HYDROGEOLOGY OF THE VERNA WELL-FIELD AREA AND MANAGEMENT ALTERNATIVES FOR IMPROVING YIELD AND QUALITY OF WATER, SARASOTA COUNTY, FLORIDA

By C. B. Hutchinson

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Factors for converting inch-pound units to International System of Units (SI) and abbreviations of units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft]	0.00006309	cubic meter per second per meter [(m^3/s)/m]
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Leakance	
gallon per day per cubic foot [(gal/d)/ft^3]	0.1337	meter per day per meter [(m/d)/m]
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter [(m/d)/m]
	Radiation	
picocurie (pCi)	0.037	bequerel (Bq)

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National Geodetic Vertical Datum of 1929 (NGVD of 1929).--A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

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ABSTRACT

The Verna well field, in the northeastern corner of Sarasota County about 17 miles east of the city of Sarasota, has been in operation since 1966. About 8 million gallons of water per day is pumped from the 3-square-mile well field to supply the city of Sarasota. This amounted to only about 8 percent of the total pumpage from Manatee and Sarasota Counties during 1980. Irrigation water use is far greater than other uses combined.

Hydrogeologic units that consist of the surficial aquifer, intermediate aquifers and confining beds, and the Floridan aquifer total about 1,700 feet thick. The Verna well field contains 39 production wells, one of which taps the upper third of the 1,300-foot thick, highly transmissive Floridan aquifer. The other 38 wells tap the lower two-thirds of the moderately transmissive intermediate aquifers and the upper 100 to 200 feet of the Floridan aquifer. About 3 million gallons per day is derived from the intermediate aquifers and 5 million gallons per day from the Floridan aquifer. Sulfate-rich water moves laterally and upward within the Floridan aquifer toward the production wells.

Pumping has resulted in water-level declines and changes in water quality. Drawdowns of 20 to 30 feet have occurred in the producing zone at the well-field boundaries. Under average pumping conditions, drawdowns in the intermediate aquifers were computed to be more than 1 foot over a 90-square-mile area and more than 20 feet over a 6-square-mile area. A rising trend in sulfate concentrations has occurred in water from the production wells due to upward movement from deep in the Floridan aquifer. Concentrations have increased from about 200 milligrams per liter in 1966 to about 400 milligrams per liter in 1982 in the western part of the well field. In the eastern part, sulfate concentrations have increased from about 300 to 350 milligrams per liter during this period. The increases roughly coincide with increases in pumping rates.

Some feasible water-management alternatives to improve yield and water quality from the producing zone include installation of a network of connector wells, development of computer models of ground-water flow or solute transport, and maintenance of a monitor-well network. If an estimated 1.4 million gallons per day could be recharged to the intermediate aquifers from the surficial aquifer by gravity drainage through a network of connector wells, the size of the

cone of depression around the well field would be reduced, and the dissolved-solids concentration of water in the producing zone possibly would be reduced from about 820 milligrams per liter to about 700 milligrams per liter. Models would be useful for optimizing distributions of pumping so that maximum yield is attained and mineralization is minimized. Models could also be used for assessing the effects of nearby irrigation pumpage on the well field. The outlook for using a model as a tool for developing additional quantities of water on the existing property is not very promising. A monitoring network would be useful in detecting vertical, areal, and temporal changes in water levels and water quality in each aquifer. Information gained through the network could be used to develop models for management of ground-water resources.

INTRODUCTION

The city of Sarasota, on the Gulf Coast of Florida, began in about 1900 to obtain its water supply from wells within 1 mile of the coast. There was no scarcity of water, well yields were high, and additional supplies were available by drilling more wells. However, the chemical quality of water near the coast had high concentrations of sulfate and chloride.

Exploration for a water supply with chemical quality that conformed with Florida State Board of Health standards began in 1962 near the community of Verna in northeastern Sarasota County (fig. 1). Aquifers were tested for yield, water quality, and hydraulic characteristics. The well field was located about 17 miles east of the city of Sarasota on a topographic high between the Manatee and Myakka Rivers.

The purpose of the report is to describe the hydrogeology of the Verna well-field area, to show changes in the flow system and water quality that have occurred since development of the well field, and to evaluate some possible management alternatives for improving yield and water quality from the well field. The alternatives evaluated include: (1) evaluation and use of connector wells, (2) development of ground-water flow and solute-transport models, and (3) improvement of the data-collection network. This assessment of the Verna well-field area is in cooperation with the Southwest Florida Water Management District.

An analysis is presented of the water-supply potential of the Verna well field based on hydrologic records collected during 1962-82. The well field consists of two parts, and for this report, they are referred to as part A and part B. Part A is rectangular in shape and is about 0.5 mile wide and 4 miles long. Part B is about 500 feet southeast of part A and is roughly 1 mile square. The total area of the Verna well field is 3 mi^2 or about 1,900 acres. The hydrologic framework is described, and aquifer hydraulic properties and water quality are evaluated. A conceptual model is developed for the flow system and is the basis for assessing potential impacts of well-field pumping. Although the project is limited in areal extent to northeast Sarasota County, results will be transferable to most of southwest Florida.

PREVIOUS STUDIES

The first comprehensive studies of water resources in Sarasota County were performed by Stringfield (1933a; 1933b). Those early reports foretold of potential negative impacts of developing additional water supplies in the county and documented flow rates of several artesian wells. Another major study was done

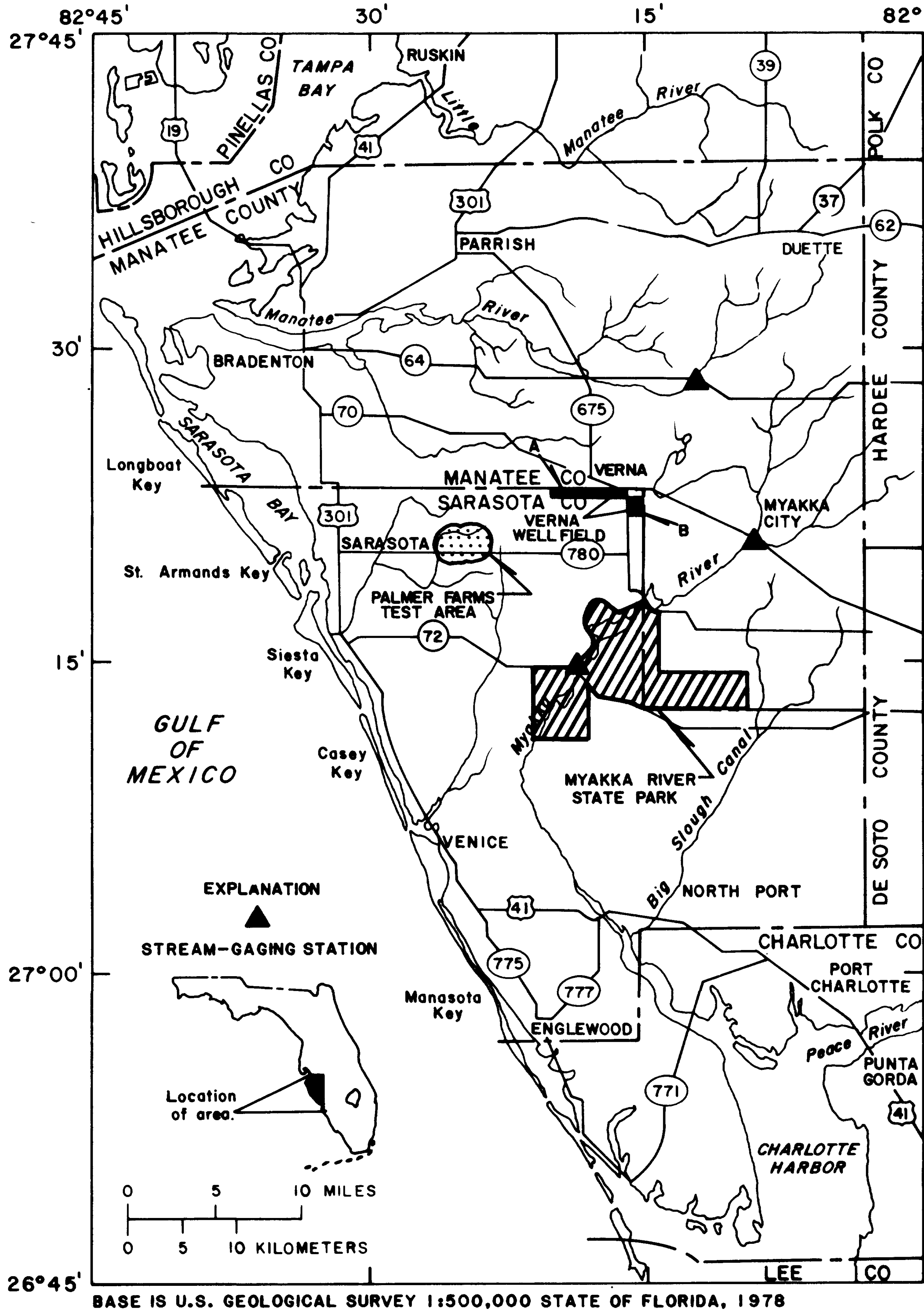


Figure 1.--Location of the Verna well-field study area.

by Smally, Wellford, and Nalven (1963). They concluded that one of the more favorable areas for development of a well field was in the northeast corner of the county. Following construction of the Verna well field, various feasibility studies and development schemes were analyzed by Geraghty and Miller, Inc. (1974; 1975) and Smith and Gillespie Engineers, Inc. (1975). A series of reports that contain comprehensive lists of data concerning construction and testing of wells was prepared by Sutcliffe and Buono (1979), Barker and others (1981), and Sutcliffe and Miller (1981). Coincident with the development of the Verna well field was a regional study by Joyner and Sutcliffe (1976) that identified five artesian water-bearing zones in the Myakka River Basin that includes the well-field area. The hydraulic characteristics and aquifer interflow were quantified in a study by Wolansky (1983).

Other studies that have potential for application in the Verna well-field area, as well as in other parts of the State, show that connector wells are a promising method for augmenting ground-water supplies. A test-connector well in northeastern De Soto County, proposed by Hutchinson and Wilson (1974) and eventually drilled in 1975, sustained a recharge rate of about 60 gal/min from the surficial aquifer to the Floridan aquifer. Knochenmus (1975) also showed the feasibility of recharging the Floridan aquifer from the surficial aquifer through connector wells. A feasibility study by Hutchinson (1977) indicated that the central Florida phosphate area in Hillsborough, Polk, and Hardee Counties was hydrologically suitable for connector wells. The study also indicated that by 1975 recharge through 86 connector wells totaled about 20 Mgal/d. Sinclair (1977) indicated that connector wells in northwest Hillsborough County could effectively recharge the Floridan aquifer. Watkins (1977) showed the technical feasibility of using connector wells to artificially recharge the Floridan aquifer in a case study in central Florida. In a statewide inventory of connector wells, Kimrey and Fayard (1982) found two connector wells in Manatee County and none in Sarasota County.

HYDROLOGIC CYCLE

Basic elements of the hydrologic cycle in west-central Florida are rainfall, runoff, evapotranspiration, and water use. These parameters form the data base for analysis of steady-state hydrologic systems by the annual water-budget method, where:

$$\text{RAINFALL} = \text{RUNOFF} + \text{EVAPOTRANSPIRATION} + \text{PUMPING}$$

$$56 = 15 + 39 + 2$$

The left and right sides of the equation represent inflow to and outflow from the hydrologic system, respectively. Numbers are in inches per year.

Rainfall

Measurement of rainfall began in mid-1943 at Myakka River State Park (fig. 1) about 6 miles south of the Verna well field. Between 1944 and 1981, rainfall records were complete for all but 5 years. The average rainfall for 34 years with complete record was 55.97 inches (U.S. Department of Commerce, 1956; 1964; National Oceanic and Atmospheric Administration, 1958-81). Rainfall is unevenly distributed as about 7 inches occurs in winter, 10 inches in spring, 25 inches in summer, and 14 inches in autumn (Hughes and others, 1971). For the period of record, minimum annual rainfall of 36.97 inches was recorded in 1961, and a maximum annual rainfall of 77.59 inches was recorded in 1959.

Runoff

Surface runoff drains radially from the well field. The surrounding pasturelands contain extensive ditch systems that facilitate drainage. One such ditch enters the north side of part A of the well field, turns west for about 1 mile, then exits on the north side, carrying water to Gum Slough and eventually emptying into the Gulf of Mexico (fig. 2). Flow in the ditch has not been measured; however, it is unlikely that it carries a large amount of water. The drainage area of the ditch upstream of the well field is about 3 mi^2. Flow is generally sluggish and ceases during the dry months when the water table is below the bed of the ditch. In the wet months, the water table is near land surface, and flow in the ditch is at maximum.

