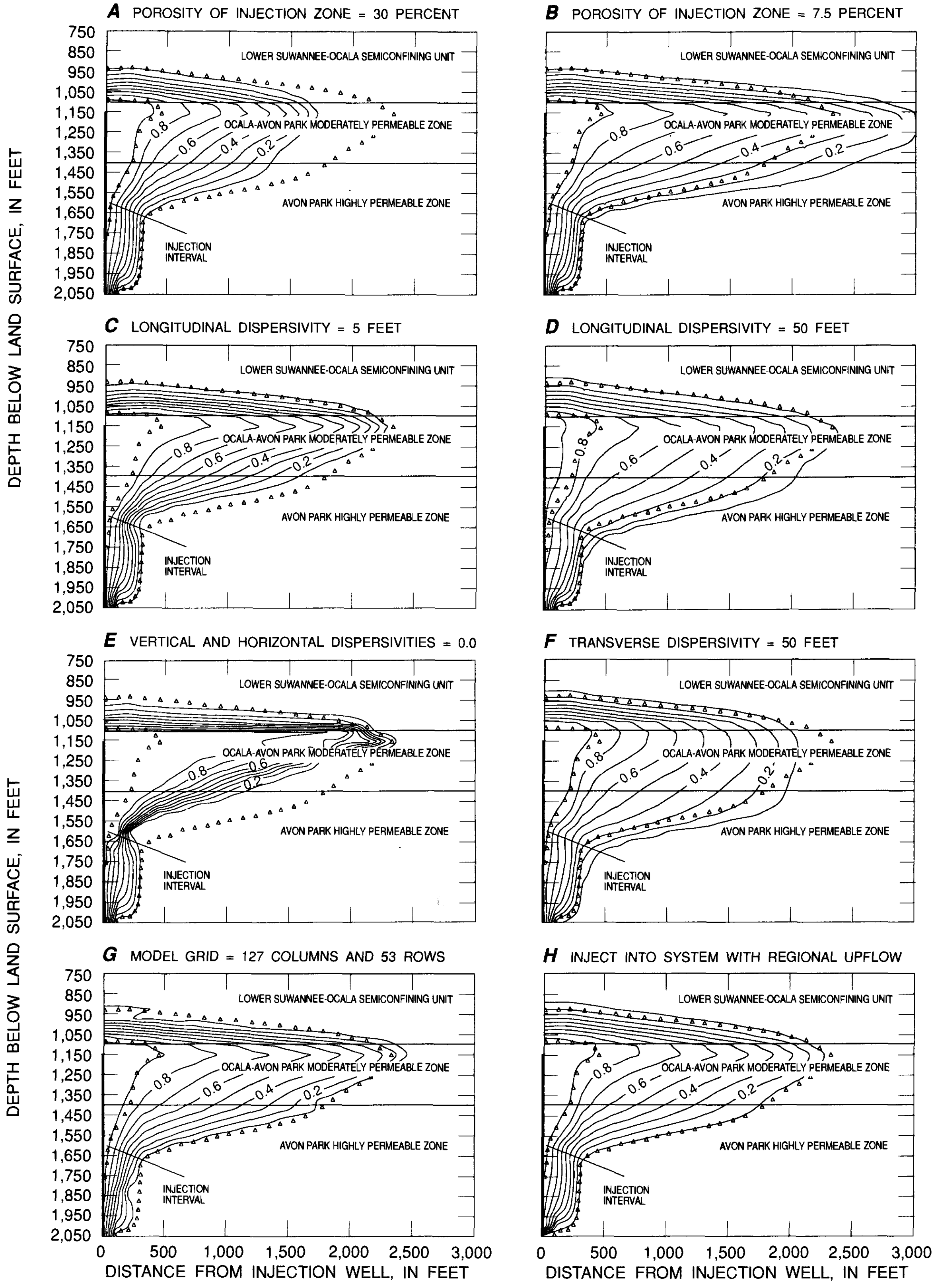
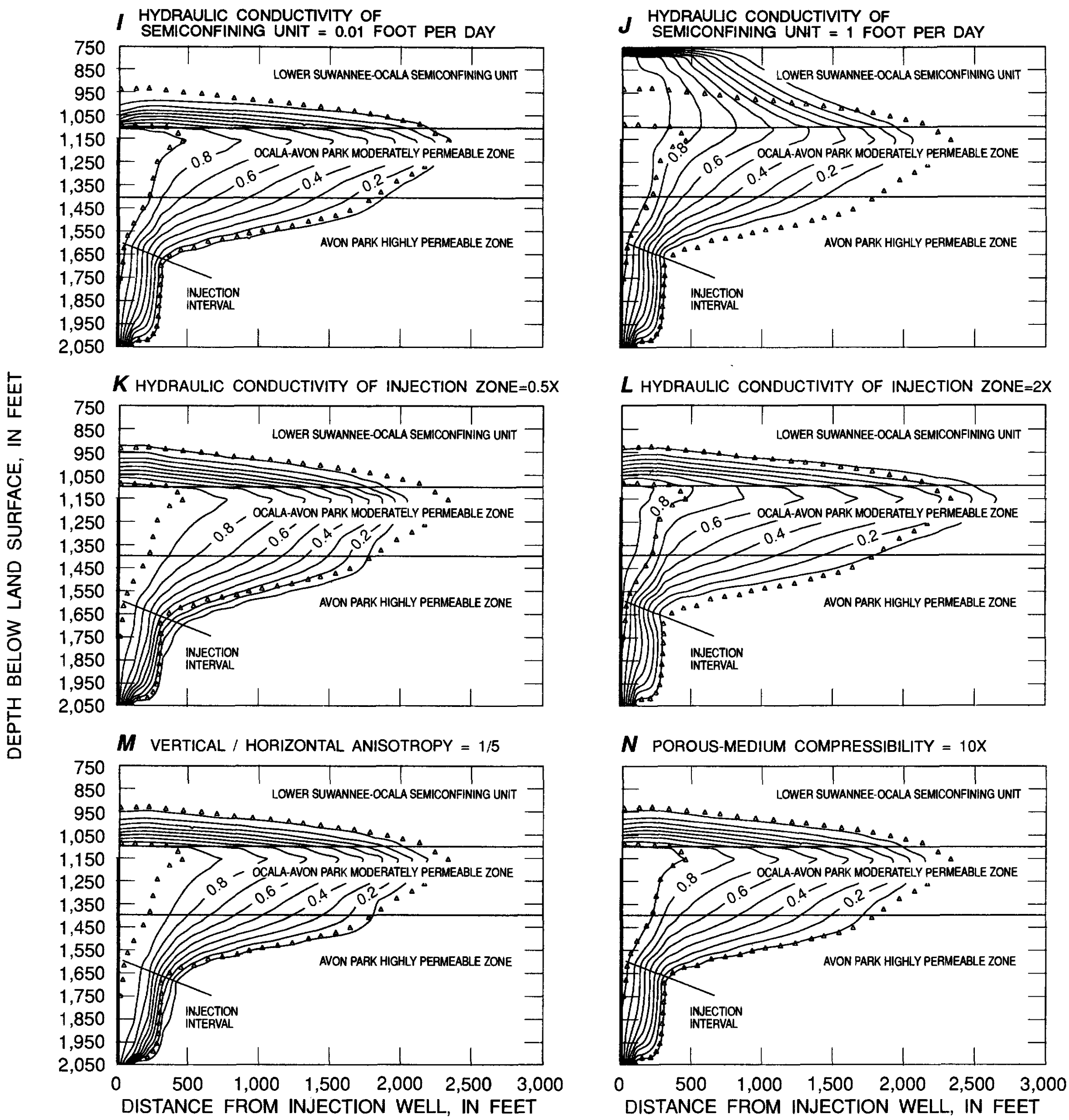


Figure 34. Radial sections showing the simulated concentration of injected wastewater indicating model sensitivity to changes in input parameters.



EXPLANATION

——0.6—— LINE OF EQUAL SCALED SOLUTE CONCENTRATION—Shows scaled solute concentration after a parameter is changed, representing the fraction of wastewater distributed radially around a well injecting 10 million gallons per day for 10 years. Interval 0.1, or 10 percent.

ΔΔΔΔΔ COMPARATIVE SCALED SOLUTE CONCENTRATION—Shows scaled solute concentrations from the best-estimate model with baseline parameters. The 0.1 and 0.9 lines of equal concentration are shown for comparison with concentrations simulated in each sensitivity test

Figure 34. Radial sections showing the simulated concentration of injected wastewater indicating model sensitivity to changes in input parameters—Continued.

Results of sensitivity tests are shown in figure 34 as scaled solute-concentration distributions. The 0.1 and 0.9 lines of equal scaled solute concentration, derived from the previously described best-estimate model, are superimposed for comparison. The sensitivity test results are summarized in table 9, which lists simulated lateral and upward distances of injectant movement.

