Assessment of the Hydrogeology and Water Quality in a Near-Shore Well Field, Sarasota, Florida

By James C. Broska and L.A. Knochenmus

U.S. Geological Survey

Water-Resources Investigations Report 96-4036

Prepared in cooperation with the
City of Sarasota

Tallahassee, Florida
1996

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ABBREVIATIONS

in.	inch
ft	foot
mi	mile
mi^2	square mile
gal/min	gallon per minute
Bgal/d	billion gallons per day
Mgal/d	million gallons per day
mg/L	milligram per liter

ACRONYMS

ETB WUCA	Eastern Tampa Bay Water Use Caution Area
MODFLOW	U.S. Geological Survey modular ground-water flow model
MODPATH	U.S. Geological Survey postprocessor particle tracker
FGS	Florida Geological Survey
PVC	polyvinylchloride
PZ1, PZ2, PZ3	Producing zone 1, 2, or 3
ROMP	Regional Observation Monitoring-Well Program
SDWF	Sarasota downtown well field
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey

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Abstract

The city of Sarasota, Florida, operates a downtown well field that pumps mineralized water from ground water sources to supply a reverse osmosis plant. Because of the close proximity of the well field to Sarasota Bay and the high sulfate and chloride concentrations of ground-water supplies, a growing concern exists about the possibility of lateral movement of saltwater in a landward direction (intrusion) and vertical movement of relict sea water (upconing).

In 1992, the U.S. Geological Survey began a 3-year study to evaluate the hydraulic characteristics and water quality of ground-water resources within the downtown well field and the surrounding 235-square-mile study area. Delineation of the hydrogeology of the study area was based on water-quality data, aquifer test data, and extensive borehole geophysical surveys (including gamma, caliper, temperature, electrical resistivity, and flow meter logs) from the six existing production wells and from a corehole drilled as part of the study, as well as from published and unpublished reports on file at the U.S. Geological Survey, the Southwest Florida Water Management District, and consultant's reports.

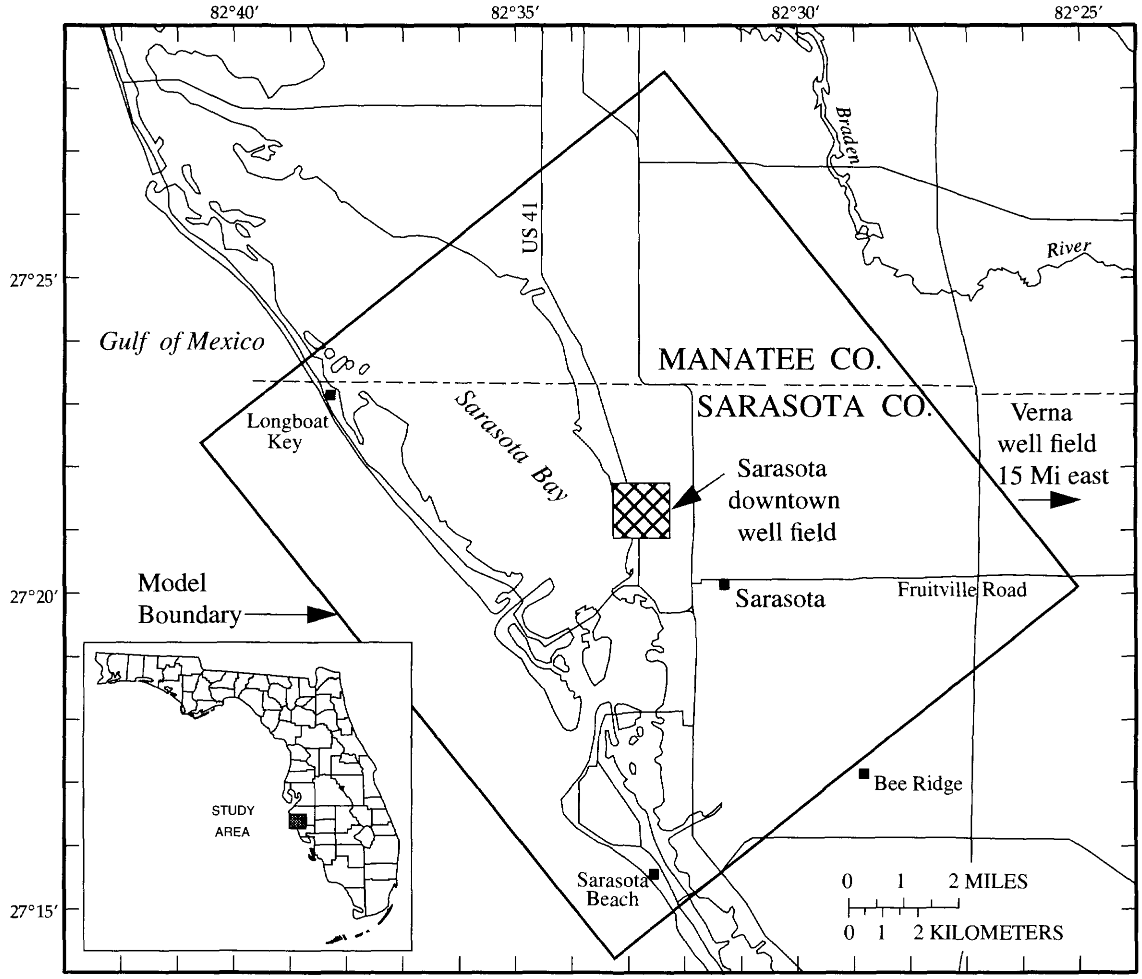
Water-quality data were examined for spatial and temporal trends that might relate to the mechanism for observed water-quality changes. Water quality in the study area appears to be dependent upon several mechanisms, including upconing of higher salinity water from deeper zones within the aquifer system, interborehole flow between zones of varying water quality through improperly cased and corroded wells, migration of highly mineralized waters through structural deformities, and the presence of unflushed relict seawater.

A numerical ground-water flow model was developed as an interpretative tool where field-derived hydrologic characteristics could be tested. The conceptual model consisted of seven layers to represent the multilayered aquifer systems underlying the study area. Particle tracking was utilized to delineate the travel path of water as it enters the model area under a set of given conditions. Within the model area, simulated flow in the intermediate aquifer system originates primarily from the northwestern boundary. Simulated flow in the Upper Floridan aquifer originates in lower model layers (deeper flow zones) and ultimately can be traced to the southeastern and northwestern boundaries.

Volumetric budgets calculated from numerical simulation of a hypothetical well field indicate that the area of contribution to the well field changes seasonally. Although ground-water flow patterns change with wet and dry seasons, most water enters the well-field flow system through lower parts of the Upper Floridan aquifer from a southeastern direction. Moreover, particle tracking indicated that ground-water flow paths with strictly lateral pathlines in model layers correspond to the intermediate aquifer system, whereas particles traced through model layers corresponding to the Upper Floridan aquifer had components of vertical and lateral flow.

INTRODUCTION

The city of Sarasota is located on the coast of the Gulf of Mexico in west-central Florida in Sarasota County (fig. 1). Historically, the city has obtained potable water from wells penetrating the intermediate and Upper Floridan aquifers underlying the city in an area



Base from Southwest Florida Water Management District digital data, 1:500,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 1. Location of study area, model area, and the Sarasota downtown well field, west-central Florida.

designated in this report as the Sarasota downtown well field (SDWF). The SDWF is located within 1 mi (mile) of Sarasota Bay. Ample supplies of ground water have been available; however, ground water near the coast has high concentrations of sulfate and chloride. In 1966, the SDWF was placed on standby status and water was piped from the Verna well field 15 mi east of the city. By 1979, population growth necessitated obtaining additional quantities of water to meet the demands and the SDWF was reactivated. Currently (1996), Sarasota utilizes the ground-water resources from both the SDWF and Verna well fields. Water from the SDWF undergoes reverse-osmosis treatment, whereas the water from the Verna well field is passed through an ion exchange system. The water from the two well fields is then blended, generating 4.5 Mgal/d (million gallons per day) of potable water. Withdrawals within the SDWF, as well as those from locations upgradient and downgradient of the SDWF, continue to affect ground-water levels and ground-water quality.

In 1992, the U.S. Geological Survey (USGS), in cooperation with the city of Sarasota, began a study to assess the distribution of hydraulic characteristics and ground-water quality of the study area, and to numerically simulate the flow system. The study area encompasses 235 mi^2 (square miles) in southwestern Manatee and northwestern Sarasota Counties. A ground-water flow model was developed covering 130 mi^2, which includes the SDWF and adjacent areas affected by pumping (fig. 1). Additionally, a discussion of the hydrologic characteristics is presented for the SDWF, a 1-mi^2 area on Sarasota Bay that is used by the city of Sarasota as a source of water supply (fig. 1).

Purpose and Scope

This report describes the hydrogeologic framework and factors affecting the distribution of hydraulic characteristics and water quality in the heterogeneous, multilayered aquifer systems underlying the study area. A digital ground-water flow model was developed and used to evaluate the lateral and vertical movement of ground water supplying the SDWF. The specific objectives of this report are given below:

1. Describe the hydrogeologic framework and hydraulic characteristics of the study area.
2. Discuss the effects of ground-water development on water levels and ground-water flow patterns in the study area.
3. Define the distribution of flow zones and confining units in the SDWF.
4. Discuss the distribution and present spatial and temporal changes in ground-water quality in the SDWF.
5. Discuss mechanisms for saltwater intrusion in the study area.
6. Estimate the sources and movement of ground water to wells in the SDWF.

Information presented in this report was obtained from data collected during this investigation, from unpublished data on file at the USGS, and from published USGS, Southwest Florida Water Management District (SWFWMD), and consultants' reports. Data collected during this investigation included core samples, lithologic and geophysical logs, water-quality samples, and aquifer-test information from wells in the study area and from a deep corehole. A conceptual model of the ground-water system was developed to organize the concepts of the physical system's behavior and relate those concepts to the framework of the numerical model. The ground-water flow system was simulated using the USGS model code MODFLOW (McDonald and Harbaugh, 1988) and the USGS post-processor particle tracker MODPATH (Pollock, 1989). The model was utilized in understanding the sources and flow of ground water supplying the SDWF.

Description of the Study Area

The study area (fig. 1) includes parts of Manatee and Sarasota Counties and encompasses the SDWF located in the center of the study area. High density residential, recreational, and commercial development characterize the coastal areas, whereas inland areas are characterized by mostly agricultural land use.

Coastal Manatee and Sarasota Counties are part of the Gulf Coastal Lowlands physiographic province. The land surface of this province is characterized by scarps and terraces created during Pleistocene sea-level stands. The topographic surface in the study area ranges from sea level to 25 ft (feet) above mean sea level.

Delineation of the geologic units in the study area, and specifically those underlying the SDWF, was provided by the Florida Geological Survey (FGS). The FGS, in cooperation with the USGS and the city of Sarasota, drilled and analyzed a deep corehole located near the center of the study area. The test hole penetrated the lithostratigraphic units corresponding to the surficial, intermediate, and Upper Floridan aquifers to a total depth of 1,101 ft below land surface.

The FGS generated a lithologic description using a binocular microscope to analyze cores collected during drilling of the 1,101-ft test hole, herein referred to as the Sarasota corehole. Three alternate names for this well are the Saline Monitor (city of Sarasota designation), W-16999 (FGS), and well 52 (SWFWMD identification number). The following is a description of the geologic units presented by the FGS (Campbell and others, 1994).

The Avon Park Formation extends downward from a depth of 1,028 ft below land surface and consists of interbedded limestones and dolostones. The limestones are fine to medium-grained, moderately to well indurated packstones. The dolostones are fine-grained, well indurated, variably porous, and recrystallized. The limestones and dolostones are fossiliferous with benthic foraminifera, echinoids, and molds. The contact between the Avon Park Formation and overlying Ocala Group is conformable.

The Ocala Group is present from 781 to 1,028 ft below land surface and consists primarily of limestone with a limited amount of dolostone. The limestone is fine- to medium-grained, fossiliferous, moderately indurated grainstones and packstones. Common fossils in the unit are benthic foraminifera, bryozoans, echinoids, and mollusks. The contact between the Ocala Group and overlying Suwannee Limestone is gradational.

The Suwannee Limestone is present from 549 to 781 ft below land surface. The limestone is moderately to well indurated, fossiliferous packstones to grainstones. Foraminifera, mollusk fragments and molds are common faunal constituents. The contact between the Suwannee Limestone and the Hawthorn Group is unconformable.

The Hawthorn Group underlying the city of Sarasota consists of the Arcadia Formation and its component Tampa Member. In this report, the designation of undifferentiated Arcadia Formation refers to the Arcadia Formation, excluding the Tampa Member.
The Tampa Member occurs from 376 to 548.5 ft below land surface. The undifferentiated Arcadia Formation occurs from about 6.8 to 376 ft below land surface.

The Tampa Member consists of sandy, clayey, fossiliferous limestones. Fossils include mollusk fragments and molds, benthic foraminifera, and coral. Dolostones are present at two intervals near the base of the Tampa Member and are very fine-grained and moderately to well indurated.

The undifferentiated Arcadia Formation contains various lithologies. Carbonates dominate the sequence with interbedded siliciclastic sediments less abundant. Dolostones are the most prominent lithology of the formation and are sandy, clayey, well indurated, fine- to very fine-grained. Phosphate concentration ranges from 3 to 10 percent. The contact between the Hawthorn Group and the thin overlying terrace deposits is characterized as an erosional disconformity. The terrace deposits, which are present from land surface to 6.8 ft below land surface, consist of medium-grained quartz sand, minor clay, and shells.

HYDROGEOLOGIC FRAMEWORK AND HYDRAULIC PROPERTIES

Water-bearing formations in west-central Florida consist of a thick sequence of sedimentary units including sands, clays, and carbonates. These lithostratigraphic units form a multilayered sequence of aquifers and confining units. The hydrogeologic framework of the study area (fig. 2) is composed of the surficial, intermediate, and Upper Floridan aquifers. Each of these aquifer systems contains one or more permeable zones separated by lower-permeability units. Data from geologic and geophysical logs are used to identify the distribution of permeable zones and confining units. Natural gamma logs were correlated with lithologic logs to determine which lithostratigraphic units make up the confining units. Large increases in gamma radiation from logs delineate the top and bottom of the intermediate aquifer system and the top of the Suwannee-Ocala confining unit.

Geophysical logs from 16 wells were used to delineate the distribution of aquifers and confining units in the study area. Well location and construction data are shown and listed in figure 3 and table 1, respectively. Five generalized hydrogeologic sections were prepared based on data from 12 of the 16 wells (fig. 3). The distribution of hydrogeologic units correlated to gamma logs are shown in figures 4-8. In west-central Florida, gamma ray emissions can be related to lithologies with high clay or phosphate content. Units with high clay and phosphate content usually have low permeabilities and, hence, usually are confining units. Furthermore, the gamma ray logs in figures 4-8 were correlated to lithologic logs and other geophysical logs not shown. The descriptions of the three aquifer systems in the study area are provided below.

Surficial Aquifer System

The surficial aquifer system, consisting of sand, clay, shell, and phosphate gravel, has an average thickness of 10 ft, and is the uppermost water-bearing unit in the study area. The water table is near the land surface and annually fluctuates generally less than 5 ft. Recharge to the aquifer system is from rainfall and upward leakage from the underlying aquifer system where the altitude of the potentiometric surface of underlying aquifers is higher than the water table.

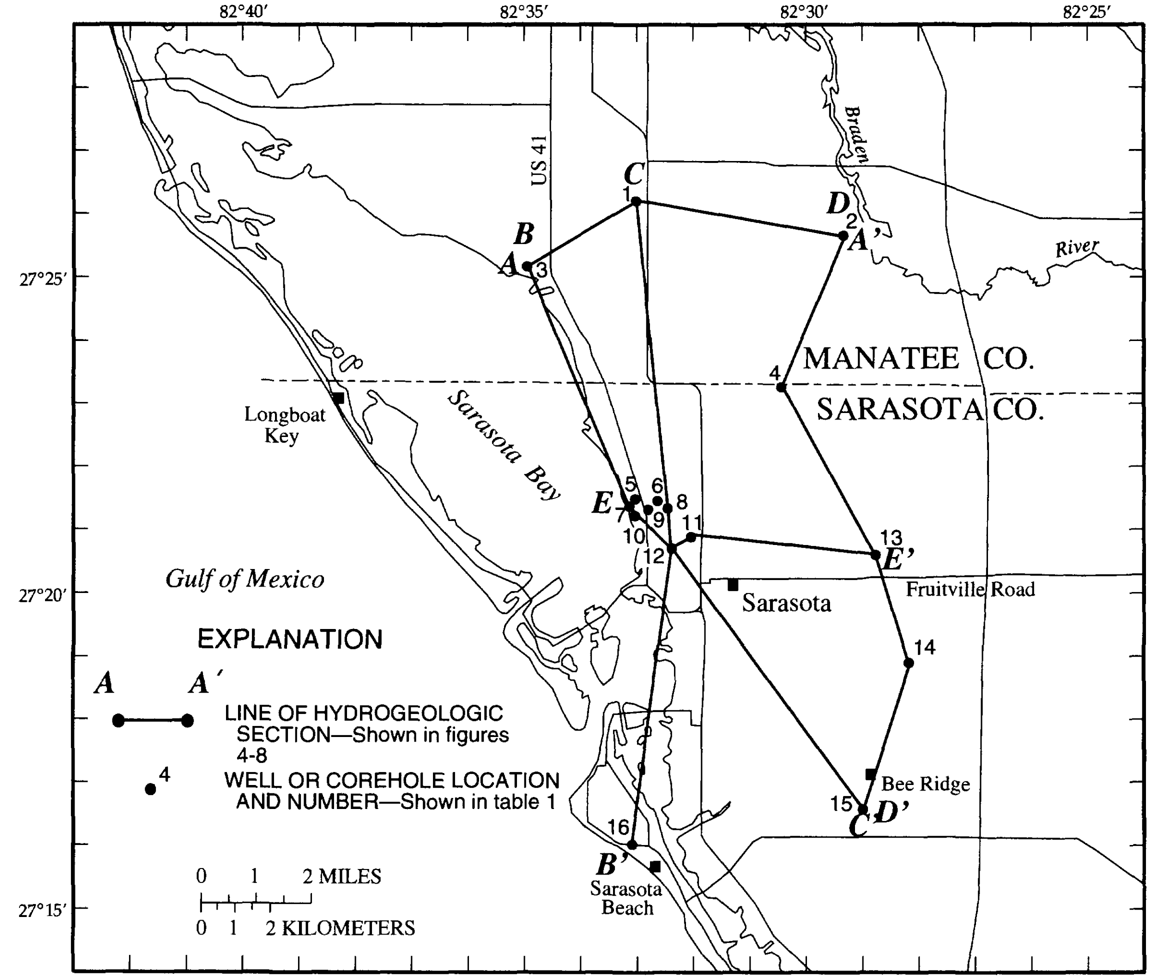
Intermediate Aquifer System

The intermediate aquifer system includes all water-bearing and confining units that lie between the surficial aquifer and the underlying Upper Floridan aquifer (fig. 2). In the study area, the intermediate aquifer system consists of interbedded clastic sediments and carbonate rocks of the undifferentiated Arcadia Formation and Tampa Member. Discontinuous confining units separate the intermediate aquifer system into two producing zones, designated the upper Hawthorn and Tampa permeable zones (fig. 2). The intermediate aquifer system is approximately 400 ft thick in the vicinity of the city of Sarasota. Interpretations of geophysical logs indicate that the intermediate aquifer system contains multiple zones of high and low permeability (figs. 4-8). Confining units consist of sandy clays, clays, and marls that restrict the vertical movement of ground water between permeable zones. No natural recharge from the surficial aquifer system results because of the upward head gradient. The intermediate aquifer system is recharged by upward leakage from the underlying Upper Floridan aquifer and by lateral ground-water inflow from adjacent areas.

System	Series	Stratigraphic Unit	Hydrogeologic Unit	Hydrogeologic Unit of Northern Sarasota County[5]
Quaternary	Holocene Pleistocene	Terrace Deposits	Surficial Aquifer System	Surficial Aquifer System
Tertiary	Miocene	Hawthorn Group[1,6]: Undifferentiated Arcadia Formation[6]	Intermediate Aquifer System[2]	Confining Unit
				Upper Hawthorn Permeable Zone
				Confining Unit
	Oligocene	Hawthorn Group[1,6]: Tampa Member[6]		Tampa Permeable Zone
				Lower Tampa Confining Unit
		Suwannee Limestone	Floridan Aquifer System[3]: Upper Floridan Aquifer[3]	Suwannee Permeable Zone
	Eocene	Ocala Group[6]		Lower Suwannee-Ocala Confining Unit
				Ocala-Avon Park Moderately Permeable Zone
		Avon Park Formation[4]		Avon Park Highly Permeable Zone
			Floridan Aquifer System[3]: Middle Confining Unit[3]	Middle Confining Unit[3]
	Paleocene	Oldsmar and Cedar Keys Formations	Floridan Aquifer System[3]: Lower Floridan Aquifer[3]	Lower Floridan Aquifer[3]

[1] Based on nomencalture of Scott (1988).
[2] Based on nomencalture of Southeastern Geological Society (1986).
[3] Based on nomencalture of Miller (1986).
[4] Based on nomencalture of Wolansky (1983).
[5] Based on nomencalture of Hutchinson (1992)
[6] Based on nomenclature of Campbell, Scott, and Green (1994).

Figure 2. Hydrogeologic framework in the vicinity of Sarasota, Florida. (Modified from Hutchinson, 1992.)



Base from Southwest Florida Water Management District digital data, 1:500,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 3. Location of selected wells, cores, and hydrogeologic sections, west-central Florida.

The altitude of the potentiometric surface of the intermediate aquifer system ranges from 10 to 25 ft above sea level. Potentiometric-surface levels generally increase with depth; however, localized reversals in head gradient occur in the study area in areas of intensive ground-water withdrawal. Relatively large head differences (10-25 ft) between producing zones in the intermediate aquifer system indicate hydraulic separation of aquifer units; however, water-level trends are similar between the producing zones indicating that the aquifers are interconnected or affected by the same stresses (Hutchinson, 1992).

Floridan Aquifer System

The Floridan aquifer system consists of about a 3,000 ft thick sequence of carbonate rocks primarily of Tertiary age (Miller, 1986). The Floridan aquifer system includes the Upper Floridan aquifer, middle confining unit and Lower Floridan aquifer (fig. 2). Only the Upper Floridan aquifer, which includes the lithologies of the Suwannee Limestone, Ocala Group, and Avon Park Formation, is considered in this study. The Upper Floridan aquifer is about 1,000 ft thick in northwestern Sarasota County (Miller, 1986). Geophysical logs and hydraulic testing indicate that the Upper Floridan

Table 1. Records of selected wells and coreholes in the study area
[Identification number with X indicates coreholes. NA: not applicable. ROMP: Regional Observation and Monitoring Well Program]

Well and core number	Well name	Identification number	Land surface elevation, in feet	Depth, in feet below land surface	Casing depth, in feet below land surface
1	ROMP TR 7-2	27261208233010X	19	1,094	NA
2	ROMP TR 7-4	27253908229200X	15	1,250	NA
		272539082292001	15	1,250	1,162
		272539082292002	15	800	560
		272539082292003	15	500	380
		272539082292004	15	268	213
3	ROMP TR 7-1	27251008234570X	8	634	NA
		272510082345701	8	340	320
4	County Test 1	272317082302401	35	603	40
5	SDWF Production 3	272129082330201	18	591	270
6	SDWF Production 5	272127082323803	10	649	246
7	SDWF Production 1	272122082330801	5	626	324
8	SDWF Production 6	272120082322703	12	561	261
9	SDWF Production 4	272119082324801	10	612	302
10	SDWF Production 2	272113082330202	5	537	306
11	Test injection	272053082320202	24	1,230	1,106
12	Corehole	27204208232230X	20	1,101	NA
	Saline monitor	272042082322301	20	590	353
13	Bobby Jones test	272036082284701	22	1,088	394
14	Atlantic Utilities	271854082281001	16	1,902	NA
15	ROMP TR 6-3	271634082285901	34	604	60
16	ROMP TR 6-1	27160108233050X	5	561	NA
		271601082330501	5	315	300

aquifer contains four distinct hydrogeologic units: (1) the Suwannee permeable zone, (2) the lower Suwannee-Ocala confining unit, (3) the Ocala-Avon Park moderately permeable zone, and (4) the Avon Park highly permeable zone (Hutchinson, 1992). The lower Suwannee-Ocala confining unit restricts the vertical movement between the overlying and underlying permeable zones. However, zones may be locally connected by vertical solution features where the degree of interconnection is sufficient to allow hydraulic equilibrium between these zones. Recharge to the Upper Floridan aquifer is by lateral flow from adjacent areas, whereas discharge from this unit is upward to the intermediate aquifer system in the form of diffuse leakage or along preferential flow zones. However, localized reversals in head gradient occur in the study area, causing downward leakage from the intermediate aquifer system into the Upper Floridan aquifer. Results of a recent study based largely on geophysical logs and flowmeter logs indicate that seasonal reversals in head gradients occur in Sarasota County (P.A. Metz, USGS, written commun., 1994).

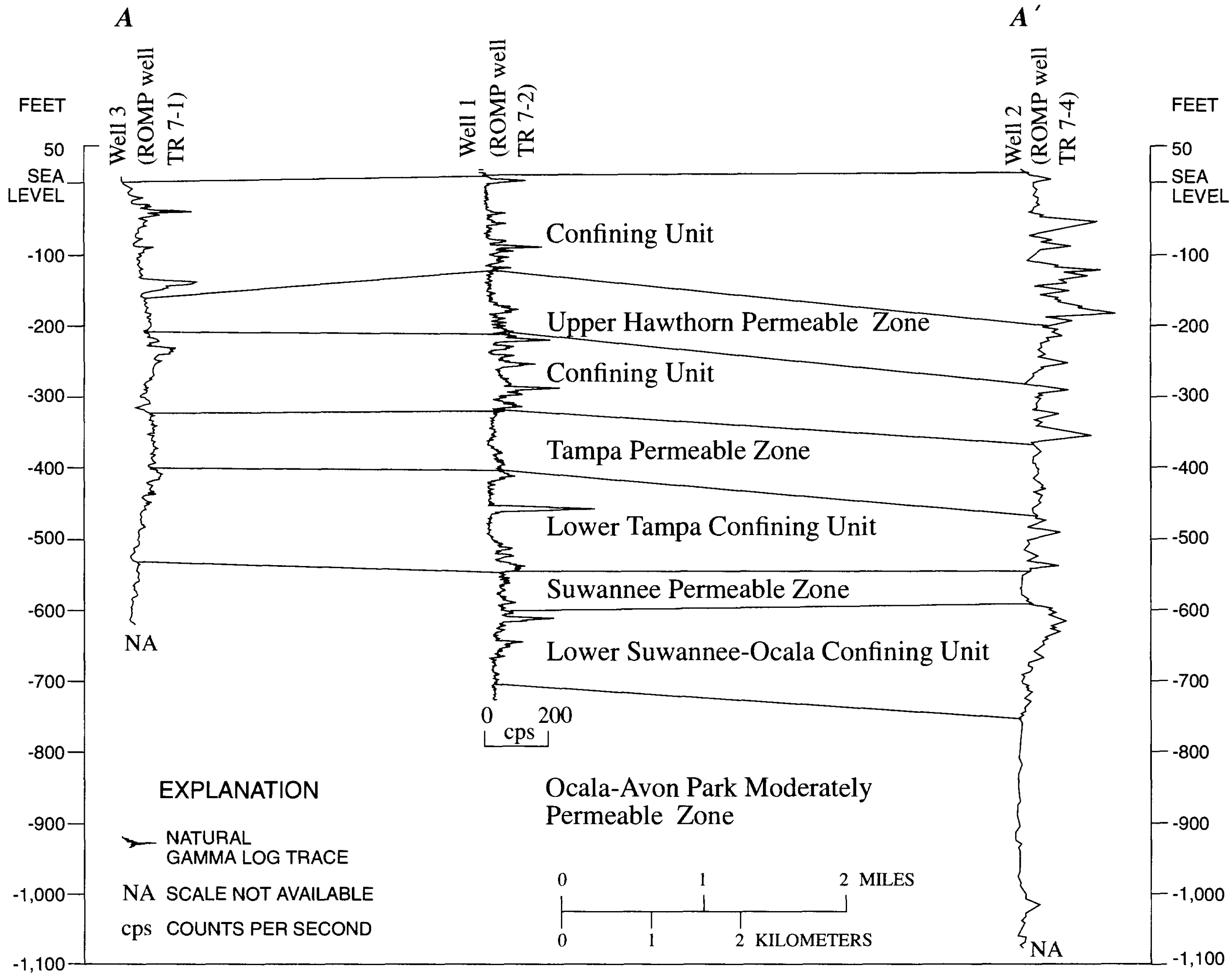


Figure 4. Natural gamma log trace correlated to permeable units of hydrogeologic section A-A′. (Modified from Hutchinson, 1992. Line of section shown in fig. 3.)