Surface runoff from the Verna well field was estimated to be approximately 15 in/yr. This estimate was based on average discharge recorded at stream-gaging stations (fig. 1) on the Manatee and Myakka Rivers as follows:

Stream-gaging station	Period of record (years)	Drainage area (mi^2)	Average discharge (ft^3/s)	Average discharge (in/yr)
Manatee River at State Road 64	15	65.3	64.2	13.35
Myakka River at State Road 70	7	125	118	12.82
Myakka River near State Road 72	45	229	250	14.82

The streamflow data are condensed from records by the U.S. Geological Survey (1982). Greater weight was given to the stage-discharge relation for Myakka River near State Road 72 than to other stations because the gage has a period of record close to that for rainfall. Less weight was given to records at the other stream-gaging stations in determining the average runoff because the periods of record at these gaging stations coincide with events of low rainfall. Some years there is no flow in the Myakka River for many days, and minimum discharge at the Manatee River gaging station frequently is less than 1 ft^3/s. The low-flow data indicate that ground-water contributions to streamflow are small.

Evapotranspiration

Evapotranspiration is the major item in the hydrologic cycle. Evapotranspiration depends upon depth to the water table, soil type, type of vegetation, humidity, the amount of incoming energy (sunlight and wind), and the availability

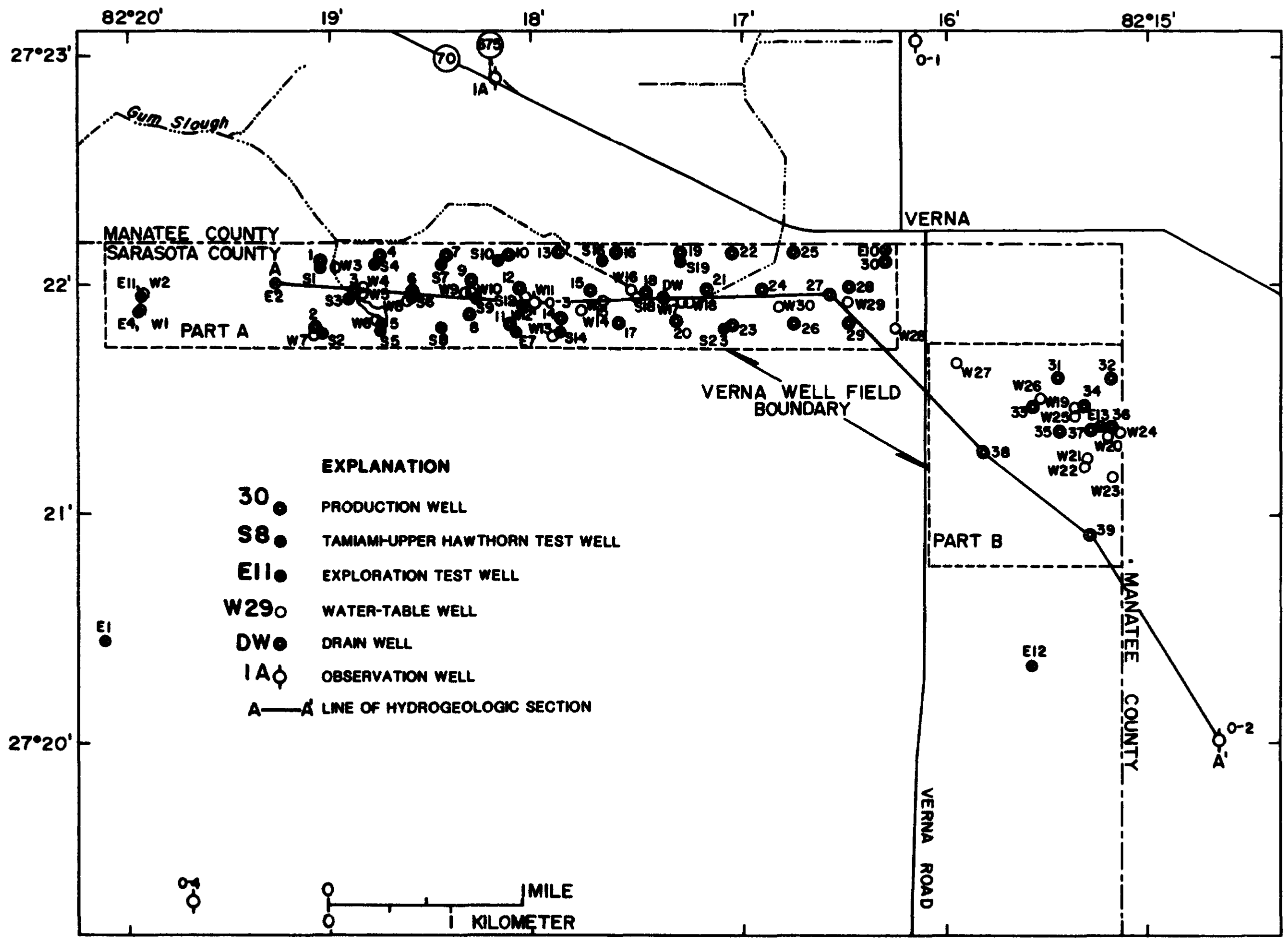


Figure 2.--Locations of selected wells in the Verna well-field area.

of water subject to evapotranspiration. With so many variables to be considered, scientists have had much difficulty in measuring evapotranspiration in the field and the laboratory. Instead, evapotranspiration has been determined analytically through water-budget or energy-balance methods.

Three types of evapotranspiration rates have been used in hydrologic studies in Florida: (1) maximum potential evapotranspiration, (2) actual evapotranspiration, and (3) minimum evapotranspiration. The maximum potential evapotranspiration would be equivalent to evaporation from a free water surface and in the vicinity of Sarasota is about 47 in/yr (National Oceanic and Atmospheric Administration, 1958-81; Dohrenwend, 1977). However, potential evapotranspiration is not at the maximum because, in much of the area, the water table is below land surface. The estimated actual evapotranspiration rate in the Verna is about 39 in/yr (Dohrenwend, 1977).

No matter how far the water table lies below land surface, there most likely is some minimum or base rate of evapotranspiration. This base rate is determined by evaporation and transpiration that take place before any water can percolate to the water table. Estimates of this base rate of evapotranspiration for central Florida range from 25 to 35 in/yr (Tibbals, 1978).

Water Use

Both ground water and surface water are used consumptively in the Verna well-field area. Because the well field is approximately in the center of the 1,300-mi^2 area of Manatee and Sarasota Counties, water availability at Verna is likely to be affected by other water users within the counties. Duerr and Trommer (1981) estimated ground-water use for 1980 as follows:

Water-use category	Manatee County (Mgal/d)	Sarasota County (Mgal/d)
Industrial	0.19	0.10
Rural	5.08	1.59
Public	0	11.07
Irrigation	64.92	20.38
Total	70.19	33.14

The total water withdrawn in 1980 averaged 1.6 in/yr over the Manasota Basin (a water-management unit consisting of Manatee and Sarasota Counties). Irrigation water use is far greater than the other uses combined. Because irrigation is seasonal, short-term pumping rates may be several times the average rate, and water levels and hydraulic gradients at Verna are likely to be affected by regional withdrawals. The source of water for public-supply systems in Manatee County is a surface reservoir on the Manatee River. Of the 11 Mgal/d public supply for Sarasota County, about 8 Mgal/d was from the Verna well field. Pumping from Verna is small when compared with the total daily pumping rate of about 103 Mgal from the Manatee-Sarasota County area.

HISTORY OF DRILLING AND DEVELOPMENT

More than 100 wells have been drilled in the Verna well-field area for a variety of purposes (fig. 2). The first well, commonly referred to as the "drain well," was drilled in 1944 as part of an artificial recharge experiment. The experiment involved installing a 10-inch diameter well in the bed of the drainage ditch that runs through the well field. When water in the ditch rose above the top of the well casing, it would flow down the 691-foot deep well into the Suwannee Limestone. It was hoped that water pumped from aquifers 10 miles coastward would be replenished by the recharge method. The recharge experiment was not successful because the drain well became clogged shortly after it became operative (H. Sutcliffe, Jr., U.S. Geological Survey, oral commun., 1982).

The drain well was cleaned out in the middle 1960's and was further modified in 1975 to determine the quality of water in deep formations (Geraghty and Miller, Inc., 1975). The well was deepened to a depth of 1,207 feet. Between 825 and 1,207 feet, water-quality tests made at 50-foot intervals as the well was deepened indicated that sulfate concentrations of composite samples from the open hole increased with depth from about 500 to 750 mg/L. Currently, the well is used to monitor water levels and to sample for water-quality analyses.

Between 1963 and 1964, 12 exploration test wells were drilled in the Verna area as described by Sutcliffe and Buono (1979). The test wells were used to determine zones of good quality water in order to develop specifications for production wells.

In 1966, 30 production wells were completed in part A of the well field, including 4 exploration test wells that were converted to production wells by plugging back or extending the well casings. Nine additional wells were drilled in part B, and by 1975, there were 39 production wells (fig. 2). All production wells, except number 27, average 10 inches in diameter, are cased to a depth of about 140 feet, and are completed open hole between depths of 460 and 714 feet. Production well 27 is 12 to 16 inches in diameter and taps a zone that is 620 to 1,000 feet below land surface. The average depth of the production wells is 550 feet, and the average open-hole interval is 410 feet. The production wells are not as deep in part A, averaging 530 feet in depth, as they are in part B where they average 614 feet in depth.

During 1970-71, sixteen 6-inch test wells (fig. 2), were installed in the top of the Tamiami-upper Hawthorn aquifer in part A to determine the availability and quality of water in formations just above the producing zone. Exploration continued in 1973 when 31 wells were augered to determine the thickness of unconsolidated overburden deposits. Development of these units for a water supply was not recommended because of their low potential yield (Geraghty and Miller, Inc., 1975, p. 35).

Well-field withdrawals increased from an average of 5 Mgal/d in 1967 to 8 Mgal/d in 1981. In 1977, because of the increasing demand for water, further test drilling was begun to determine areal water-level declines in the aquifers. During December 1977 and January 1978, observation wells 0-1, 0-2, 0-3, and 0-4 were drilled at sites north, east, south, and inside the well field (fig. 2). Test wells had been drilled earlier west of the well field.

A schematic of Sarasota's water-treatment and distribution facilities is shown in figure 3. The facilities accept 7.9 Mgal/d of raw water from Verna that is aerated and chlorinated prior to transmission from the well field. Of the 7.9 Mgal/d, about 5.6 Mgal/d flow through a zeolitic water softener that exchanges calcium and magnesium ions for sodium ions and produces 5.2 Mgal/d of product water. The product water is blended with the remaining 2.3 Mgal/d of the chlorinated water and 4.5 Mgal/d of water from a reverse-osmosis treatment facility. That facility treats 6 Mgal/d of slightly saline water that is pumped from wells near the coast. Thus, the 13.9 Mgal/d of raw, mineralized well water yields 12 Mgal/d of potable water to the city of Sarasota.

HYDROGEOLOGIC FRAMEWORK

The water-bearing formations in west-central Florida consist chiefly of Tertiary limestone overlain by marine and nonmarine sand. Regionally, the sediments form a wedge that thickens from central Florida southwest beneath the Verna well field. The deposits compose three major hydrogeologic units that total about 1,700 feet thick at the well field (table 1).

Surficial Aquifer

The surficial aquifer consists primarily of unconsolidated sand, clay, shell, and phosphate gravel intermixed with stringers of limestone and marl. The aquifer is generally unconfined; however, lenses of sand, marl, and limestone contain water under confined conditions in some areas. At the Verna well field, the surficial aquifer is about 60 feet thick and contains a water table that is about 5 feet below land surface. Based on a porosity of about 30 percent, which is common for Florida sands, the amount of water stored in the surficial aquifer is about 10 billion gallons. Transmissivity of the aquifer, determined in five pumping tests (Geraghty and Miller, Inc., 1975, p. 15), ranges from 150 to 530 ft^2/d with an average of about 270 ft^2/d, which indicates aquifer yield would be too low to supply large production wells.

Intermediate Aquifers and Confining Beds

The intermediate aquifers and confining beds are about 360 feet thick. This hydrogeologic unit contains discontinuous permeable sand, gravel, shell, and limestone and dolomite beds of the Tamiami Formation, the upper and lower parts of the Hawthorn Formation, and the Tampa Limestone where it is in hydraulic connection with the Hawthorn Formation. The intermediate aquifers and confining beds retard vertical movement of ground water between the surficial aquifer and Floridan aquifer (fig. 4 and table 1). Although the intermediate aquifers and confining beds are considered to be a single hydrogeologic unit, the intermediate aquifers are the important water-bearing zones.