1. Porosity.—Porosity of the injection zone was set at 0.075 and 0.3 to bracket the best estimate of 0.15. The ratio of permeability to porosity controls velocity of injectant flow and, hence, the rate of solute transport. High porosity produces a low velocity because it increases the cross-sectional area through which flow occurs. Correspondingly, it simply takes a longer time to replace the large volume of native water in a given volume of aquifer. Low porosity has the opposite effect. Figure 34*A* and *B* and table 9 indicate that lateral movement of injectant is very sensitive to porosity. The range in lateral movement between 1,700 and 3,000 ft was produced over a range in porosity from 0.3 to 0.075.
2. Dispersivity.—Dispersivity is a scale-dependent property of the porous medium that controls dispersion of the injected fluid. Transverse dispersivity was increased from 5 ft in the best-estimate model to 50 ft, and longitudinal dispersivity was varied between 5 and 50 ft with respect to 20 ft in the best-estimate model. A fourth test was made with zero dispersivity. The resulting scaled solute-concentration distributions (fig. 34*C–F*; table 9) show thicker and wider (more dispersed) spreads of injectant when transverse and longitudinal dispersivities are increased, respectively. When dispersivities are lowered, there is less dispersion, which results in a narrowing of the transition zone between the injectant and native formation water. Under zero dispersivity, the model would be expected to simulate a sharp interface. Simulation of a transition zone several cells wide in figure 34*F* may provide a clue as to the degree of temporal truncation error inherent in the centered-in-space and backward-in-time finite-difference approximation. Although the low-dispersivity conditions violate rules-of-thumb, which guarantee spatial stability, the model seems to have achieved valid solutions. Vertical and lateral movement of the injectant front does not appear to be very sensitive to the narrow range of dispersivity tested; however, dispersivity is a major control on the distribution of solute within the injectant lens.
3. Spatial subdivision.—The model grid was made finer to see if this change would affect the distribution of scaled solute concentration. First, the grid was increased to 127 columns in the radial direction to halve grid spacing in the zone between 100 and 700 ft. This includes the area where oscillations in the flow field were seen (fig. 32). The model was run under CIS-CIT differencing, and the resulting flow field and scaled solute plots were similar to those shown in figure 32. Next, the grid was increased to 53 rows (maintaining 127 columns) to check the model's sensitivity to vertical subdivision. The model was run under CIS-BIT differencing, and the resulting plot of scaled solute concentration was similar to that of the best-estimate model (fig. 34*G*). CPU time increased from 83 minutes to 2,126 minutes, and time steps increased from 244 to 856. It was concluded that the 27 by 98 grid is adequate and the model is not significantly improved by finer subdivision.
4. Vertical flow conditions.—The model does not account for natural upward flow in the hydrologic system, although the potential for such flow is evident from the many deep flowing wells and very saline springs in and near the study area. A test of the model's sensitivity to those conditions was made by increasing the model-computed pressure at the bottom of the model from 912.4 to 916.8 lb/in^2. This is equivalent to imposing a head difference of about 10 ft between the bottom and top of the model. Compared to the best-estimate nonartesian model (fig. 34*H*; table 9), the injectant would move about 40 ft higher (200 ft compared to 160 ft) and 50 ft less laterally (2,250 ft compared to 2,300 ft) under conditions of natural upward flow after 10 yr.
5. Hydraulic conductivity of the semiconfining unit.—The lower Suwannee-Ocala semiconfining unit caps the injection zone, thereby restricting upward movement of injected wastewater. Sensitivity tests included varying the vertical and horizontal hydraulic conductivities between 0.01 and 1 ft/d to bracket the best-estimate model value of 0.1 ft/d. The rate of upward movement of injectant through the semiconfining unit (fig. 34*I* and *J*; table 9) is sensitive to changes in hydraulic conductivity within the plausible range. Injectant would move upward only about 100 ft under tightly confined conditions and completely through the 350-ft-thick unit if hydraulic conductivity was 1 ft/d.
6. Hydraulic conductivity of the injection zone.—Sensitivity tests included halving and doubling vertical and horizontal hydraulic conductivities of the Ocala-Avon Park moderately permeable zone and the Avon Park highly permeable zone (fig. 34*K* and *L*; table 9). These changes produced approximately the same results as the porosity sensitivity tests. Although approximately the same volumes of aquifer are contaminated with the injectant, compared to the best-estimate model, the distribution of the solute has changed. Reducing hydraulic conductivity results in a thick snub-nosed concentration front, which apparently is caused by retardation of bouyancy. Increasing hydraulic conductivity produces a thin lens at the top of the injection reservoir due to enhanced bouyancy. Because hydraulic conductivity may vary over an order of magnitude, it is potentially a more important parameter than is porosity, which probably lies within a fairly narrow range.
7. Vertical-horizontal anisotropy.—Anisotropy can influence hydraulic properties of sedimentary aquifer systems. Hickey (1989) introduced vertical-horizontal anisotropy as a 1:5 ratio in an injection study of a carbonate system in Pinellas County. A test was made of the sensitivity of the model to anisotropy by setting vertical hydraulic conductivity of all zones at one-fifth the horizontal hydraulic conductivity.

The resulting scaled solute-concentration distribution (fig. 34*M*; table 9) varies slightly from the isotropic best-estimate model in that upward movement of injectant is reduced from 160 to 150 ft. The sensitivity analysis demonstrates that anisotropy inhibits upward movement of bouyant wastewaters, but the model is relatively insensitive to changes in the ratio.

8. Porous medium compressibility.—Vertical compressibility is a model input parameter that controls the degree to which stress varies storage within the hydrogeologic system. Injection increases hydraulic head, lowers effective stress borne by the granular skeleton of the porous medium, and causes expansion of pores and an associated increase in porosity. Therefore, it may be anticipated that increasing the matrix compressibility will attenuate the injectant plume and reducing compressibility will expand it. Results of such sensitivity tests (fig. 34*N*; table 9) demonstrate that a tenfold reduction and increase in compressibility produce little change in the distribution of the scaled solute concentration. The model is not sensitive to large changes in compressibility, probably because of the relatively small maximum pressure change of 5 lb/in^2 imposed on the system at the well bore. Although the percent change in pore volume is very small, it will be numerically large over a large region.
9. Radial boundary conditions.—Tests were made to assess the sensitivity of the model to changes in dimensions of the outer and inner aquifer region. The first test consisted of changing the thickness of the outer aquifer region from 1,300 to 2,000 ft. A second test was then conducted by changing the radius of the inner aquifer region from 3,000 to 4,000 ft and increasing the radial grid from 98 to 118 columns. Neither test produced a noticeable change in the distribution of the scaled solute concentration, as indicated in table 9. Because the model is insensitive to changes in radial boundary conditions, those of the best-estimate model were deemed to be adequate.

Limitations of the Model Application

A conceptual approach to solute-transport modeling was used in the application of this model. The hydrogeologic system was conceptualized, its properties were identified and estimated, and it was transformed into the mathematical

Table 9. Results of sensitivity tests

[ft, feet; ft/d, feet per day; lb/in^2, pound per square inch]

Diagram in figure 34	Parameter[1]	Injectant movement[2] Lateral[3] (ft)	Upward[4] (ft)
--	Best-estimate model	2,300	160
A	Injection zone porosity = 0.075 (0.15)	3,000	160
B	Injection zone porosity = 0.3 (0.15)	1,700	160
C	Transverse dispersivity = 50 ft (5 ft)	2,100	200
D	Longitudinal dispersivity = 50 ft (20 ft)	2,400	200
E	Longitudinal dispersivity = 5 ft (20 ft)	2,200	150
F	Dispersivity = 0.0		
G	Model grid 53×127 (27×98)	2,400	170
H	Increase pressure at bottom of model to 916.8 lb/in^2 (912.4 lb/in^2).	2,250	200
I	Hydraulic conductivity of semiconfining unit = 0.01 ft/d (0.1 ft/d).	2,300	100
J	Hydraulic conductivity of semiconfining unit = 1 ft/d (0.1 ft/d).	2,100	>350
K	Hydraulic conductivity of injection zone = 0.5×	2,000	170
L	Hydraulic conductivity of injection zone = 2×	2,700	160
M	Vertical:horizontal anisotropy = 1:5 (1:1)	2,200	150
N	Porous-medium compressibility = 10×	2,100	150
--	Porous-medium compressibility = 0.1×	2,300	160
--	Boundary of inner aquifer region = 4,000 ft (3,000 ft).	2,300	160
--	Thickness of outer aquifer region = 2,000 ft (1,300 ft).	2,300	160

[1]Parameter in parentheses is value used in the best-estimate model.

[2]Freshwater injected into very saline water between depths of 1,150 and 2,050 ft at a rate of 1 Mgal/d for 10 yr.

[3]Represents maximum distance of the 0.1 scaled solute concentration line outward from the injection well. The model is sensitive to parameter changes that produce lateral movement less than 2,050 ft or more than 2,550 ft.

[4]Represents maximum distance of the 0.1 scaled solute concentration line upward above the top of the injection zone at 1,100 ft. The model is sensitive to parameter changes that produce upward movement above 190 ft.

analog. The mathematical model approximates the physical processes that control the conceptual model, but it is only an approximate representation of the prototype hydrogeologic system.

The hydrogeology has been simplified to the extent that an operational mathematical model can be constructed. Hydrogeologic data from several sources within and near the study region were used to construct a model that simulates injection through a representative well. Results should not be construed as valid for a specific injection site. Also, because the model was not calibrated against observed distributions of solute and pressure, a sensitivity approach was relied upon to test the reliability of a best-estimate model.

Two limitations are recognized that could considerably reduce confidence in simulated results. The first is that the simulated hydrogeologic system is represented as a porous medium rather than a block and fracture system with dual porosity. Hickey (1989) used the parent INTERCOMP model to simulate observed pressures and concentrations in the highly fractured system in Pinellas County. He concluded that the system responded to injection stresses as an equivalent porous medium. Injection in the study area is into the same zone of crystalline dolomite, although it is less transmissive and appears in borehole video surveys to be less fractured than in Pinellas County.

A second important limitation is the assumption that regional horizontal flow is negligible. The magnitude of the regional lateral flow may be estimated by using Darcy's equation:

$$\bar{v} = (K\,I)/n \qquad (1)$$

where:

$\bar{v}$ = average linear velocity, in feet per day;
K = horizontal hydraulic conductivity, in feet per day;
I = hydraulic gradient, in feet per foot; and
n = porosity.