Hydraulic Properties

Hundreds of aquifer tests have been conducted in Florida to define the hydraulic properties of aquifer systems. Hydraulic properties, including values of transmissivity, storativity, hydraulic conductivity, and leakance coefficients for the intermediate aquifer system and Upper Floridan aquifer were reported by the Southwest Florida Water Management District (1987) and by Hutchinson (1992).

Tampa Member of the Arcadia Formation and Suwannee Limestone Permeable Zones

Results of three aquifer tests conducted in 19[illegible]7 in the vicinity of the city of Sarasota were reported by the SWFWMD. The pumped wells are open to the permeable zones in the Tampa Member (intermediate aquifer system) and the upper part of the Suwannee Limestone (Upper Floridan aquifer) (fig. 2). The wells pumped for

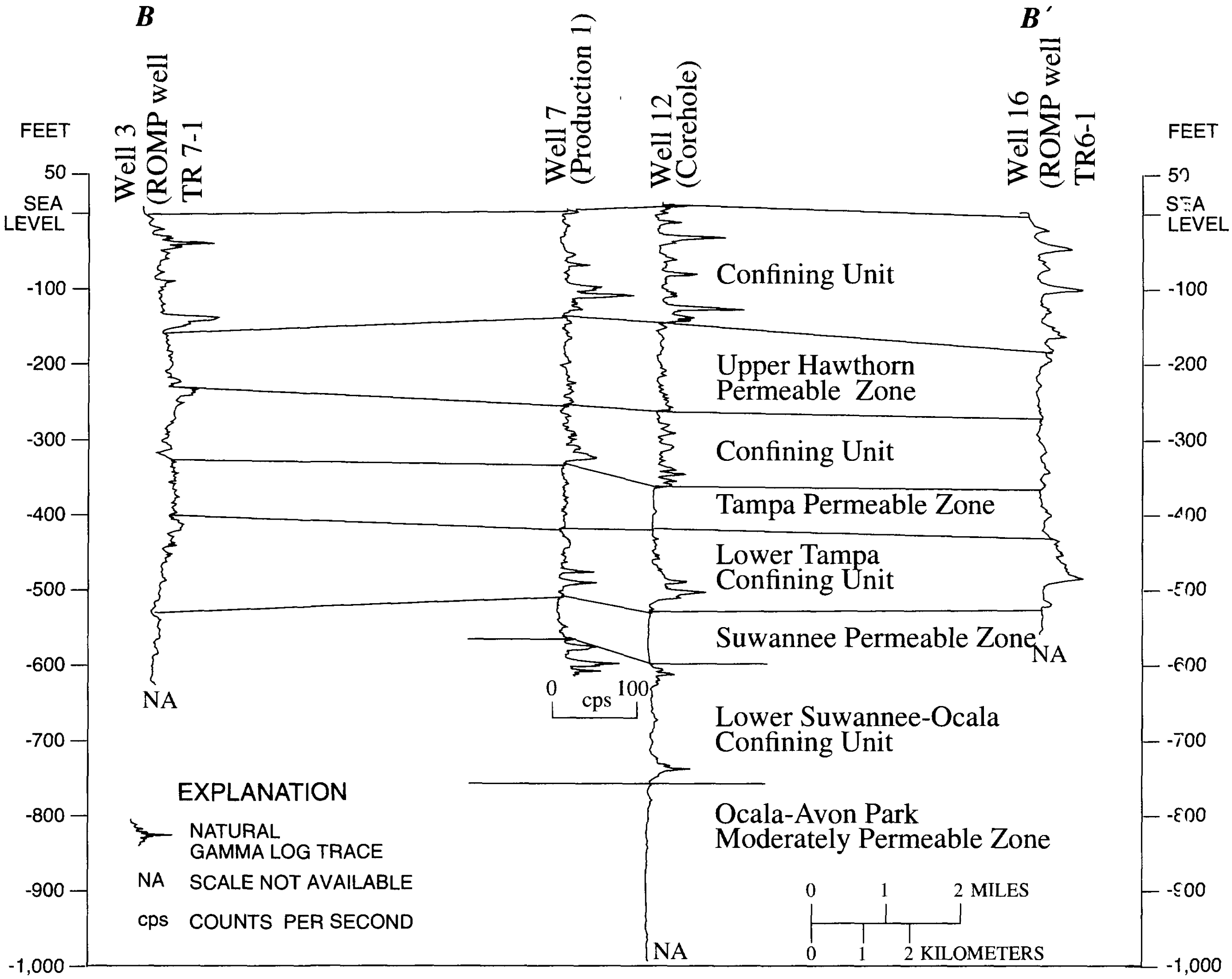


Figure 5. Natural gamma log trace correlated to permeable units of hydrogeologic section B-B′. (Modified from Hutchinson, 1992. Line of section shown in fig. 3.)

the three aquifer tests are designated the Evers Reservoir well, the Sarasota County Line test well, and Sarasota production well 5. All of these wells have similar depths (659, 606, and 649 ft, respectively) and corresponding casing lengths (360, 350, 246 ft). Reported transmissivities for these wells are 37,000, 4,900, and 35,000 ft^2/d (feet squared per day), storativity values are $5.5x10^{-4}$, $2.2x10^{-4}$, and $6.5x10^{-4}$, and leakance coefficients are $3.7x10^{-5}$, $2.2x10^{-3}$, and $1.3x10^{-4}$ ft/d/ft (feet per day per foot), respectively. The highly variable values of hydraulic properties are probably due to aquifer heterogeneity. Permeability may be largely affected by fractures and solution features near formational contacts between the undifferentiated Arcadia Formation, Tampa Member, and Suwannee Limestone. The sources of ground water to wells utilized for municipal supply in the vicinity of Sarasota are from permeable zones in both the intermediate and Upper Floridan aquifer.

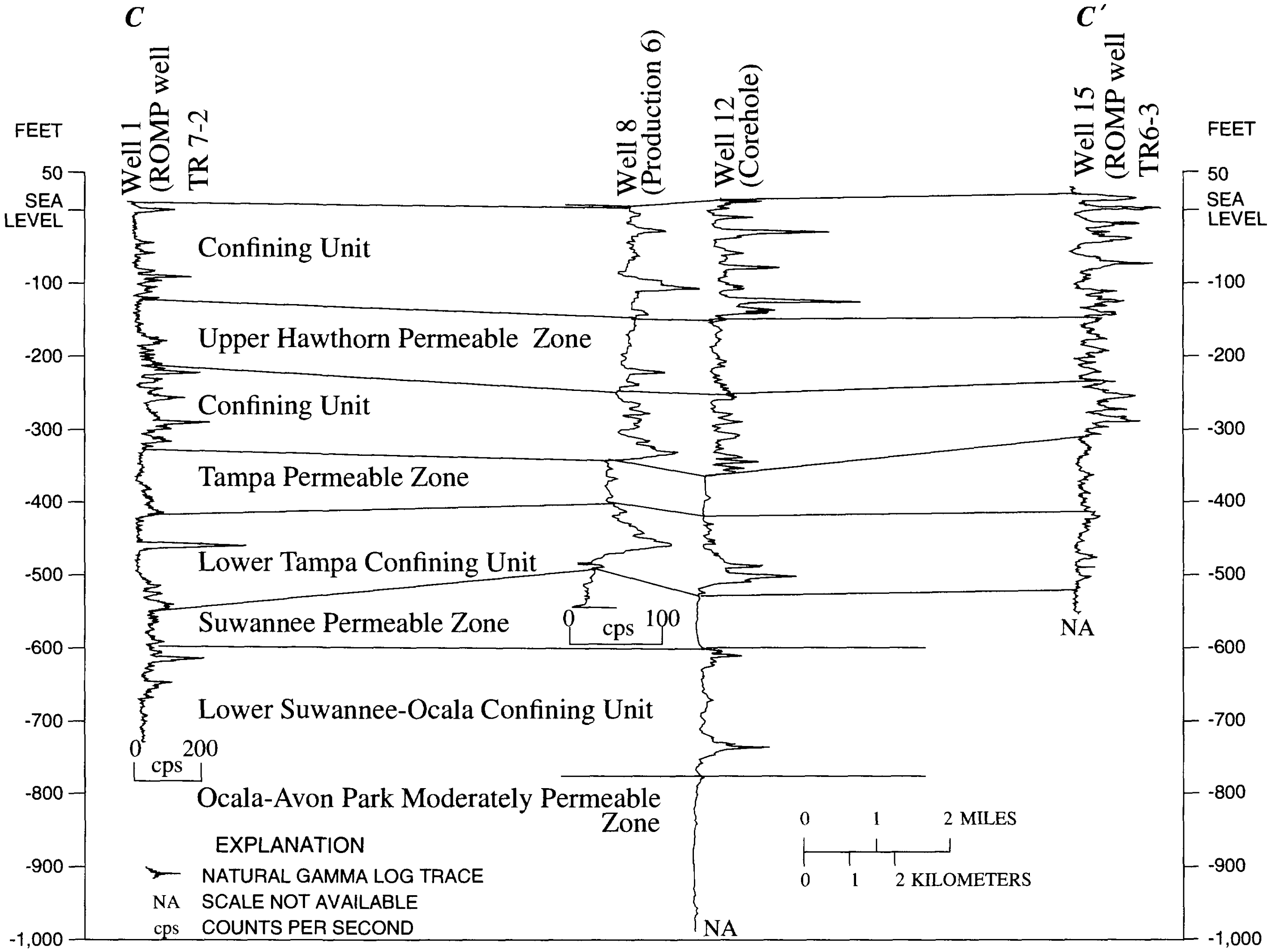


Figure 6. Natural gamma log trace correlated to permeable units of hydrogeologic section C-C'. (Modified from Hutchinson, 1992. Line of section shown in fig. 3.)

Lower Suwannee-Ocala Confining Unit

The lower Suwannee-Ocala confining unit separates the overlying Tampa Member-Suwannee Limestone permeable zones from the underlying Ocala-Avon Park permeable zone. Based on analytical techniques, calculations of hydraulic properties for confining units can be difficult; however, numerical methods are often used to estimate hydraulic properties. Hutchinson and Trommer (1992) numerically simulated the vertical hydraulic conductivity of the lower Suwannee-Ocala confining unit in Sarasota County as 0.1 ft/d. The values of vertical and horizontal hydraulic conductivities measured in cores and determined from packer tests range from 0.1 to 0.25 ft/d (Hutchinson, 1992). These values are higher than hydraulic conductivities determined from cores from the Sarasota corehole for this study. Results from core analyses are discussed in detail in the core analysis section of this report. Generally, horizontal hydraulic conductivity is three to four orders of magnitude lower for the confining unit than for the overlying and underlying permeable zones (Hutchinson, 1992, p. 28).

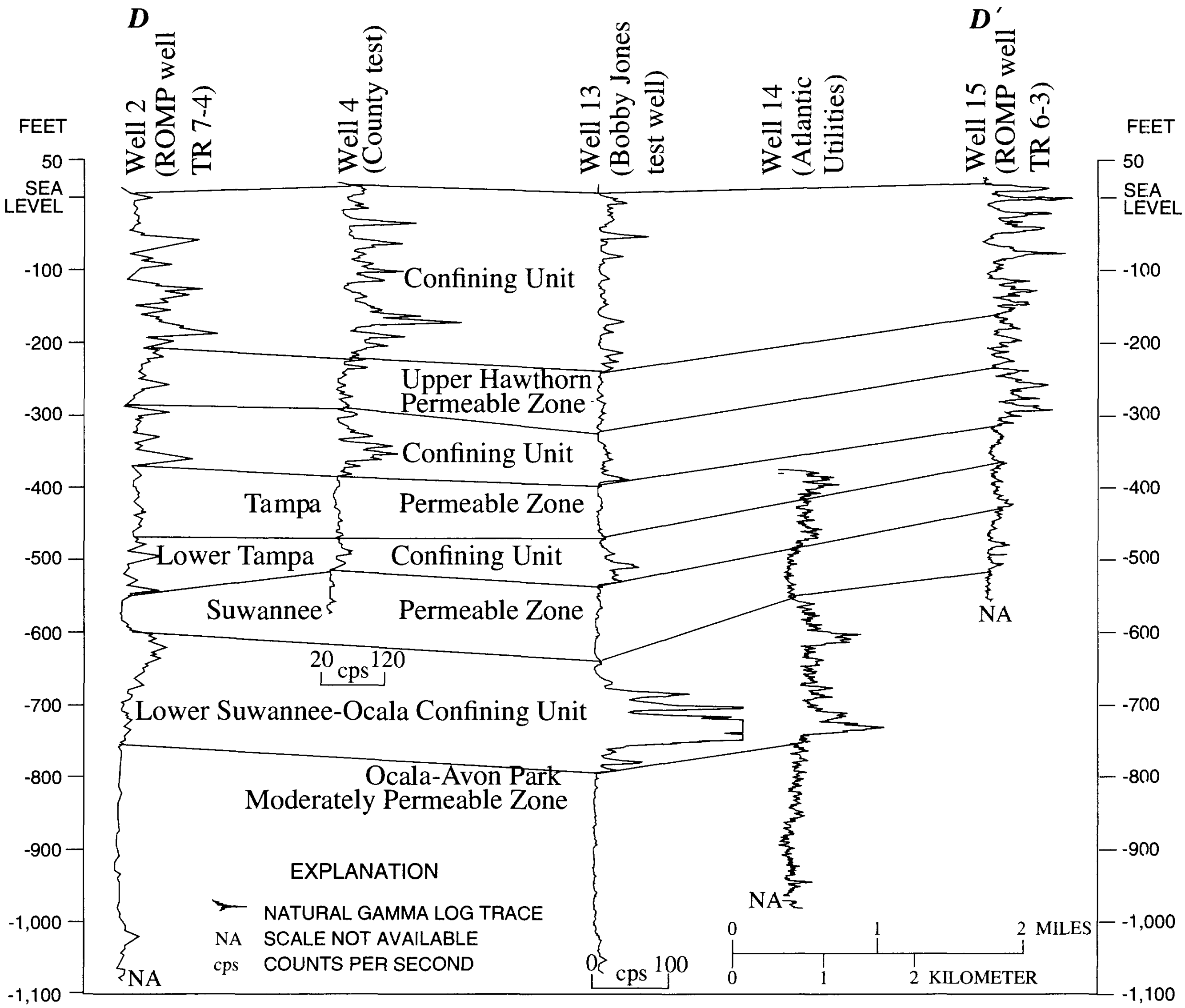


Figure 7. Natural gamma log trace correlated to permeable units of hydrogeologic section D-D'. (Modified from Hutchinson, 1992. Line of section shown in fig. 3.)

Ocala-Avon Park Moderately Permeable and Avon Park Highly Permeable Zones

Underlying the lower Suwannee-Ocala confining unit are the Ocala-Avon Park moderately permeable and Avon Park highly permeable zones. Transmissivity values that range from 48,000 to 80,000 ft^2/d and from 140,000 to 370,000 ft^2/d, respectively, were determined from aquifer tests of those zones and were higher than for any overlying zone. Values for storativity and leakance were not obtained because storage values are extremely difficult to calculate in lithologies where fluid flow is affected by fractures (Hutchinson, 1992).

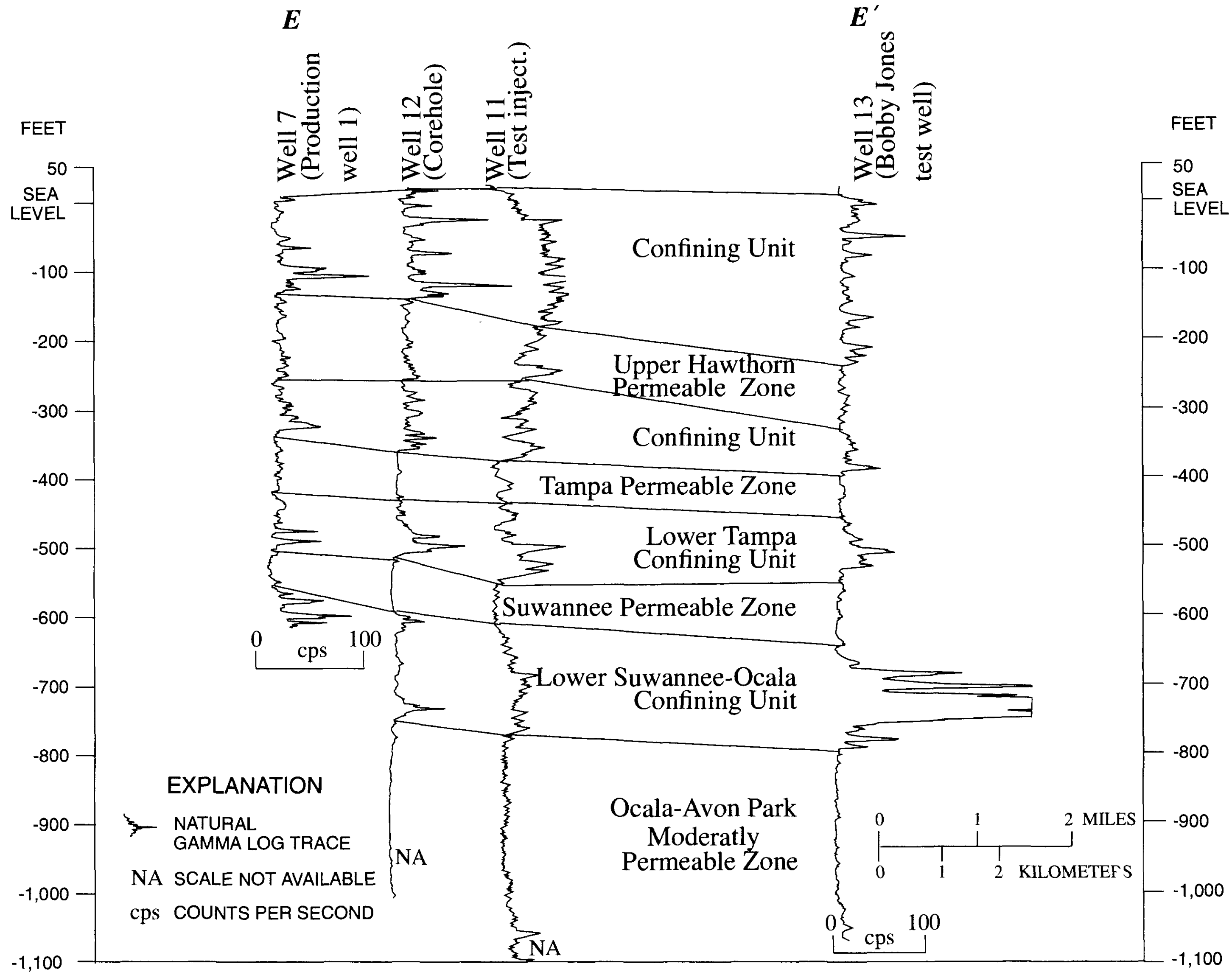


Figure 8. Natural gamma log trace correlated to permeable units of hydrogeologic section E-E'. (Modified from Hutchinson, 1992. Line of section shown in fig. 3.)

EFFECTS OF GROUND-WATER DEVELOPMENT ON WATER LEVELS AND GROUND-WATER FLOW PATTERNS

The study area is part of the Eastern Tampa Bay Water Use Caution Area (ETB WUCA), an area of about 1,320 mi^2 that includes southern Hillsborough, Manatee, and northern Sarasota Counties. In 1989, estimated aquifer withdrawals in the ETB WUCA and in counties in the southern part of the SWFWMD were approximately 210 and 799 Mgal/d, respectively (Southwest Florida Water Management District, 1993). In the study area, the intermediate aquifer system and Upper Floridan aquifer are the primary sources of water for public supply, agriculture, industrial, and recreation. That year, water use in Sarasota County derived from the intermediate aquifer system was 9.8 Mgal/d for public supply, 5.7 Mgal/d for agriculture,

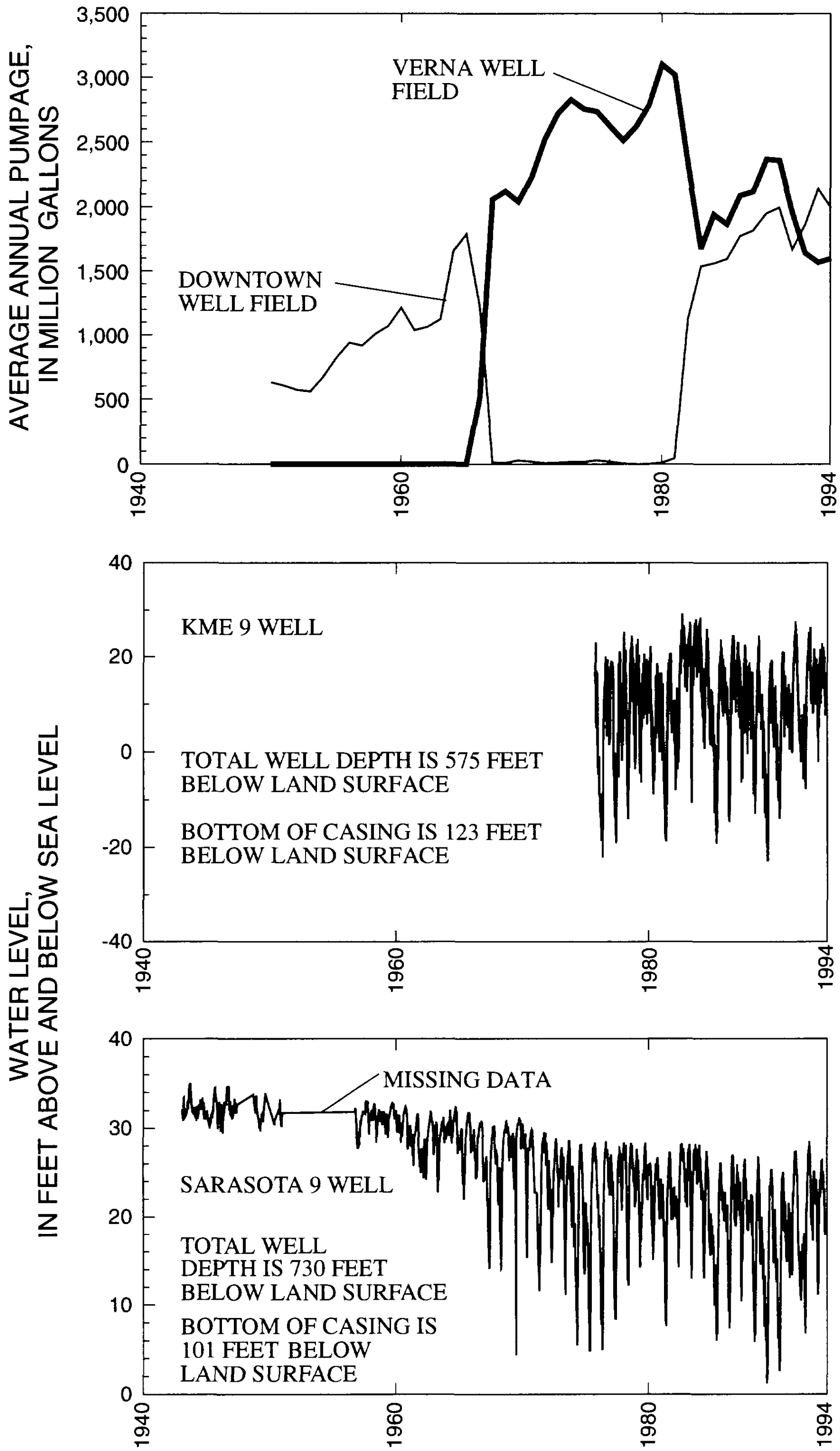


Figure 9. Average annual pumpage and water levels from wells in and near the study area.

0.8 Mgal/d for industry, and 3.9 Mgal/d for recreation, whereas water use from the Upper Floridan aquifer was 12.9 Mgal/d for public supply, 8 Mgal/d for agriculture, less than 0.01 Mgal/d for industry, and 1.7 Mgal/d for recreation (Southwest Florida Water Management District, 1993). Total withdrawals from the intermediate and Upper Floridan aquifer in Sarasota County were 20.2 and 22.6 Mgal/d, respectively. Currently (1996), permitted pumpage upgradient from coastal Sarasota County is greater than 0.5 Bgal/d (billion gallons per day) (Southwest Florida Water Management District, 1993). Water levels and ground-water flow patterns have changed from predevelopment conditions as a result of ground-water development within, upgradient from, and downgradient from the SDWF.

Changes in Water Levels

Water-levels have changed because of ground-water development in the study area. Long-term hydrographs for Sarasota 9 and KME 9 wells (not shown on fig. 3) and average annual withdrawals from the SDWF and Verna well field indicating patterns of head declines are shown in figure 9. Although Sarasota 9 and KME 9 are not within the SDWF, these wells were selected as indicators of water-level response to regional and local pumpage. Sarasota 9 is located in the southeastern part of the study area at latitude 27°19′38″ and longitude 82°25′18″. KME 9 is located about 10 mi east of the study area at latitude 27°22′20″ and longitude 82°15′14″.

Water levels in the Upper Floridan aquifer have been declining in the coastal areas of southern Hillsborough, Manatee, and northern Sarasota Counties since the early 1930's (fig. 9). Data prior to 1940 are not shown on the figure but are available from the files of the USGS. Between 1940 and 1960, water-level changes in the Sarasota 9 well are probably in response to withdrawals in the SDWF. The range of water-level fluctuations was small compared to subsequent years. The rate of decline greatly accelerated beginning in the early 1960's, when ground-water withdrawals increased. In addition to water-level declines, seasonal water-level fluctuations dramatically increased as a result of expanded permitted pumpage upgradient and downgradient from the SDWF. Seasonal fluctuations in water levels from KME 9 have remained nearly unchanged during the period of continuous record (1975-94); however, water levels measured in well KME 9 seasonally fall below sea level (fig. 9). Beginning in the mid-1970's, long-term declines in water levels stabilized. Although seasonal effects are indicated, overall declining trends are not obvious since that time.