Drilling and testing during 1971-72 indicated that the hydraulic connection between zones within the intermediate aquifers and confining beds is highly variable (Geraghty and Miller, Inc., 1975). Water levels in some shallow artesian

Table 1.--Hydrogeologic framework at the Verna well field and vicinity

Series	Stratigraphic unit	Hydrogeologic unit		Approximate thickness (feet)	Hydrogeologic characteristics
Holocene Pleistocene Pliocene	Surficial sand Caloosahatchee Marl Bone Valley Formation	Surficial aquifer		60	Marine and nonmarine unconsolidated quartz sand, clay, shells, and phosphorite, with stringers of marl and limestone. Wells yield less than 20 gal/min. Transmissivity averages 270 ft^2/d. Excellent water quality. Unit is cased off in production wells.
Miocene	Tamiami Formation	Upper confining bed	Intermediate aquifers and confining beds	20	Sand, clay, and marl. Low permeability. Cased off in production wells. Leakance coefficient $1.3x10^{-5}$ to $4.0x10^{-5}$ (ft/d)/ft.
	Tamiami Formation; Hawthorn Formation	Tamiami-upper Hawthorn aquifer		200	Sandy, clayey, phosphatic limestone and dolomite. Wells yield about 100 gal/min. Transmissivity 825 ft^2/d. Water quality is good. Lower part of aquifer is tapped by production wells.
	Hawthorn Formation	Middle confining bed		20	Discontinuous sand, clay, and marl. Low permeability. Open to production wells. Leakance coefficient $1.3x10^{-6}$ (ft/d)/ft.
	Hawthorn Formation; Tampa Limestone	Lower Hawthorn-upper Tampa aquifer		100	Sandy, phosphatic limestone. Wells yield about 100 gal/min. Transmissivity is about 800 ft^2/d. Water quality is fair to good. Aquifer is fully tapped by production wells.
	Tampa Limestone	Lower confining bed		20	Dense, sandy clay, marl, and chert. Low permeability. Open to production wells. Leakance coefficient $2.6x10^{-5}$ to $4.0x10^{-6}$ (ft/d)/ft.

Oligocene	Suwannee Limestone	Floridan aquifer	1,300	Limestone and dolomite. Wells could possibly yield up to 5,000 gal/min. Transmissivity is about 200,000 ft^2/d. Water quality is fair to poor, generally increasing in sulfate with depth. Upper 100 to 200 feet is tapped by production wells. Water levels are affected by regional pumping for irrigation.
Eocene	Ocala Limestone			
	Avon Park Limestone			
	Lake City Limestone	Confining bed	300	Dolomite and limestone with intergranular gypsum and anhydrite. Considered to be impermeable.

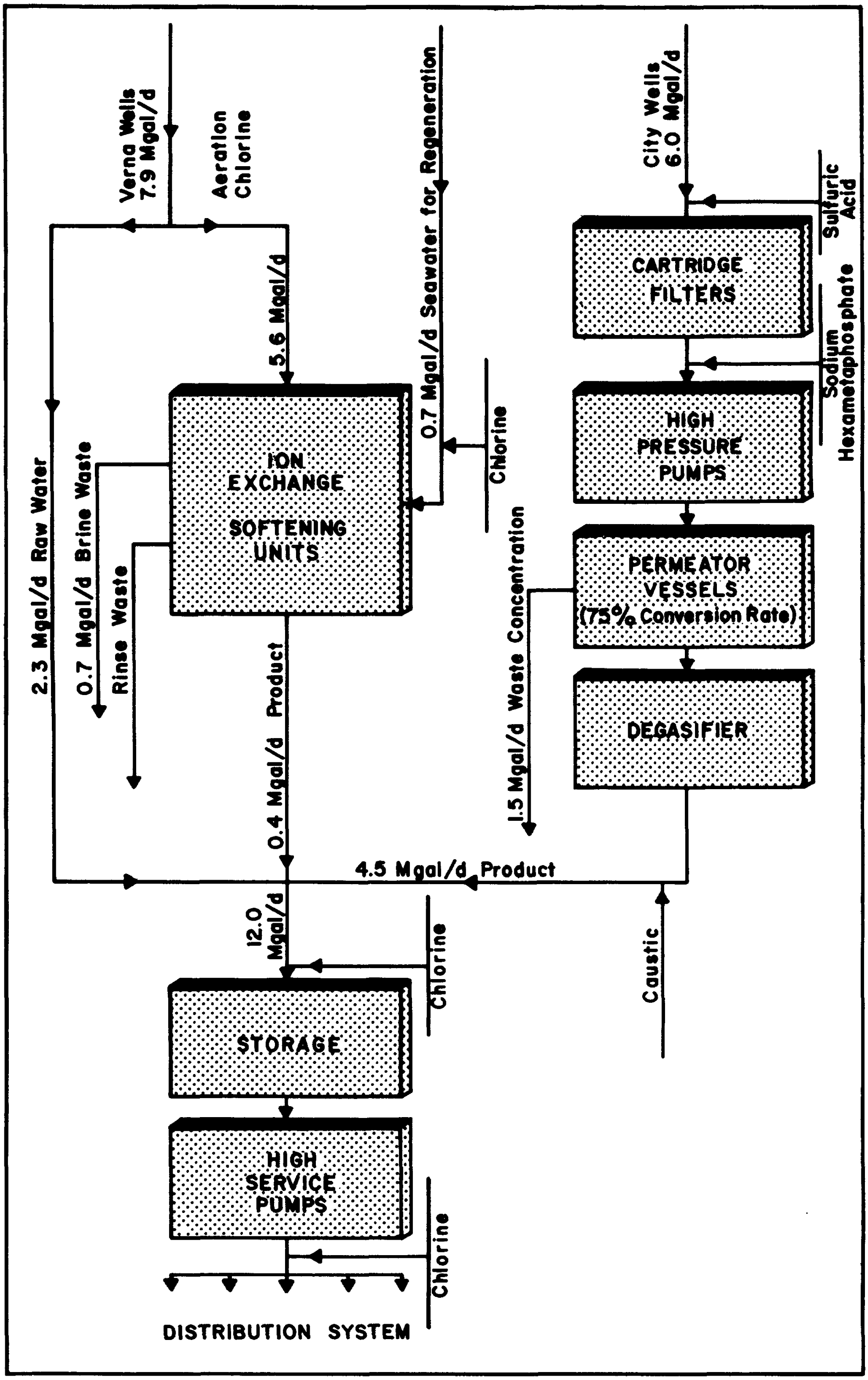


Diagram courtesy of City of Sarasota

Figure 3.--City of Sarasota water-treatment and distribution facilities, July 1982.

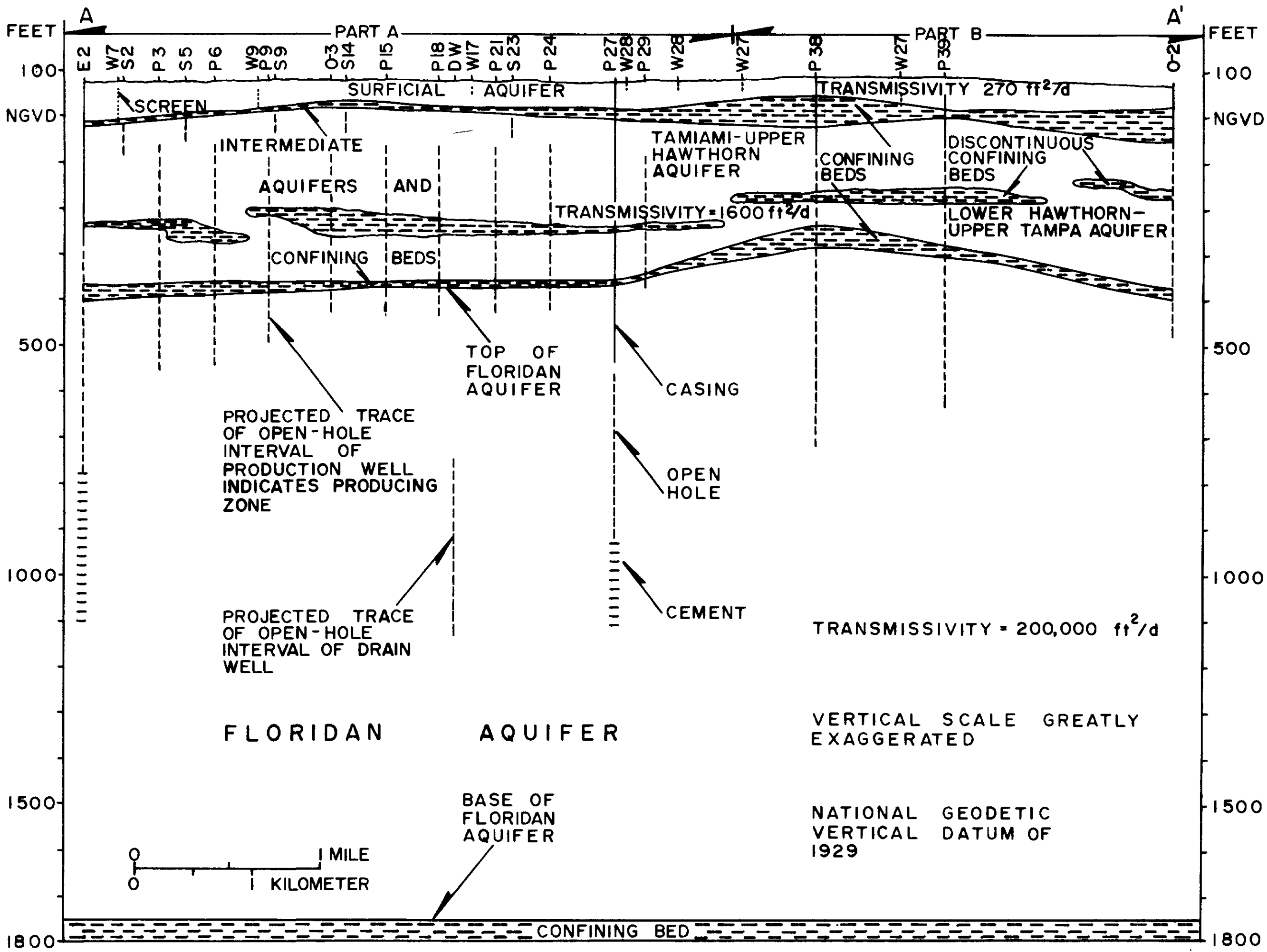


Figure 4.--Hydrogeologic section. (Location of section is shown in figure 2.)

wells respond rapidly to pumping from below, whereas others seem to have little response. It is probable that a discontinuous confining bed generally separates the intermediate aquifers and confining beds into two aquifer units: (1) the Tamiami-upper Hawthorn aquifer and (2) the lower Hawthorn-upper Tampa aquifer (Wolansky, 1983).

The transmissivity of the Tamiami-upper Hawthorn aquifer is about 825 ft^2/d and the average storage coefficient is $2x10^{-4}$, which indicates this aquifer is a relatively low-yielding artesian aquifer (Geraghty and Miller, Inc., 1975, p. 16). The total transmissivity of the intermediate aquifers and confining beds hydrogeologic unit was determined from a pumping test of well E11. The well is cased to a depth of 91 feet and is open-hole from 91 to 440 feet. Analysis of drawdown and recovery data indicates a transmissivity in the range of 1,300 to 2,600 ft^2/d (Geraghty and Miller, Inc., 1975, p. 17). Thus, it can be inferred that, if transmissivity is doubled when both aquifers are tested, the transmissivity of the lower Hawthorn-upper Tampa aquifer is about the same as that of the Tamiami-upper Hawthorn aquifer.

The hydraulic properties of the confining beds have not been measured directly, but have been estimated by using digital models of ground-water flow. The regional leakance coefficients estimated by Wolansky (1983, p. 18) for the upper, middle, and lower confining beds within the hydrogeologic unit are $1.3x10^{-5}$, $1.5x10^{-6}$, and $5.0x10^{-6}$ (ft/d)/ft, respectively. Ryder (1981) calibrated a digital model of predevelopment flow in southwest Florida using a leakance coefficient of the upper confining bed at Verna ranging from $2.7x10^{-5}$ to $4.0x10^{-5}$ (ft/d)/ft and a leakance coefficient of the lower confining bed ranging from $2.7x10^{-5}$ to $6.7x10^{-6}$ (ft/d)/ft. The low leakance coefficients in the Verna area indicate potentially low rates of recharge to the confined aquifers and the likelihood that deep, extensive cones of depression would occur in the producing zone during pumping. Using confining-bed thickness as the criterion, Stewart (1980) designated northern Sarasota County as an area of very low recharge. The intermediate aquifers and confining beds are tapped by production wells at the Verna well field. Deeper, more transmissive zones are not fully tapped because they contain poor quality water. Concentrated pumping from the intermediate aquifers has resulted in large cones of depression around the well field for many years.

Floridan Aquifer

The Floridan aquifer consists of a thick sequence of carbonate rocks. Originally defined by Parker and others (1955, p. 189) as the Floridan aquifer, it includes, in ascending order, all or parts of the Lake City, Avon Park, Ocala, and Tampa Limestones and permeable parts of the Hawthorn Formation that are in hydrologic contact with the rest of the aquifer. This early definition characterized a thick, areally extensive sequence of limestone and dolomite that underlies much of Florida. Wolansky (1983) recognized confining beds within the upper limestones in Sarasota County and, thus, defined the top of the Floridan aquifer as the first vertically persistent carbonate section below which clay confining beds do not occur. This surface generally coincides with the lower part of the Tampa Limestone or the top of the Suwannee Limestone. Permeabilities are moderate in the Tampa and Suwannee Limestones, relatively low in the Ocala Limestone, and very high in fractured dolomitic zones within the Avon Park Limestone. Although there are large permeability contrasts, aquifer tests indicate that there is sufficient vertical interconnection between formations to consider the Floridan aquifer as a single hydrologic unit on a regional basis (P. D. Ryder, U.S. Geological Survey, written commun., 1984). Underlying the Floridan aquifer is a lower confining bed that occurs in the Lake City Limestone where anhydrite and gypsum fill voids in the limestone.