For the Ocala-Avon Park moderately permeable zone, where the injectant accumulates, horizontal velocity is about 0.06 ft/d, based on K of 25 ft/d, n of 0.15, and I of 0.0004 ft/ft (2 ft/mi). After 10 yr, the injectant front would move about 200 ft farther downgradient and 200 ft less upgradient, thereby shifting an otherwise radially symmetrical lens of injectant downgradient. The shift is small compared to the 2,300-ft simulated radial spread. Injection near a discharge point, such as Warm Mineral Springs where the hydraulic gradient is steep, may considerably alter the configuration of the injectant lens. For much of the area, the gradient is uniform and relatively low; therefore, regional flow will not greatly affect the shape and position of the injectant lens.

Potential Effects of Injection

The solute-transport model was used to simulate the hydrologic system's response to wastewater injection. Objectives of this predictive modeling phase were to assess the potential for upward movement of injectant to potable aquifers and lateral movement outward from injection wells. A single-well model was used to represent local flow and transport given a range of estimated or measured input values. Results were used to assess potential regional movement of injected wastewater from existing and proposed wells in the study area. The model input file is listed in the Appendix .

Combinations of assumed hydrologic conditions and injection-well designs and operations that were simulated include:

1. Injecting through an ideal well that fully penetrates the injection zone to assess system response to a highly efficient injection system.
2. Injecting through single wells with various cased and open-hole sections to test a variety of well designs.
3. Injecting through a single well beneath a well field where pumping for reverse-osmosis product water increases the potential for upward leakage of injectant.
4. Injecting through an array of 10 waste-disposal wells proposed for the study area and nearby communities to estimate the potential areal spread of injected wastewater.

Interpretation of model results includes assessment of the direction of flow and the concentration of injectant. The injectant front is considered to occur where the scaled solute concentration in the formation is 0.1, or 10 percent of injected water. Results are used to provide guidelines for injection well and monitor well construction and calculation of traveltimes.

Injection Through an Ideal Well

The ideal injection well is defined as cased from land surface through the lower Suwannee-Ocala semiconfining unit, with the open-hole section fully penetrating the injection zone. The well would have a 1-ft radius and about 1,150 ft of casing and be about 2,050 ft deep. The model simulated injection through an ideal well to define the development and expansion of a lens of relatively fresh wastewater. Figure 35 illustrates the scaled solute concentration in the ground-water flow field after 1 (fig. 35*A*) and 10 (fig. 35*B*) yr of injection at a rate of 1 Mgal/d and then 10 yr after ceasing injection (fig. 35*E*). Also shown are scaled solute concentration diagrams that represent injection of 2 Mgal/d for 10 yr (fig. 35*D*) and 1 Mgal/d for 20 yr (fig. 35*C*).

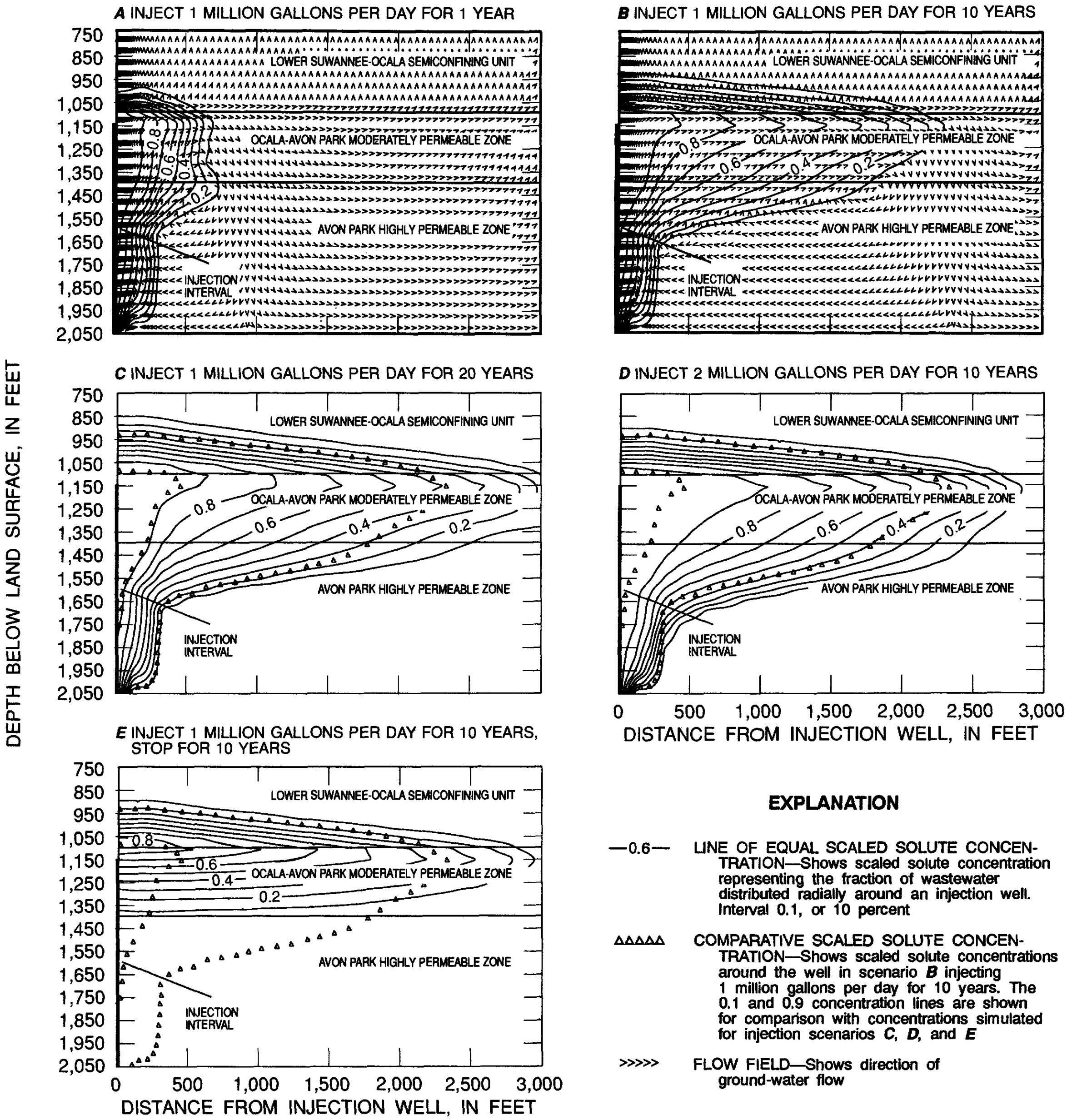


Figure 35. Radial sections showing the simulated flow field and concentration of wastewater injected through an ideal, fully penetrating well.

Convection caused by the density contrast between the injected freshwater and native saltwater is readily evident from the direction of movement in the flow field in figure 35*A* and *B*. After 1 yr, a convection cell in the flow field is well defined, with buoyant wastewater pooled about the base of the lower Suwannee-Ocala semiconfining unit and denser formation water moving toward the bottom of the well (fig. 35*A*). The injectant moved about 75 ft above the top of the injection zone to a depth of 1,025 ft. After 10 yr, the lens has extended outward to a radius of 2,300 ft and moved upward about 160 ft into the semiconfining unit to a depth of 940 ft (fig. 35*B*). Pressure build-up was a maximum of 5 lb/in^2 at the bottom of the casing. At a radius of 500 ft, the maximum build-up was 4 lb/in^2 at the top of the injection zone. During the periods of 1–20 and 10–20 yr, the simulated injectant front moved upward from 1,025 to 850 ft and from 940 to 850 ft, respectively (compare fig. 35*A* and *C*, *B* and C, fig. 35). The computed steady-state rate of upward movement is 0.025 ft/d, or 9 ft/yr. Because vertical movement through the semiconfining unit is a function of hydraulic conductivity, the rate of upward movement could likely vary over an order-of-magnitude range as indicated by the range in hydraulic conductivities listed in table 7.

Model simulations indicate that the injectant moves 75 ft upward in the first year, and afterwards the steady rate of upward movement is 9 ft/yr. At this rate, it would take about

31 yr for the injectant to move through the 350-ft-thick semiconfining unit to the Suwannee permeable zone. A 31-year simulation indicated that indeed the injectant had moved to the top of the semiconfining unit. Injecting at a rate of 1 Mgal/d for 20 yr produces a lens with a radius beyond the model boundary (fig. 35*C*). Although the same volume was injected under the 2-Mgal/d-for-10-yr injection scenario, the simulated 2-Mgal/d lens moves upward about 30 ft less, and the radial spread does not reach the model boundary (compare fig. 35*C* and *D*).

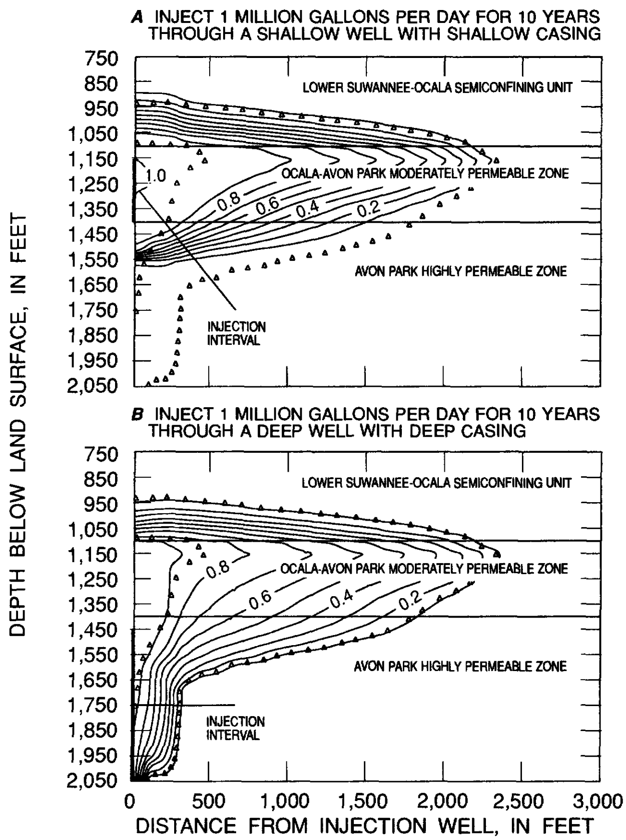
Vertical and horizontal movement proceeds even after injection stops. The simulated front moves up from 940 to 900 ft and outward from 2,300 to 2,900 ft in the 10-yr interval following injection (fig. 35*E*). The steady-state rate of upward movement under buoyant flow conditions with no injection is 0.011 ft/d, or 4 ft/yr. Model results indicate that, if injection were stopped after 10 yr, injectant could travel from 940 to 750 ft to reach the Suwannee permeable zone about 48 yr after injection ceased.