Changes in Ground-Water Flow Patterns

Changes in ground-water flow patterns are the direct result of changing water levels caused by ground-water development. Estimates of predevelopment ground-water flow patterns in the Upper Floridan aquifer are shown in figure 10. Predevelopment regional ground-water flow was from the ridge areas of central Florida (recharge areas) toward the Gulf of Mexico (discharge areas). Potentiometric surfaces are high in the ridge areas, whereas potentiometric surfaces are low in the coastal areas.

Large changes in water levels from predevelopment levels have resulted in alteration of the natural flow gradient, produced seasonal flow reversals, and reduced available water resources to the coastal areas of Sarasota County. In some areas, water levels in the Upper Floridan aquifer have declined as much as 50 ft and seasonal fluctuations can exceed 40 ft. Changes in the natural flow gradients are indicated when comparing the predevelopment potentiometric-surface map and the September 1990 potentiometric-surface map (fig. 10). The general flow direction is still primarily coastward; however, large deviations in the potentiometric contours are apparent. A major change is the landward shift in location of the 20- and 30-ft contours. Seasonal flow reversals are indicated when comparing the September 1990 potentiometric-surface map and the May 1990 potentiometric-surface map (fig. 10). In May 1990, the flow direction was the reverse of the flow in September in a large area of the ETB WUCA. In May, the flow was eastward toward the large depression in the potentiometric surface produced by irrigation pumpage. This flow reversal results in reduction in coastal ground-water discharge, restricting available water to coastal well fields. Reversals in the regional potentiometric surface during the dry, irrigation season may result in the isolation of the SDWF from the regional ground-water system. Therefore, ground water laterally flows to the SDWF from areas north and south of the city of Sarasota or vertically from overlying and underlying permeable zones rather than from lateral flow from the east or west.

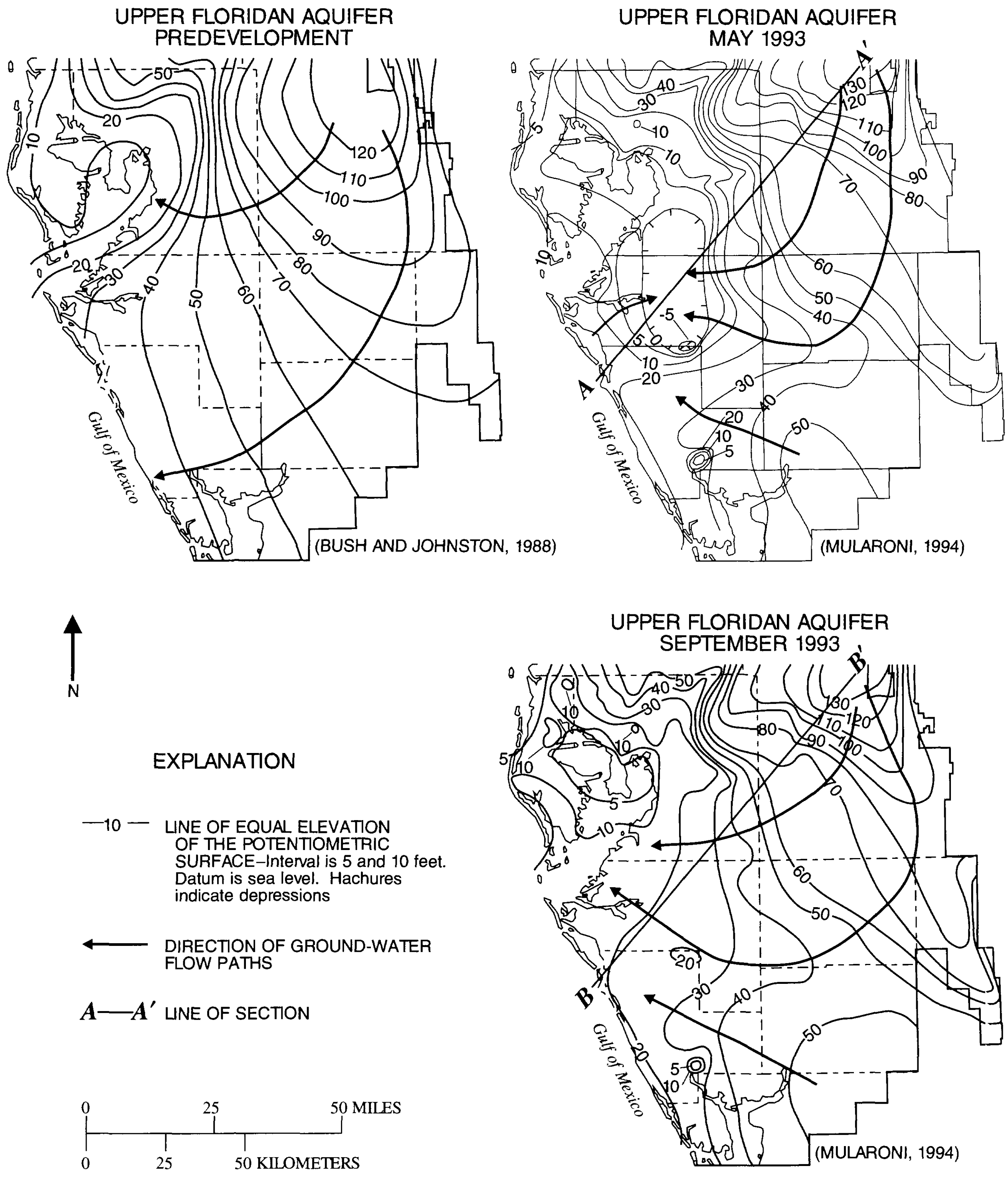


Figure 10. Potentiometric surfaces of the Upper Floridan aquifer, west-central Florida; predevelopment, May and September 1993.

THE CITY OF SARASOTA DOWNTOWN WELL FIELD

The SDWF encompasses a 1-mi^2 area in the central part of the study area (figs. 1 and 11). An important aspect of this study was to delineate the hydrogeologic units and distributions of water quality in the aquifers underlying the SDWF. Geologic and geophysical logs, core samples, water levels, and geochemical data were collected, where possible, from the six SDWF production wells and the Sarasota corehole. These data indicated that local heterogeneities strongly affect hydraulic responses and the quality of water in the aquifer systems underlying the downtown well field.

The SDWF is located in the city limits of Sarasota and within 1 mi of Sarasota Bay. In 1990, the SDWF consisted of six production wells ranging in depth from 537 to 649 ft, with casing depths ranging from 246 to 324 ft below land surface. Prior to resumption of pumping in 1979, five of the six original production wells were renovated and an additional well was drilled in 1991.

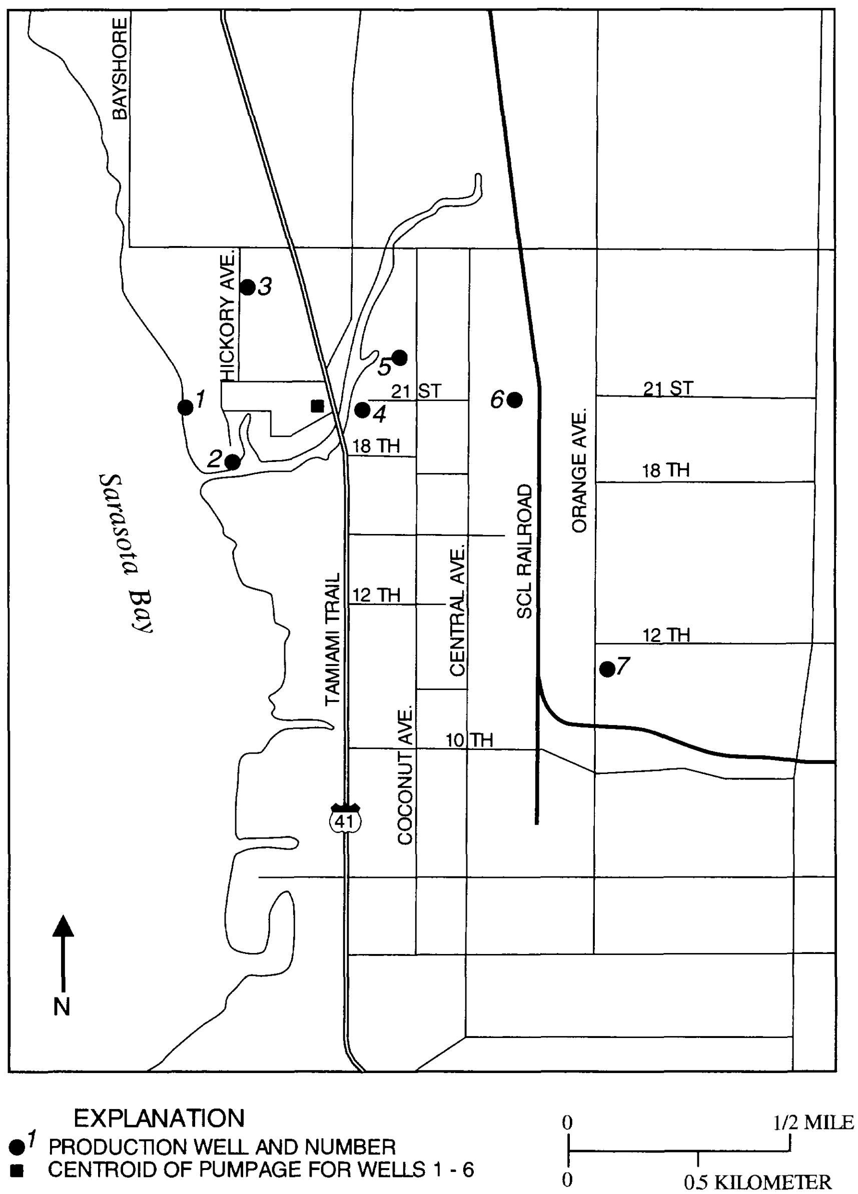


Figure 11. Location and number of the Sarasota production wells and centroid of pumping for wells 1-6. (Modified from SDI Environmental Services Inc., 1993.)

Hydrogeologic Units and Producing Zones

The hydrogeologic units supplying ground water to wells in the SDWF are comprised of the undifferentiated Arcadia Formation, Tampa Member, and Suwannee Limestone lithostratigraphic units. Ground water is derived from the intermediate aquifer system and uppermost Upper Floridan aquifer. The average open hole interval of a production well in the SDWF is 312 ft. Natural-gamma ray, caliper, static and pumping temperature and fluid resistivity, flowmeter logs and borehole-television geophysical log surveys from the Sarasota corehole and the six production wells indicate that the sources of flow within the open hole intervals are from a number of vertically spaced, discrete producing zones. The locations of these discrete producing zones in the Sarasota corehole are shown in figure 12. The locations and relative distribution of discrete producing zones are plotted on caliper logs for the six production wells and are shown in figure 13. Often large, open diameters, indicated by kicks on caliper logs, delineate locations of fractures in the borehole. However, the largest kicks on the caliper logs do not necessarily correspond to locations of producing zones in the borehole.

Ground water enters the borehole from a number of vertically spaced and discrete water-producing intervals. The variability in both the vertical positions and relative contributions from these producing zones are indicative of the heterogeneous nature of the intermediate aquifer system and Upper Floridan aquifer in the study area.

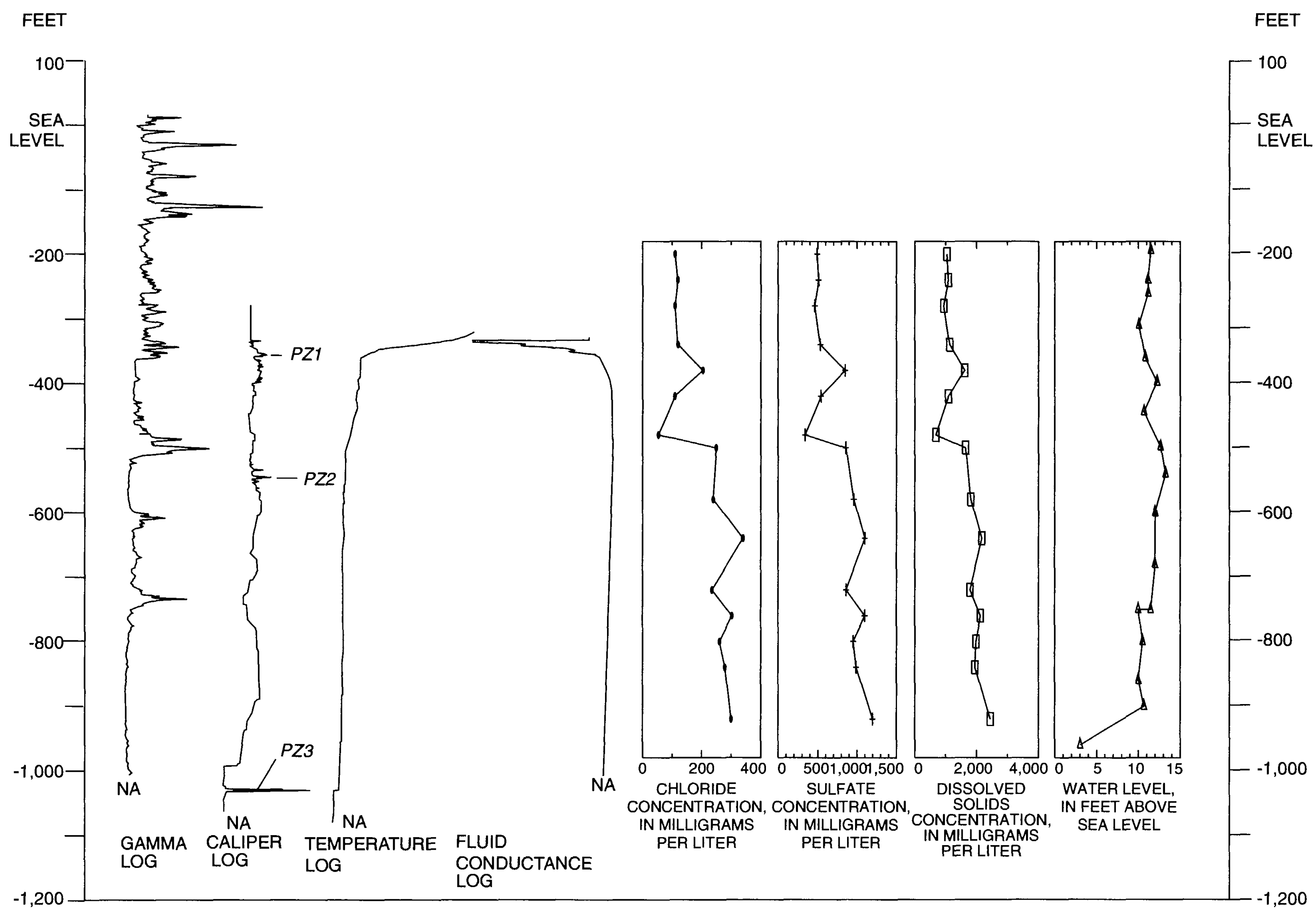
Three major producing zones were identified in the Sarasota corehole and two major producing zones were identified in each of the six production wells. In addition, wells 1, 2, 4, and 6 have a third, minor producing zone. Generally, the producing zones are near contacts between lithostratigraphic units. Producing zone 1 (PZ1), is located near the contact of the Tampa Member and overlying undifferentiated Arcadia Formation; however, location varies somewhat. Producing zone 2 (PZ2), is located near the contact between the Suwannee Limestone and overlying Tampa Member and is less variable among the wells. Producing zone 3 (PZ3), is located near the contact of the Avon Park Formation and overlying Ocala Group. The variability in the vertical positions of PZ1 and PZ2 indicates that ground-water flow in that zone may occur through a network of random anastomosing permeable pathways. Little information is available about the nature of permeable pathways supplying ground water to wells. However, the wells with shorter cased intervals may withdraw water primarily from the intermediate aquifer system rather than the Upper Floridan aquifer. The percentage of flow estimated from flowmeter logs from each of the permeable zones also is variable. PZ1 contributes 10 percent to the Sarasota corehole, 50 percent to well 1, 25 percent to well 2, 60 percent to well 3, 40 percent to well 4, 66 percent to well 5, and 40 percent to well 6. PZ2 contributes 40 percent to the Sarasota corehole, 40 percent to well 1, 65 percent to well 2, 40 percent to well 3, 50 percent to well 4, 34 percent to well 5, and 40 percent to well 6.

Core Analyses

Hydraulic characteristics of confining units affect the movement of water between producing zones. The horizontal and vertical conductances and porosities of confining units were quantified using cores from the Sarasota corehole selected for hydraulic testing. The cores were selected to be representative of thick units comprised of fine sediments or well consolidated lithologies. Analyses of hydraulic properties of core permeabilities and porosities were provided by the FGS and are listed in table 2.

Falling-head permeameter tests were utilized to determine horizontal hydraulic conductivity (Kh) and vertical hydraulic conductivity (Kv) on two replicate lithologic samples from 13 depth intervals taken from the Sarasota corehole. Six horizontal and four vertical samples did not saturate during the test period of 31 days. The averaged horizontal and vertical hydraulic conductivities from the two replicate samples range from 8.8×10^{-4} to 9 ft/d and from 1.08×10^{-5} to 4.7 ft/d, respectively. Highest horizontal hydraulic conductivities were from units within the Suwannee Limestone and Ocala Group. Highest vertical hydraulic conductivities were from units within the Ocala Group and Avon Park Formation.

Effective porosities were measured by first drying the core samples and then resaturating the core samples with de-ionized water. Following resaturation, the core samples were removed from the water, reweighed, and then placed in a known volume of water to determine the saturated volume. Effective porosity values were highly variable within and among stratigraphic units and range from 0.8 to 32 percent. Porosities were highest in samples from the undifferentiated Arcadia Formation and Ocala Group and lowest in samples from the Avon Park Formation.



EXPLANATION

PZ1 - PRODUCING ZONE 1
PZ2 - PRODUCING ZONE 2
PZ3 - PRODUCING ZONE 3
NA - SCALE NOT AVAILABLE

Figure 12. Geophysical logs, water-quality data, and water levels collected during drilling from the Sarasota corehole.

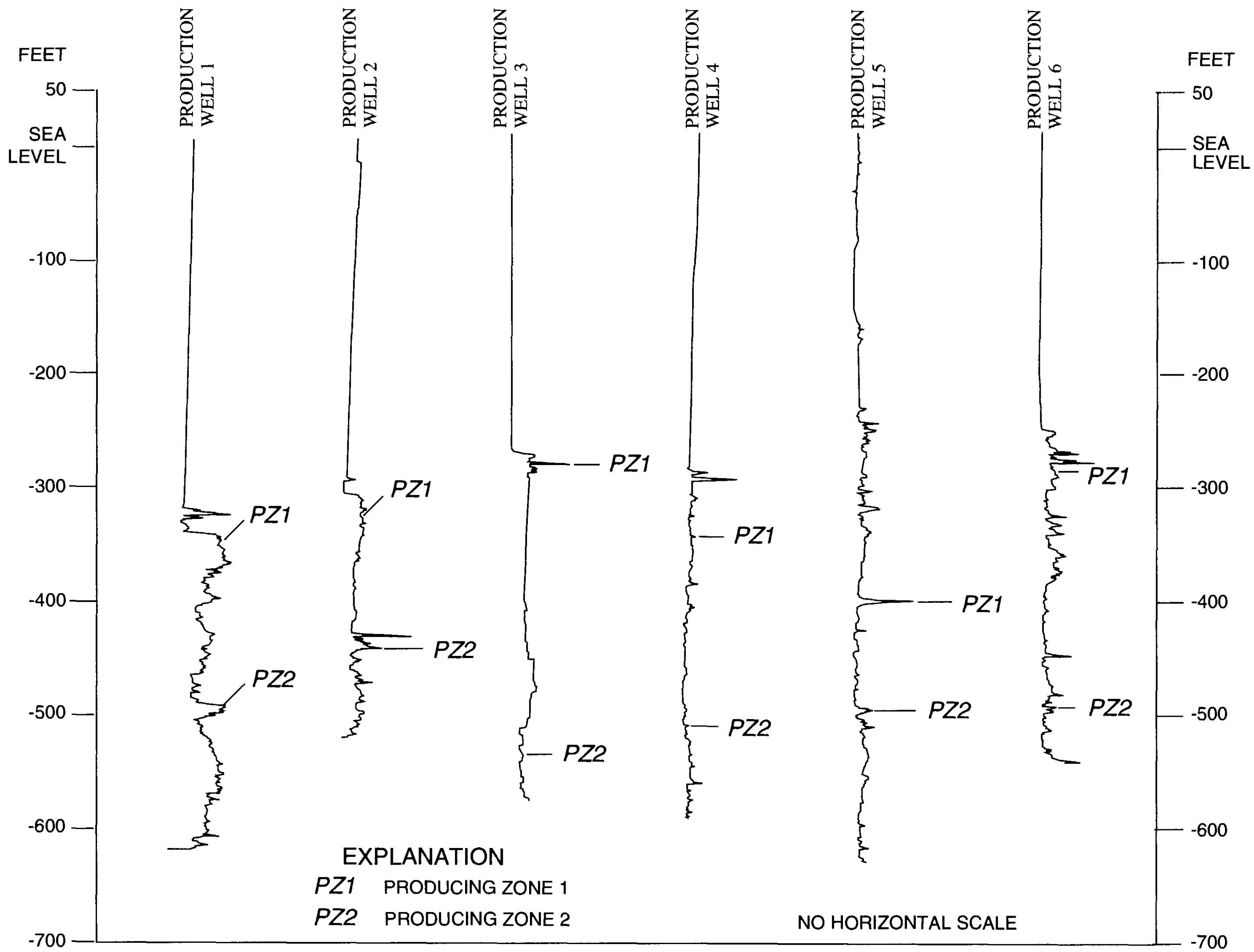


Figure 13. Vertical distribution of producing zones as indicated on caliper logs from six production wells in the Sarasota downtown well field.

Table 2. Core depths, stratigraphic units, and laboratory values of horizontal and vertical hydraulic conductivities and effective porosities of Sarasota corehole

[Alternative names for the Sarasota corehole: Saline Monitor and W-16999 by the city of Sarasota personnel and Florida Geological Survey, respectively.

Location of the Sarasota corehole: Identification number 272042082322301; T36S R18E, SE, SE, SW, SECTION 18; northwest of 10th Street and Orange Avenue intersection at old water plant.

Construction information for the Sarasota corehole: Cored to 1,101 feet below land surface; Current (1996) well diameter is 4 inches; cased to 353 ft; depth is 590 feet below land surface.

NA: not applicable.
BDL: below detection limits]

Core depth, in feet below land surface	Stratigraphic unit	Horizontal hydraulic conductivity, in feet per day	Vertical hydraulic conductivity, in feet per day	Effective porosity, in percent
316	Arcadia Formation	NA	NA	32
465	Tampa Member	BDL	BDL	12
495	Tampa Member	8.8×10^{-4}	2.8×10^{-4}	23
756	Suwannee Limestone	0.78×10^{1}	BDL	9
779	Suwannee Limestone	3.8×10^{-2}	1.2×10^{-2}	20
807	Ocala Group	2.1×10^{-2}	BDL	30
847	Ocala Group	1.4×10^{-1}	BDL	31
895	Ocala Group	6.8×10^{-1}	1.4×10^{-2}	31
953	Ocala Group	BDL	1.1×10^{-5}	18
980	Ocala Group	2.0×10^{-3}	0.47×10^{1}	13
1,025	Ocala Group	0.90×10^{1}	8.6×10^{-4}	9
1,035	Avon Park Formation	BDL	1.2×10^{-1}	9
1,095	Avon Park Formation	BDL	BDL	1

Laboratory analyses indicate that hydraulic properties determined from cores are highly variable and that no relation can be determined between horizontal and vertical hydraulic conductivity. Some cores have higher horizontal than vertical hydraulic conductivities, whereas other cores have higher vertical than horizontal hydraulic conductivities; still others have similar vertical and horizontal hydraulic conductivities. The variability in hydraulic properties determined from the cores indicates that hydraulic conductivities and porosities determined from cores should be used cautiously and values may not characterize formation-scale properties.

Aquifer Tests

The most representative method for determining field values of hydraulic properties is by aquifer testing in which a well is pumped and the drawdown and/or recovery of water levels in one or more wells are recorded and analyzed. Successful aquifer tests of the hydrogeologic units underlying the SDWF are difficult to conduct because the aquifer system is layered and a nonuniform permeability distribution exists. Furthermore, partial penetration of wells and the approximations involved with the application of analytical solutions cause problems. Additionally, characterizing hydraulic properties is more difficult for heterogeneous, fractured rock than for homogeneous, granular rock. At small scales, on the order of inches to feet, contrasts in hydraulic conductivity could result from the presence or absence of fractures. At larger scales, on the order of tens to hundreds of feet, contrasts in hydraulic conductivity values could arise from differences between zones of numerous, open, well connected fractures instead of sparse, tight, poorly connected fractures within which wells may be completed. Consequently, hydraulic properties determined with quantitative analytical methods at a particular location in the aquifer may not be representative of properties at an adjacent location (P.A. Hsieh, USGS, written commun., 1992).

Aquifer tests were performed at production wells 1, 3, 4, 5, and 6 as part of this study. All of the tested production wells are similarly constructed and are open to both the intermediate aquifer system (Tampa Member) and the Upper Floridan aquifer (Suwannee Limestone). Single-well tests were performed at production wells 1 and 4 and multiwell tests were performed at production wells 3, 5, and 6. The observation wells measured near the production wells are approximately the same depth as the pumped wells but the open hole intervals are much longer in the observation wells than in the pumped wells.

The production wells were pumped at different times during the period from October 1992 to September 1993. Submersible pumps were provided by the city of Sarasota and water-level data were recorded by USGS personnel. Semi-log plots of water-level changes over time caused by pumping at the production wells are shown in figure 14. The water-level changes ranged from 9 to 47 ft. In addition to the wide range of water-level changes among the wells, the shapes of the drawdown curves are appreciably different. In production well 1, water levels dropped rapidly for 3 minutes followed by a steady water-level decline that persisted to the end of the test. In production wells 3 and 4, water-level declines show a curvilinear pattern. In production well 4, water-level declines indicate a "stairstep" pattern in response to the pumping rate change. In production well 5, water-level declines are erratic and may indicate an over- or under-damped well response resulting in oscillation of water levels in the well (Van der Kamp, 1976). In production well 6, water levels declined steadily in response to pumping. Variations in water-level changes appear to be affected by anisotropy and heterogeneity in the aquifer. A brief discussion of each of the aquifer tests is provided below.

Production well 1 (fig. 11) is located at latitude 27°21′22″ and longitude 82°33′08″ at the intersection of 22nd Street and Bay Avenue near Sarasota Bay. The well is 626 ft deep with 324 ft of 10-in. polyvinyl chloride (PVC) casing. The production well was pumped at a rate of 400 gal/min (gallons per minute) for 180 minutes on December 16, 1992. Water levels were measured in the production well using a steel tape during pumping and for 92 minutes after the end of pumping. Changes in water levels during pumping are shown in figure 14. The measured maximum water-level change was 47 ft.

Production well 3 (fig. 11) is located at latitude 27°21′29″ and longitude 82°33′02″ on Hickory Avenue, about 0.25 mi east of Sarasota Bay. The production well is 591 ft deep with 270 ft of 10-in. PVC casing. An observation well is 28 ft east of the production well. The observation well is 599 ft deep with 46 ft of 6-in. PVC casing. The production well was pumped at a rate of 420 gal/min for 180 minutes on May 3, 1993. Water levels were measured in the production and observation well using a digital recorder and steel tape during pumping and for 120 minutes after the end of pumping. Changes in water level in the pumped well during pumping are shown in figure 14. The measured maximum water-level change was 35 ft.