The Floridan aquifer is the most productive aquifer in the Verna area. Many irrigation wells in the vicinity of the well field tap this aquifer. Water from the aquifer improves production from the Verna well field. When wells are drilled into the upper 100 to 200 feet of the aquifer, yields increase significantly. The top part of the aquifer is tapped by virtually all of the production wells and is the only aquifer tapped by production well 27 (fig. 4). The problem with penetrating deeply into the aquifer is that water quality deteriorates with depth, especially with respect to increasing sulfate concentrations.

Producing Zone

The producing zone is the interval tapped by the 38 Verna production wells, excluding deep production well number 27 (fig. 4). Represented by an average open-hole interval of 410 feet, the zone includes approximately the lower 300 feet of the intermediate aquifers and confining beds and the upper 100 feet of the Floridan aquifer. The zone is about 100 feet thinner in part A of the well field than in part B.

Specific-capacity tests performed on 36 production wells (Sutcliffe and Buono, 1979, p. 119-121) indicate that transmissivity of the producing zone changes between parts A and B of the well field (table 2). Average specific capacities of wells in parts A and B are 9.2 and 24.2 (gal/min)/ft of drawdown, respectively. Pumping a well at 500 gal/min would produce 54 feet of drawdown in part A and 21 feet of drawdown in part B, which indicates the transmissivity of the producing zone in part A is less than half that in part B.

Table 2.--Summary of specific-capacity tests on production wells

	Average open-hole interval (feet)	Lowest specific capacity [(gal/min)/ft]	Average specific capacity [(gal/min)/ft]	Highest specific capacity [(gal/min)/ft]	Drawdown in a 500 gal/min well[1/] (feet)
Part A (27 wells)	392	3.0 (well no. 8)	9.2	19.7 (well no. 13)	54
Part B (9 wells)	468	10.0 (well no. 36)	24.2	60.0 (well no. 39)	21

[1/] Drawdown is computed by dividing 500 gal/min by average specific capacity.

The higher transmissivity in part B may be related to a suspected fault that strikes a northeast-southwest diagional through part B of the well field (H. Sutcliffe, Jr., U.S. Geological Survey, oral commun., 1982). Wells that penetrate the suspected fault zone would have a higher specific capacity due to the higher transmissivities encountered in the brecciated zone. Good stratigraphic evidence of such a fault is lacking, although the altitude of the top of the Floridan aquifer is as much as 50 feet higher in part B than in part A (fig. 4).

HYDROLOGY

Ground-Water Levels and Movement

Water levels in wells and their relation to pumping and rainfall are shown by hydrographs in figures 5 and 6. Figure 5 shows long-term water levels in observation well 1A and exploration test well E2 that are completed in the producing zone composed of the intermediate aquifers and the upper part of the Floridan aquifer. Since pumping began in 1966, the average water level in exploration test well E2, which is the only reliable long-term monitor, declined almost 20 feet. Seasonal fluctuations are directly influenced by pumping and range from about 10 feet to about 30 feet. Water levels are lowest during the dry spring months when lawn and crop irrigation are at a maximum and recharge from rainfall is low. During the wet summer months, recharge is high and pumping for irrigation is minimal, which results in recovery of water levels to seasonal highs.

The hydrograph of water levels in observation well 1A indicates that there was a rise in water levels in 1970. H. Sutcliffe, Jr. (U.S. Geological Survey, oral commun., 1983) indicated that the original well, drilled in 1965, was only 4 inches in diameter. It was suspected that a broken coupling in the well casing allowed water to leak into the 6-inch annulus around the 409-foot casing. When the coupling was repaired, the water level in the well rose. During 1970, the well was deepened by 30 feet; however, the rise in water level is attributed to repair of the coupling rather than deepening of the well.

Figure 6 shows water levels from 1977 to 1982 in recently constructed wells in the center of part A of the well field. The hydrographs reflect head relations in water-table well W9 developed in the surficial aquifer, well S14 in the upper part of the Tamiami-upper Hawthorn aquifer above the producing zone, observation well 0-3 in the producing zone, and the drain well in the Floridan aquifer below the producing zone. Water levels in all aquifers except the surficial aquifer respond rapidly to pumping. The lowest water-level elevations are in observation well 0-3. Head gradients indicate that, under pumping conditions, water in the producing zone is derived through: (1) upward leakage from deep in the Floridan aquifer (water level in drain well higher than water level in observation well 0-3), (2) downward leakage from the surficial aquifer and permeable zones in the Tamiami-upper Hawthorn aquifer (water levels in W9 and S14 higher than that in 0-3), and (3) lateral inflow across the well-field boundary. Downward leakage from the surficial aquifer appears to be low because there is not a long-term water-level decline, and seasonal amplitudes are small compared to those in the producing zone. Conversely, in well-field areas near Tampa, where leakage is moderate to high, distinct cones of depression have developed in the water table and seasonal amplitudes are higher than those in unaffected areas.

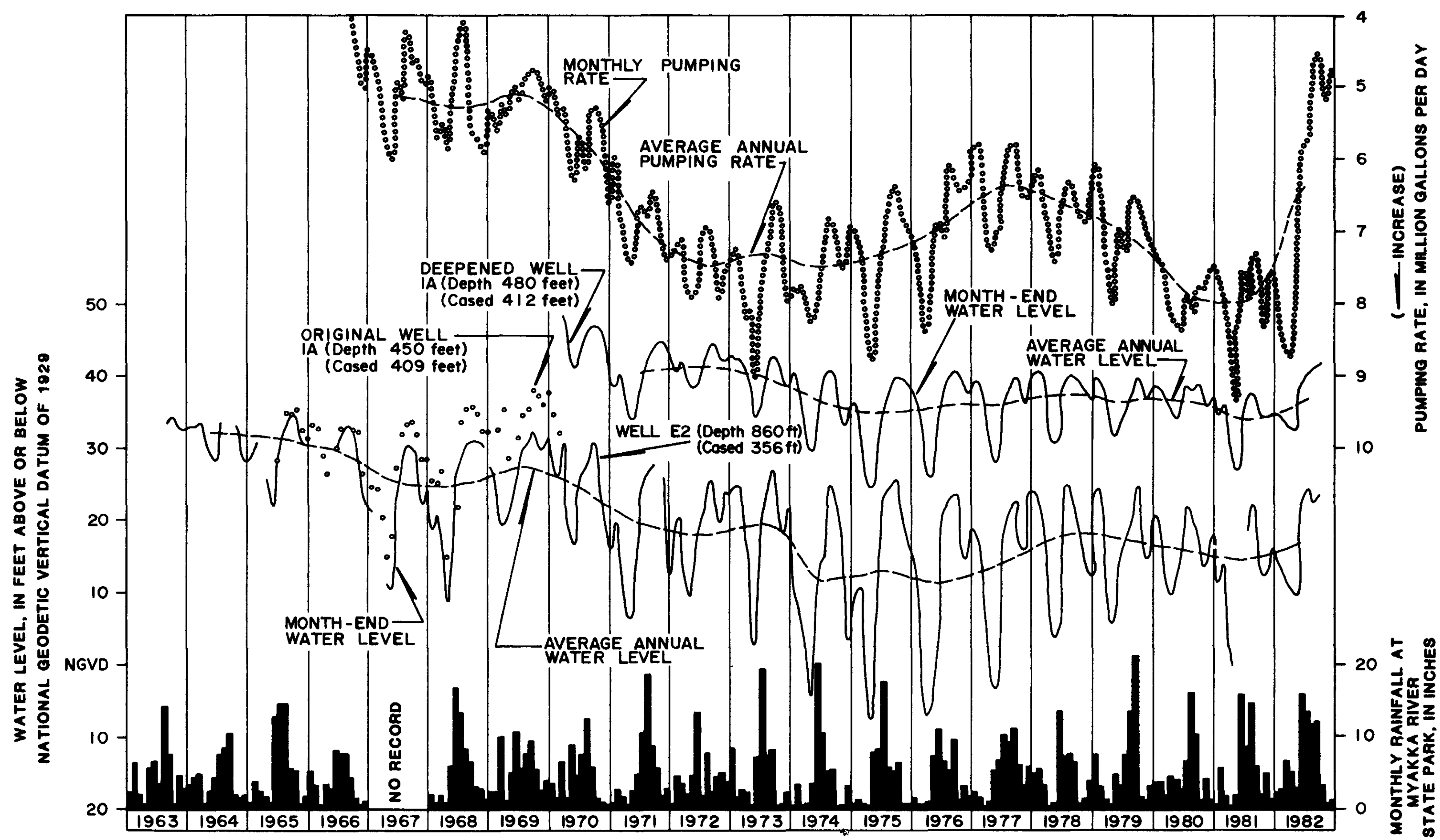


Figure 5.--Water levels, pumping, and rainfall in the Verna well-field area, 1963-82.

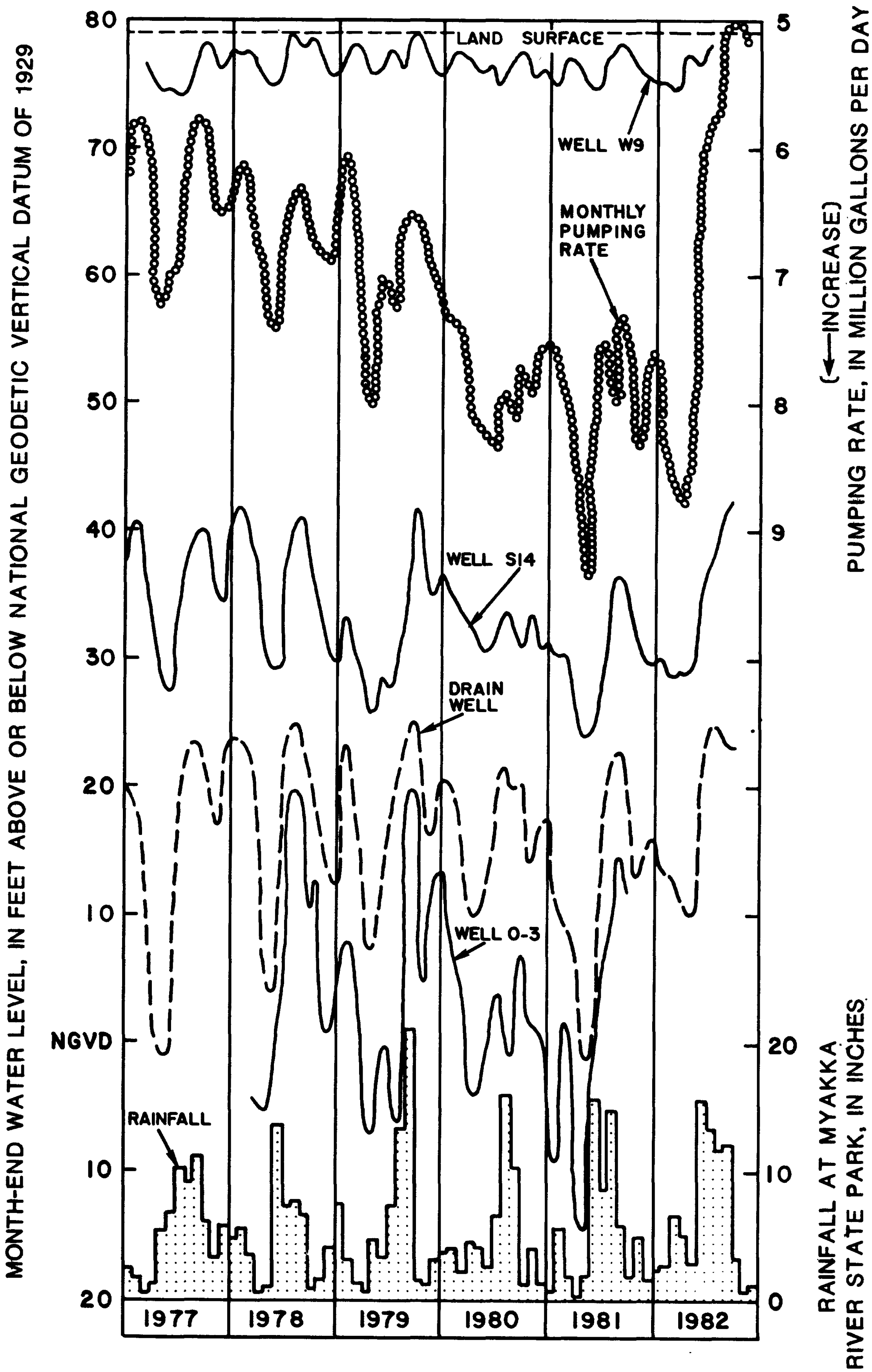


Figure 6.--Water levels near the center of Verna well field, as related to pumping and rainfall, 1977-82.