Significance of Injection Well Design

The cost of a 1,500-ft-deep, 12-in.-diameter injection well and monitor well system is about $1 million (R.L. Westly, Law Environmental, Inc., oral commun., 1988). Regulations require that the injection tubing be doubly cased through zones that contain water with less than 10,000 mg/L of dissolved solids and that the well be tested for mechanical integrity. The cost given above includes the cost of designing and testing the injection wells. A review of initial designs for 12 of the 13 injection wells in figure 5 indicated that these designs generally propose injection through a partially penetrating well that is cased through the lower Suwannee-Ocala semiconfining unit to the first permeable zone containing water with greater than 10,000 mg/L dissolved solids. In the study area, this zone often occurs in the lower part of the Ocala Limestone. The Florida Department of Environmental Regulation (FDER) Technical Advisory Committee for underground injection control that reviews the designs often recommends that wells fully penetrate or be cased to the Avon Park highly permeable dolomite, which substantially increases construction costs.

Figure 36 shows a comparison of model-simulated transport of relatively fresh wastewater injected in the study area at a rate of 1 Mgal/d for 10 yr under two well designs: (1) 1,400 ft deep with 1,150 ft of casing and open to the Ocala-Avon Park moderately permeable zone (fig. 36*A*), and (2) 2,050 ft deep with 1,450 ft of casing and open to the Avon Park highly permeable zone (fig. 36*B*). Results of each simulation also are compared to the ideal, fully penetrating well model defined previously. The figure shows that the relatively buoyant injectant forms a circular lens around the injection well. Approximate dimensions of each lens and position of its top within the lower Suwannee-Ocala semiconfining unit after 10 yr of injection are compared as follows:

	Open-hole interval of injection well (ft below land surface)		
	1,150–1,400	1,150–2,050	1,450–2,050
Maximum radius of lens (ft)	2,280	2,300	2,320
Thickness of lens at 1,000-ft radius (ft)	525	570	570
Depth to top of lens (ft)	890	940	950
Upward movement through semiconfining unit (ft)	210	160	150
Pressure build-up at bottom of casing (lb/in^2)	9.1	5.1	2.7
Pressure build-up at 500-ft radius and depth of 1,150 ft (lb/in^2)	4.1	4.1	4.0



EXPLANATION

—0.6— LINE OF EQUAL SCALED SOLUTE CONCENTRATION—Shows scaled solute concentration representing the fraction of wastewater distributed radially around an injection well. Interval 0.1, or 10 percent

ΔΔΔΔΔ COMPARATIVE SCALED SOLUTE CONCENTRATION—Shows scaled solute concentrations around an ideal fully penetrating injection well with an injection depth interval from 1,150 feet to 2,050 feet. The 0.1 and 0.9 concentration lines are shown for comparison with concentrations simulated for each type of well construction

Figure 36. Radial sections showing the simulated concentration of injected wastewater as influenced by well construction.

Conclusions drawn from the model simulations are that the configuration and position of the lens are not greatly affected by well construction. Although the deeply cased well (1,450–2,050 ft) injects into the lower part of the injection zone, convective forces due to density contrasts buoy the injectant above the bottom of the casing to the lower Suwannee-Ocala semiconfining unit, which partially constrains and flattens the lens. The short-cased well (1,150–1,400 ft) injects a lens that is configured similarly to both the deeply cased well and the ideal well. The main differences are that the top of the injectant lens is about 60 ft higher and the injectant is more concentrated around the short-cased well than around the deeply cased well. Injection pressures would be highest in the short-cased well because the injection interval is less transmissive than the other two well configurations. Pressure build-up in the injection zone is not affected by well design, as indicated by the equivalent pressure build up of 4 lb/in^2 at the top of the zone at a radius of 500 ft under each well design.

Traveltime of the injectant front from the injection zone through the lower Suwannee-Ocala semiconfining unit to the potable water-bearing Suwannee permeable zone varies slightly with casing depth. Under the previously described ideal well conditions, the steady-state upward rate of movement was 9 ft/yr, and estimated traveltime was about 31 yr. Analogous traveltimes for shallow-cased and deep-cased wells are estimated to be 26 and 32 yr, respectively.

Injecting Beneath a Reverse-Osmosis Supply Field

The study area encompasses four sites where reverse-osmosis wastewater is injected directly below a well field, which draws feed water from the Suwannee permeable zone. Pumping for supply lowers head (pressure) at the bottom of the Suwannee permeable zone, which coincides with the top of the injection model. There is potential for a significant increase in upward movement of injectant from the injection zone through the lower Suwannee-Ocala semiconfining unit to the Suwannee permeable zone. A model simulation was made to assess this potential effect.

The model was originally set up to simulate injecting 1 Mgal/d as treated sewage with physical properties similar to those of freshwater. To simulate pumping from a well field, the constant pressure at the top of the model was reduced from 333 to 325 lb/in^2 to represent a drawdown of 20 ft at the top of the semiconfining unit. Other differences are that density of the injectant was increased from 62.4 (freshwater) to 63.0 lb/ft^3 (very saline reverse-osmosis wastewater) and increasing viscosity from 0.9039 to 0.9289 cP to approximate the physical characteristics of the wastewater, which had a dissolved-solids concentration of about 14,000 mg/L. These changes were required because the best-estimate model was based on physical characteristics of relatively fresh treated sewage.

Figure 37 shows the radial distribution of injected reverse-osmosis wastewater simulated by the model after injecting 1 Mgal/d for 10 yr. The 0.1 and 0.9 scaled solute concentrations simulated previously for the ideal injection well are superimposed for comparative purposes. Results indicate that, even though the injectant is very saline, it is relatively buoyant in the injection zone where the native water density is 64.0 lb/ft^3. A 20-ft reduction in head that may be caused by pumping for reverse-osmosis supply would induce upward movement through the lower Suwannee-Ocala semiconfining unit. The simulation results indicate that the front would move upward into the semiconfining unit to a depth of 860 ft, or about 80 ft higher during the same period than at a site where less dense treated sewage was injected with no pumping from above the injection zone.

Areal Effect of Proposed Injection

Seven active and proposed injection sites within the study area were shown to have a combined projected injection capacity of 28.8 Mgal/d (table 2). Injection capacities range from a low of 0.8 Mgal/d at Plantation to a high of 14 Mgal/d at the proposed West Port site (table 2). An objective of this study was to estimate what the areal spread of injected wastewater might be with all sites fully operational. To achieve this goal, the ideal single-well radial model was used to draw inferences about the fate of injected fluid at the seven injection sites within the study area injecting 28.8

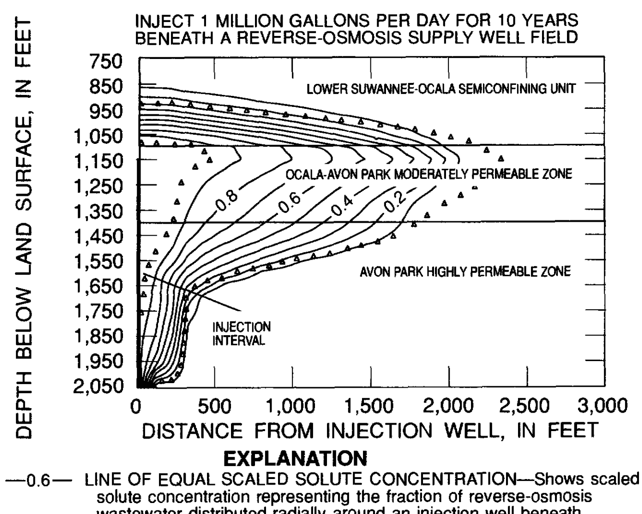


Figure 37. Radial section showing the simulated concentration of reverse-osmosis wastewater injected beneath a supply field where pumping stress increases upward movement of the injectant.