Production well 4 (fig. 11) is located at latitude 27°21′19″ and longitude 82°32′48″ near the intersection of Panama Street with Whitaker Bayou. The well is 612 ft deep with 302 ft of 12-in. PVC casing. The production well was pumped at a rate of 190 gal/min for 10 minutes then at a rate of 205 gal/min for 50 minutes on October 22, 1992. Water levels were measured in the production well using a steel tape during pumping and for 33 minutes after the end of pumping. Changes in water levels during pumping are shown in figure 14. The measured maximum water-level change was 14 ft.

Production well 5 (fig. 11) is located at latitude 27°21′27″ and longitude 82°32′38″ near the intersection of 23rd Street and Coconut Avenue. The production well is 649 ft deep with 246 ft of 10-in. PVC casing. An observation well is located approximately 84 ft north of the production well. The observation well is 570 ft deep with 45 ft of 4-in. casing. The production well was pumped at a rate of 480 gal/min for 210 minutes on September 8, 1993. Water levels were measured in the production well using a pressure

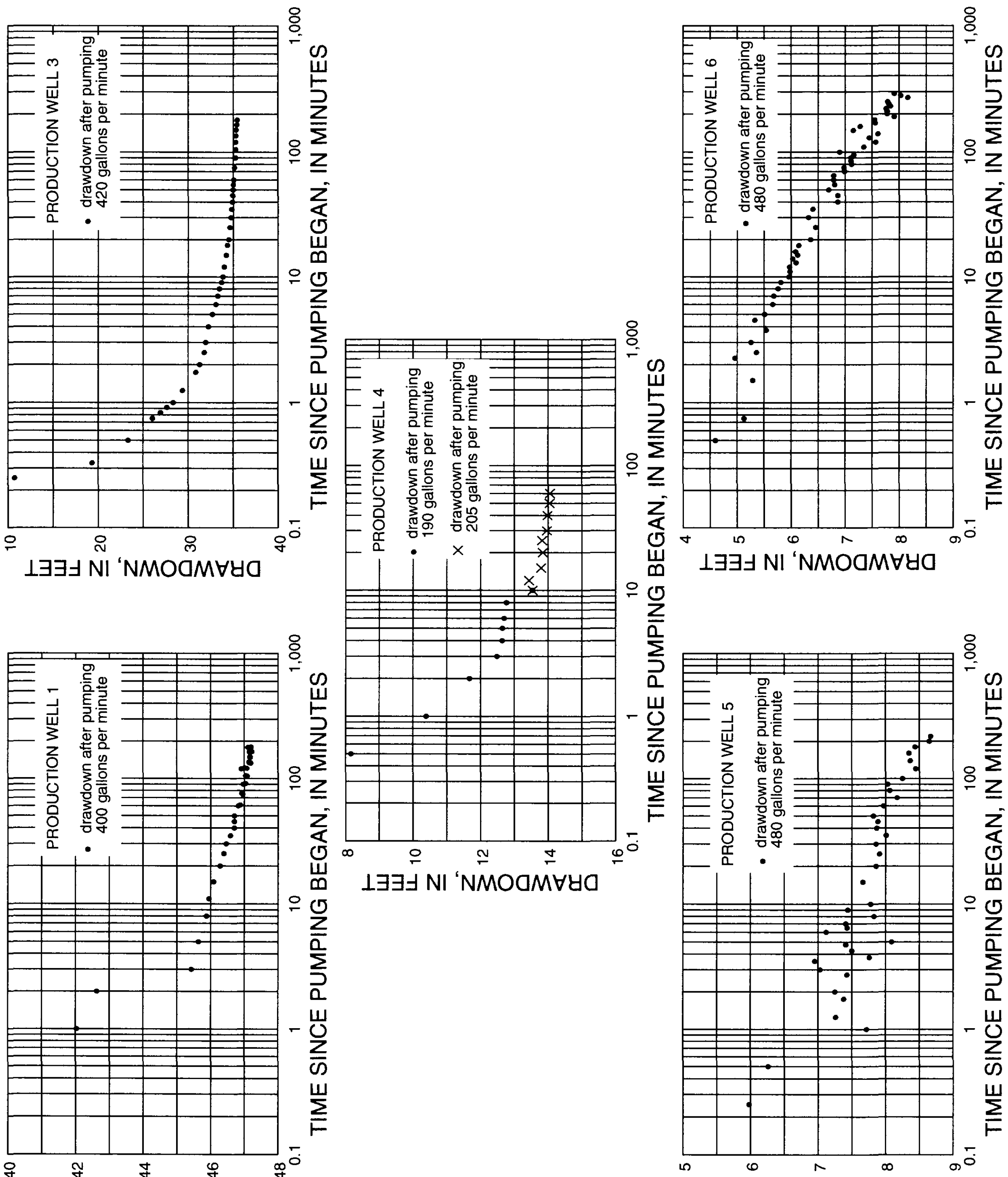


Figure 14. Aquifer-test data from Sarasota production wells from October 1992 to September 1993.

transducer and steel tape and in the observation well by a digital recorder and steel tape during pumping and for 160 minutes after the end of pumping. Changes in water level in the pumped well during pumping are shown in figure 14. The measured maximum water-level change was 9 ft.

Production well 6 (fig. 11) is located at latitude 27°21′20″ and longitude 82°32′27″ on 21st Street near the railroad line. The production well is 561 ft deep with 261 ft of 10-in. PVC casing. An observation well is located 43 ft north of the production well. Construction of the observation well is unknown. The production well was pumped at a rate of 480 gal/min for 300 minutes on August 10, 1993. Water levels in the observation well were measured by a digital recorder and steel tape during pumping and for 240 minutes after the end of pumping. Changes in water level in the pumped well during pumping are shown in figure 14. The measured maximum water-level change was 8 ft.

Results of the data collected during the aquifer tests indicate that local scale heterogeneity precludes the determination of reliable hydraulic properties of the hydrogeologic units underlying the SDWF using standard analytical techniques. Possible reasons include: analytical methods may be limited if aquifer-test duration is too short; the hydrologic system being analyzed is multilayered; observation wells are not optimally placed; the assumption of analytical methods that confining units do not store water is false; and the degree of aquifer anisotropy and heterogeneity is great (Hutchinson and Trommer, 1992). Furthermore, differing boundary conditions, tidal effects, and barometric-pressure changes complicated interpretation of observed responses.

GROUND-WATER QUALITY

The geochemical properties and subsequent evolution of ground water is affected by many factors. Some of these factors are the initial chemical composition of water entering the aquifer, the composition and solubility of rocks through which the water moves, and the length of time it remains in contact with the rocks. Additionally, the quality of water may also be affected by mixing of the freshwater with modern seawater, residual seawater, and connate water.

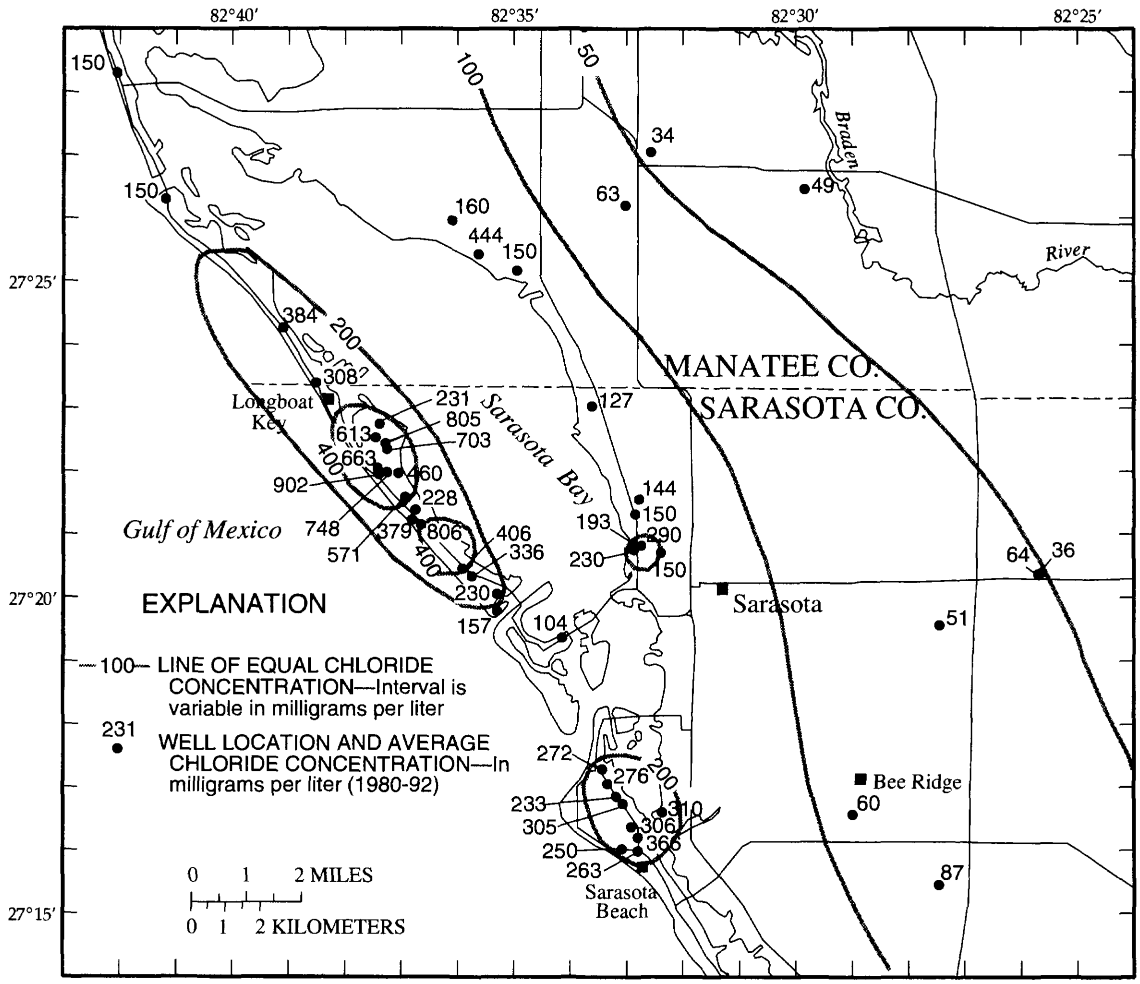
A general geochemical model of the evolution of ground-water quality in a carbonate aquifer system was utilized to describe the observed spatial and temporal water-quality changes. As a result of mineral dissolution, calcium, magnesium, and bicarbonate concentrations increase with residence time. Sulfate concentrations increase as ground water, deep in the regional flow system, comes in contact with the evaporites of the Floridan aquifer system middle confining unit. Upwelling of these waters occur as pressures in the Upper Floridan aquifer become less than in units below. Sodium and chloride concentrations in ground water increase near the coast particularly in the proximity to the freshwater-saltwater transition zone.

Lateral Distribution of Chloride Concentrations in the Study Area

Chloride concentrations in ground water underlying the study area are indicative of transitional type waters. Transitional type waters are a mixture of freshwater and saltwater, with chloride concentrations ranging from 25 to 19,000 mg/L (milligrams per liter). The region occupied by this mixture is designated as the transition zone. Concentrations in the intermediate aquifer system and producing zones tapped by the SDWF were mapped and contoured to show the lateral distribution of chloride in ground water underlying the study area (figs. 15 and 16). Values represent average concentrations in water collected from wells since 1980 (Southwest Florida Water Management District, 1993).

Chloride concentrations in water from wells penetrating only the intermediate aquifer system range from 34 to 902 mg/L. Concentrations are highest where pumpage is concentrated and then decrease away from these well clusters; however, concentrations in water from adjacent wells are often different even though well construction is similar (fig. 15).

Chloride concentrations in water from wells penetrating the permeable zones of the lower intermediate aquifer system (Tampa Member) and uppermost Upper Floridan aquifer (Suwannee Limestone) range from 27 to 1,000 mg/L. Highest concentrations are from ground water in the vicinity of the SDWF where pumpage is greatest (fig. 16). Again, similarly constructed wells have water with differing concentrations. Relatively low concentrations occur in water from some wells in close proximity to Sarasota Bay, whereas a reentrant of higher concentrations occur in northwestern Sarasota and southwestern Manatee Counties (fig. 16). In the southern part of the study area, higher concentrations occur far inland from the coast (fig. 17).



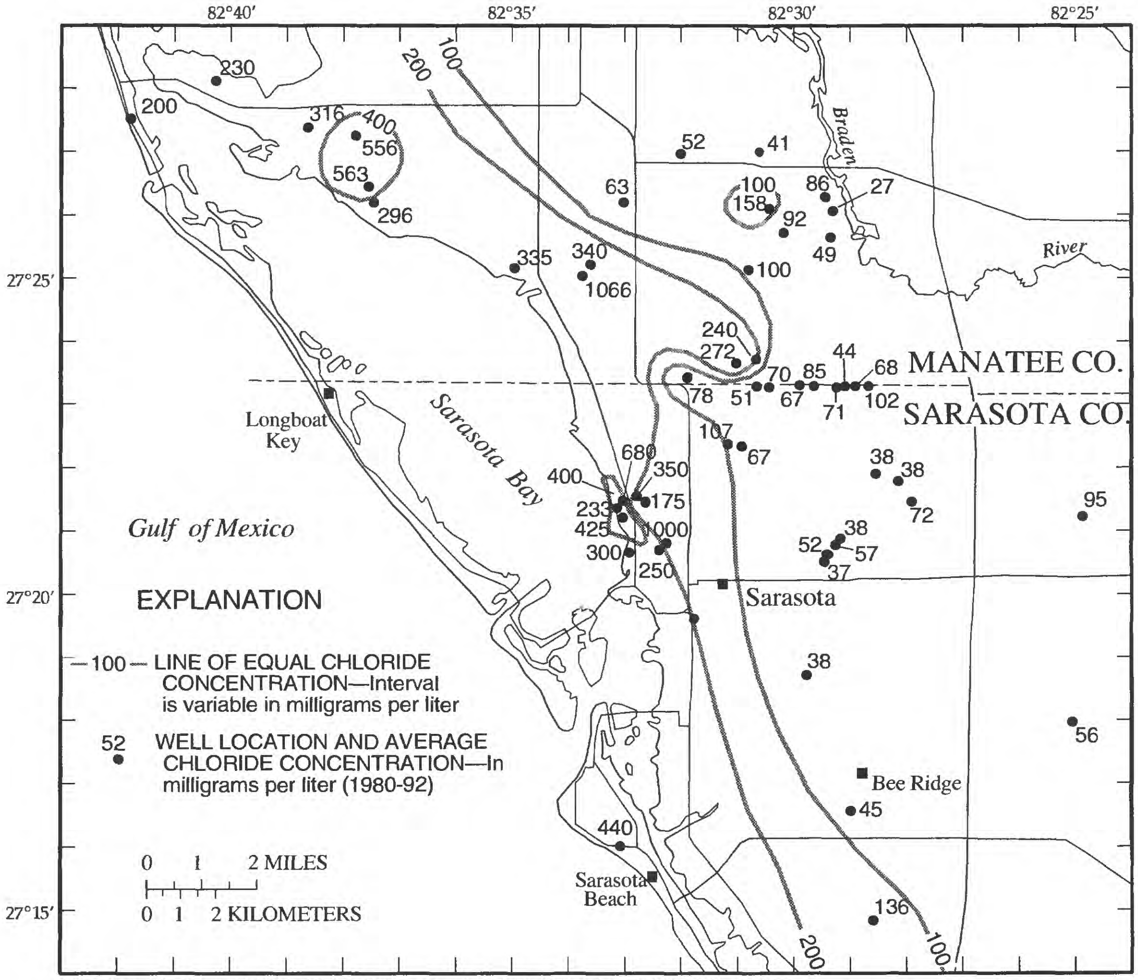
Base from Southwest Florida Water Management District digital data, 1:500,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 15. Well locations and chloride concentrations in water from wells penetrating the intermediate aquifer system.

No relation between chloride concentrations and relative distance from Sarasota Bay is apparent. Chloride concentrations of composite samples collected as part of this study from production wells 1, 2, 3, 4, 5, 6, and the Sarasota corehole are 233, 415, 680, 1,000, 410, 175, and 250 mg/L, respectively. Samples from production wells 1, 2, and 3 have lower concentrations than production well 4 even though the wells are similarly constructed, down gradient from production well 4, and closer to Sarasota Bay than production well 4 (fig. 16). Reasons for these concentrations might be any of the following: differences in water quality among the flow zones penetrated by wells, changes over time in hydraulic gradients between flow zones within a well that may affect the relative contribution from discrete flow zones with different water quality, and changes over time in water quality of specific flow zones.

Vertical Distribution of Selected Chemical Constituents in the Study Area

The water-quality samples previously discussed represent a mixture of water from all zones penetrated by wells. Delineation of the vertical water-quality changes in the aquifers underlying the study area was accomplished by evaluating the distribution of selected chemical constituents in water samples collected during well construction and from discrete permeable zones.



Base from Southwest Florida Water Management District digital data, 1:500,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 16. Well locations and chloride concentrations in water from wells penetrating the Tampa and Suwannee permeable zones.

Chloride concentrations in water samples collected during drilling were available from seven wells in the study area: the Regional Observation and Monitoring Well Project (ROMP) sites TR7-1, TR7-2, TR7-4, TR6-1, and TR6-3; the Bobby Jones test well; and the Sarasota corehole (fig. 18). All of the wells with sufficient chloride data in shallow zones (50-450 ft below land surface) indicate elevated chloride in the intermediate aquifer system. In most wells, chloride decreased in the uppermost parts of the Upper Floridan aquifer (about 450 ft below land surface) and then gradually increased with depth. Data from the Atlantic Utilities and the city of Sarasota injection wells indicate that high salinity water (with chloride concentrations as high as 19,000 mg/L) occurs below a depth of 1,500 ft. Well information is listed in table 1 and locations are shown on figure 3.

For this study, water-quality samples were collected with a thief sampler at selected intervals from the Sarasota corehole and six production wells to characterize the vertical distribution of chemical constituents from discrete permeable zones. Sampling intervals correspond to locations of producing zones indicated by geophysical logs and flowmeter logs. The vertical distribution of the concentrations of major ions in water from the Sarasota corehole are shown by Stiff diagrams in figure 19. The vertical distributions of concentrations of chloride and sulfate in water from samples from the six production wells are shown in figure 20. Sampling depths and corresponding chloride and sulfate concentrations are given, and ranges in chloride and sulfate concentrations and trends with depth are reported for each of the production wells.

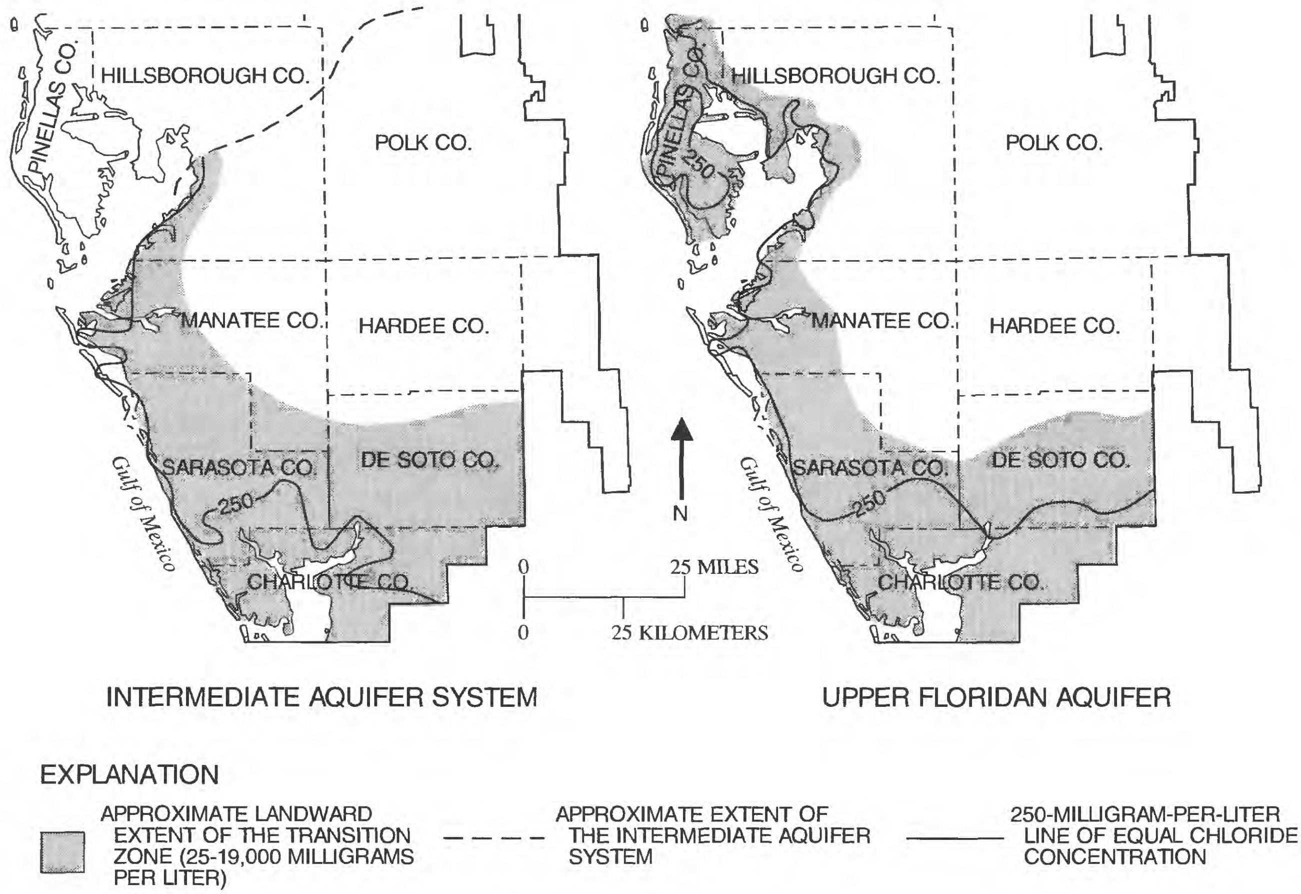


Figure 17. Approximate landward extent of the transition zone and 250-milligram per liter isochlor in the intermediate aquifer system and Upper Floridan aquifer, west-central Florida, 1987-90. (Modified from Trommer, 1993.)

Chloride and sulfate concentrations in milligrams per liter in water samples collected at discrete zones in the production wells ranged, respectively, as follow: well 1 (156-233; 680-710), well 2 (320-435; 834-942), well 3 (820-1,400; 830-930), well 4 (880-1,080; 860-980), well 5 (230-380; 900-1,000), and well 6 (200-205; 770-840). At wells 1, 2, and 5, chloride concentrations decreased but sulfate concentrations increased with depth. At wells 3 and 4, chloride and sulfate concentrations increased with depth. At well 6 chloride and sulfate concentrations decreased with depth.

Composite samples were also collected from the production wells and represent a mixture of water from discrete producing zones penetrated by the wells. Chloride concentrations in composite samples were outside the range of concentrations for the discrete zone samples at production wells 3, 5, and 6 (fig. 20), indicating that not all of the sources of water to the wells were from the discrete producing zones.

Temporal Variation in Selected Chemical Constituents in the Study Area

Pumpage data, and chloride and sulfate concentration data have been collected for more than 40 years in the SDWF. Temporal changes in chloride and sulfate concentrations, as an indicator of saltwater intrusion, have been monitored during this same period. The frequency of data collection varies among wells from year to year.

The SDWF operations are divided into two distinct periods of aquifer withdrawals, one from 1951-66 and the other from 1982-94. Pumpage data from specific wells are not available for the period 1951-66; however, total pumpage increased from 1.8 Mgal/d in 1951 to 4.5 Mgal/d in 1966 (Leggette, Brashears, and Graham, 1979).

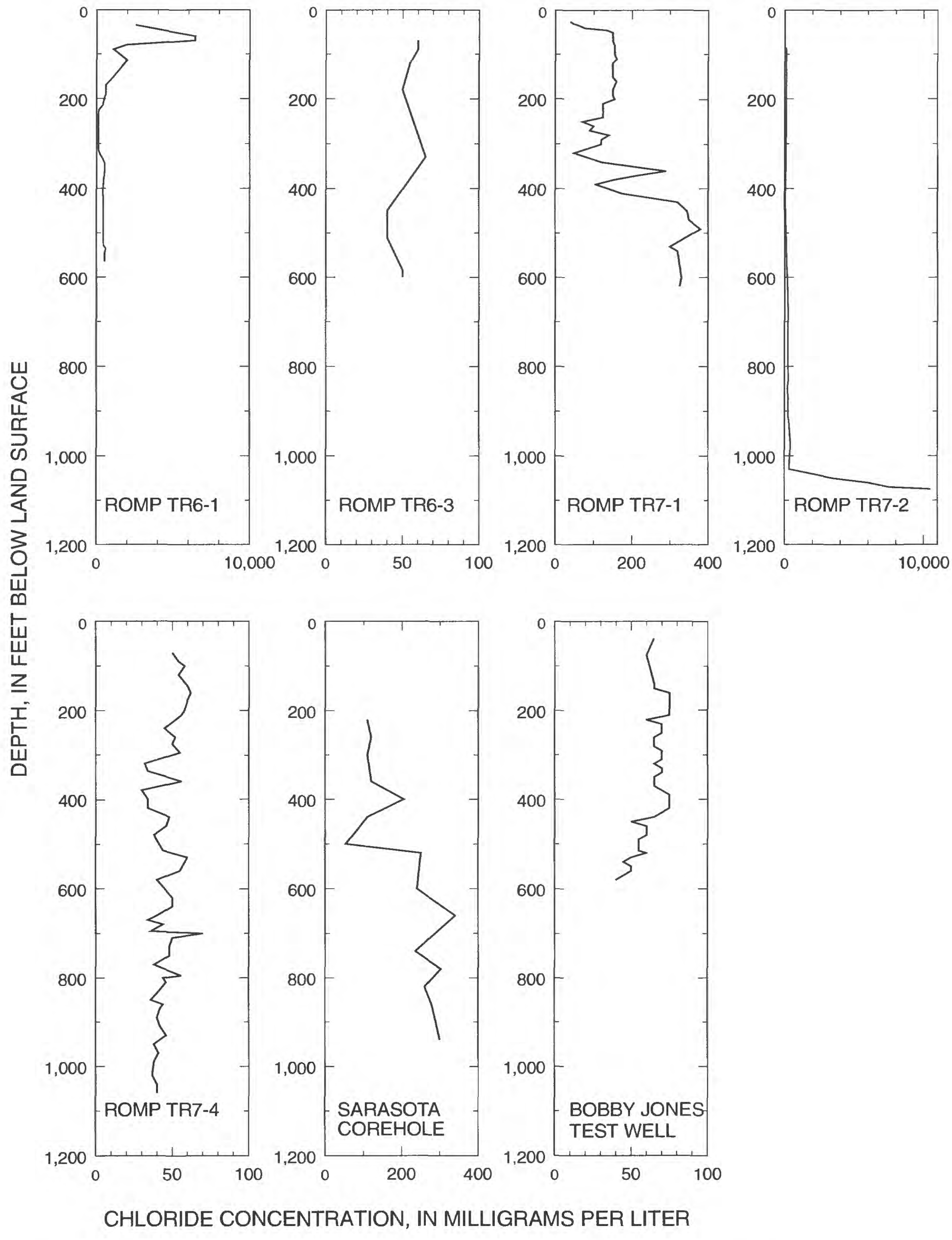


Figure 18. Vertical chloride concentration distribution in water from selected wells in the study area.