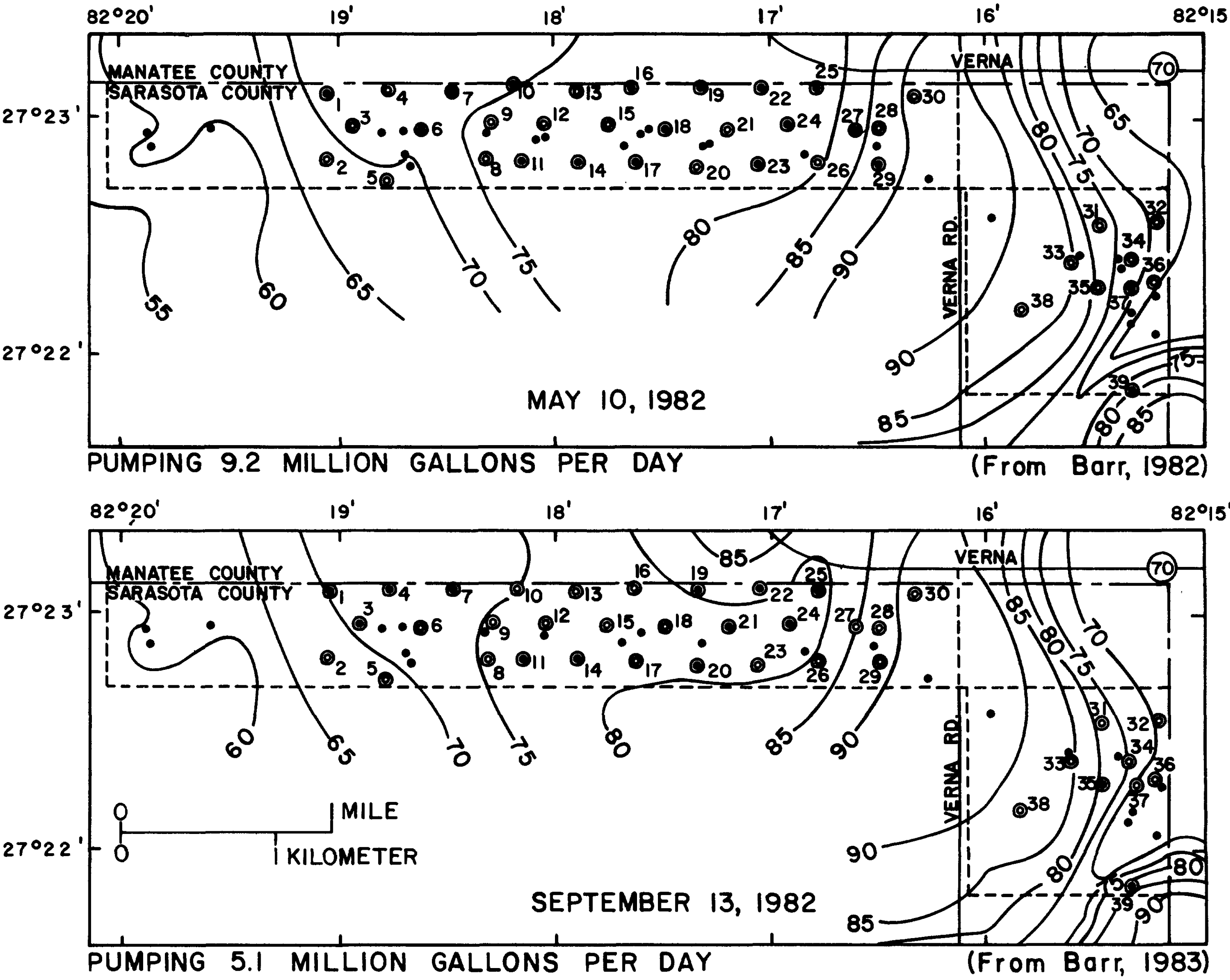
High and low water-level conditions in 1982 in the surficial aquifer and in the producing zone for 1982 are shown in figures 7 and 8, respectively. Water in the surficial aquifer moves laterally away from an area of high levels where part A and part B of the well field meet. A comparison of levels shown on the maps indicates that there was less than 5 feet of seasonal fluctuation from the May low level to the September high level.

Cones of depression have not developed in the water table, which indicates the surficial aquifer is not significantly affected by pumping. The water levels in all surficial aquifer observation wells were within 10 feet of land surface near the end of the dry season in May 1982.

The composite May 1982 potentiometric-surface map for the intermediate and Floridan aquifers (fig. 8) indicates that water moves laterally into large cones of depression in the well field. At its deepest point, in the western part of part A, the potentiometric surface is more than 60 feet below sea level or 130 feet below land surface. The pumping rate on May 10, 1982, was 9.2 Mgal/d, one of the highest rates in the history of the well field. In September 1982, pumping was 5.1 Mgal/d, and there was a 10- to 40-foot recovery in the potentiometric surface above the May level. The nonpumping potentiometric surface, measured in exploration test wells near the well field in 1963 and 1966, was about 30 feet above sea level. Pumping since 1966 has resulted in drawdown at the well-field boundary of about 20 to 30 feet in May 1982 and about 5 to 10 feet in September 1982.

Maps that show water levels in the Floridan aquifer for May and September 1982, prepared by Barr and Schiner (1982a; 1982b), represent head conditions in the Floridan aquifer (figs. 9 and 10; also see fig. 4). The aquifer is barely tapped by production wells at the Verna well field. The maps indicate that water in the Floridan aquifer moves from southeast to northwest in the vicinity of the well field. Both 1982 maps show southeast-northwest trending troughs with axes through the well field. During 1982, the potentiometric surface in the vicinity of the Verna well field rose from a seasonal low in May of about 5 to 10 feet above sea level to a high in September of about 25 feet above sea level. The bending of contours near the well field indicates that pumping at Verna may have a subtle impact on the potentiometric surface of the Floridan aquifer.

The potentiometric surface of the Floridan aquifer is estimated to have declined seasonally 20 to 50 feet along a north-south line from the Verna well field to Hillsborough County (figs. 9 and 10). Areas affected by pumping from the Floridan aquifer were delineated by superimposing an estimated average predevelopment potentiometric-surface map (Johnston and others, 1980) upon 1982 seasonal levels. The differences between the two maps represent the approximate decline in the potentiometric surface that resulted from pumping. Declines ranged from 40 to 50 feet in May 1982 to 20 to 30 feet in September 1982 (figs. 11 and 12). The declines are greatest in Manatee County where the average annual pumping rate was about 70 Mgal/d, as estimated from the 1980 rate reported by Duerr and Trommer (1981). The large decline in May reflects a high pumping rate at the peak of the irrigation season, whereas the smaller September decline reflects a lower pumping rate. The Floridan aquifer at Verna is impacted by regional pumping for irrigation in addition to withdrawals for municipal supply.



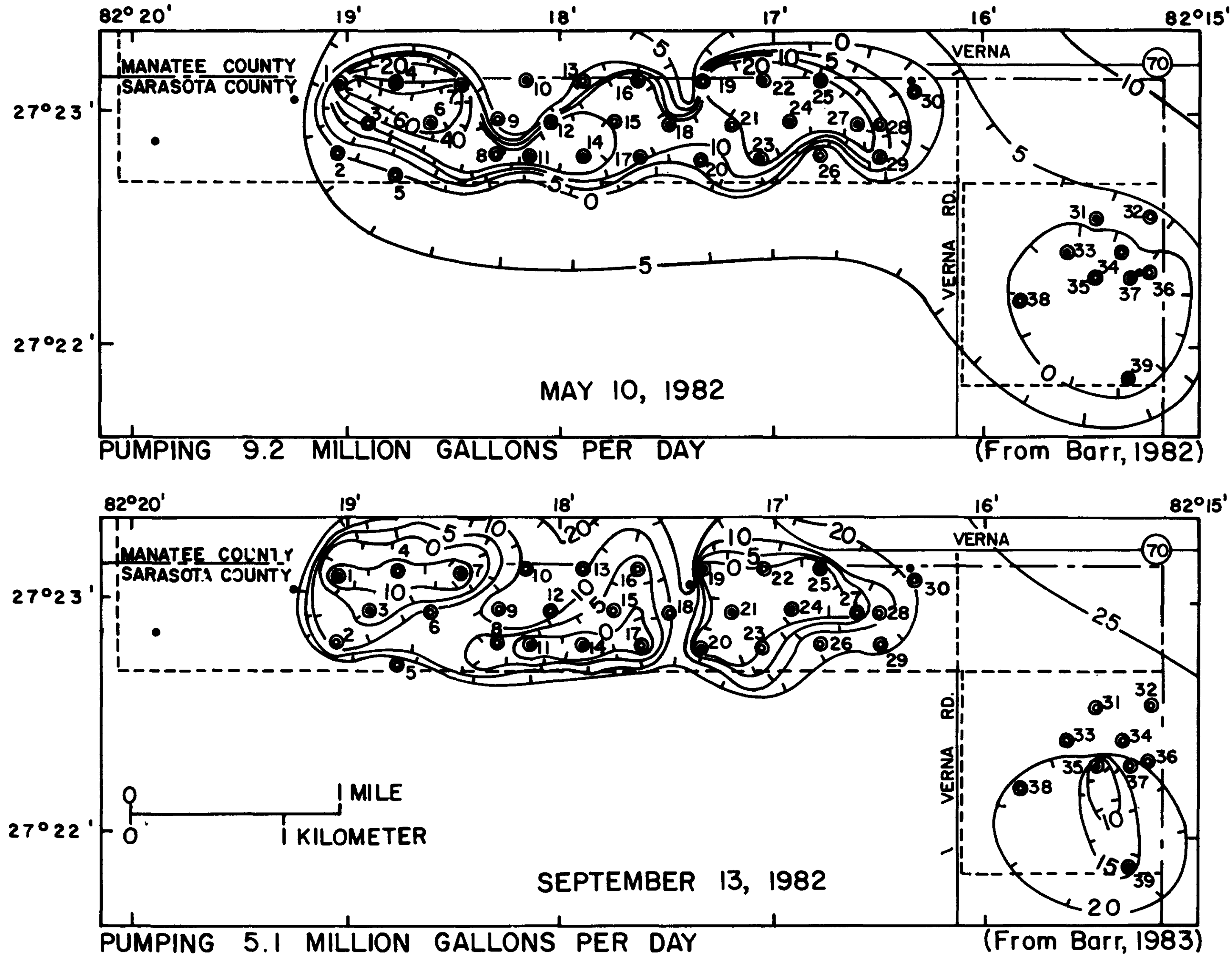
EXPLANATION

—60— WATER-TABLE CONTOUR-- SHOWS ALTITUDE OF WATER TABLE IN THE SURFICIAL AQUIFER. CONTOUR INTERVAL 5 FEET. NATIONAL GEODETIC VERTICAL DATUM OF 1929

◎12 MUNICIPAL SUPPLY WELL AND NUMBER-- OPEN SYMBOL INDICATES WELL WAS NOT PUMPING.
●17 SOLID SYMBOL INDICATES WELL WAS PUMPING

• OBSERVATION WELL-- WELL USED AS DATA POINT FOR MAPPING

Figure 7.--Water table in the surficial aquifer at Verna well field during May and September 1982.