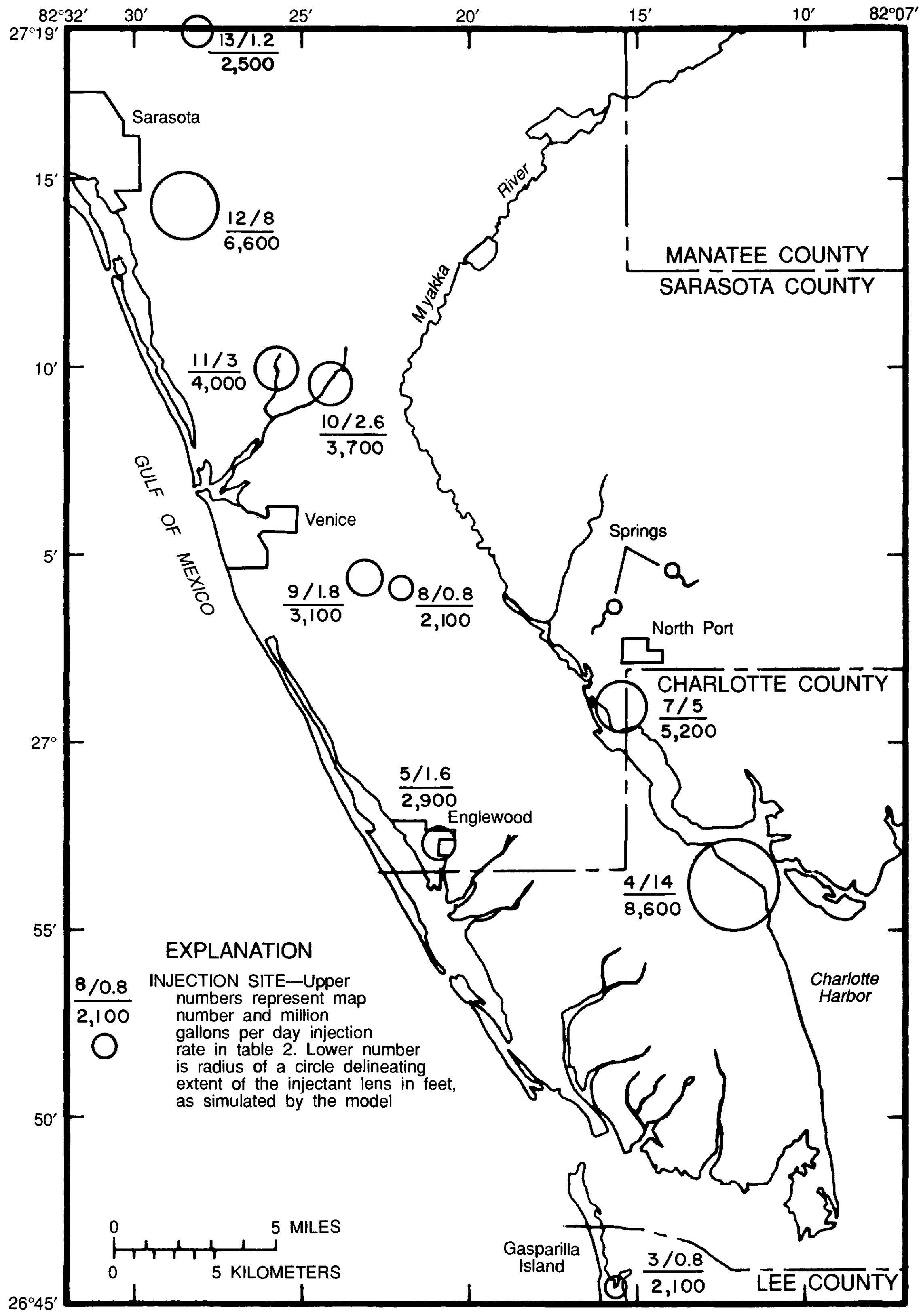


Figure 38. Estimated areal spread of wastewater after 10 yr of injection at projected rates.

Mgal/d and three sites just to the north and south of the study area injecting 10 Mgal/d.

It was shown earlier that, after 10 yr of injecting 1 Mgal/d, fluid would rise to the top of the injection zone and form a lens about 600 ft thick and have a radius of about 2,300 ft. The areal spread of such a lens is approximately 0.6 mi^2. Assuming there is direct proportionality between injection rate and area of spread, the 14-Mgal/d site should be underlain by a lens 600 ft thick and spread over an area of about 8.4 mi^2. The method of linear extrapolation was used to roughly approximate the potential spread of injectant around the 10 injection sites within and near the study area, as depicted in figure 38. The figure gives some insight as to what the lateral extent of injectant in the system would be if all wells began injecting at the same time and operated at projected maximum capacities for 10 yr. Approximately 17 mi^2, or 7 percent, of the 250-mi^2 study area would be underlain by injected wastewater. Areas would be doubled for a 20-year projection. Although the spread of injectant is delineated by circles on the figure, it should be noted that regional lateral flow in the injection zone would tend to distort them. Regional lateral flow, estimated previously to be 0.06 ft/d, would tend to offset and distort the circles about 200 ft to the west, or downgradient as indicated by figure 17. Injected sewage at North Port has the potential for moving northward to Warm Mineral Springs, but should be detected years beforehand in the satellite monitor well (index no. 58 in fig. 6 and table 3) between the injection well and the spring.

GROUND-WATER-QUALITY PROBLEMS AND SOME MANAGEMENT CONSIDERATIONS

A diversity of potential water-quality problems arises due to both natural phenomena and human activity. Shallow freshwater that is used primarily for public supplies and irrigation is subject to contamination by upconing of saline water beneath pumping centers and through abandoned or improperly constructed artesian wells. Contamination also may occur naturally, as much of the land is low lying and subject to tidal flooding. Slightly to moderately saline ground water, tapped by irrigation and reverse-osmosis supply wells, is subject to contamination by upconing of very saline water induced by pumping, especially where the underlying water is unconfined. Model results imply that upconing may be accelerated by injecting wastewater through deep wells, thereby forçing very saline water upward in areas of pressure buildup. Deep, very saline water, although it is an unused resource, may be contaminated by the injection of nutrient-rich treated sewage and radium-rich reverse-osmosis wastewater.

Local and State agencies manage the hydrologic system through a system of regulation, permitting, and conformance monitoring. Regular observations of water quality and water levels commonly are required and actions are taken to correct or mitigate imminent problems. Water-use permits are issued by the Southwest Florida Water Management District on the basis of projected drawdown, or the effect that pumping might have on encroachment of very saline water. When water levels decline below those specified in the permit, or water-quality constraints are exceeded, pumping restrictions may be imposed. Sarasota County further requires that irrigation wells be deeply cased to preserve the freshest water for public supply and that municipalities that own public-supply well fields maintain water-level and water-quality observation-well networks. The Southwest Florida Water Management District additionally has established the previously described ROMP network of permanent observation wells and is plugging uncontrolled flowing artesian wells as part of its QWIP. Reverse-osmosis source water is continually sampled and analyzed out of concern that high concentrations of dissolved solids will require the conversion of low pressure systems to more expensive high pressure systems. Injection of wastewater is managed by the Florida Department of Environmental Regulation, which requires that (1) permittees demonstrate that the well will not be damaged by a multiple of the anticipated injection pressure, (2) there is an alternate method of disposal if the injection well fails, (3) the injection zone contains water having 10,000 mg/L or greater dissolved-solids concentration and is adequately confined so that upward movement will be prevented, and (4) water levels and water quality in the permeable zone above the injection zone will be monitored periodically to provide advance warning of injectant movement toward formations that contain potable water.

This report provides information that may be useful for management of ground-water resources, especially with respect to wastewater injection. Maps of the hydrogeologic framework and water quality of the injection zone may aid in siting injection wells and estimating casing depths. Model simulations indicate that construction of a shallow, partially penetrating injection well does not greatly alter the distribution of injected fluid or rate of upward movement compared to the more expensive, fully penetrating or deeply cased well. Injecting beneath a reverse-osmosis supply well field would accelerate upward movement of wastewater. Modeling can provide insight in selecting locations of observation wells and for designing sampling programs. Simulations show that the best place to monitor movement is in the upper part of the injection zone because the injectant is relatively bouyant and tends to form a lens that is partly constrained by the lower Suwannee-Ocala semiconfining unit from rising further. Model-simulated movement of the lens of injectant shows that it probably will take more than 20 yr for the injectant to travel 4,000 ft from a 1-Mgal/d injection well. It was also demonstrated that an observation well located at a distance less than 2,000 ft from the injection well would be required to monitor movement within the first 10 yr of operation. The rate of upward movement at a representative injection site is about 9 ft/yr in the lower Suwannee-Ocala semiconfining unit, as simulated by the model. Therefore, the lower

Suwannee-Ocala semiconfining unit slows but does not prevent injected fluid movement into the overlying freshwater aquifers.

SUMMARY AND CONCLUSIONS

A 250-mi^2 area of southwest Sarasota and west Charlotte Counties is underlain by a complex hydrogeologic system that contains water with a wide variation in quality. Conditions or actions that could alter ground-water quality include flooding by storm tides, upward movement of poor quality water toward pumping centers from deep zones by leakage or by short circuit through uncased or improperly constructed and abandoned artesian wells, and lateral and vertical movement of treated sewage and reverse-osmosis desalinization wastewater injected into deep zones. This study has been specifically directed toward (1) defining the hydrogeologic framework in the area, (2) describing the ground-water quality and the effects of uncontrolled flowing artesian wells or the quality, and (3) demonstrating the usefulness of a solute-transport model as a tool for understanding the effects of wastewater injection on the aquifer system. The findings of this study are briefly summarized as they pertain to these objectives in the following paragraphs.

The hydrogeologic framework.—The study area is underlain by the surficial, intermediate, and Floridan aquifer systems, which contain six separate aquifers or permeable zones. The 50-ft-thick surficial aquifer system has a transmissivity of about 1,500 ft^2/d and contains potable water in areas where tidal flooding does not occur. The intermediate aquifer system consists of permeable quartz and phosphatic sands and carbonate deposits interlayered with discontinuous clay confining units that separate the system into the Tamiami-upper Hawthorn aquifer and the lower Hawthorn-upper Tampa aquifer. The 450- to 600-ft-thick intermediate aquifer system has a transmissivity generally less than 10,000 ft^2/d and exhibits storage characteristics of a confined aquifer. Water in the upper part of the intermediate system is fresh. In the lower part, slightly to moderately saline water is used for reverse-osmosis feed water and irrigation. The Upper Floridan aquifer has a maximum thickness of 1,600 ft within the Floridan aquifer system and comprises four hydrogeologic units: (1) the 250-ft-thick Suwannee permeable zone, (2) the 350-ft-thick lower Suwannee-Ocala semiconfining unit, (3) the 300-ft-thick Ocala-Avon Park moderately permeable zone, and (4) the 700-ft-thick Avon Park highly permeable zone. The Suwannee permeable zone has an approximate transmissivity of 13,000 ft^2/d and is tapped by irrigation and reverse-osmosis supply wells. A 100-ft offset in a dolomitic marker bed within the zone was mapped to portray the trace of an east-west fault through the study area. The underlying lower Suwannee-Ocala semiconfining unit has a vertical hydraulic conductivity of about 0.1 ft/d and generally encompasses the transition zone between freshwater and very saline water and may be breached by the fault. The lower two hydrogeologic units have hydraulic conductivities of 25 and 100 ft/d and constitute the injection zone, which contains very saline water.