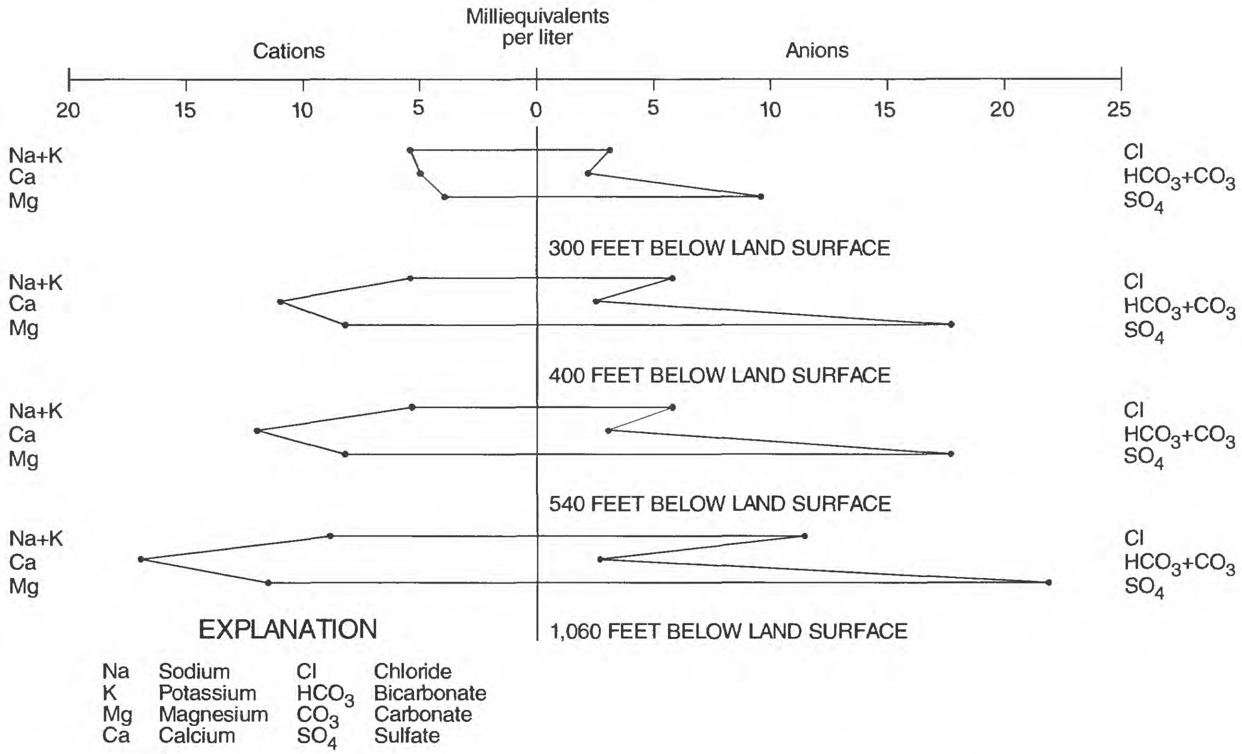


Figure 19. Stiff diagrams of major ions in water from selected well depths in the Sarasota corehole.

The water quality of the SDWF production wells has generally deteriorated over time. Chloride data from ground-water samples collected in 1961 and 1966 and well construction information for the production wells during the same period are listed in table 3. Initial chloride concentrations were greater than 50 mg/L, indicating that the wells penetrated the transition zone prior to pumping. Water-quality samples collected in 1961 indicate that highest concentrations occurred in wells 5 and 6 (table 3). These two wells are farthest from the coastal margin (fig. 11). Historical chloride and sulfate concentrations in conjunction with pumpage data from the six production wells tapping the intermediate aquifer system and Upper Floridan aquifer are shown in figure 21 and listed in table 3. The data in table 3 indicate that chloride for production wells 1, 3, 5, and 6 have increased during the period 1961-66 whereas production well 2 and 4 have decreased slightly during the same period. The graphs (fig. 21) for production wells 1, 2, 3, 5, and 6 indicate similar trends as described above; however, production wells 5 and 6 have had periods of both increasing and decreasing chloride concentrations. The graph for production well 4 represents the new well.

In 1982, the SDWF was reactivated; however, prior to the beginning of pumping, the location and construction features of some of the SDWF production wells were altered. Production well 4 was abandoned and redrilled, casing was deepened at production wells 3 and 6, and production well 1 was back plugged. Annual average chloride and sulfate concentrations and pumpage for each production well are shown in figure 21 and chloride data from 1982 and 1993 are listed in table 4. There is a distinct rate of change in chloride concentrations in water samples from production wells 2 and 3 coinciding with the relocation of production well 4. Chloride concentrations in water samples from production wells 5 and 6 also increased gradually since 1982. With the possible exception of production well 2, no apparent relation is indicated between increasing chloride concentrations and pumping rates. A reduction in pumpage from production wells 3 and 4 has not resulted in stabilization nor declines in chloride concentrations. Chloride data from water samples collected in 1982 and 1993 and well construction information for the production wells during the same period are listed in table 4. Historically, sulfate concentrations were significantly higher than

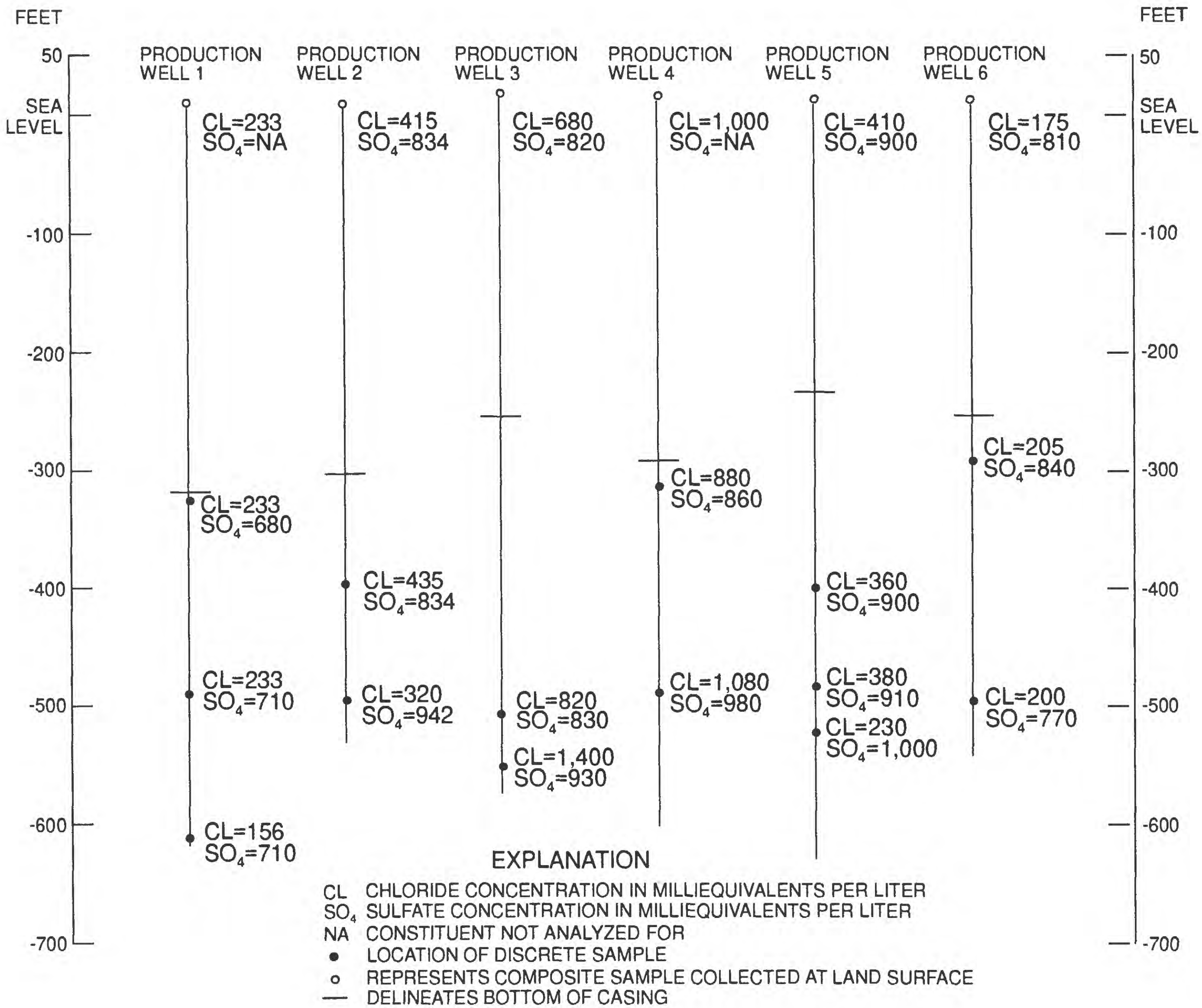


Figure 20. Chloride and sulfate data collected during logging of the Sarasota downtown well field production wells, utilizing a thief sampler.

Table 3. Chloride concentrations and well construction data for the Sarasota downtown well field (1961-66)

[Well 4 is not in the same location as the currently designated production well 4. Construction information for well 4 is from Leggette, Brashears, and Graham, Inc., (1979)]

Production well number	Chloride concentration for 1961 (in milligrams per liter)	Chloride concentration for 1966 (in milligrams per liter)	Casing depth (in feet)	Depth (in feet)
1	140	205	317	804
2	165	135	296	534
3	135	215	39	582
4	165	145	48	343
5	190	200	246	649
6	200	225	120	557

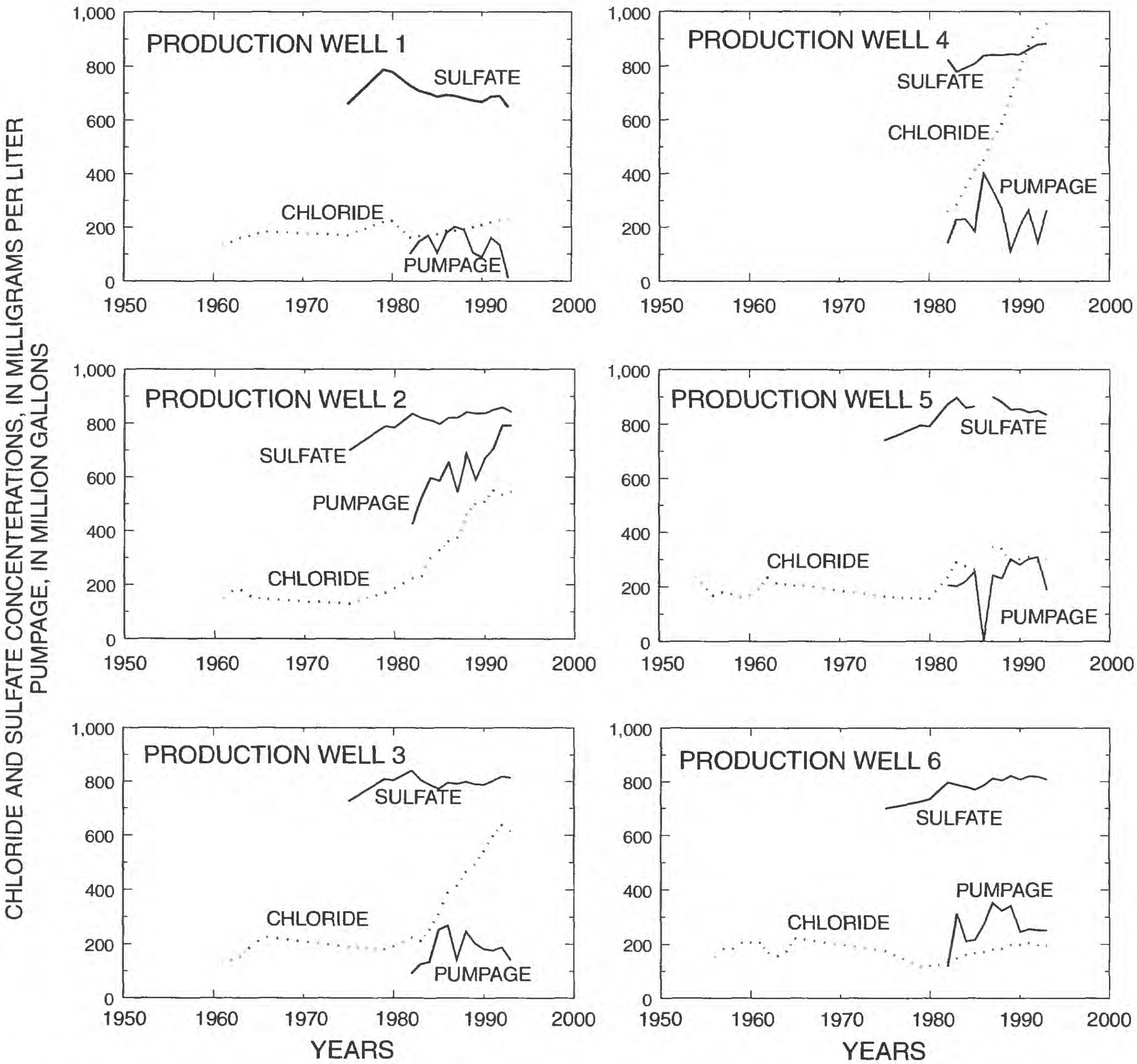


Figure 21. Annual average chloride and sulfate concentrations and total annual pumpage for the Sarasota downtown well field.

Table 4. Chloride concentrations and well construction data for the Sarasota downtown well field (1982-93)

[Chloride concentration data for 1993 was collected as part of this study. Well depths from geophysical logs collected as part of this study]

Production well number	Chloride concentration for 1982 (in milligrams per liter)	Chloride concentration for 1993 (in milligrams per liter)	Casing depth (in feet)	Depth (in feet)
1	170	233	324	626
2	200	415	306	537
3	210	680	270	591
4	240	1,000	302	612
5	220	410	246	649
6	120	175	261	561

chloride concentrations in water samples from the SDWF; however, at production wells 2, 3, and 4 chloride concentrations have increased at a faster rate than sulfate concentrations.

Changes in water quality, especially chloride concentrations in water from wells in the SDWF, indicate that saltwater is gradually intruding into the producing zones; however, it is difficult to determine whether this trend will continue. The increase in chloride concentrations in the past indicates that further increases are possible. Various mechanisms for saltwater movement that explain the increases in chloride concentrations are discussed in the next section.

MECHANISMS FOR SALTWATER INTRUSION

Water-quality changes in wells along coastlines are of growing concern to water managers in Florida. Consequently, the origin of elevated chloride concentration in water from wells has been heavily debated in recent years. Five possible mechanisms could cause the movement of saltwater in aquifers and observed water-quality changes as indicated by increases in chloride concentrations: (1) unflushed relict seawater in the aquifer system; (2) lateral movement of the freshwater-saltwater interface; (3) upconing of saltwater from deeper parts of the aquifer system; (4) upward leakage from deeper, saline water-bearing zones through failed, uncased, improperly plugged, or improperly constructed wells; and (5) upward or downward leakage from poor water-quality zones through confining units that are thin, or are breached by joints, fractures, collapse features, or faults (Spechler, 1994).

Relict Seawater

Unflushed relict seawater could be a source of chloride in some parts of the study area, because sea levels are higher today than during past epochs when permeable zones in the aquifers were filled with seawater. Relict seawater may not have been completely flushed, especially in zones of stagnation or zones of slow ground-water flow. Higher chloride concentrations in the intermediate aquifer system than in the underlying Upper Floridan aquifer indicates the presence of relict seawater from past tidal inundations (fig. 18). Additionally, the landward extent of the transition zone in both the intermediate aquifer system and Upper Floridan aquifer underlying Sarasota, De Soto, and Charlotte Counties coincident with a low hydraulic gradient may be the result of incomplete flushing (fig. 17).

Lateral Movement

Lateral movement of modern seawater into the lower intermediate aquifer system and uppermost Upper Floridan aquifer as the mechanism for temporal changes in chloride concentrations seems unlikely in coastal Sarasota County. If modern seawater were moving laterally through the intermediate aquifer system and the Upper Floridan aquifer from outcrops in the Gulf of Mexico, chloride concentrations should be highest in samples from wells nearest the coast. However, concentrations from the coastward production wells 1, 2, and 3 have lower chloride concentrations than production well 4 (fig. 20; table 4) and concentrations in samples from the Sarasota corehole did not exceed 400 mg/L at a depth of 1,100 ft. Additionally, strontium isotope signatures in water samples collected from discrete intervals in the city of Sarasota injection well, the Sarasota corehole, Atlantic Utilities well, and Sarasota production well 3 support the assumption that water pumped from the Tampa Member of the Hawthorn Group of Miocene-age rocks and those of the Suwannee Limestone of Oligocene-age rocks originated from depths corresponding to Eocene-age rocks. All samples have strontium isotope signatures characteristic of Eocene-age rocks rather than signatures characteristic of modern seawater or post-Eocene rocks (Eldridge, 1986). This indicates upward movement of water from lower depths within the Florida aquifer system.

Upconing

Upconing is defined as the upward vertical movement of ground water (Fetter, 1988). Rapid temporal changes in chloride concentrations in ground water underlying the study area are indicative of upconing, because chloride concentrations have a larger rate of change in the vertical direction than in the lateral direction. Vertical changes in chloride concentrations (from freshwater to saltwater) occur in a distance on the order of hundreds of feet, whereas lateral changes occur over a distance on the order of miles (SDI Environmental Services, Inc., 1993). Highest and relatively rapid changes in concentrations are coincident with localized, heavy ground-water withdrawals. Evidence supporting the likelihood of this mechanism is the strong relation between elevated chloride concentrations and locations of the centroid of pumping. The centroid of pumping is defined as the location of largest withdrawals resulting from the combined effects of multiple pumping wells. The location of the centroid of pumping in the SDWF is nearest production well 4 and is shown in figure 11 (SDI Environmental Services, Inc., 1993). The rapid rate of change in chloride concentrations from 240 to 960 mg/L in samples from production well 4 indicates an abrupt change in flow conditions in the SDWF. The 1993 average chloride concentration of 960 mg/L is larger than any previously reported concentration in ground water underlying the SDWF. Prior to construction and development of production well 4, chloride concentrations of 960 mg/L or higher did not occur laterally at the penetration depths of the production wells but rather in rocks 200 to 700 ft lower in the aquifer (Sutcliffe, 1979; Causseaux and Fretwell, 1983; SDI Environmental Services, Inc., 1993). This increase in chloride concentrations implies upconing of waters with elevated concentrations from lower zones in the aquifer system. Circular isochlors of elevated chloride concentrations were plotted for the SDWF as well as on Longboat Key and Siesta Key (figs. 15 and 16) and coincide with the locations of greatest aquifer withdrawals.

Upward or Downward Leakage Through Wells

Contamination of freshwater zones by saltwater can originate through failed, uncased, improperly plugged, or improperly constructed wells by creating a conduit for flow among several water-producing zones of differing water quality. Wells with corroded or shallow casings allow saltwater from deeper permeable zones to move up under higher artesian pressures and leak into freshwater permeable zones from which the saltwater can move laterally away from the borehole. Such movement is most pronounced when wells of similar construction are closely spaced. Conversely, corroded casing may allow flow of ground water with elevated chloride concentrations from shallow zones into deeper zones in the aquifer. Joyner and Sutcliffe (1967) found that water-quality problems in Siesta Key (south Florida) have resulted because of perforation of the galvanized iron casing in zones of corrosive water in the surficial deposits and upper Hawthorn Group and that saline water has moved into lower zones during periods of head gradient reversals. The dramatic increase in aquifer withdrawals both upgradient (landward) and downgradient (from the barrier islands) may change head gradients between discrete flow zones and increase vertical exchange of water among the zones.

Upward Leakage Through Structural Features

Random areal and vertical variability in chloride concentrations indicate that isolated geologic or structural features could be a mechanism for saltwater intrusion and be the cause for the occurrence and distribution of saltwater in the intermediate aquifer system and in the Upper Floridan aquifer. Field observations that support this mechanism are: variable chloride concentrations in water samples from wells with similar construction (figs. 15 and 16), the occurrence and extent of zones of water with higher chloride concentrations layered between zones of water with lower chloride concentrations (fig. 18), and the occurrence of structural features that provide hydraulic connection between zones of varying water quality (Spechler, 1994). Locations of inferred fractures in or near the study area are shown in figure 22. An elongated area of relatively high chloride concentrations in southwestern Manatee and northwestern Sarasota Counties coincides with the general direction of the inferred fractures (figs. 16 and 22).

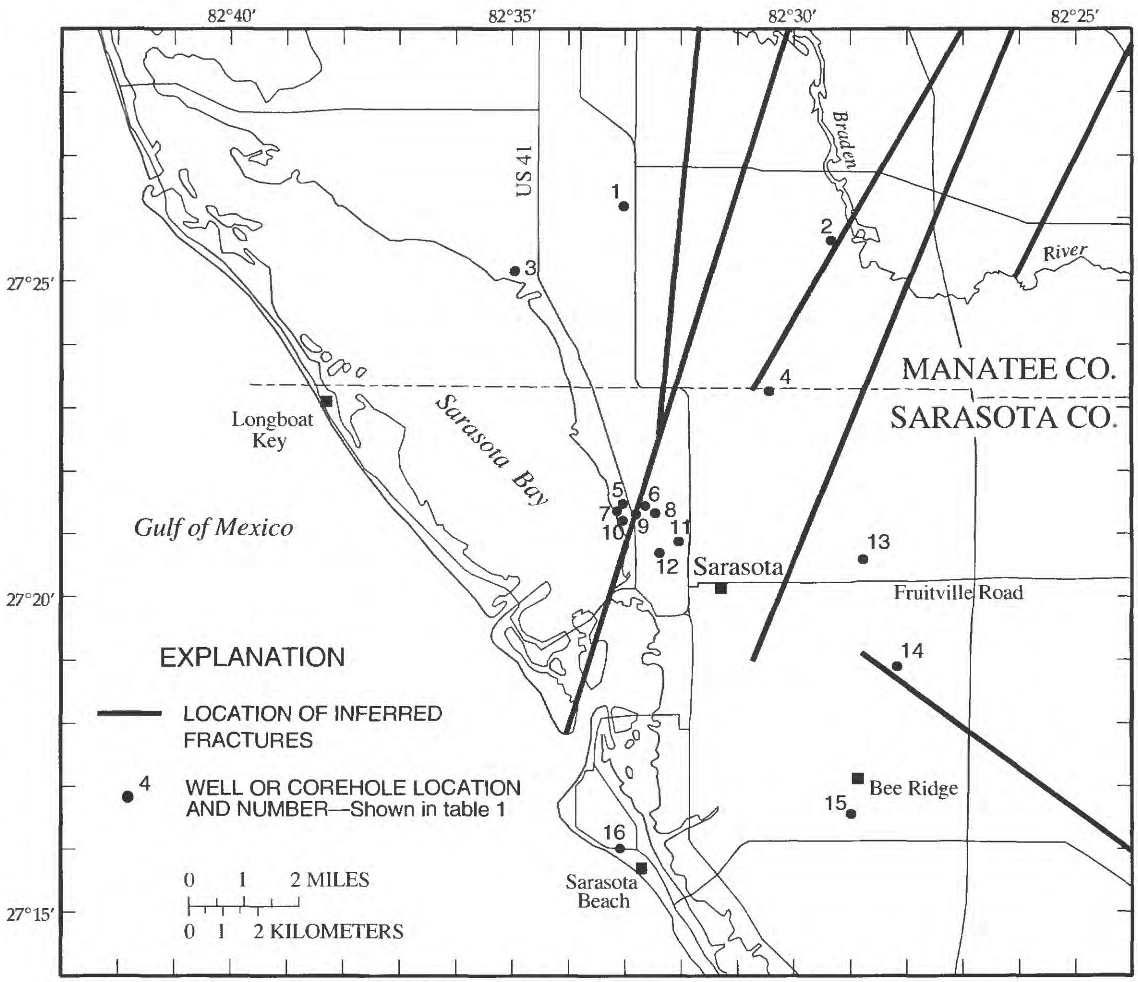
Generally, flow between aquifers is impeded by confining units. However, the confining units may be breached in many areas by fracture systems, creating linear zones of increased vertical permeability that serve as major discharge or recharge pathways between aquifers. Pumping near fracture systems could degrade ground-water quality by increasing upward and downward flow of highly mineralized water.

NUMERICAL SIMULATION OF A NEAR-SHORE WELL FIELD

One of the objectives of this study was to estimate the sources and movement of ground water that ultimately supplies the SDWF. Because of the limited amount of field data available, a numerical, ground-water flow model was prepared to develop and refine a conceptualization of the hydrogeologic system of the study area. The model was developed as an interpretive tool in which field-derived hydrologic characteristics (such as transmissivity and storativity from aquifer tests) could be tested against a distribution of known heads. The model was calibrated to steady-state conditions and then used to simulate transient conditions.

Numerical Methods

A numerical, finite-difference, ground-water flow model was developed to simulate the flow system of a hypothetical near-shore well field. The model was prepared utilizing geologic and hydrologic data collected from the Sarasota study area. The USGS computer



Base from Southwest Florida Water Management District digital data, 1:500,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 22. Location of selected wells and cores, and location of inferred fractures, in the study area. (Modified from Culbreath, 1988.)

code MODFLOW (McDonald and Harbaugh, 1988) was used to simulate three-dimensional flow in the intermediate and Upper Floridan aquifers. A block-centered, finite-difference approach to solve partial-differential equations governing ground-water flow is used in modeling with MODFLOW. The reader is referred to McDonald and Harbaugh (1988) for a complete overview of numerical methods and model code.

In addition to simulating flow conditions, travel paths of water particles were simulated using MODPATH (Pollock, 1989). MODPATH is a postprocessing package for calculating three-dimensional path lines on the basis of steady-state output from MODFLOW. A semi-analytical particle tracking method is used by MODPATH to calculate the position and travel time of a particle at any point within a model cell.

Model-Grid Discretization

The model area was divided into an orthogonal grid with seven layers to simulate a multilayered aquifer system (fig. 23). The grid, consisting of 32 rows and 29 columns, was discretized so that smallest cell sizes (1,056 ft) are centered near the well field with increasingly larger cell sizes (2,640 ft) moving outward toward model boundaries. Smaller cell sizes are used near the well field to provide greater detail in areas where steep hydraulic gradients are anticipated (Anderson and Woessner, 1992). The grid is oriented so that the southwestern boundary lies parallel to the Gulf Coast, with the northeastern boundary parallel to the southwestern boundary. This aligned the model boundaries with the principal flow directions of ground water.