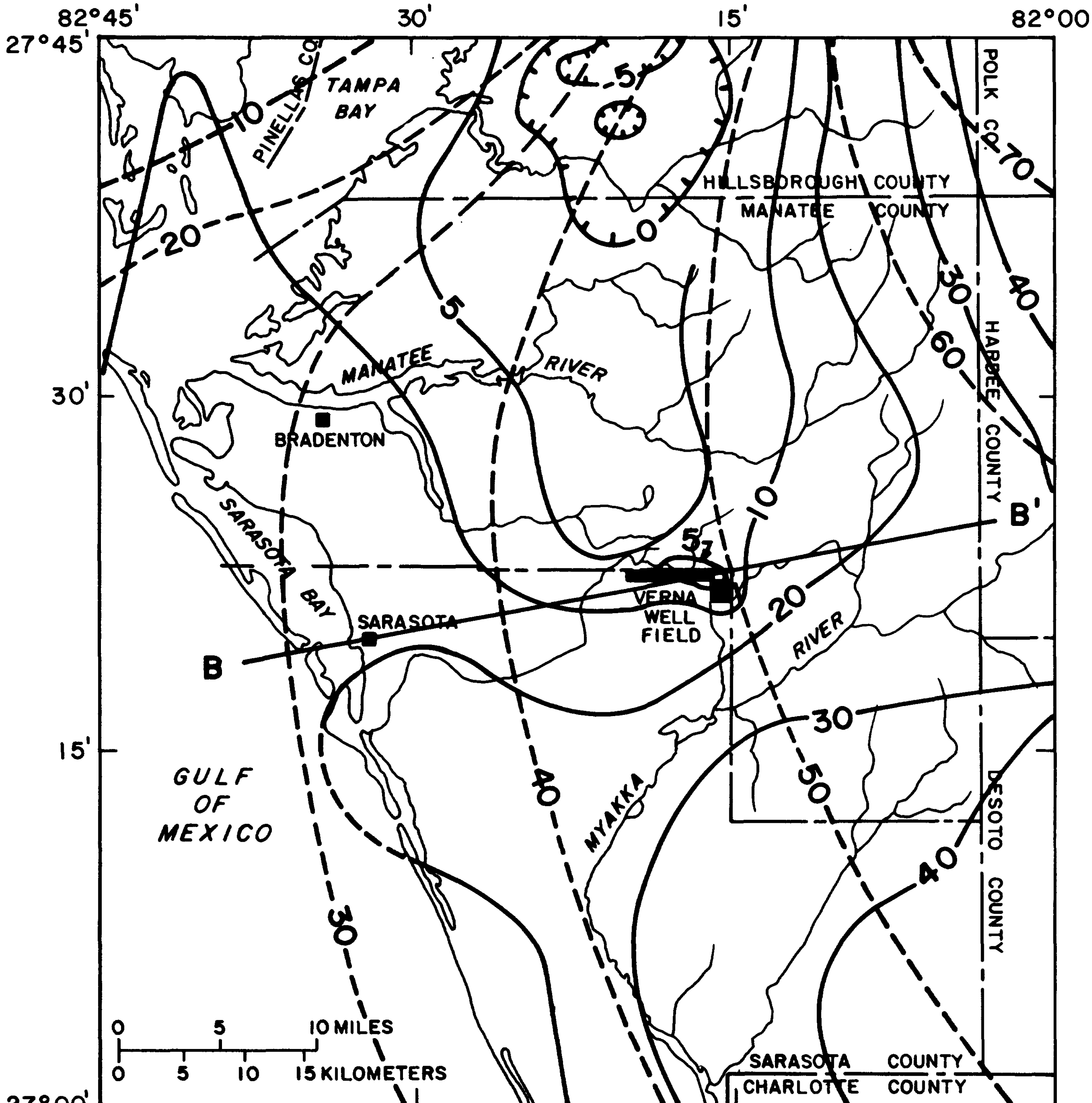
EXPLANATION

—5— POTENTIOMETRIC CONTOUR--SHOWS ALTITUDE OF COMPOSITE POTENTIOMETRIC SURFACE OF THE INTERMEDIATE AQUIFERS AND FLORIDAN AQUIFER. CONTOUR INTERVALS 5, 10, AND 20 FEET. NATIONAL GEODETIC VERTICAL DATUM OF 1929

9, 14 MUNICIPAL SUPPLY WELL AND NUMBER--OPEN SYMBOL INDICATES WELL WAS NOT PUMPING. SOLID SYMBOL INDICATES WELL WAS PUMPING

• OBSERVATION WELL--WELL USED AS DATA POINT FOR MAPPING

Figure 8.--Composite potentiometric surface of the intermediate aquifers and Floridan aquifer at the Verna well field during May and September 1982.



EXPLANATION

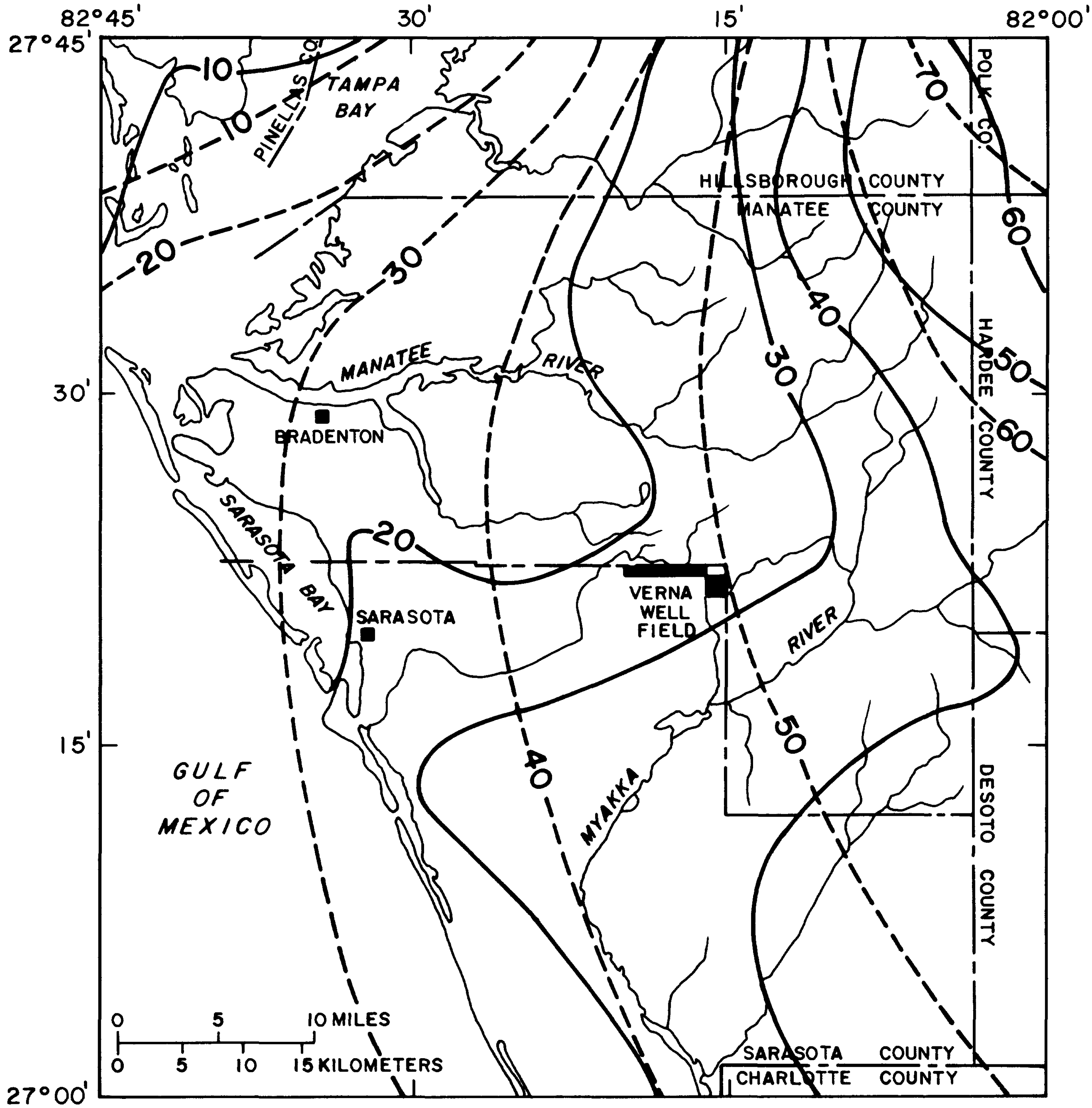
——70——

PREDEVELOPMENT POTENTIOMETRIC CONTOUR-- SHOWS APPROXIMATE ALTITUDE OF THE POTENTIOMETRIC SURFACE OF THE FLORIDAN AQUIFER PRIOR TO DEVELOPMENT. CONTOUR INTERVAL 10 FEET. NATIONAL GEODETIC VERTICAL DATUM OF 1929 (FROM JOHNSTON AND OTHERS, 1980).

——20——

MAY 1982 POTENTIOMETRIC CONTOUR-- SHOWS ALTITUDE OF THE POTENTIOMETRIC SURFACE OF THE FLORIDAN AQUIFER, MAY 1982. CONTOUR INTERVAL 5 AND 10 FEET. NATIONAL GEODETIC VERTICAL DATUM OF 1929. HACHURES INDICATE DEPRESSIONS (FROM BARR AND SCHINER, 1982a).

Figure 9.--Predevelopment and May 1982 potentiometric surfaces of the Floridan aquifer, representing average nonpumping and seasonal low water-level conditions in the zone barely penetrated by production wells at the Verna well field. (B-B' is line of section shown in figures 21 and 22.)



EXPLANATION

--70--

PREDEVELOPMENT POTENTIOMETRIC CONTOUR -- SHOWS APPROXIMATE ALTITUDE OF THE POTENTIOMETRIC SURFACE OF THE FLORIDAN AQUIFER PRIOR TO DEVELOPMENT. CONTOUR INTERVAL 10 FEET. NATIONAL GEODETIC VERTICAL DATUM OF 1929 (FROM JOHNSTON AND OTHERS, 1980).

—60—

SEPTEMBER 1982 POTENTIOMETRIC CONTOUR -- SHOWS ALTITUDE OF THE POTENTIOMETRIC SURFACE OF THE FLORIDAN AQUIFER, SEPTEMBER 1982. CONTOUR INTERVAL 10 FEET. NATIONAL GEODETIC VERTICAL DATUM OF 1929 (FROM BARR AND SCHINER, 1982b).

Figure 10.--Predevelopment and September 1982 potentiometric surfaces of the Floridan aquifer, representing average nonpumping and seasonal high water-level conditions in the zone barely penetrated by production wells at the Verna well field.

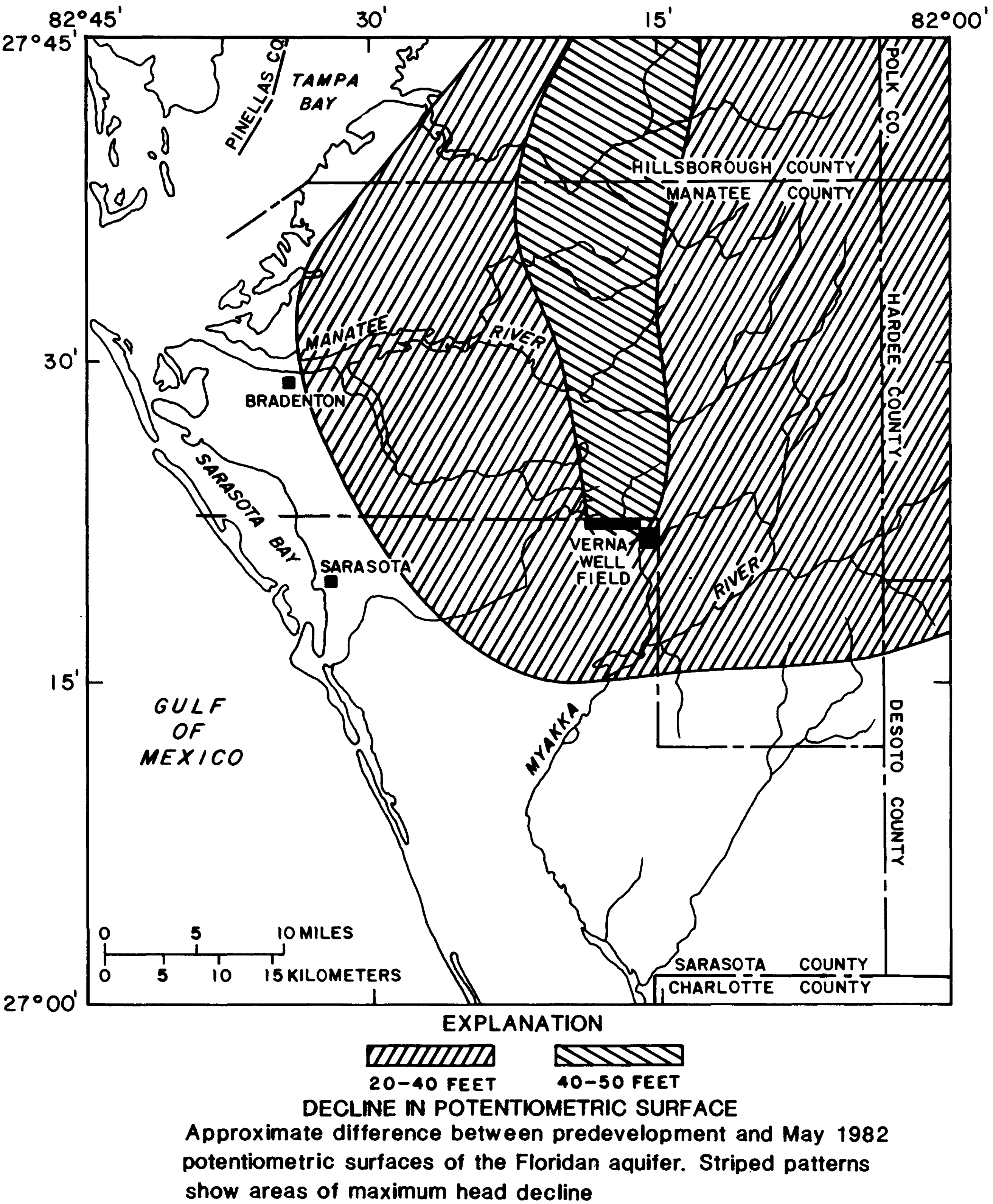


Figure 11.--Estimated decline in the potentiometric surface of the Floridan aquifer from predevelopment to May 1982 conditions.