Ground-water quality.—The study area is in a coastal peninsular setting where a shallow freshwater lens in upper aquifers grades downward and coastward to very saline water. Median dissolved-solids concentrations were identified as follows: (1) surficial aquifer system, less than 500 mg/L; (2) Tamiami-upper Hawthorn aquifer, 660 mg/L; (3) composite of both aquifers of the intermediate aquifer system, 2,170 mg/L; (4) Suwannee permeable zone, 3,210 mg/L; and (5) injection zone, 32,800 mg/L. Water generally grades from a calcium sulfate type in the north to a sodium chloride type in the south, with chloride increasing from about 30 to 19,000 mg/L where there is probably residual seawater in the system. Little Salt and Warm Mineral Springs, just east of the study area, discharge waters similar in quality to those in the Suwannee permeable zone and the injection zone, respectively. Approximately 100 deep uncontrolled flowing artesian wells that discharge continuously at land surface or leak internally from one aquifer to another have been identified in the study area. As of 1986, about half the wells that allowed upward flow of saline water from deep zones into shallow aquifers were plugged as part of the Southwest Florida Water Management District's Quality of Water Improvement Program. Flowmeter surveys in 14 wells measured internal flow rates in the well bore between 0 and 350 gal/min; the median flow rate was about 10 gal/min. The highest rates of internal flow were measured in the Venice area and were not limited to a specific depth interval.

The usefulness of a solute-transport model.—The study area encompasses seven wastewater injection sites having a projected capacity for injecting 28.8 Mgal/d of treated sewage and reverse-osmosis wastewater into the zone 1,100 to 2,050 ft below land surface. A numerical model of ground-water flow and solute transport (HST3D) was used to evaluate injection well design and potential for movement of injected wastewater within the hydrogeologic framework. Various well design scenarios were simulated with the model for a hypothetical prototype well injecting 1 Mgal/d of treated sewage for 10 yr.

The model simulated development of a convection cell around the injection well with the relatively bouyant fresh injectant rising to form a lens within the injection zone below the lower Suwannee-Ocala semiconfining unit. Around an ideal, fully penetrating well cased 50 ft into the injection zone and open from a depth of 1,150 to 2,050 ft, simulations show that the injectant moves upward to a depth of 940 ft, forms a lens about 600 ft thick, and spreads radially outward to a distance of 2,300 ft after 10 yr. The rate of upward movement through the overlying lower Suwannee-Ocala semiconfining unit was estimated to be 9 ft/yr and has the potential to vary over an order of magnitude range in the study area. Comparison simulations of injection through wells with open-depth intervals of 1,150 to 1,400 ft and 1,450 to 2,050 ft demonstrated that well construction has little effect on the areal spread of the injectant lens or the rate and extent of upward movement, probably because the injection zone is very permeable. Simulations also indicated that wastewater injected beneath the lower Suwannee-Ocala semiconfining unit at a reverse-osmosis supply well field, where water levels above the semiconfining unit are lowered 20 ft by pumpage, would move upward into the semiconfining unit to a depth of 860 ft, or about 80 ft higher over the same time period than at a site with no withdrawals above the injection zone. Areal extrapolation of various injection rates indicated that about 7 percent of the study area would be underlain by injected wastewater after 10 yr of injection at the maximum projected capacity. Observation wells in the injection zone would need to be open to the upper part of the zone and located within 2,000 ft of the injection well if movement of the injectant within the first 10 yr of operation is to be monitored. The conclusion drawn from the modeling that, in general, the lower Suwannee-Ocala semiconfining unit retards but does not prevent the upward movement of injected fluid into the overlying freshwater aquifers.

The model analysis has demonstrated how, by using numerical methods, various hydrologic conditions can affect movement of wastewater injected into a deep saline aquifer. Modeling is also a useful tool for design of injection and monitor well systems. To obtain these results through operational tests would have been costly. The validity of computer modeling results is somewhat less certain than site-specific testing, but because results are general, they are transferable. Despite this reservation, the study is a practical example of the application of a transport model in ground-water investigations.

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Appendix

APPENDIX: LISTING OF MODEL INPUT FILE

A sample input-data listing is provided for the predictive run where 10 Mgal/d of treated sewage is injected for 10 yr. The listing contains 351 lines, of which 245 lines are comments that aid construction of the data file. Critical comments are keyed to input record descriptions of Kipp (1986a, p. 189). The following order generally is observed for data input: (1) fundamental and dimensioning information, (2) spatial geometry and mesh information, (3) fluid properties, (4) porous medium properties, (5) source information, (6) boundary condition information, (7) initial condition information, (8) calculation parameters, and (9) output specifications.