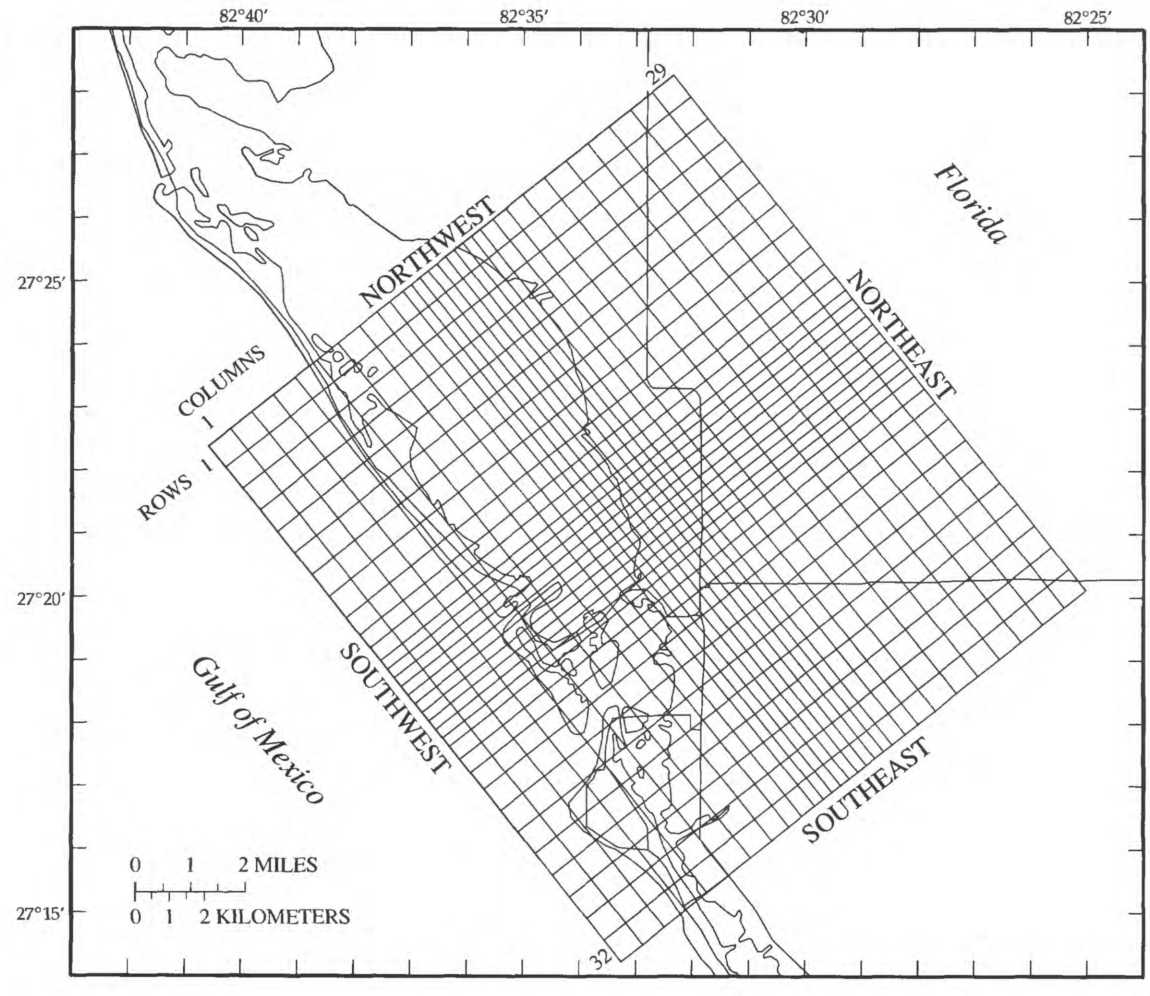


Figure 23. Model grid of the study area.

The hydrogeologic framework of the study area is represented by allocating each model layer to coincide with permeable zones (fig. 24). Where single hydrologic units have two zones of different permeability, a model layer was assigned to each zone. For example, in the case of the Tampa and Suwannee permeable zones, the discrete permeable zone was modeled as a thin layer overlying the remainder of the unit, represented by a thicker layer. Data from gamma, caliper, temperature, and flowmeter logs support this interpretation of zonation of varying permeabilities within single hydrologic units.

The model consists of seven layers with varying hydraulic conductivities and thicknesses. Layer 1 represents the Hawthorn Group less the Tampa Member. Layers 2 and 3 represent the Tampa Member of the Hawthorn Group, where layer 2 is a zone of higher permeability within the Tampa Member, and layer 3 represents the remainder of the Tampa Member. Layers 4 and 5 represent two discrete permeable zones within the Suwannee Limestone, where layer 4 has a higher permeability than the remainder of the Suwannee Limestone represented by layer 5. Layers 6 and 7 represent the Ocala Group and the Avon Park Formation, respectively.

Subdivision in Time

Steady-state and transient models were prepared to better understand the flow system of the study area. The steady-state model was prepared to define the local flow system, analyze field data, and define possible flow paths corresponding to specific head values and pumping conditions. The steady-state model was conceptualized as a "snap shot" in time, where initial head values and pumping conditions were taken from data recorded for the month of May 1993.

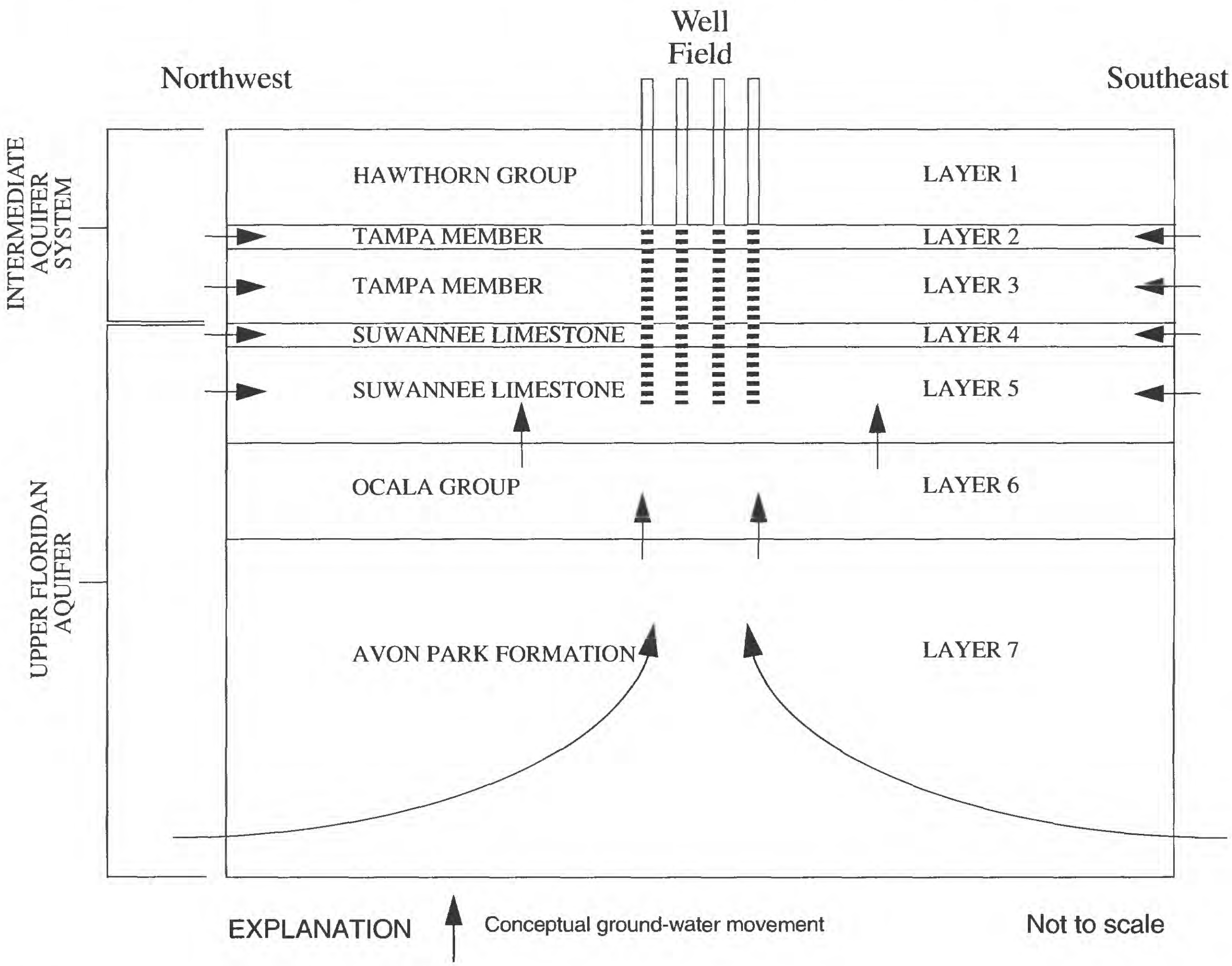


Figure 24. Conceptualized ground-water movement through the study area and diagram of model layering scheme.

The transient model was prepared to gain a better understanding of the flow system and to develop a water budget estimate for the flow system as it changes seasonally. The transient model includes 13 stress periods to correspond with 13 monthly data sets of head values. The data sets consist of head values for both the intermediate and Upper Floridan aquifers with output from the steady-state model used as initial conditions. Simulated pumping rates were varied for each stress period to correspond to the monthly pumping rates of Sarasota production wells.

Boundary Conditions

Boundaries for both the steady-state and transient models were established to encompass the area of contribution to the well field without extending unreasonably beyond the localized cone of depression or into areas where heads have not changed appreciably over a 10-year period. Boundary conditions were identical for both models except that head values for the general-head boundaries of the transient model changed with each stress period. Layer 1 represents the lower part of the Hawthorn Group excluding the Tampa Member. Heads at boundaries for layer 1 were based on water level information from wells open specifically to that zone of the lower Hawthorn. Layers 2 and 3 represent the Tampa Member of the undifferentiated Arcadia Formation of the Hawthorn Group. Heads at boundaries for layers 2 and 3 were identical and based on water-level information from wells open in the Tampa Member. Layers 4 to 7 represent the Upper Floridan aquifer. Heads at boundaries for layers 4 to 7 were identical and based on water-level information from wells open in the Upper Floridan aquifer. A detailed description of boundary conditions is provided below with boundary directions referenced to figure 23.

A freshwater head at sea level was thought to be located considerably offshore because potentiometric levels in the study area were higher (up to 13 ft) than sea level in wells at the barrier islands. The southwestern boundary was assigned a general-head boundary for all layers with the external controlling freshwater head at sea level, estimated to be about 30 mi from the model boundary. This value was chosen by extrapolating the hydraulic gradient of an estimated predevelopment potentiometric-surface map of the Upper Floridan aquifer (Johnston and others, 1980) and comparing this with head values for May 1993.

General-head boundaries were used at the northeastern and southeastern boundaries for model layers 2 to 7. External heads used for general-head boundaries were estimated at a fixed distance of 5 mi from the model boundary on the basis of well data from May 1993. The conductance values used at the general-head boundaries were based on equations found in the MODFLOW documentation using hydraulic conductivity values assigned to each model layer. These conductance values are given in appendix A.

The northwestern boundary of the model was assigned a specified-head for layers 1 to 3, whereas layers 4 to 7 were assigned general-head boundaries. Layers 2 and 3 were specified-head boundaries because data from May through September indicated that the potentiometric surface of the intermediate aquifer did not change appreciably and could be considered constant for the model simulation. Layers 4 to 7 were assigned a general-head boundary because heads within the model area are believed to be partially dependent on heads to the northwest of the model boundary. The northwest, northeast, and southeast boundaries in layer 1 were modeled as specified-head boundaries to simulate the effects of any lateral recharge moving into the system from the upper regions of the flow system, namely the upper portion of the Hawthorn Group and the surficial aquifers. The top of layer 1 was considered a no-flow boundary because it is believed no appreciable amount of water would enter the system through the upper confining units of the intermediate aquifer system. The base of the model corresponds to the low permeability confining unit underlying the Upper Floridan aquifer and is considered a no-flow boundary.

Hydrologic conditions within the study area, utilized in the transient simulation, were assumed to be dependent on conditions outside the study area. The area contributing ground water to the study area is assumed to change with time because hydrologic conditions change seasonally in Florida, with rising water levels coinciding with the yearly wet season and declining water levels coinciding with the yearly dry season (fig. 10). The potential change in direction of conceptualized ground-water flow paths corresponding to the potentiometric-surface maps of the Upper Floridan aquifer for May and September 1993 are shown in figure 25. The sections illustrated in figure 25 refer to section lines drawn in figure 10.

The northwestern, northeastern, and southeastern boundaries in the transient model were assigned identical conditions to those used in the steady-state model, but with head arrays developed for each stress period where general-head boundaries were assigned.

To simulate the changing direction and gradient of the potentiometric surfaces of the intermediate and Upper Floridan aquifers throughout the 13 simulated stress periods, 13 head arrays were generated for the southeast and northeast general-head boundaries for layers 2 to 7, and for layers 4 to 7 for the northwestern boundary. These head arrays correspond to 13 months of water level data collected from observation wells adjacent to the study area between May 1993 and May 1994. Water levels were plotted at each well location for each month and hydraulic gradients were linearly interpolated between wells to provide heads for individual cells along boundaries. The southwestern boundary, as with the steady-state model, was assigned a general-head boundary for all layers with the external controlling freshwater head at sea level, estimated to be about 30 mi from the model boundary.

Input Parameters

Model input parameters (including horizontal and vertical hydraulic conductivity, aquifer thickness, vertical leakance, storativity, and water levels for starting heads and general-heads) are based on published data, field measurements, and estimations from rock core analysis. Aquifer-test data were used to determine hydraulic properties for all model layers. Rock cores were examined to define porosity and vertical leakance values. Ultimately, some values for model input were adjusted during model calibration.

Hydraulic Coefficients of Model Layers

Initially, hydraulic coefficient values for individual model layers were based on field data obtained during this investigation and previously published USGS reports (Sutcliffe, 1979; Ryder, 1982; Wolansky, 1983; Hutchinson, 1992). Initial estimates of transmissivity ranged from 80,000 to 500,000 ft^2/d for the Upper Floridan aquifer and from 500 to 10,000 ft^2/d for the intermediate aquifer system. Estimates of storativity ranged from 1×10^{-4} to 1.8×10^{-2} for the Upper Floridan aquifer and from 5×10^{-5} to 3×10^{-4} for the intermediate aquifer system.

Seven layers with varying thicknesses were simulated to represent a multilayered aquifer system (fig. 24). Layer thicknesses and porosities had to be specified for each model layer for particle-tracking simulations. Layer 1 represents a part of the Hawthorn Group excluding the Tampa Member with an assigned

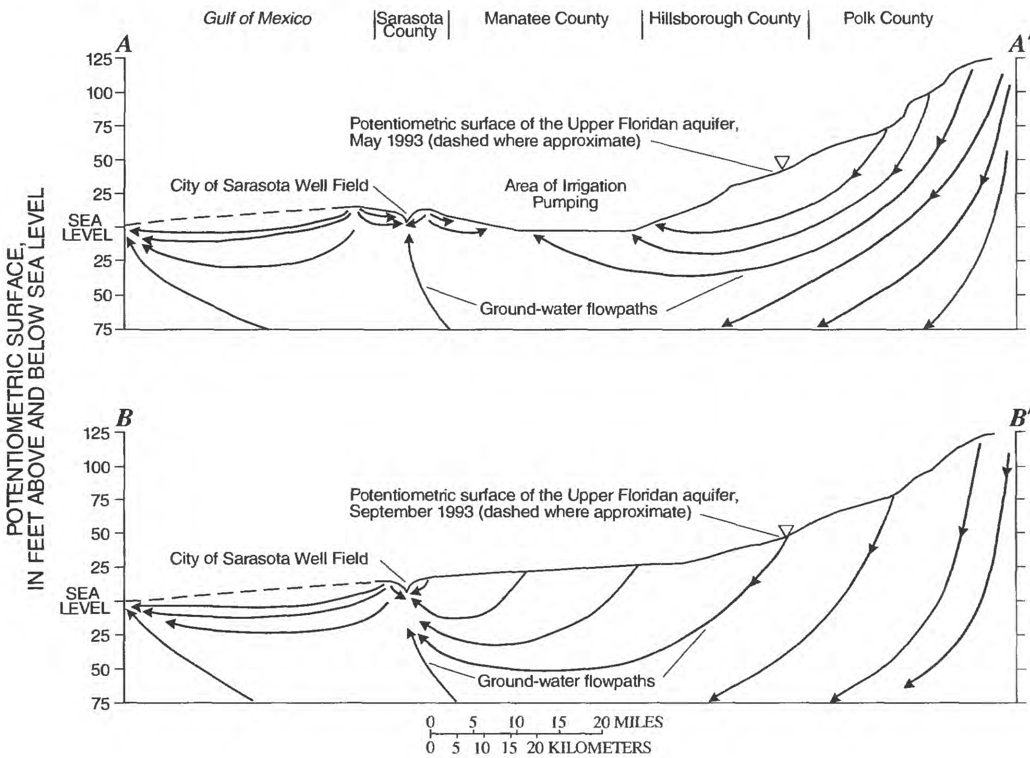


Figure 25. Potentiometric surface of the Upper Floridan aquifer and conceptualized direction of ground-water flow paths in west-central Florida for May and September, 1993.

thickness of 200 ft and a porosity of 20 percent. Layer 2 has an assigned porosity of 10 percent and represents a discrete 50-ft flow zone within the Tampa Member, whereas layer 3 represents the remainder of the Tampa Member with a representative thickness of 150 ft and a porosity of 20 percent. Layer 4, with a 50-ft thickness, represents a highly conductive zone within the Suwannee Limestone with an assigned porosity of 10 percent. Layer 5 represents the remainder of the Suwannee with an assigned thickness of 200 ft and a porosity of 20 percent. Layer 6, which represents the lower permeable Ocala Group of the Upper Floridan, has an assigned thickness of 200 ft and a porosity of 20 percent. Layer 7 represents the highly transmissive Avon Park Formation with an assigned thickness of 700 ft and a porosity of 15 percent.

Vertical Leakance Between Model Layers

To simulate the confinement of hydrologic units and the natural vertical-to-horizontal anisotropy within hydrologic units, vertical leakance values were calculated by applying documented equations (McDonald and Harbaugh, 1988; Anderson and Woessner, 1992) and were compared with published values and values estimated from rock core data (Ryder, 1982; Wolansky, 1983; Hutchinson, 1992). Initial values of vertical leakance ranged from 1×10^{-6} to 1×10^{-4} d^{-1} for the intermediate aquifer system and from 1×10^{-6} to 1×10^{-3} d^{-1} for the Upper Floridan aquifer.

Distribution of Well Field Pumping

The production wells in the SDWF pump about 6 Mgal/d of water from the underlying aquifers. The wells have cased boreholes with open intervals in both the Tampa Member and the Suwannee Limestone aquifers. Geophysical logs indicate discrete producing zones that probably supply most of the water to production wells. Most of the city of Sarasota's water supply probably originates in the Suwannee Limestone part of the open hole; therefore, 75 percent of the discharge rate was designated to layer 4 and 25 percent to layer 2. Distribution of pumping rates per model layer was determined on the basis of a simple transmissivity to discharge ratio (McDonald and Harbaugh, 1988). Only cells corresponding to layers 2 and 4 were designated to simulate the effects of discretized pumping of highly permeable flow zones. Individual cells were assigned individual pumping rates for each of the Sarasota production wells. During the transient model simulation, pumping rates were adjusted for each cell corresponding to that particular month's pumping rate.

Initial Conditions

Starting heads and heads used for general-head boundaries were estimated from specific data points that were extrapolated over a larger area to create assumed hydraulic gradients. Heads based on the May 1993 potentiometric-surface map were assigned to each model cell as an initial head. These same heads were used to extrapolate heads based on assumed gradients used with the general-head boundaries. Initial conditions for the transient model were the model computed heads from the steady-state model. Water levels for May 1993 were chosen as starting heads in the steady-state model simulation because the head values could be correlated to mass water-level measurements taken in May 1993 and were within the 10-year averages (1984-93) for May conditions in the study area.

Results of Model Simulation

Input parameters including transmissivity, vertical leakance, and general-head boundary conductance were methodically adjusted from initial estimates during calibration of the steady-state model to obtain a best-fit set of parameters. A best-fit model contains input parameters that are within a plausible range for the study area, with simulated heads that closely match observed heads (within 2 ft), and an overall configuration of simulated potentiometric surfaces that closely match the potentiometric surfaces drawn with observed heads. The final set of input parameters determined through calibration are shown in figure 26.

Particle tracking was utilized in the steady-state model to help define the flow of water as it enters and exits the local flow system. Furthermore, fluxes across boundaries of both the steady-state and transient model were calculated using Zone Budget, a program designed to calculate water budgets with results from MODFLOW output. The reader is referred to the original report for details on calculations made in Zone Budget (Harbaugh,1990). Volumetric budgets calculated from the transient model simulation were utilized to estimate the seasonal changes in areas of contribution to the local flow system.

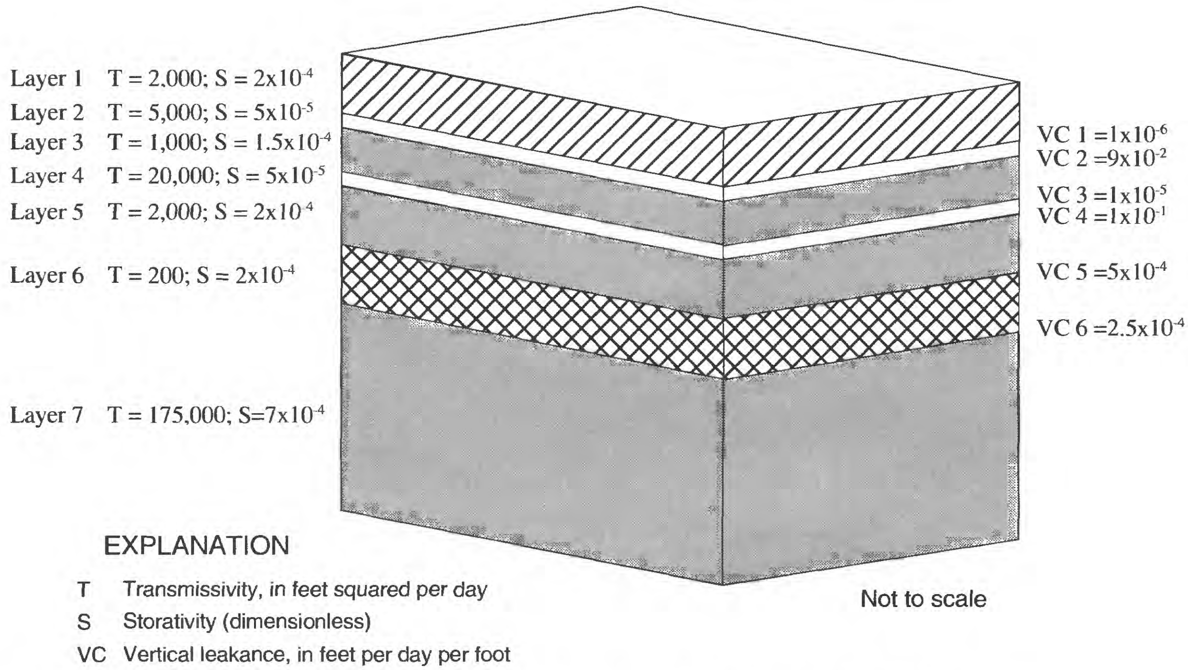


Figure 26. Diagram of model layering scheme with calibrated values of hydraulic coeffcients.

Steady-State Model

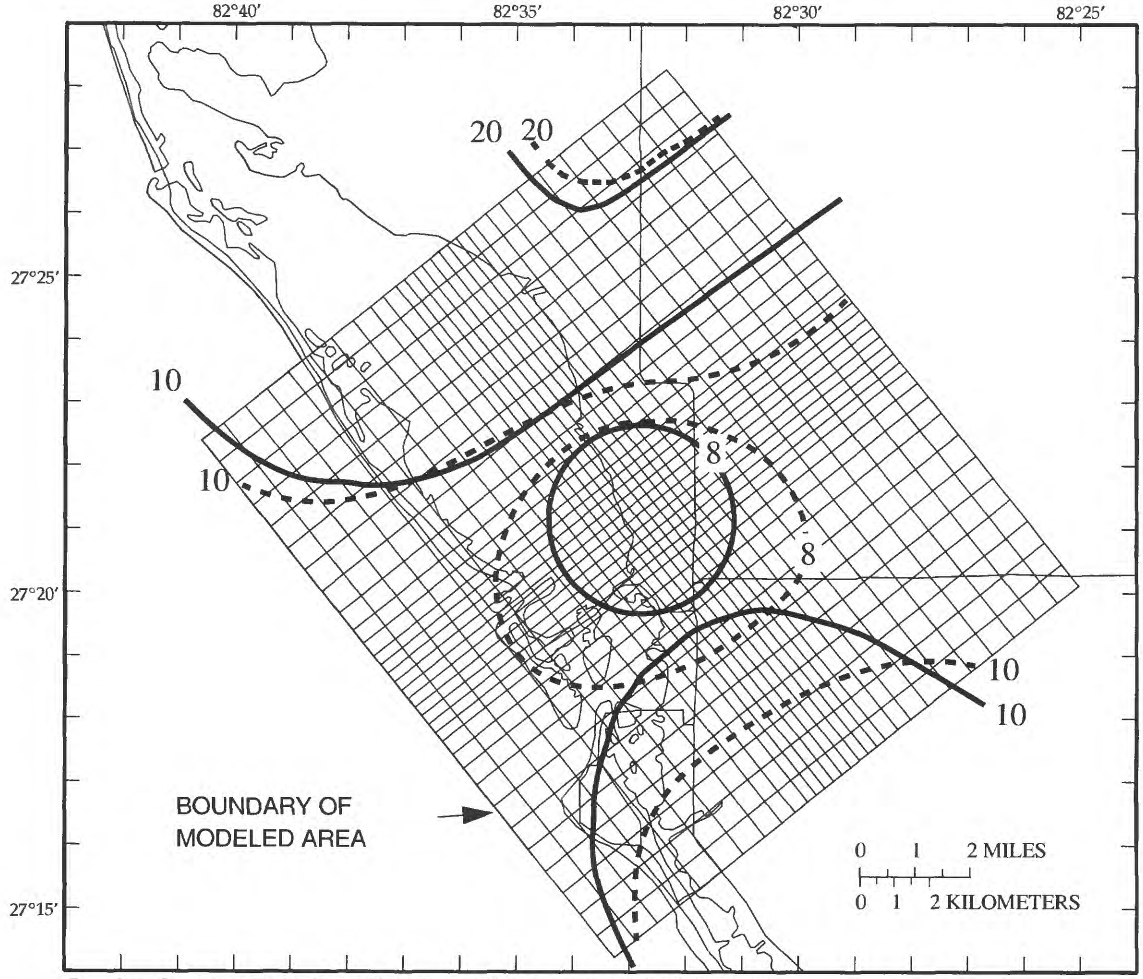
The potentiometric surfaces simulated in the steady-state model compare well with the potentiometric surfaces drawn with observed heads for both the intermediate aquifer system and the Upper Floridan aquifer for May 1993. The relation between observed and simulated heads for model layer 2 and the intermediate aquifer system and model layer 4 and the Upper Floridan aquifer are shown in figures 27 and 28, respectively. Layers 2 and 4 were used for comparison because these layers represent the pumped zones within the intermediate and Upper Floridan aquifers.

Flow paths were simulated in the steady-state model by using MODPATH. Particles were placed within model cells corresponding to well locations and tracked backward through time to recharge areas. These pathlines were used to help define the vertical and lateral movement of water within the modeled area. The flow lines of particles simulated within the cells corresponding to the city production wells for the best-fit model and for a model run with a change in vertical conductance between layer 5 and 6 to simulate only horizontal flow in the Suwannee Limestone (layers 4 and 5) are shown in figure 29. As illustrated by backward tracking pathlines in the best-fit scenario, most particles traced from well cells in layer 2 were derived laterally from the northwestern boundary of the model. However, most particles from well cells in layer 4 followed pathlines that originated vertically from lower model layers with sources traced to the southeastern and northwestern boundaries.

Volumetric budgets were calculated for the steady-state model according to model layer and model boundary. The positive fluxes (inflows) and negative fluxes (outflows) for the best-fit steady-state model and for sensitivity tests conducted with the steady-state model are provided in appendix B1. The percentages of inflows and outflows are given in appendix B2.