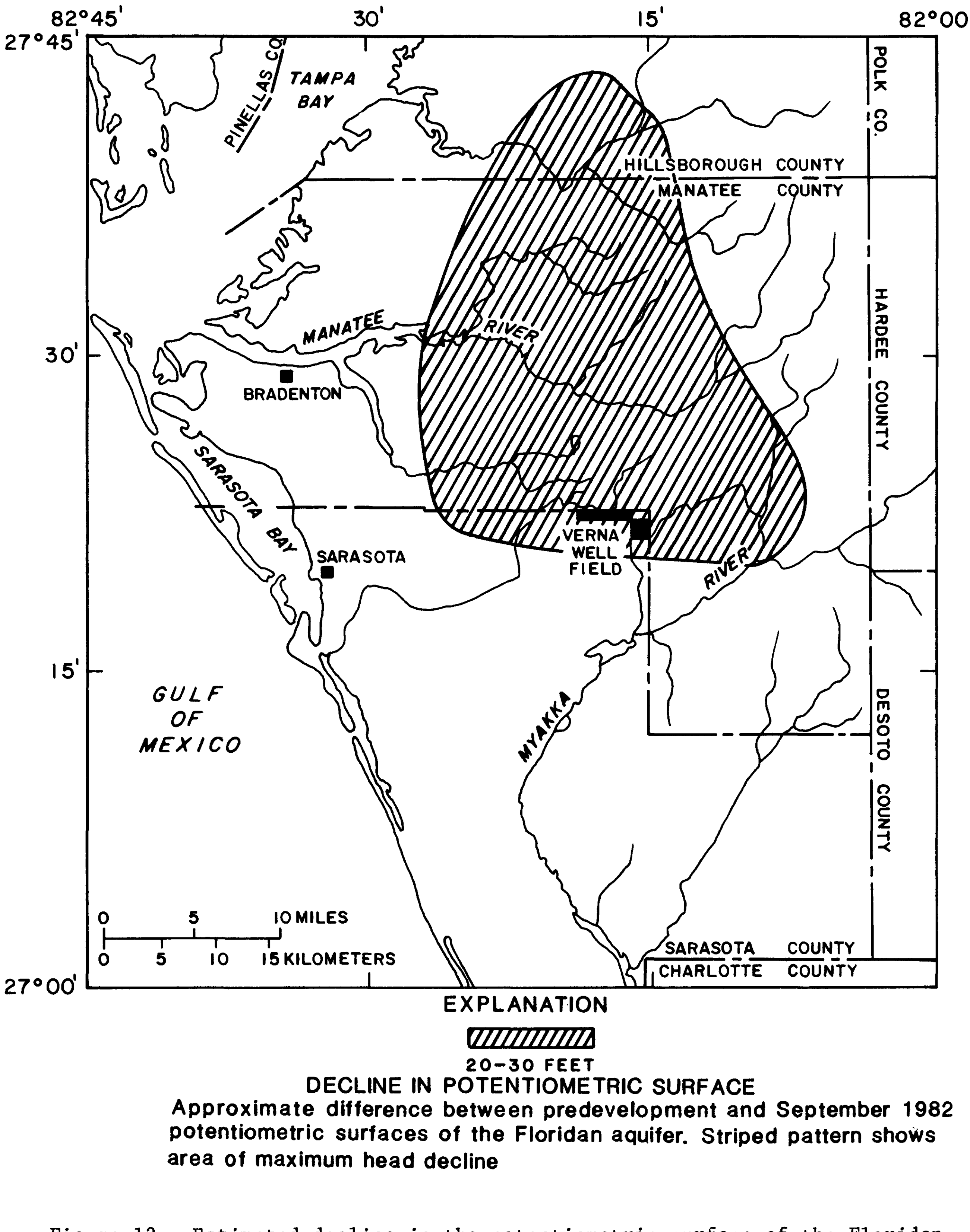


Figure 12.--Estimated decline in the potentiometric surface of the Floridan aquifer from predevelopment to September 1982 conditions.

Water Quality

The chemical constituents in water at the Verna well field vary areally, vertically, and with time. Water in the producing zone generally is more mineralized with depth, is of better quality in part B of the well field than in part A, and has become less potable with time.

The Verna well field probably taps the best quality water available from the Floridan aquifer in Sarasota County. Steinkampf (1982) shows that water in the upper part of the Floridan aquifer generally becomes more mineralized as it moves from inland recharge areas toward the Gulf Coast (fig. 13). The isolated area of dissolved solids greater than 1,000 mg/L around the Verna well field indicates that pumping has induced upward movement of poor quality water from the lower part of the Floridan aquifer.

Water quality in the surficial aquifer has been analyzed for three samples. A sample from water-table well W11 had a dissolved-solids concentration of 62 mg/L. Water samples collected at shallow depths during drilling of Tamiami-upper Hawthorn test wells S1 and S14 had dissolved-solids concentrations of 120 mg/L and 285 mg/L, respectively (Sutcliffe and Buono, 1979, p. 128). Although there are few analyses of water from the surficial aquifer, it apparently contains water of excellent quality. The average dissolved-solids concentration of the three samples was about 150 mg/L. The samples are considered to be representative of the average dissolved-solids concentration in the surficial aquifer at the well field.

The areal distribution of dissolved solids in the producing zone is shown in figure 14. Dissolved-solids concentrations increase toward the center of the well field where pumping is concentrated and where deep cones of depression occur (fig. 8). North and east of the well field, dissolved-solids concentrations apparently are less than at observation well 0-4 southwest of the well field. The average concentration of dissolved solids in water from 36 production wells was 824 mg/L. The highest concentration was 1,340 mg/L in a sample collected in May 1981 from production well 27 that is 1,000 feet deep. The highest dissolved-solids concentration in a composite water sample from the intermediate and Floridan aquifers was 1,250 mg/L in the 501-foot deep production well 21. The average concentration of dissolved solids exceeds the secondary standard for potable water (500 mg/L) recommended by the U.S. Environmental Protection Agency (1979). Secondary standards are based on esthetics, such as taste and odor, rather than health hazards. Excessive hardness, taste, mineral deposition, or corrosion are common properties of water with high levels of dissolved solids.

The relation between concentration of dissolved solids (mineral content) and depth is shown by Stiff diagrams in figure 15. The concentration of specific ions depends primarily on the composition of the aquifer, solubility of the rocks, length of flow path, and time of contact with the aquifer. Water in the surficial aquifer is less mineralized because the aquifer is composed of fairly insoluble silica and contains water that has recently infiltrated from the surface. As water percolates downward through the Tamiami-upper Hawthorn aquifer, it dissolves calcium and magnesium from the carbonate rocks. Deeper percolation brings the water in contact with gypsum-rich deposits that release sulfate. Production well 27 and the drain well tap the upper part of the Floridan aquifer and were the deepest wells sampled. These samples contained calcium magnesium sulfate type water and were more mineralized than samples from shallower depths.

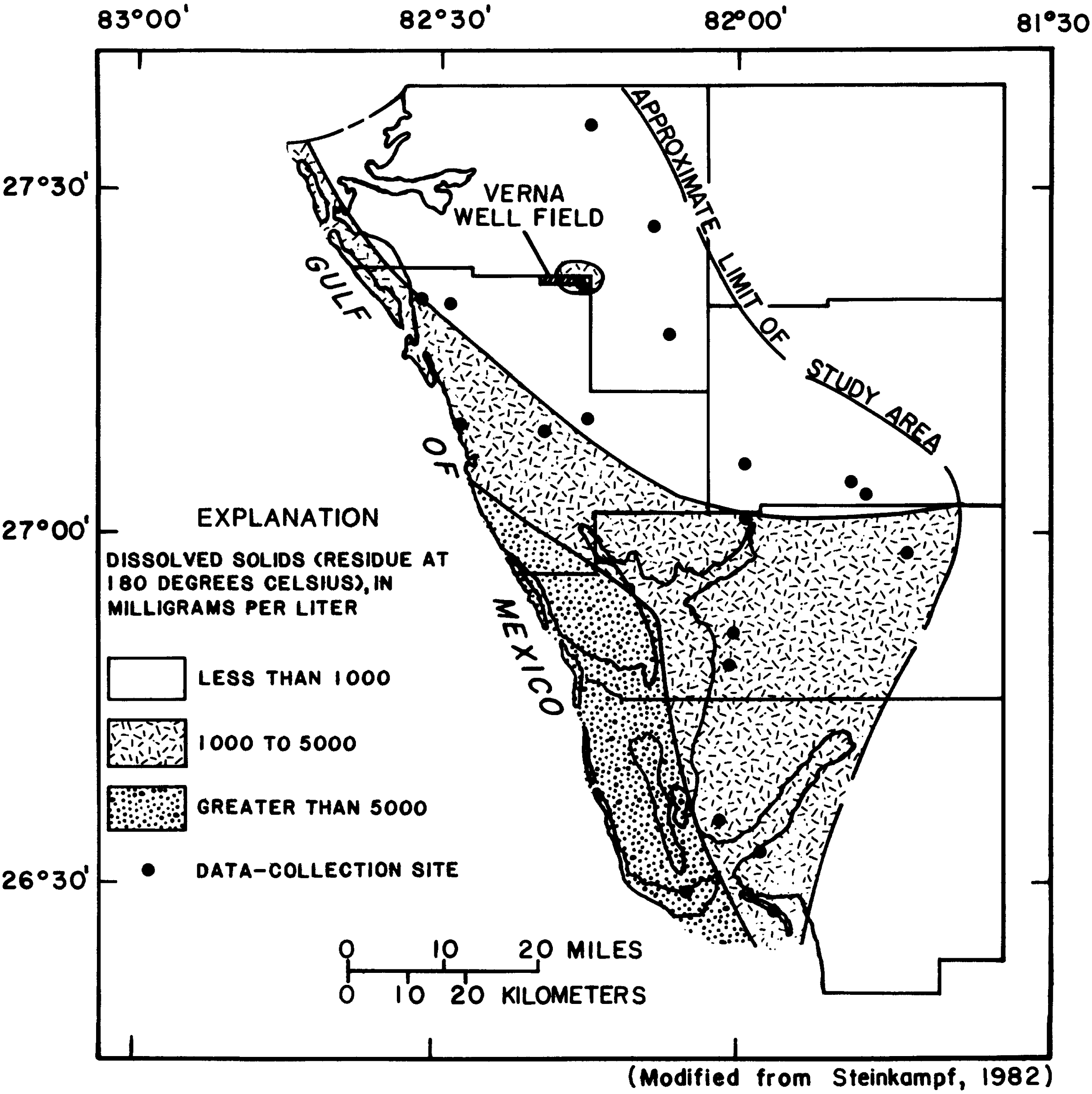


Figure 13.--Estimated distribution of dissolved solids (residue at 180°C) in the upper part of the Floridan aquifer, July-November 1980.