SAMPLE INPUT FILE: INJECT 1 MGAL/DAY FOR 10 YR THROUGH
AN IDEAL, FULLY PENETRATING WELL

```
C.....START OF THE DATA FILE
C.....DIMENSIONING DATA - READ1
C.1.1 .. TITLE LINE 1
INJECT 1 MGAL/D SEWAGE INTO OCALA-AVON PARK
C.1.2 .. TITLE LINE 2
FOR 10 YEARS
C.1.3 .. RESTRT(T/F),TIMRST
F 0
C.1.4 .. HEAT,SOLUTE,EEUNIT,CYLIND,SCALMF; ALL (T/F)
F T T T T
C.1.5 .. NX,NY,NZ,NHCN
98,,27,0
C.1.6 .. NPTCBC,NFBC,NAIFC,NLBC,NHCBC,NWEL
98 0 26 0 0 7
C.1.7 .. NPMZ
3
C.1.8 .. SLMETH[I],LCROSD(T/F)
1 T
C.1.9 .. IBC BY I,J,K RANGE {0.1-0.3} ,WITH NO IMOD PARAMETER, FOR EXCLUDED CELLS
0 /
C.1.10 .. RDECHO(T/F)
T
C--------------------------------------------------------------------------------
C.....STATIC DATA - READ2
C.....OUTPUT INFORMATION
C.2.1 .. PRTRE(T/F)
T
C.....COORDINATE GEOMETRY INFORMATION
C..... RECTANGULAR COORDINATES
C.2.2A.1 .. UNIGRX,UNIGRY,UNIGRZ; ALL (T/F); (O) - NOT CYLIND [1.4]
C.2.2A.2A .. X(1),X(NX);(O) - UNIGRX [2.2A.1]
C.2.2A.2B .. X(I);(O) - NOT UNIGRX [2.2A.1]
C.2.2A.3A .. Y(1),Y(NY);(O) - UNIGRY [2.2A.1]
C.2.2A.3B .. Y(J);(O) - NOT UNIGRY [2.2A.1]
C.2.2A.4A .. Z(1),Z(NZ);(O) - UNIGRZ [2.2A.1]
C.2.2A.4B .. Z(K);(O) - NOT UNIGRZ [2.2A.1]
C.....CYLINDRICAL COORDINATES
C.2.2B.1A .. R(1),R(NR),ARGRID(T/F);(O) - CYLIND [1.4]
1 3000 F
C.2.2B.1B .. R(I);(O) - NOT ARGRID [2.2B.1A];(O) - CYLIND [1.4]
   1.00   1.14   1.30   1.49   1.70   1.94   2.22   2.53   2.89   3.31
   3.78   4.31   4.92   5.62   6.42   7.33   8.38   9.57  10.93  12.48
  14.25  16.28  18.59  21.23  24.24  27.69  31.62  36.12  41.25  47.11
  53.80  61.44  70.17  80.14  91.52 104.53 119.38 136.34 155.71 177.83
 203.09 231.94 264.90 302.53 350.   400.   450.   500.   550.   600.
 650.   700.   750.   800.   850.   900.   950.  1000.  1050.  1100.
1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800
1850 1900 1950 2000 2050 2100 2150 2200 2250 2300 2350 2400 2450 2500
2550 2600 2650 2700 2750 2800 2850 2900 2950 3000
C.2.2B.2 .. UNIGRZ(T/F);(O) - CYLIND [1.4]
T
C.2.2B.3A .. Z(1),Z(NZ);(O) - UNIGRZ [2.2B.3A],CYLIND [1.4]
-2050 -750
C.2.2B.3B .. Z(K);(O) - NOT UNIGRZ [2.2B.3A],CYLIND [1.4]
C.2.3.1 .. TILT(T/F);(O) - NOT CYLIND [1.4]
C.2.3.2 .. THETXZ,THETYZ,THETZZ;(O) - TILT [2.3.1] AND NOT CYLIND [1.4]
C.....FLUID PROPERTY INFORMATION
C.2.4.1 .. BP
3.03E-6
C.2.4.2 .. P0,T0,W0,DENF0
0 77 0 64.0
C.2.4.3 .. W1,DENF1;(O) - SOLUTE [1.4]
.005 62.4
C.2.5.1 .. NOTV0,TVF0(I),VISTF0(I),I=1 TO NOTV0;(O) - HEAT [1.4] OR HEAT [1.4] AND SOLUTE [1.4] OR .NOT.HEAT
CAND .NOT.SOLUTE [1.4]
C.2.5.2 .. NOTV1,TVF1(I),VISTF1(I),I=1 TO NOTV1;(O) -  SOLUTE [1.4] AND HEAT [1.4]
C.2.5.3 .. NOCV,TRVIS,CVIS(I),VISCTR(I),I=1 TO NOCV;(O) - SOLUTE [1.4]
2 77 0 .9500 1 .9039
C.....REFERENCE CONDITION INFORMATION
C.2.6.1 .. PAATM
0
C.2.6.2 .. P0H,T0H
0 77
C.....FLUID THERMAL PROPERTY INFORMATION
C.2.7 .. CPF,KTHF,BT;(O) - HEAT [1.4]
C.....SOLUTE INFORMATION
C.2.8 .. DM,DECLAM;(O) - SOLUTE [1.4]
8.75E-7 0
C.....POROUS MEDIA ZONE INFORMATION
C.2.9.1 .. IPMZ,I1Z(IPMZ),I2Z(IPMZ),J1Z(IPMZ),J2Z(IPMZ),K1Z(IPMZ),K2Z(IPMZ)
1 1 98 1 1 1 14
2 1 98 1 1 14 20
3 1 98 1 1 20 27
```

```
0 /
C.....USE AS MANY 2.9.1 LINES AS NECESSARY
C.2.9.2 .. END WITH 0 /
C.....POROUS MEDIA PROPERTY INFORMATION
C.2.10.1 .. KXX(IPMZ),KYY(IPMZ),KZZ(IPMZ),IPMZ=1 TO NPMZ [1.7]
3.5E-10,,3.5E-10
8.75E-11,,8.75E-11
3.372E-13,,3.372E-13
C.2.10.2 .. POROS(IPMZ),IPMZ=1 TO NPMZ [1.7]
.15 .15 .25
C.2.10.3 .. ABPM(IPMZ),IPMZ=1 TO NPMZ [1.7]
5.5E-7 6.2E-6 1.5E-5
C.....POROUS MEDIA THERMAL PROPERTY INFORMATION
C.2.11.1 .. RCPPM(IPMZ),IPMZ=1 TO NPMZ [1.7];(O) - HEAT [1.4]
C.2.11.2 .. KTXPM(IPMZ),KTYPM(IPMZ),KTZPM(IPMZ),IPMZ=1 TO NPMZ [1.7];(O) - HEAT [1.4]
C.....POROUS MEDIA SOLUTE AND THERMAL DISPERSION INFORMATION
C.2.12 .. ALPHL(IPMZ),ALPHT(IPMZ),IPMZ=1 TO NPMZ [1.7];(O) - SOLUTE [1.4] OR HEAT [1.4]
20 5
20 5
20 5
C.....POROUS MEDIA SOLUTE PROPERTY INFORMATION
C.2.13 .. DBKD(IPMZ),IPMZ=1 TO NPMZ [1.7];(O) - SOLUTE [1.4]
3*0.0
C.....SOURCE-SINK WELL INFORMATION
C.2.14.1 .. RDWDEF(T/F);(O) - NWEL [1.6] > 0
T
C.2.14.2 .. IMPQW(T/F);(O) - NWEL [1.6] > 0 AND NOT CYLIND [1.4]
C.2.14.3. .. IWEL,IW,JW,LCBOTW,LCTOPW,WBOD,WQMETH[I];(O) - RDWDEF [2.14.1],
C.2.14.4 .. WCF(L);L = 1 TO NZ (EXCLUSIVE) BY ELEMENT
C1 1 1 1 19 2 11
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0
2 30 1 18 19 .1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0
3 30 1 12 13 .1 0
0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4 30 1 5 6 .1 0
0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
5 41 1 18 19 .1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0
6 48 1 18 19 .1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0
7 58 1 18 19 .1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0
0 /
C.2.14.5 .. WRISL,WRID,WRRUF,WRANGL;(O) - RDWDEF [2.14.1] AND WRCALC(WQMETH [2.14.3] >30)
C.2.14.6 .. HTCWR,DTHAWR,KTHAWR,KTHWR,TABWR,TATWR;(O) - RDWDEF [2.14.1]  WRCALC(WQMETH [2.14.3] >30) AND HEAT [1.4]
C.....USE AS MANY 2.14.3-6 LINES AS NECESSARY
C.2.14.7 .. END WITH 0 /
C.2.14.8 .. MXITQW{14},TOLDPW{6.E-3},TOLFPW{.001},TOLQW{.001},DAMWRC{2.},DZMIN{.01},EPSWR{.001};(O) - RDWDEF [2.14.1]
C.....          AND WRCALC(WQMETH[2.14.3] >30)
C.....BOUNDARY CONDITION INFORMATION
C.....      SPECIFIED VALUE B.C.
C.2.15 .. IBC BY I,J,K RANGE {0.1-0.3} WITH NO IMOD PARAMETER,;(O) - NPTCBC [1.6] > 0
1 98 1 1 27 27
101 1
0 /
C.....      SPECIFIED FLUX B.C.
C.2.16 .. IBC BY I,J,K RANGE {0.1-0.3} WITH NO IMOD PARAMETER,;(O) - NFBC [1.6] > 0
C.....      AQUIFER AND RIVER LEAKAGE B.C.
C.2.17.1 .. IBC BY I,J,K RANGE {0.1-0.3} WITH NO IMOD PARAMETER;(O) - NLBC [1.6] > 0
C.2.17.2 .. KLBC,BBLBC,ZELBC BY I,J,K RANGE {0.1-0.3};(O) - NLBC [1.6] > 0
C.....          RIVER LEAKAGE B.C.
C.2.17.3 .. I1,I2,J1,J2,KRBC,BBRBC,ZERBC;(O) - NLBC [1.6] > 0
C.2.17.4 .. END WITH 0 /
C.....      AQUIFER INFLUENCE FUNCTIONS
C.2.18.1 .. IBC BY I,J,K RANGE {0.1-0.3} WITH NO IMOD PARAMETER;(O) - NAIFC [1.6] >0
98 98 1 1 1 26
100400
0 /
C.2.18.2 .. UVAIFC BY I,J,K RANGE {0.1-0.3};(O) - NAIFC [1.6] > 0
98 98 1 1 1 26
1 1
0 /
C.2.18.3 .. IAIF;(O) - NAIFC [1.6] > 0
2
C.....TRANSIENT, CARTER-TRACY A.I.F.
C.2.18.4 .. KOAR,ABOAR,VISOAR,POROAR,BOAR,RIOAR,ANGOAR;(O) - IAIF [2.18.3] = 2
3.5E-10 5.5E-7 .9500 .15 1300 3000 360
C.....      HEAT CONDUCTION B.C.
C.2.19.1 .. IBC BY I,J,K RANGE {0.1-0.3} ,WITH NO IMOD PARAMETER ,FOR HCBC NODES;(O) - HEAT [1.4] AND NHCBC [1.6] > 0
C.2.19.2 .. ZHCBC(K);(O) - HEAT [1.4] AND NHCBC [1.6] > 0