Transient Model

Simulated potentiometric surfaces corresponding to stress periods 1 and 5 of the transient model were compared with potentiometric surfaces drawn with head levels for May and September 1993. Simulated surfaces from stress period 1 (May 1993) closely matched surfaces simulated with the steady-state model. Simulated potentiometric surfaces corresponding to stress period 5 were compared to potentiometric surfaces drawn from head levels for September 1993. The relation between observed and simulated heads for model layer 2 and the intermediate aquifer system and model layer 4 and the Upper Floridan aquifer is shown in figures 30 and 31, respectively.



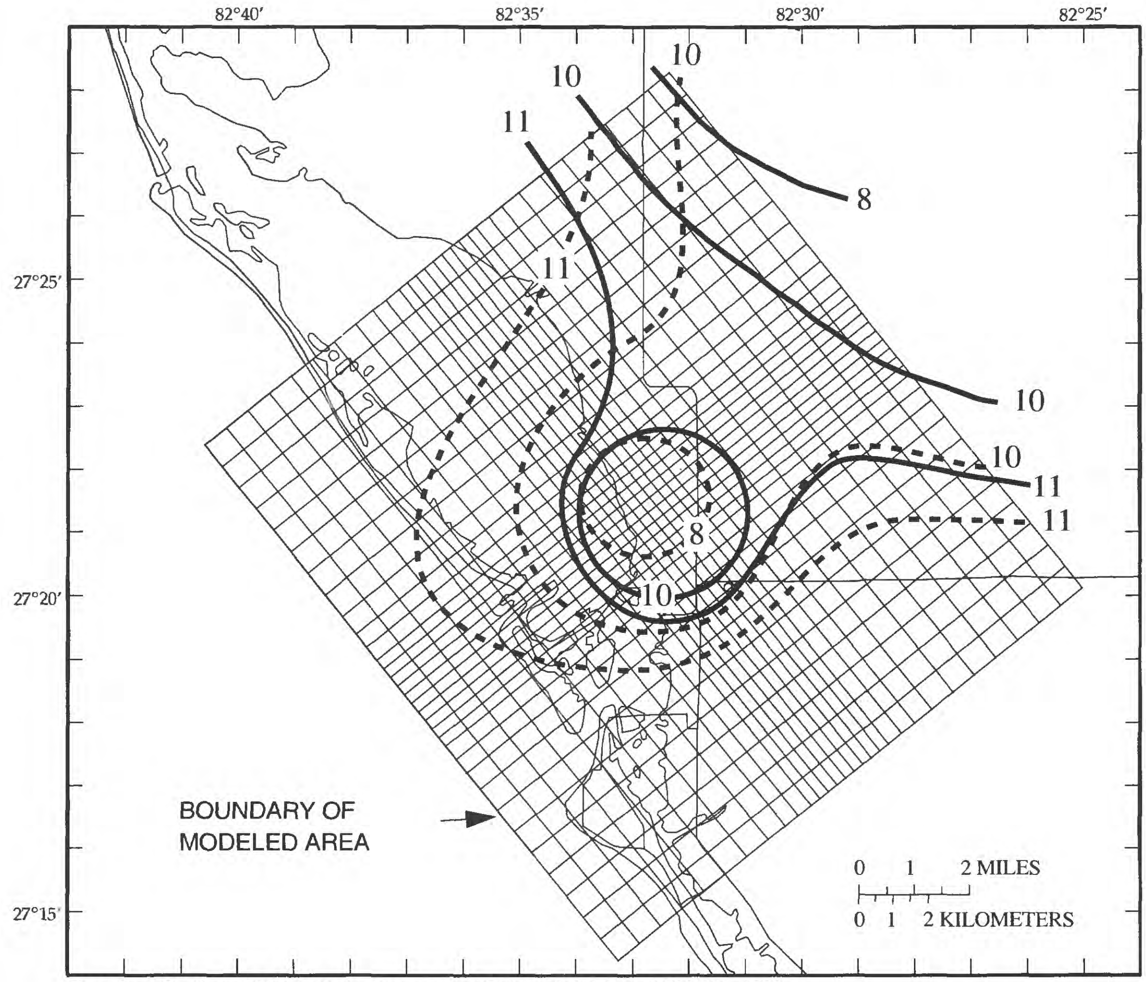
Base from Southwest Florida Water Management District digital data, 1:500,000, 1992
Universal Transverse Mercator projection, Zone 17

EXPLANATION

—10— POTENTIOMETRIC CONTOUR— Shows the elevation at which water would have stood in tightly cased wells, in feet above sea level, May 1993. Interval is variable

----10---- SIMULATED POTENTIOMETRIC CONTOUR— Model simulated potentiometric surface, in feet above sea level, May1993. Interval is variable

Figure 27. Observed and simulated potentiometric surfaces of the intermediate aquifer system simulated in the steady-state model.



Base from Southwest Florida Water Management District digital data, 1:500,000, 1992
Universal Transverse Mercator projection, Zone 17

EXPLANATION

——10—— POTENTIOMETRIC CONTOUR— Shows the elevation at which water would have stood in tightly cased wells, in feet above sea level, May 1993. Interval is variable

----10---- SIMULATED POTENTIOMETRIC CONTOUR— Model simulated potentiometric surface, in feet above sea level, May1993. Interval is 1 foot

Figure 28. Observed and simulated potentiometric surfaces of the Upper Floridan aquifer simulated in the steady-state model.

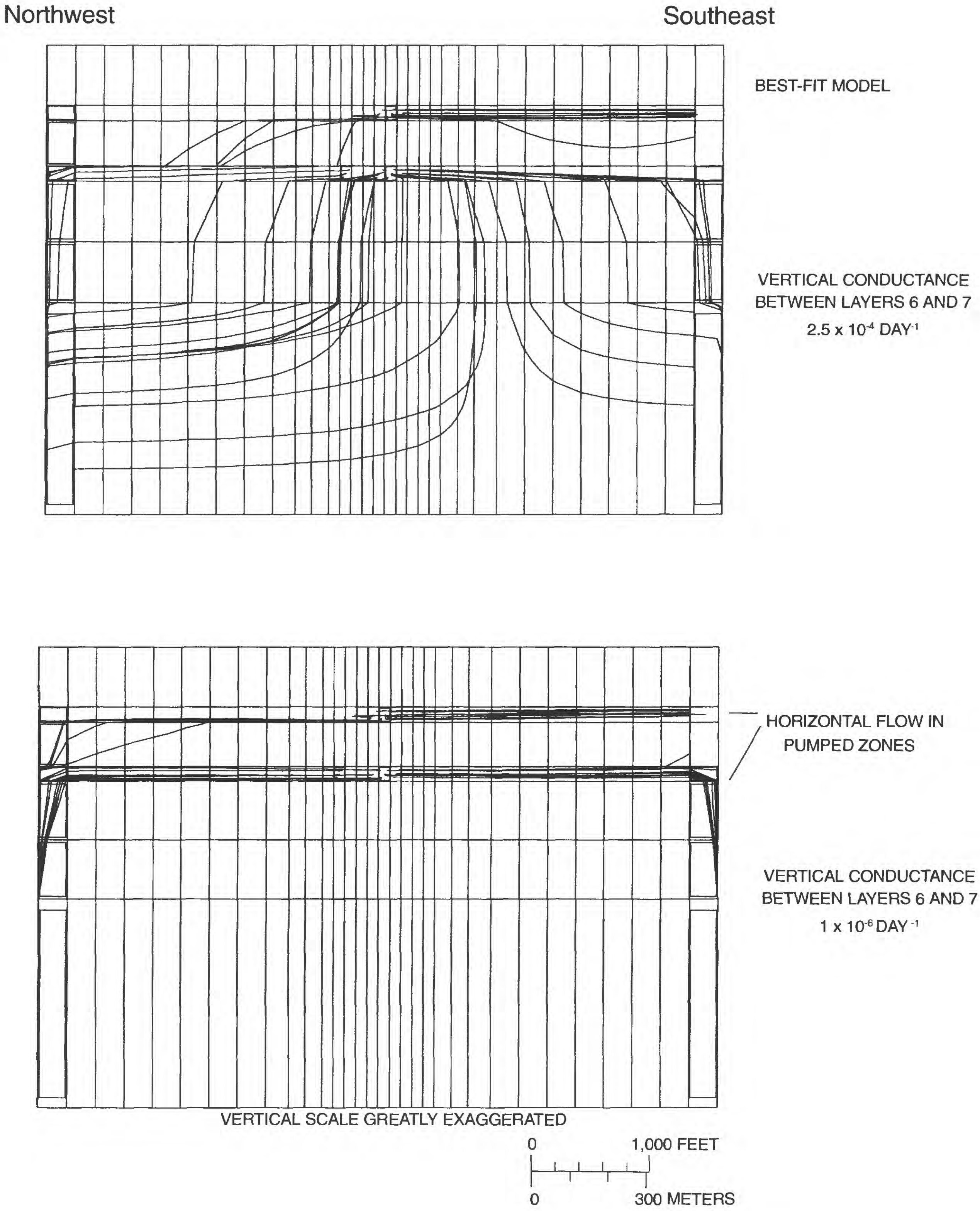
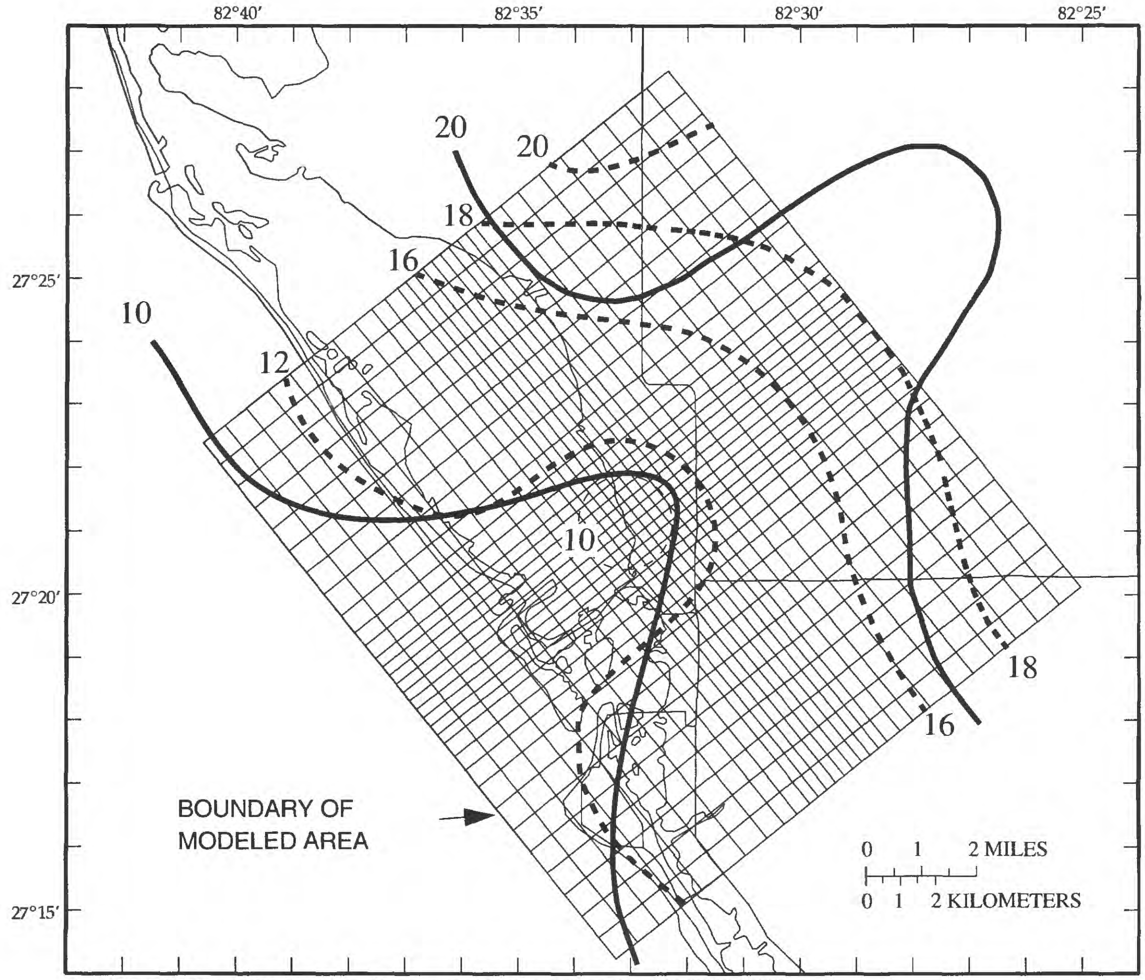


Figure 29. Sections along column 16 of steady-state model showing the changes in particle paths from changes in vertical conductance between layers 6 and 7.



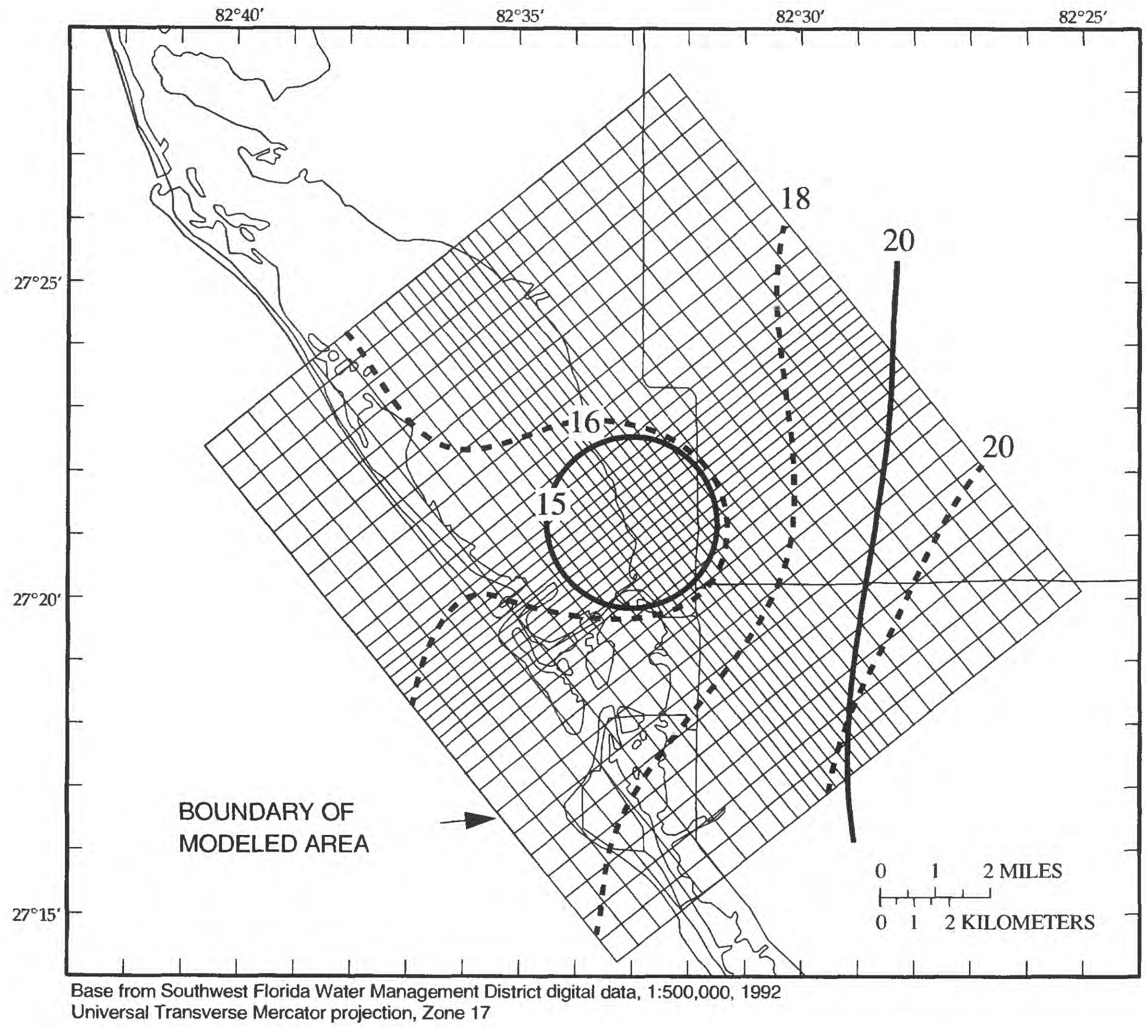
Base from Southwest Florida Water Management District digital data, 1:500,000, 1992
Universal Transverse Mercator projection, Zone 17

EXPLANATION

——10—— POTENTIOMETRIC CONTOUR—Shows the elevation at which water would have stood in tightly cased wells, in feet above sea level, September 1993. Interval is 10 feet

----10---- SIMULATED POTENTIOMETRIC CONTOUR—Model simulated potentiometric surface, in feet above sea level, September 1993. Interval is variable

Figure 30. Observed and simulated potentiometric surfaces of the intermediate aquifer system simulated in the transient model.



EXPLANATION

—10— POTENTIOMETRIC CONTOUR—Shows the elevation at which water would have stood in tightly cased wells, in feet above sea level, September 1993. Interval is 5 feet

----20---- SIMULATED POTENTIOMETRIC CONTOUR—Model simulated potentiometric surface, in feet above sea level, September 1993. Interval is 2 feet

Figure 31. Observed and simulated potentiometric surfaces of the Upper Floridan aquifer simulated in the transient model.

The changes in percentage of inflows, outflows, and storage at the transient model boundaries as designated by direction per stress period, as well as the effective changes in outflow percentages to pumping, are shown in figure 32. The inflows and outflows shown in figure 32 were generated from values given in appendix B2. Although easily observed from examination of the potentiometric-surface maps for May and September 1993 of the Upper Floridan aquifer, the resulting change in direction and magnitude of contributing areas throughout the year were estimated by calculating the volumetric budgets across model boundaries in the transient simulation.

The direction and gradient, throughout the period of simulation, changes the most along the northeastern boundary of the model area. During the dry season, an extensive low in the potentiometric surface of the Upper Floridan aquifer provides a hydraulic divide to the northeast of the model area. Consequently, ground water pumped from the SDWF is not derived from the northeast where the natural recharge area is located. Instead, the greatest volume of water for this period is derived from the southeastern model boundary (app. B2). As heads naturally rebound with the wet season, the potentiometric low to the northeast of the model area diminishes and inflow from the northeast resumes. However, fluxes across the northeastern model boundary calculated for stress periods corresponding to this rebound remain substantially lower than fluxes across the southeastern boundary (app. B2).

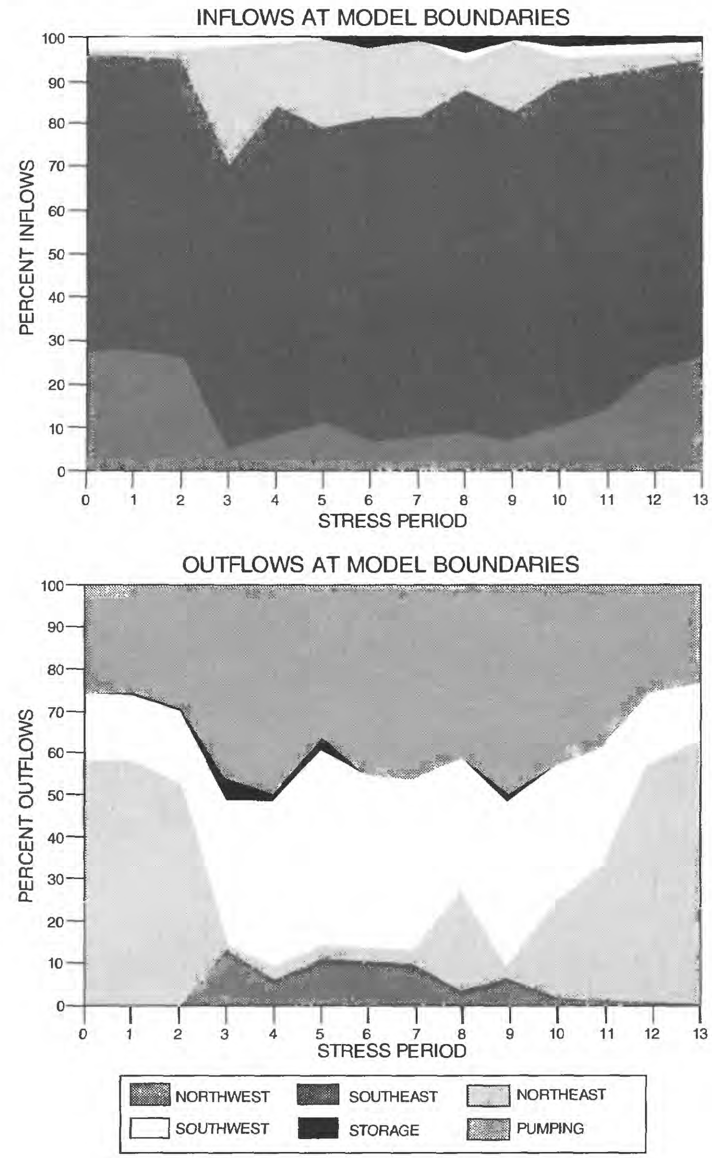


Figure 32. Changes in inflows and outflows at model boundaries per stress period.

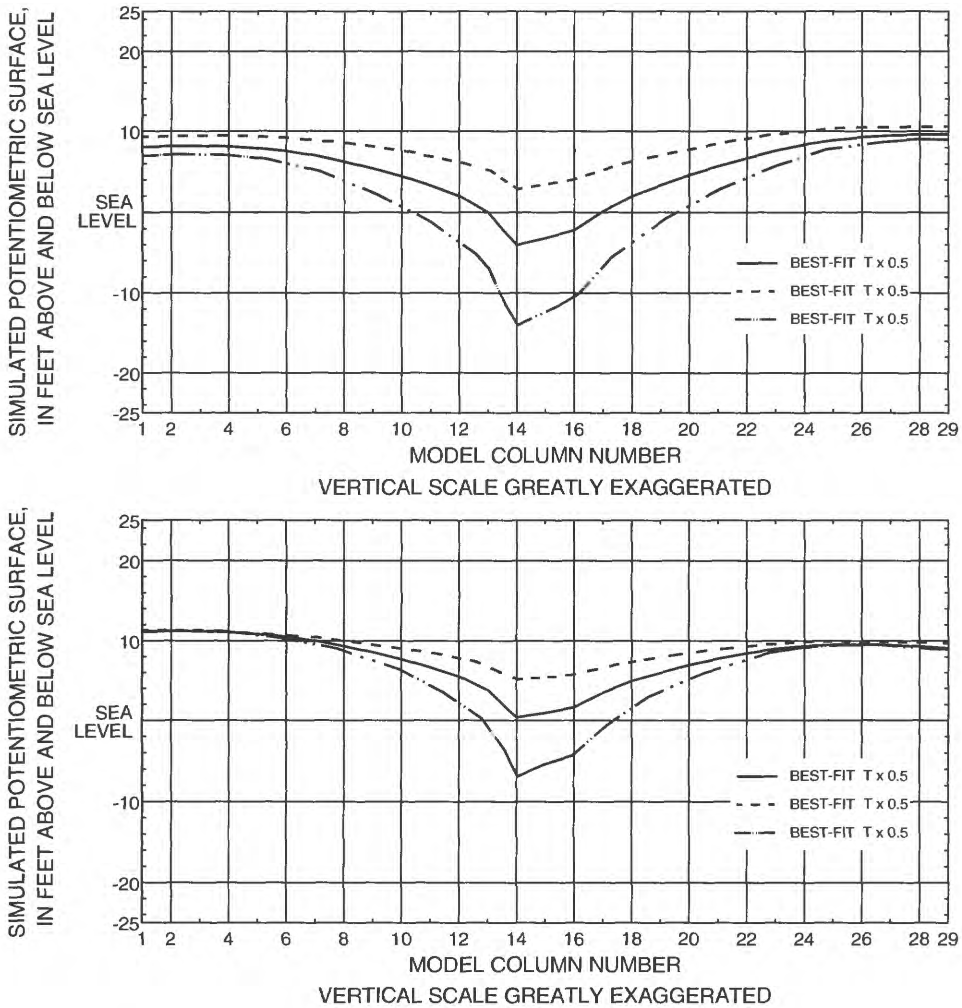


Figure 33. Changes in water levels for layers 2 and 4 from changes in best-fit transmissivity (T).

Sensitivity Analysis

The hydraulic parameters in the model were based on a combination of published data, standard calculations, and rock-core data of varying quality and completeness. Accordingly, it was necessary to determine which parameters had the greatest effect on model output. After a best-fit model was developed, transmissivity, vertical conductance, and storage coefficients were tested one at a time over a reasonable range of values to determine the sensitivity of the model to these parameters.

Porosity values were not tested in the sensitivity analysis because particle travel paths are calculated in MODPATH on the basis of a semianalytical method. Although travel times are greatly affected by porosity changes, porosity values have no effect on particle-path direction.

Transmissivity

The changes in potentiometric surfaces of layers 2 and 4 of the steady-state model when the "best-fit" transmissivities of each layer were multiplied by 2 and by 0.5 are shown in figure 33. As expected, an increase in layer transmissivity produced a decrease in the gradient and depth of the central depression of the potentiometric surface. Furthermore, a decrease in layer transmissivity produced an increase in the gradient and depth of the central depression of the potentiometric surface. The best-fit values were acceptable and within a range of field determined values (Sutcliffe, 1979; Wolansky, 1983) and model simulated values for the study area (Ryder, 1982). The change in head values and volumetric fluxes across model boundaries for the steady-state model are given in appendix B1.

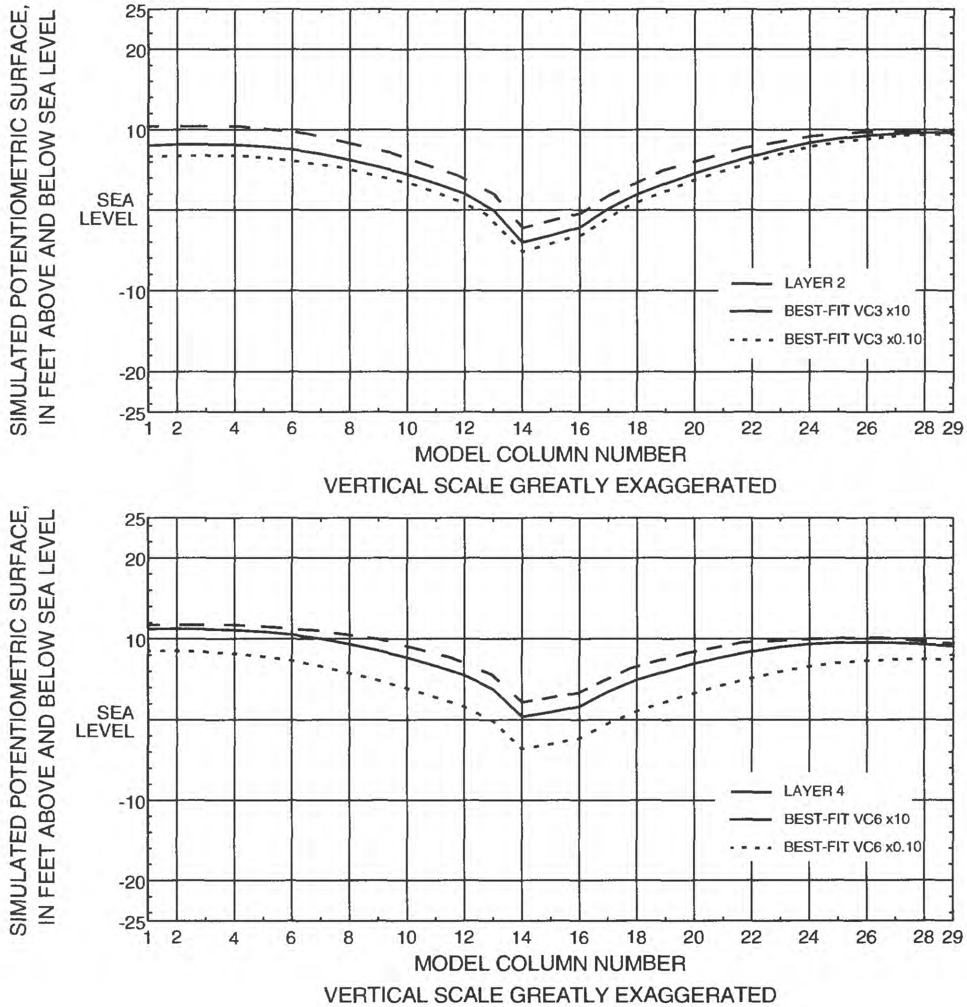


Figure 34. Changes in water levels for layers 2 and 4 from changes in vertical conductance (VC).