C.2.19.3 .. UDTHHC BY I,J,K RANGE {0.1-0.3} FOR HCBC NODES;(O) - HEAT [1.4]  AND NHCBC [1.6] > 0
C.2.19.4 .. UKHCBC BY I,J,K RANGE {0.1-0.3} FOR HCBC NODES;(O) - HEAT [1.4] AND NHCBC [1.6] >0
C.....FREE SURFACE B.C.
C.2.20 .. FRESUR(T/F),PRTCCM(T/F)
F F
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C.....INITIAL CONDITION INFORMATION
C.2.21.1 .. ICHYDP,ICT,ICC; ALL (T/F);IF NOT.HEAT, ICT = F, IF NOT.SOLUTE, ICC = F
T F T
C.2.21.2 .. ICHWT(T/F);(O) - FRESUR [2.20]
C.2.21.3A .. ZPINIT,PINIT;(O) - ICHYDP [2.21.1] AND NOT ICHWT [2.21.2]
0 0
C.2.21.3B .. P BY I,J,K RANGE {0.1-0.3};(O) - NOT ICHYDP [2.21.1] AND NOT ICHWT [2.21.2]
C.2.21.3C .. HWT BY I,J,K RANGE {0.1-0.3};(O) - FRESUR [2.20] AND ICHWT [2.21.2]
C.2.21.4A .. NZTPRO,ZT(I),TVD(I),I=1,NZTPRO;(O) - HEAT [1.4] AND NOT ICT [2.21.1], LIMIT OF 10
C.2.21.4B .. T BY I,J,K RANGE {0.1-0.3};(O) - HEAT [1.4] AND ICT [2.21.1]
C.2.21.5 .. NZTPHC, ZTHC(I),TVZHC(I);(O) - HEAT [1.4] AND NHCBC [1.6] > 0,LIMIT OF 5
C.2.21.6 .. C BY I,J,K RANGE {0.1-0.3};(O) - SOLUTE [1.4] AND ICC [2.21.1]
1 98 1 1 1 27
0 1
0 /
C.....CALCULATION INFORMATION
C.2.22.1 .. FDSMTH,FDTMTH
.5 1
C.2.22.2 .. TOLDEN{.001},MAXITN{5}
.005 10
C.2.22.3 .. NTSOPT{5},EPSSOR{.00001},EPSOMG{.2},MAXIT1{50},MAXIT2{100};(O) - SLMETH [1.8] = 2
C.....OUTPUT INFORMATION
C.2.23.1 .. PRTPMP,PRTFP,PRTIC,PRTBC,PRTSLM,PRTWEL; ALL (T/F)
6*T
C.2.23.2 .. IPRPTC,PRTDV(T/F);(O) - PRTIC [2.23.1]
201 T
C.2.23.3 .. ORENPR[I];(O) - NOT CYLIND [1.4]
C.2.23.4 .. PLTZON(T/F);(O) - PRTPMP [2.23.1]
F
C.2.23.5 .. OCPLOT(T/F)
T
C---------------------------------------------------------------------------------------
C..... TRANSIENT DATA - READ3
C.3.1 .. THRU(T/F)
F
C.....IF THRU IS TRUE PROCEED TO RECORD 3.99
C.....THE FOLLOWING IS FOR NOT THRU
C.....SOURCE-SINK WELL INFORMATION
C.3.2.1 .. RDWFLO(T/F),RDWHD(T/F);(O) - NWEL [1.6] > 0
T F
C.3.2.2 .. IWEL,QWV,PWSUR,PWKT,TWSRKT,CWKT;(O) - RDWFLO [3.2.1] OR RDWHD [3.2.1]
1 133690 0 500 0 1
0 /
C.....USE AS MANY 3.2.2 LINES AS NECESSARY
C.3.2.3 .. END WITH 0 /
C.....BOUNDARY CONDITION INFORMATION
C.....      SPECIFIED VALUE B.C.
C.3.3.1 .. RDSPBC,RDSTBC,RDSCBC,ALL(T/F);(O) - NOT CYLIND [1.4] AND NPTCBC [1.6] > 0
T F F
C.3.3.2 .. PNP B.C. BY I,J,K RANGE {0.1-0.3};(O) - RDSPBC [3.3.1]
1 98 1 1 27 27
333.5141 1
0 /
C.3.3.3 .. TSBC BY I,J,K RANGE {0.1-0.3}; (O) - RDSPBC [3.3.1] AND HEAT [1.4]
C.3.3.4 .. CSBC BY I,J,K RANGE {0.1-0.3}; (O) - RDSPBC [3.3.1] AND SOLUTE [1.4]
1 98 1 1 27 27
0 1
0 /
C.3.3.5 .. TNP B.C. BY I,J,K RANGE {0.1-0.3};(O) - RDSTBC [3.3.1] AND HEAT [1.4]
C.3.3.6 .. CNP B.C. BY I,J,K RANGE {0.1-0.3};(O) - RDSCBC [3.3.1] AND SOLUTE [1.4]
C.....      SPECIFIED FLUX
C.3.4.1 .. RDFLXQ,RDFLXH,RDFLXS,ALL(T/F);(O) - NFBC [1.6] > 0
C.3.4.2 .. QFFX,QFFY,QFFZ B.C. BY I,J,K RANGE {0.1-0.3};(O) - RDFLXQ [3.4.1]
C.3.4.3 .. UDENBC  BY I,J,K RANGE {0.1-0.3};(O) - RDFLXQ [3.4.1]
C.3.4.4 .. TFLX B.C. BY I,J,K RANGE {0.1-0.3};(O) - RDFLXQ [3.4.1] AND HEAT [1.4]
C.3.4.5 .. CFLX B.C. BY I,J,K RANGE {0.1-0.3};(O) - RDFLXQ [3.4.1] AND SOLUTE [1.4]
C.3.4.6 .. QHFX,QHFY,QHFZ B.C. BY I,J,K RANGE {0.1-0.3};(O) - RDFLXH [3.4.5]
C.3.4.7 .. QSFX,QSFY,QSFZ B.C. BY I,J,K RANGE {0.1-0.3};(O) - RDFLXS [3.4.1]
C.....      LEAKAGE BOUNDARY
C.3.5.1 .. RDLBC(T/F);(O) - NLBC [1.6] > 0
C.3.5.2 .. PHILBC,DENLBC,VISLBC BY I,J,K RANGE {0.1-0.3};(O) - RDLBC [3.5.1]
C.3.5.3 .. TLBC BY I,J,K RANGE {0.1-0.3};(O) - RDLBC [3.5.1] AND HEAT [1.4]
C.3.5.4 .. CLBC BY I,J,K RANGE {0.1-0.3};(O) - RDLBC [3.5.1] AND SOLUTE [1.4]
C.....      RIVER LEAKAGE
C.3.5.5 .. I1,I2,J1,J2,HRBC,DENRBC,VISRBC,TRBC,CRBC;(O) - RDLBC [3.5.1]
C.....USE AS MANY 3.5.5 LINES AS NECESSARY
C.3.5.6 .. END WITH 0 /
C.....      A.I.F. B.C.
C.3.6.1 .. RDAIF(T/F); (O) - NAIFC [1.6] > 0
T
C.3.6.2 .. DENOAR BY I,J,K RANGE {0.1-0.3};(O) - RDAIF [3.6.1]
98 98 1 1 1 26
64.0 1
0 /
C.3.6.3 .. TAIF BY I,J,K RANGE {0.1-0.3};(O) - RDAIF [3.6.1] AND HEAT [1.4]
C.3.6.4 .. CAIF BY I,J,K RANGE {0.1-0.3};(O) - RDAIF [3.6.1] AND SOLUTE [1.4]
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98 98 1 1 1 26
0 1
0 /
C.....CALCULATION INFORMATION
C.3.7.1 .. RDCALC(T/F)
T
C.3.7.2 .. AUTOTS(T/F);(O) - RDCALC [3.7.1]
T
C.3.7.3.A .. DELTIM;(O) - RDCALC [3.7.1] AND NOT AUTOTS [3.7.2]
C.3.7.3.B .. DPTAS{5E4},DTTAS{5.},DCTAS{.25},DTIMMN{1.E4},DTIMMX{1.E7};(O) - RDCALC [3.7.1] AND AUTOTS [3.7.2]
.05 1 .05 .0001 36.5
C.3.7.4 .. TIMCHG
3650
C.....OUTPUT INFORMATION
C.3.8.1 .. PRIVEL,PRIDV,PRISLM,PRIKD,PRIPTC,PRIGFB,PRIWEL,PRIBCF; ALL [I]
-1 -1 -1 -1 -1 -1 -1 -1
C.3.8.2 .. IPRPTC;(O) - IF PRIPTC [3.8.1] NOT = 0
201
C.3.8.3 .. CHKPTD(T/F),NTSCHK,SAVLDO(T/F)
CT 1500 T
T -1 T
C.....CONTOUR MAP INFORMATION
C.3.9.1 .. RDMPDT,PRTMPD; ALL (T/F)
F F
C.3.9.2 .. MAPPTC,PRIMAP[I];(O) - RDMPDT [3.9.1]
C.3.9.3 .. YPOSUP(T/F),ZPOSUP(T/F),LENAX,LENAY,LENAZ;(O) - RDMPDT [3.9.1]
C.3.9.4 .. IMAP1{1},IMAP2{NX},JMAP1{1},JMAP2{NY},KMAP1{1},KMAP2{NZ},AMIN,AMAX,NMPZON{5}:(O) - RDMPDT [3.9.1]
C.....ONE OF THE 3.9.4 LINES REQUIRED FOR EACH DEPENDENT VARIABLE
C.....     TO BE MAPPED
C.....END OF FIRST SET OF TRANSIENT INFORMATION
C- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
C.....READ SETS OF READ3 DATA AT EACH TIMCHG UNTIL THRU  (LINES 3.N1.N2)
C.....END OF CALCULATION LINES FOLLOW, THRU=.TRUE.
C.3.99.1 .. THRU
T
C.....TEMPORAL PLOT INFORMATION
C.3.99.2 .. PLOTWP,PLOTWT,PLOTWC; ALL (T/F)
T F T
C.....PLOT INFORMATION; (O) - PLOTWP [3.99] OR PLOTWT [3.99] OR PLOTWC [3.99]
C.4.1 ..  IWEL,RDPLTP(T/F)
C.4.2 ..  IDLAB
C.4.3 ..  NTHPTO,NTHPTC,PWMIN,PWMAX,PSMIN,PSMAX,TWMIN,TWMAX,TSMIN,TSMAX,CMIN,CMAX; (O) - RDPLTP [4.1]
C.4.4 ..  TO,POW,POS,TOW,TOS,COW
C.....USE AS MANY 4.4 LINES AS NECESSARY
C.4.5 ..  END WITH -1. /
C.....READ DATA FOR ADDITIONAL WELLS,  4.1-4.5 LINES
C.4.6 ..  END WITH 0 /
2 T
 PERMEABLE ZONE MONITOR: DEPTH 1200 FT, CSG 1150 FT, RADIUS 47 FT, COL 30
0 1 1
0 0 0 0 0 0 0 0 0 1
-1. /
3 T
 PERMEABLE ZONE MONITOR: DEPTH 1500 FT, CSG 1450 FT, RADIUS 47 FT, COL 30
0 1 1
0 0 0 0 0 0 0 0 0 1
-1. /
4 T
 PERMEABLE ZONE MONITOR: DEPTH 1850 FT, CSG 1800 FT, RADIUS 47 FT, COL 30
0 1 1
0 0 0 0 0 0 0 0 0 1
-1. /
5 T
 PERMEABLE ZONE MONITOR: DEPTH 1500 FT, CSG 1450 FT, RADIUS 203 FT, COL 41
0 1 1
0 0 0 0 0 0 0 0 0 1
-1. /
6 T
 PERMEABLE ZONE MONITOR: DEPTH 1500 FT, CSG 1450 FT, RADIUS 500 FT, COL 48
0 1 1
0 0 0 0 0 0 0 0 0 1
-1. /
7 T
 PERMEABLE ZONE MONITOR: DEPTH 1500 FT, CSG 1450 FT, RADIUS 1000 FT, COL 58
0 1 1
0 0 0 0 0 0 0 0 0 1
-1. /
0 /
 /
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