Vertical Leakance

Changes in the potentiometric surfaces of layers 2 and 4 when the vertical leakance values above and below each respective layer are multiplied by 10 and 0.10 are shown on figure 34. Examination of changes to the simulated potentiometric surface of layer 2 shows that changes to the vertical leakance have little effect, with the largest change noted when the vertical leakance between layers 3 and 4 was multiplied by 10. Heads in layer 4 only changed noticeably when the vertical leakance between layers 6 and 7 was multiplied by 10 or 0.10. No appreciable change was observed in layer 4 as a result of changes in the vertical leakance between layers 3 and 4 for the values tested. Appendix B1 lists the changes in head values and volumetric fluxes across model boundaries for the steady-state model when all model vertical leakance values were changed collectively.

Additionally, the vertical leakance between layers 5 and 6 was progressively decreased by several orders of magnitude to simulate only horizontal flow in the Suwannee Limestone (layers 4 and 5). A vertical leakance value of 1×10^{-6} d^{-1} was needed to simulate horizontal flow, with an extremely small component of vertical flow simulated from the Ocala Group (layer 5). The difference in particle paths of the best-fit model and the horizontal flow simulation is shown in figure 29. The vertical leakance value of 1×10^{-6} d^{-1} for the horizontal flow simulation relates to a vertical hydraulic conductivity (K_z) 1×10^{-4} ft/d for the Ocala Group. This K_z value for the Ocala Group seemed low because of the formation's fractured nature and because this value is lower than values from core data and values previously determined for the study area (Hutchinson,1992).

Storage Coefficient

Storativity values were increased and decreased by one order of magnitude from the values used in the best-fit model. The effects on volumetric budget calculations and head matches for the transient model were small and are shown in appendix B2.

Limitations of Model Application

Results from the steady-state and transient simulations are only an approximation of the actual system, because many of the input parameters used were estimated and because the hydrogeology had to be simplified for a mathematical model to be developed. Although mathematical models may be used to simulate the physical processes observed in the field, overall confidence in model results is dependent on assumptions inherent in the numerical modeling code and on the extent of simplification of the conceptualized system. Three limitations may be addressed specifically.

1. The hydrogeologic system was simulated as a multilayered system with individual layers consisting of homogeneous, isotropic, porous medium. The actual aquifer systems may be heterogeneous and anisotropic with properties of dual porosity due to fracturing and dissolution.

2. Estimated values of horizontal hydraulic conductivities and storage coefficients for individual model layers and vertical conductances between layers were assumed to be uniform over the entire model area.

3. Alternate combinations of input parameters could provide similar results to those developed by the model; therefore, model results are considered nonunique.

SUMMARY AND CONCLUSIONS

Geophysical, lithologic and water-quality data were compiled to assess the distribution of flow zones and water chemistry within the intermediate aquifer system and Upper Floridan aquifer that supply water to the Sarasota downtown well field (SDWF). Through correlation of data, the hydrogeologic framework of the study area is conceptualized as a multilayered aquifer system containing a sequence of aquifers and confining units, each containing discrete zones of varying permeabilities. Permeabilities vary as a result of heterogeneities largely controlled by fractures and solution features within the undifferentiated Arcadia Formation, Tampa Member, and Suwannee Limestone. Furthermore, data revealed that local heterogeneities strongly affect observed hydraulic responses and chemical characteristics in the aquifer systems underlying the SDWF.

The flow system underlying the study area is conceptualized as changing in direction and gradient seasonally as indicated by hydrographs and potentiometric-surface maps. With the summer rainy season during the months of May through September, the potentiometric surface of the Upper Floridan aquifer typically has a decreasing hydraulic gradient from the Highlands Ridge area to the Gulf of Mexico. However, the seasonal dry period in Florida, generally from October to April, coupled with extensive irrigation to the northeast of the study area, result in an extensive area of low heads in the Upper Floridan aquifer. Consequently, a gradient reversal results and a localized ground-water divide forms between the irrigation induced depression and the Sarasota downtown well field. In response to the gradient reversal, flow to the Sarasota area is derived preferentially from the southeast and to a lesser extent from the northwest, as indicated by the potentiometric-surface map of the Upper Floridan aquifer in 1993 and volumetric budgets calculated from the transient model.

Water-level data provide additional evidence of a localized ground-water divide between the SDWF and the regional discharge zone west of the well field. The hydraulic divide is estimated to be at the barrier islands or offshore in the Gulf of Mexico. Lateral movement of freshwater in a landward direction is probably not likely westward of this divide. Consequently, seawater cannot move laterally through the freshwater lens positioned between the well field and the discharge zone. For seawater to reach the well field, seawater would have to follow flow paths that move below the freshwater lens and vertically enter the well field.

Although the areal positions of both hydraulic divides vary annually, the hydraulic divide between the SDWF and the Gulf of Mexico remains throughout a given year. The potentiometric low northeast of Sarasota resulting from irrigation, diminishes with the yearly rainy season and a more natural hydraulic gradient from the Highlands Ridge to the Gulf of Mexico generally resumes for the Upper Floridan aquifer. Under these conditions, flow to the Sarasota area is still primarily derived from the southeast and is most likely the result of the deviation in head contours from predevelopment conditions, caused at least, in part, from ground-water development.

Chloride concentrations, ranging from 25 to 19,000 mg/L, in water underlying the study area are indicative of transitional type waters. The region where these waters are present is designated as the transition zone. Although delineation of the sources of chloride in the aquifer systems underlying the SDWF is difficult to quantify, it is highly unlikely that sources of chloride in ground-water samples collected in the vicinity of the SDWF are only the result of lateral intrusion of modern seawater. A relation between chloride concentrations and location relative to Sarasota Bay is not apparent.

The data compiled and collected as part of this study indicate the possibility of alternative sources of elevated chloride concentrations above background levels in water samples from wells. The most likely sources of elevated chloride concentrations are from upconing of higher salinity water from deeper permeable zones, unflushed relict seawater in the aquifer, inter-borehole flow among permeable zones of differing water quality in short cased or corroded wells, and movement through structural deformities in the aquifer systems.

Numerical modeling simulations were developed to gain a better understanding of the flow system underlying the study area. Steady-state and transient models were developed using the USGS ground-water flow model MODFLOW. Each model consisted of seven layers to represent the multilayered aquifer systems of the study area. Particle tracking was utilized in a steady-state model to help define the travel paths of water as it enters the local system under a set of given conditions. The results of backward tracking of particles seeded within well cells in layer 2 showed that flow in the intermediate aquifer system originates primarily from the northwestern boundary of the model, whereas particles seeded within well cells in layer 4 showed that water sources related to the Upper Floridan aquifer originated in lower model layers with sources traced to the southeastern and northwestern boundaries. Furthermore, volumetric budgets were calculated for a transient model simulation and used to estimate the seasonal changes in areas of contribution to the local flow system. Computations of fluxes across model boundaries calculated for the transient model showed that the greatest volume of water moving into the modeled area is derived from the southeastern model boundary for all stress periods.

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Appendixes

Appendix A.--Conductance values by row and column for General-Head Boundary cells.

ROW	COLUMN	COND.	ROW	COLUMN	COND.	ROW	COLUMN	COND.
			LAYER		**1**			
1-8	1	33	9	1	27	10-11	1	20
12-21	1	13	22-23	1	20	24	1	27
25-32	1	33						
			LAYER		**2**			
1-8	1	83	9	1	67	10-11	1	50
12-21	1	33	22-23	1	50	24	1	67
25-32	1	83	2-9	29	500	10	29	400
11-12	29	300	13-22	29	200	23-24	29	300
25	29	400	26-32	29	500	32	1-7	500
32	8	400	32	9-10	300	32	11-19	200
32	20-21	300	32	22	400	32	23-29	500
			LAYER		**3**			
1-8	1	83	9	1	67	10-11	1	50
12-21	1	33	22-23	1	50	24	1	67
25-32	1	83	1-9	29	500	10	29	400
11-12	29	300	13-22	29	200	23-24	29	300
25	29	400	26-32	29	500	32	1-7	500
32	8	400	32	9-10	300	32	11-19	200
32	20-21	300	32	22	400	32	23-29	500
			LAYER		**4**			
1-8	1	84	9	1	65	10-11	1	50
12-21	1	33	22-23	1	50	24	1	65
25-32	1	85	1-9	29	1000	10	29	800
11-12	29	600	13-23	29	400	24-25	29	600
26	29	800	27-32	29	1000	32	1-7	1000
32	8	800	32	9-10	600	32	11-19	400
32	20-21	600	32	22	800	1, 32	23-29	1000
1	1-7	1000	1	8	800	1	9-10	600
1	11-19	400	1	20-21	600	1	22	800

ROW	COLUMN	COND.	ROW	COLUMN	COND.	ROW	COLUMN	COND.
			LAYER		**5**			
1-8	1	85	9	1	65	10-11	1	50
12-21	1	33	22-23	1	50	24-25	1	65
26-32	1	85	1-9	29	1000	10	29	800
11-12	29	600	13-23	29	400	24-25	29	600
26	29	800	27-32	29	1000	32	1-7	1000
32	8	800	32	9-10	600	32	11-19	400
32	20-21	600	32	22	800	32	23-29	1000
1	1-7	1000	1	8	800	1	9-10	600
1	11-19	400	1	20-21	600	1	22	800
1	23-29	1000						
			LAYER		**6**			
1-8	1	3	9	1	2.7	10-11	1	2
12-21	1	1.3	22-23	1	2	24	1	2.7
25-32	1	3	1-9	29	20	10	29	16
11-12	29	12	13-22	29	8	23-24	29	12
25	29	16	26-32	29	20	32	1-7	20
32	8	16	32	9-10	12	32	11-19	8
32	20-21	12	32	22	16	1, 32	23-29	20
1	1-7	20	1	8	16	1	9-10	12
1	11-19	8	1	20-21	12	1	22	16
			LAYER		**7**			
1-9	1	1400	10	1	1100	11-12	1	750
13-22	1	600	23-24	1	750	25	1	1100
26-32	1	1400	2-9	29	17500	10	29	14000
11-12	29	10500	13-22	29	7000	23-24	29	10500
25	29	14000	26-32	29	17500	32	1-7	17500
32	8	14000	32	9-10	10500	32	11-19	7000
32	20-21	10500	32	22	14000	1, 32	23-29	17500
1	1-7	17500	1	8	14000	1	9-10	10500
1	11-19	7000	1	20-21	10500	1	22	14000

Volume = cubic feet per day
Vcont = vertical conductance (feet per day)
T = transmissivity (feet squared per day)
S = storativity (dimensionless)
Head = feet (above sea level)

Steady-State Model

Sensitivity Test	Head Match (feet)						Volume of water moving across model boundary per layer in cubic feet per day								
	Layer 2			Layer 4											
	A	B	C	A	B	C	Flux	1NW	1SE	1NE	1SW	2,3NW	2,3SE	2,3NE	2,3SW
Best Fit	15.4	8.4	9.3	9.4	11.1	11.9	In			12494		139390	33355	10116	
							Out	9276	8097	352	3866	117	887	12600	35461
T * 2	16.0	9.7	9.9	10.2	11.4	11.8	In			24665		205860	36424	7268	
							Out	17232	15812	410	3978	3297	1337	25421	39686
T * .5	14.7	6.9	8.8	8.5	10.7	12.0	In			7110		94318	24270	13867	
							Out	4524	3883	324	3546	119	702	5123	31465
Vcont * 10	14.4	10.5	12.2	9.8	11.6	12.0	In			2214		270330	5794	24416	
							Out	37410	43447	3334	5864	2343	13866	22785	45696
Vcont * .10	15.4	7.1	7.3	6.8	8.2	9.8	In			13702		134740	55301	9057	
							Out	5427	5218	36	3625			4408	29025

Sensitivity Test	Percentage of water moving across model boundary per layer									
	Well Field Pumping	Flux	1NW	1SE	1NE	1SW	2,3NW	2,3SE	2,3NE	2,3SW
Best Fit		In	0.00	0.00	0.42	0.00	4.68	1.12	0.34	0.00
	26.39	Out	0.31	0.27	0.01	0.13	0.00	0.03	0.42	1.19
T * 2		In	0.00	0.00	0.73	0.00	6.11	1.08	0.22	0.00
	23.04	Out	0.51	0.46	0.01	0.12	0.10	0.04	0.75	1.16
T * .5		In	0.00	0.00	0.29	0.00	3.87	1.00	0.57	0.00
	31.43	Out	0.18	0.16	0.01	0.14	0.00	0.03	0.20	1.26
Vcont * 10		In	0.00	0.00	0.07	0.00	8.60	0.18	0.78	0.00
	25.55	Out	1.22	1.41	0.11	0.19	0.08	0.45	0.74	1.49
Vcont * .10		In	0.00	0.00	0.46	0.00	4.54	1.86	0.31	0.00
	26.47	Out	0.18	0.18	0.00	0.12	0.00	0.00	0.15	0.98

Match Point	Layer 2 A	Layer 2 B	Layer 2 C	Layer 4 A	Layer 4 B	Layer 4 C
Row	3	24	27	11	26	1
Column	20	24	5	27	24	5

Sensitivity Test	Volume of water moving across model boundary per layer in cubic feet per day											
	Flux	4,5NW	4,5SE	4,5NE	4,5SW	6,7NW	6,7SE	6,7NE	6,7SW	Sub-Total	Pumping	Total
Best Fit	In	77129	221510		9413	624220	1776500		72999	2977126		2977126
	Out			164020	43782			1531300	381700	2191458	785825	2977283
T * 2	In	77707	260610		11455	581600	2077100		86313	3369002		3369002
	Out			196180	44057			1889200	387550	2624160	785825	3409985
T * .5	In	70806	117620		7664	606470	1431400		60886	2434411		2434411
	Out			126170	42282			1131000	364990	1714128	785825	2499953
Vcont * 10	In	63994	216850		9277	614700	1855600		79714	3142889		3142889
	Out			174350	44327			1522000	374010	2289432	785825	3075257
Vcont * .10	In	154670	300920	3489	17760	540990	1673500		62199	2966328		2966328
	Out			81183	33329			1625300	394870	2182421	785825	2968246

Sensitivity Test	Percentage of water moving across model boundary per layer									
	Flux	4,5NW	4,5SE	4,5NE	4,5SW	6.7NW	6,7SE	6,7NE	6,7SW	Total
Best Fit	In	2.59	7.44	0.00	0.32	20.97	59.67	0.00	2.45	100
	Out	0.00	0.00	5.51	1.47	0.00	0.00	51.43	12.82	100
T * 2	In	2.31	7.74	0.00	0.34	17.26	61.65	0.00	2.56	100
	Out	0.00	0.00	5.75	1.29	0.00	0.00	55.40	11.37	100
T * .5	In	2.91	4.83	0.00	0.31	24.91	58.80	0.00	2.50	100
	Out	0.00	0.00	5.05	1.69	0.00	0.00	45.24	14.60	100
Vcont * 10	In	2.04	6.90	0.00	0.30	19.56	59.04	0.00	2.54	100
	Out	0.00	0.00	5.67	1.44	0.00	0.00	49.49	12.16	100
Vcont * .10	In	5.21	10.14	0.12	0.60	18.24	56.42	0.00	2.10	100
	Out	0.00	0.00	2.74	1.12	0.00	0.00	54.76	13.30	100

Appendix B1. Sensitivity analysis of steady-state and transient models (Continued)

Transient Model

Sensitivity Test	Head			Match (feet)			Volume of water moving across model boundary per layer in cubic feet per day								
	Layer 2			Layer 4											
	A	B	C	A	B	C	Flux	1NW	1SE	1NE	1SW	2,3NW	2,3SE	2,3NE	2,3SW
Best Fit	15.5	8.5	9.2	9.4	11.1	11.95	In		8	13613		138660	32688	9670	
							Out	6227	5304	356	3410	128	795	12320	35300
S * 10	15.4	8.4	9.3	9.4	11.1	11.9	In	51	95	14485		146150	30779	8022	
							Out	2163	1984	366	2762	192	44	7032	33081
S * .10	15.7	8.7	8.9	9.5	11.1	12.2	In		5	12700		139390	33310	10075	
							Out	8787	7637	352	3795	118	875	12540	35596

Sensitivity Test	Percentage of water moving across model boundary per layer								
	Well Field Pumping	Flux	1NW	1SE	1NE	1SW	2,3NW	2,3SE	2,3NE	2,3SW
Best Fit		In	0.00	0.00	0.46	0.00	4.64	1.09	0.32	0.00
	26.48	Out	0.21	0.18	0.01	0.11	0.00	0.03	0.42	1.19
S * 10		In	0.00	0.00	0.46	0.00	4.69	0.99	0.26	0.00
	27.13	Out	0.07	0.07	0.01	0.10	0.01	0.00	0.24	1.14
S * .10		In	0.00	0.00	0.43	0.00	4.68	1.12	0.34	0.00
	26.4	Out	0.30	0.26	0.01	0.13	0.00	0.03	0.42	1.20

Sensitivity Test	Volume of water moving across model boundary per layer in cubic feet per day										
	Flux	4,5NW	4,5SE	4,5NE	4,5SW	6,7NW	6,7SE	6.7NE	6,7SW	Sub-Total	Pumping	Total
Best Fit	In	76049	223970		9361	618990	1789500		72773	2985282		2985282
	Out			165170	44027			1525400	382810	2181247	785825	2967072
S * 10	In	78213	239050	159	9251	634250	1881200	7	73548	3115260		3115260
	Out			159440	45148			1474000	384970	2111182	785825	2897007
S * .10	In	77152	221820		9410	624510	1777900		73012	2979284		2979284
	Out			165570	43800			1530100	381730	2190900	785825	2976725

Sensitivity Test	Percentage of water moving across model boundary per layer									
	Flux	4,5NW	4,5SE	4,5NE	4,5SW	6,7NW	6,7SE	6,7NE	6,7SW	Total
Best Fit	In	2.55	7.50	0.00	0.31	20.73	59.94	0.00	2.44	100
	Out	0.00	0.00	5.57	1.48	0.00	0.00	51.41	12.90	100
S * 10	In	2.51	7.67	0.01	0.30	20.36	60.39	0.00	2.36	100
	Out	0.00	0.00	5.50	1.56	0.00	0.00	50.88	13.29	100
S * .10	In	2.59	7.45	0.00	0.32	20.96	59.68	0.00	2.45	100
	Out	0.00	0.00	5.56	1.47	0.00	0.00	51.40	12.82	100

APPENDIX B2. Volumetric budgets for steady-state and transient models

[Note: Figure 32 shows data for steady-state model as stress period 0]

Steady state	In ft³/day	Out ft³/day	No storage	In total	Out total	In percent of tota	Out percent of total
Wells		785,825				0.00	26.39
Northwest	840,739	9,393				28.24	0.32
Southeast	2,031,365	8,984				68.23	0.30
Northeast	22,610	1,708,272				0.76	57.37
Southwest	82,412	464,989				2.77	15.62
Total	2,977,126	2,977,463				100.00	100.00

Stress period 1	In ft³/day	Out ft³/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		785,825					0.00	26.27	0.00	0.00
Northwest	833,700	6,355	525	4,550			27.83	0.21	0.02	0.15
Southeast	2,030,103	5,304	1,277	12,188			67.76	0.18	0.04	0.41
Northeast	39,357	1,704,055	2,461	5,257			1.31	56.96	0.08	0.18
Southwest	82,134	465,550	6,441	2,677			2.74	15.56	0.21	0.09
Total	2,985,294	2,967,089	10,704	24,672	2,995,998	2,991,761	99.64	99.18	0.36	0.82

APPENDIX B2. Volumetric budgets for steady-state and transient models (Continued)

[Note: Figure 32 shows data for steady-state model as stress period 0]

Stress period 2	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		786,441					0.00	29.88	0.00	0.00
Northwest	689,390	8,153	645	1			25.76	0.31	0.02	0.00
Southeast	1,846,203	6,985	347	2,319			68.98	0.27	0.01	0.09
Northeast	66,237	1,353,956	26	4,941			2.47	51.45	0.00	0.19
Southwest	73,174	468,060	303	857			2.73	17.79	0.01	0.03
Total	2,675,004	2,623,595	1,321	8,118	2,676,325	2,631,713	99.95	99.69	0.05	0.31

Stress period 3	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		771,085					0.00	46.46	0.00	0.00
Northwest	100,246	211,392		12,283			4.78	12.74	0.00	0.74
Southeast	1,377,600	11,098		18,610			65.76	0.67	0.00	1.12
Northeast	586,984	13,987		41,128			28.02	0.84	0.00	2.48
Southwest	30,193	565,760		14,274			1.44	34.09	0.00	0.86
Total	2,095,023	1573322	0	86,295	2,095,023	1,659,617	100.00	94.80	0.00	5.20

APPENDIX B2. Volumetric budgets for steady-state and transient models (Continued)

[Note: Figure 32 shows data for steady-state model as stress period 0]

Stress period 4	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		773,352					0.00	49.79	0.00	0.00
Northwest	119,615	83,039		6,552			7.06	5.35	0.00	0.42
Southeast	1,307,200	13,177		4,864			77.15	0.85	0.00	0.31
Northeast	249,709	45,754		6,310			14.74	2.95	0.00	0.41
Southwest	17,813	613,720		6,304			1.05	39.52	0.00	0.41
Total	1,694,337	1,529,042	0	24,030	0	0	100.00	98.45	0	1.55

Stress period 5	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		523,041					0.00	36.38	0.00	0.00
Northwest	174,851	140,146		8,721			10.42	9.75	0.00	0.61
Southeast	1,155,300	19,103		7,559			68.84	1.33	0.00	0.53
Northeast	347,601	39,733		13,814			20.71	2.76	0.00	0.96
Southwest	608	676,780		8,698			0.04	47.08	0.00	0.61
Total	1,678,360	1,398,803	0	38,792	1,678,360	1,437,595	100.00	97.30	0.00	2.70

APPENDIX B2. Volumetric budgets for steady-state and transient models (Continued)

[Note: Figure 32 shows data for steady-state model as stress period 0]

Stress period 6	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		738,191					0.00	45.87	0.00	0.00
Northwest	105,817	154,465	3,280				6.79	9.60	0.21	0.00
Southeast	1,158,400	2,985	19,856				74.38	0.19	1.27	0.00
Northeast	256,351	55,984	5,175	386			16.46	3.48	0.33	0.02
Southwest	6,127	657,090	2,463	58			0.39	40.83	0.16	0.00
Total	1,526,695	1,608,715	30,774	444	1,557,469	1,609,159	98.02	99.97	1.98	0.03

Stress period 7	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		751,014					0.00	46.60	0.00	0.00
Northwest	115,711	137,340	373				7.32	8.51	0.02	0.00
Southeast	1,178,000	23,419	463				74.49	1.45	0.03	0.00
Northeast	278,459	48,938	453				17.61	3.03	0.03	0.00
Southwest	7,274	652,440	626	18			0.46	40.44	0.04	0.00
Total	1,579,444	1,613,151	1,915	18	1,581,359	1,613,169	99.88	100.00	0.12	0.00

APPENDIX B2. Volumetric budgets for steady-state and transient models (Continued)

[Note: Figure 32 shows data for steady-state model as stress period 0]

Stress period 8	In ft³/day	Out ft³/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		742,679					0.00	41.34	0.00	0.00
Northwest	136,147	39,485	9,760				8.89	2.20	0.64	0.00
Southeast	1,214,900	22,843	11,827				79.33	1.27	0.77	0.00
Northeast	96,545	412,509	21,353				6.30	22.96	1.39	0.00
Southwest	31,498	578,960	9,468				2.06	32.23	0.62	0.00
Total	1,479,090	1,796,476	52,408		1,531,498	1,796,476	96.58	100.00	3.42	0.00

Stress period 9	In ft³/day	Out ft³/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		791,520					0.00	50.45	0.00	0.00
Northwest	113,929	81,281		4,882			6.61	5.18	0.00	0.31
Southeast	1,313,800	15,475		7,044			76.22	0.99	0.00	0.45
Northeast	277,318	39,774		13,038			16.09	2.54	0.00	0.83
Southwest	18,618	611,880	59	4,009			1.08	39.00	0.00	0.26
Total	1,723,665	1,539,930	59	28,973	1,723,724	1,568,903	100.00	98.15	0.00	1.85

APPENDIX B2. Volumetric budgets for steady-state and transient models (Continued)

[Note: Figure 32 shows data for steady-state model as stress period 0]

Stress period 10	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		747,810					0.00	43.19	0.00	0.00
Northwest	158,443	22,711	5,923				10.09	1.31	0.38	0.00
Southeast	1,246,900	12723	8,368				79.40	0.73	0.53	0.00
Northeast	96,494	376184	15,520				6.14	21.73	0.99	0.00
Southwest	33,213	571,950	5,545				2.11	33.03	0.35	0.00
Total	1,535,050	1,731,378	35,356		1,570,406	1,731,378	97.7	100.00	2.25	0.00

Stress period 11	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		712,161					0.00	38.89	0.00	0.00
Northwest	239,160	11,857	5,333				14.18	0.65	0.32	0.00
Southeast	1,299,000	10,383	6,578				77.00	0.57	0.39	0.00
Northeast	72,413	567,931	11,533				4.29	31.01	0.68	0.00
Southwest	47,458	528,960	5,497				2.81	28.88	0.33	0.00
Total	1,658,031	1,831,292	28,941		1,686,972	1,831,292	98.28	100.00	1.72	0.00

APPENDIX B2. Volumetric budgets for steady-state and transient models (Continued)

[Note: Figure 32 shows data for steady-state model as stress period 0]

Stress period 12	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		708,680					0.00	26.12	0.00	0.00
Northwest	594,510	10,527	7,152				23.81	0.39	0.29	0.00
Southeast	1,736,001	11,335	7,534				69.52	0.42	0.30	0.00
Northeast	61,711	1,501,973	19,750				2.47	55.37	0.79	0.00
Southwest	63,337	480,250	7,288				2.54	17.70	0.29	0.00
Total	2,455,559	2,712,765	41,724		2,497,283	2,712,765	98.33	100.00	1.67	0.00

Stress period 13	In ft^3/day	Out ft^3/day	In from storage	Out to storage	In total	Out total	In percent of total	Out percent of total	In percent storage	Out percent storage
Wells		785,825					0.00	23.47	0.00	0.00
Northwest	784,170	9,860	4,872				25.53	0.29	0.16	0.00
Southeast	2,134,504	8,222	5,606				69.50	0.25	0.18	0.00
Northeast	40,571	2,096,129	13,327				1.32	62.60	0.43	0.00
Southwest	82,441	448490	5,755				2.68	13.39	0.19	0.00
Total	3,041,686	3,348,526	29,560		3,071,246	3,348,526	99.04	100.00	0.96	0.00