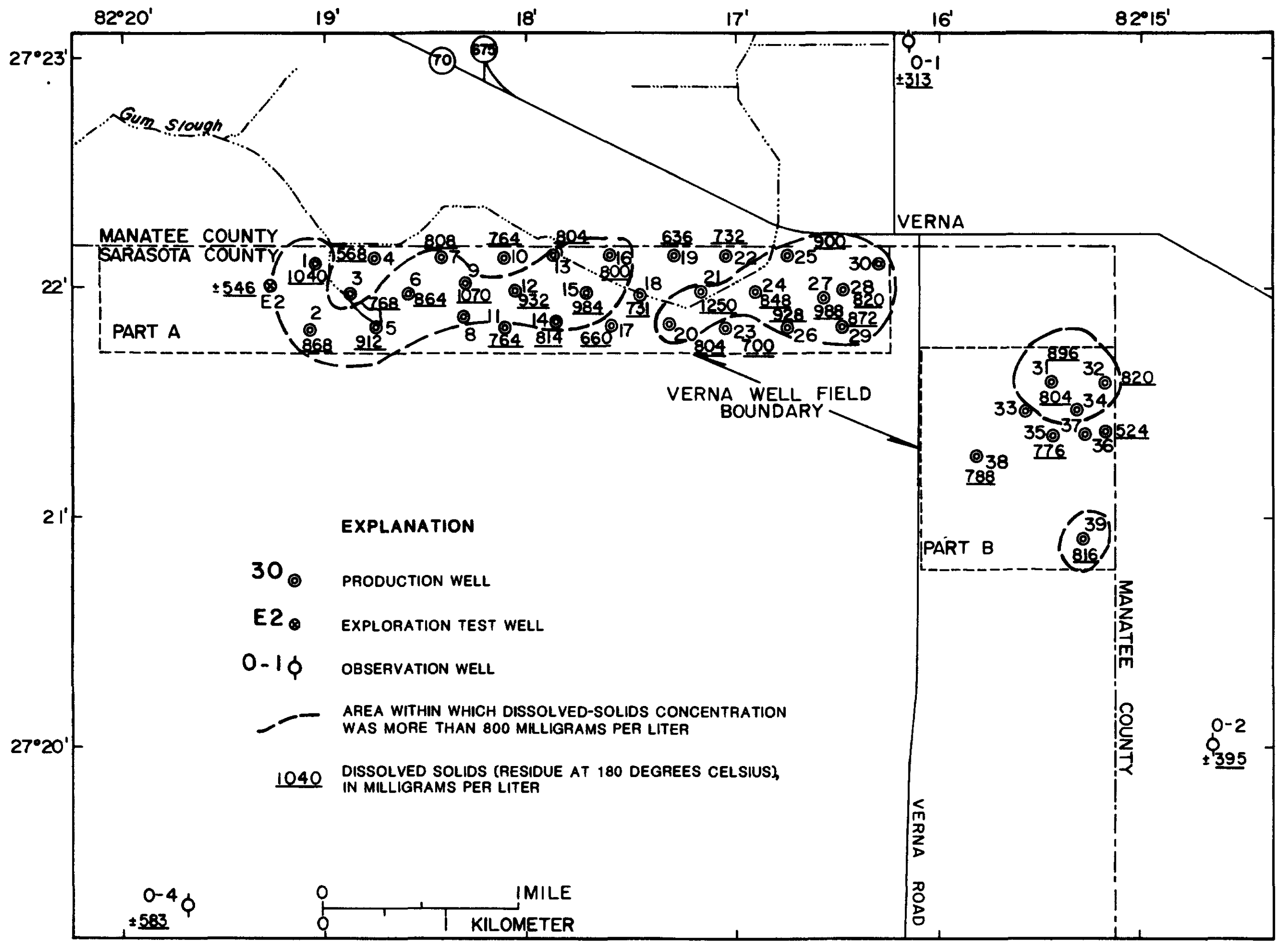


Figure 14.--Dissolved solids in the producing zone, September 1982. (± number is estimated from measurement before September 1982.)

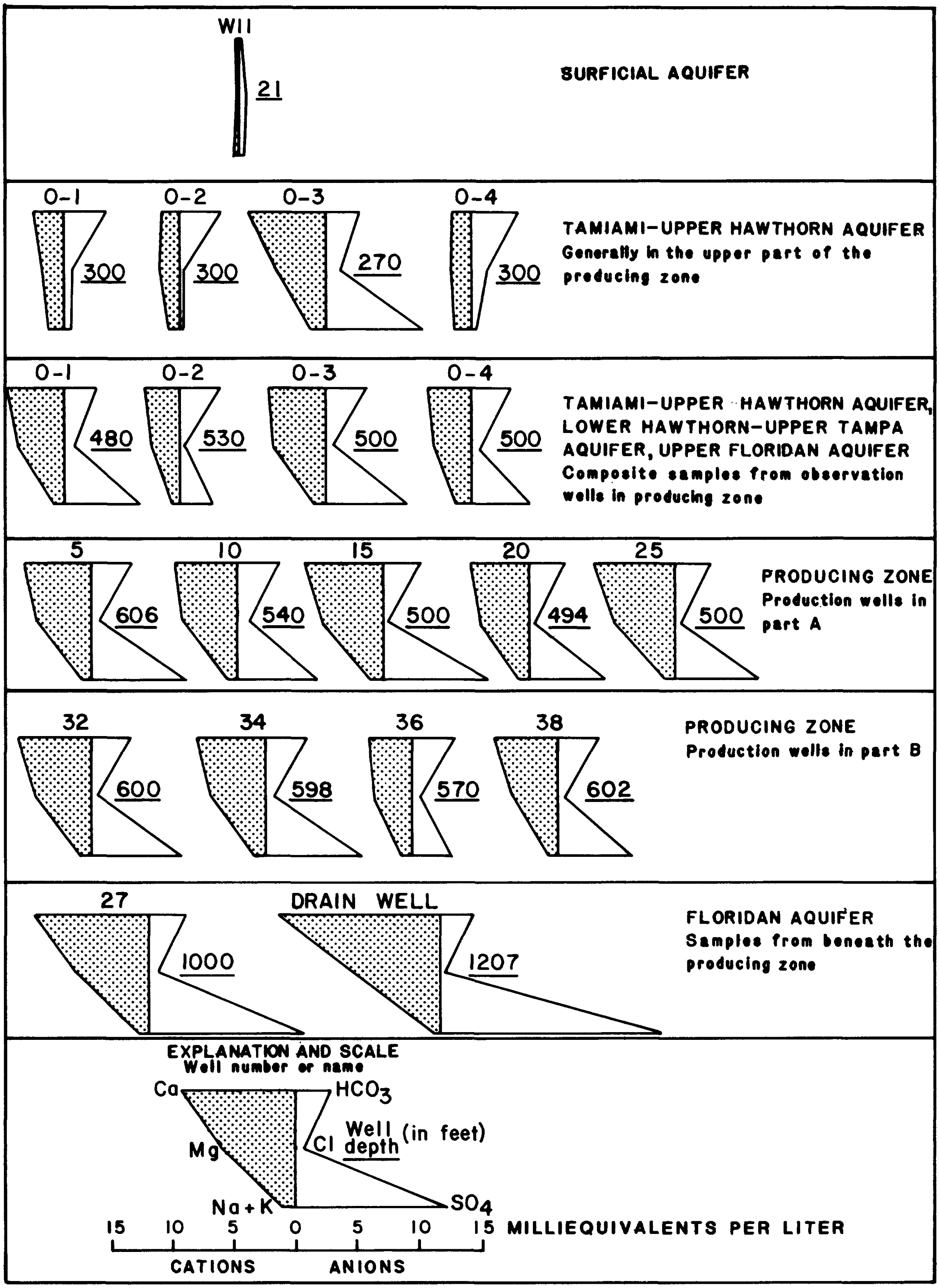


Figure 15.--Quality of water as related to aquifers tapped.

The Stiff diagrams indicate that sulfate-rich water is being drawn upward by the production wells. Observation wells 0-1, 0-2, 0-3, and 0-4 were sampled at various depths as they were drilled in 1978 (Barker and others, 1981). Water from observation well 0-3 in the center of the well field contained higher dissolved-solids concentrations than water from observation wells 0-1, 0-2, and 0-4 that were 1 mile or more from the well field. Especially conspicuous is the Stiff diagram of water from observation well 0-3 finished in the Tamiami-upper Hawthorn aquifer at a depth of 270 feet. The diagram shows that sulfate-rich water has intruded into the aquifer from below. Other wells open to the Tamiami-upper Hawthorn aquifer that are away from the center of pumping produced water that was very low in sulfate concentration.

Water-quality changes with depth are indicated graphically in figure 16. The lines on the graph connect the sulfate concentrations determined from samples collected at depths below 500 feet when eight production wells were drilled in 1966 (Sutcliffe and Buono, 1979, p. 119, 120). Each well, except production well 4, showed increases in sulfate after the 500-foot depth interval was penetrated. The end points of the lines are grouped closely together, which indicates water quality is relatively stable in the intermediate aquifers (above 500 feet). The wide spread of points in the Floridan aquifer (below 500 feet) indicates highly variable water quality in this aquifer. Based on the eight measurements, the sulfate concentration of water from the intermediate aquifers is estimated to average about 40 mg/L.

Figure 17 shows that, throughout the well field, sulfate concentrations in September 1982 exceeded background levels of 1965-66. The 1965-66 sulfate concentrations represent levels measured at the end of 24-hour pumping tests of individual production wells prior to putting the well field into operation. In September 1982, the sulfate concentrations in water from 24 production wells in part A of the well field averaged 409 mg/L, or 218 mg/L higher than the background level measured in the same wells. Sulfate concentrations in water from five production wells in part B averaged 344 mg/L, only 44 mg/L above the background level. This indicates that pumping between 1966 and 1982 has drawn sulfate-rich water upward from deeper zones. During this time period, sulfate concentrations in water from 17 production wells rose above the recommended 250-mg/L standard for potable water (U.S. Environmental Protection Agency, 1979). Concentrations in excess of 250 mg/L are undesirable because of adverse aesthetic effects. Above this level, adverse taste and laxative effects are more likely to occur.

There is a much larger difference between current and background sulfate concentrations in water from part A than from part B, possibly due to the much greater pumping (more than two times) at part A combined with the relatively low transmissivity there. The resultant rate of upward movement of sulfate-rich water in part A is higher than in part B.

Further evidence that pumping has induced aquifer contamination by upwelling of sulfate-rich water is supported by temporal changes in sulfate concentrations in water from at least 7 of the 39 production wells (fig. 18). Between 1966 and 1982, sulfate concentrations in water from production wells 2, 4, 14, 15, and 21 had increased an average of about 150 mg/L, or about 9 mg/L per year. The average sulfate-concentration trend for all wells sampled was slightly lower, increasing from about 300 mg/L in 1966 to 400 mg/L in 1982, or about 6 mg/L per year. Sulfate concentrations in water from production wells 27 and 36 varied greatly during this period, probably in response to pumping.

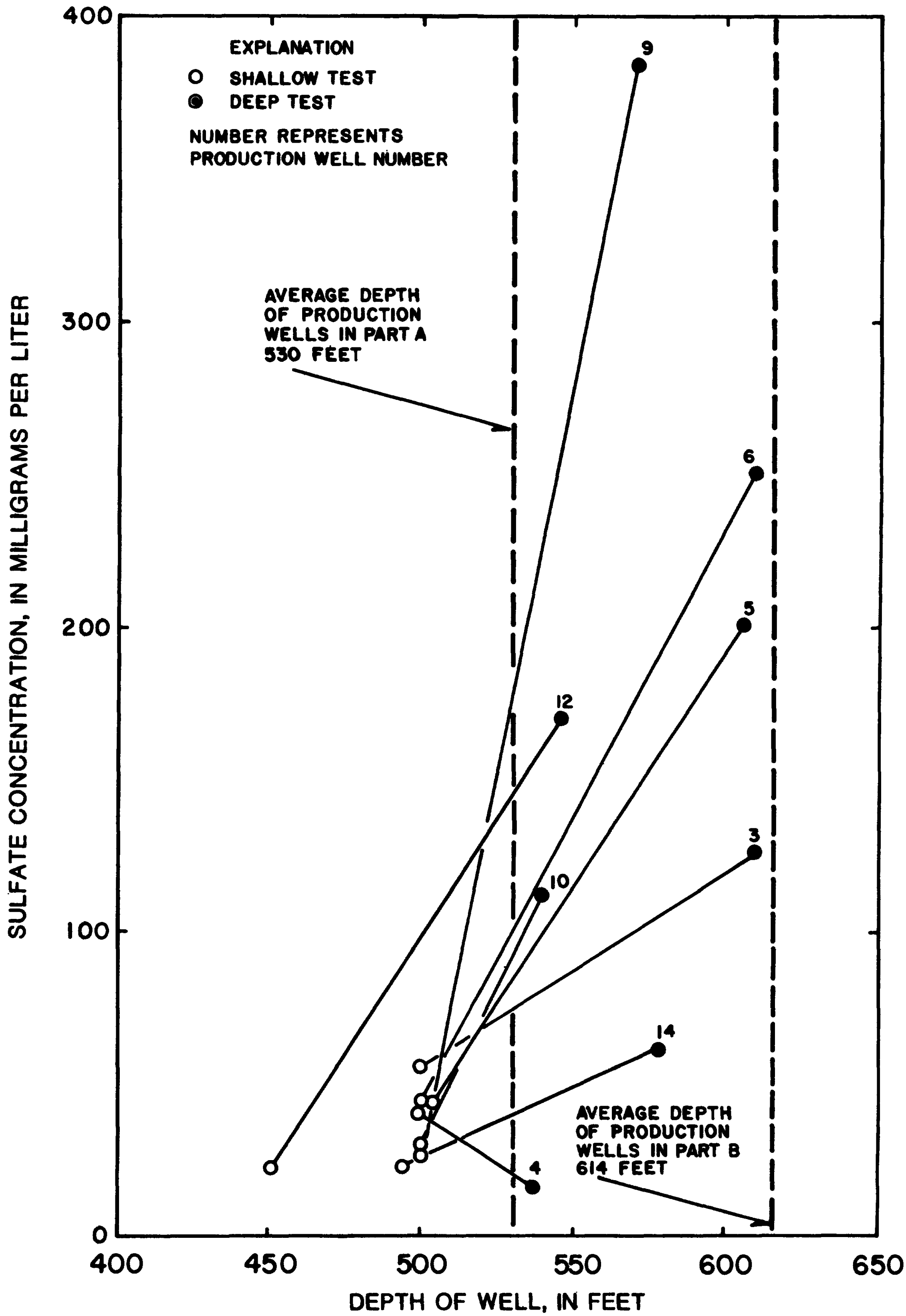


Figure 16.--Changes in sulfate concentration with depth. (Based on data in Sutcliffe and Buono, 1979.)

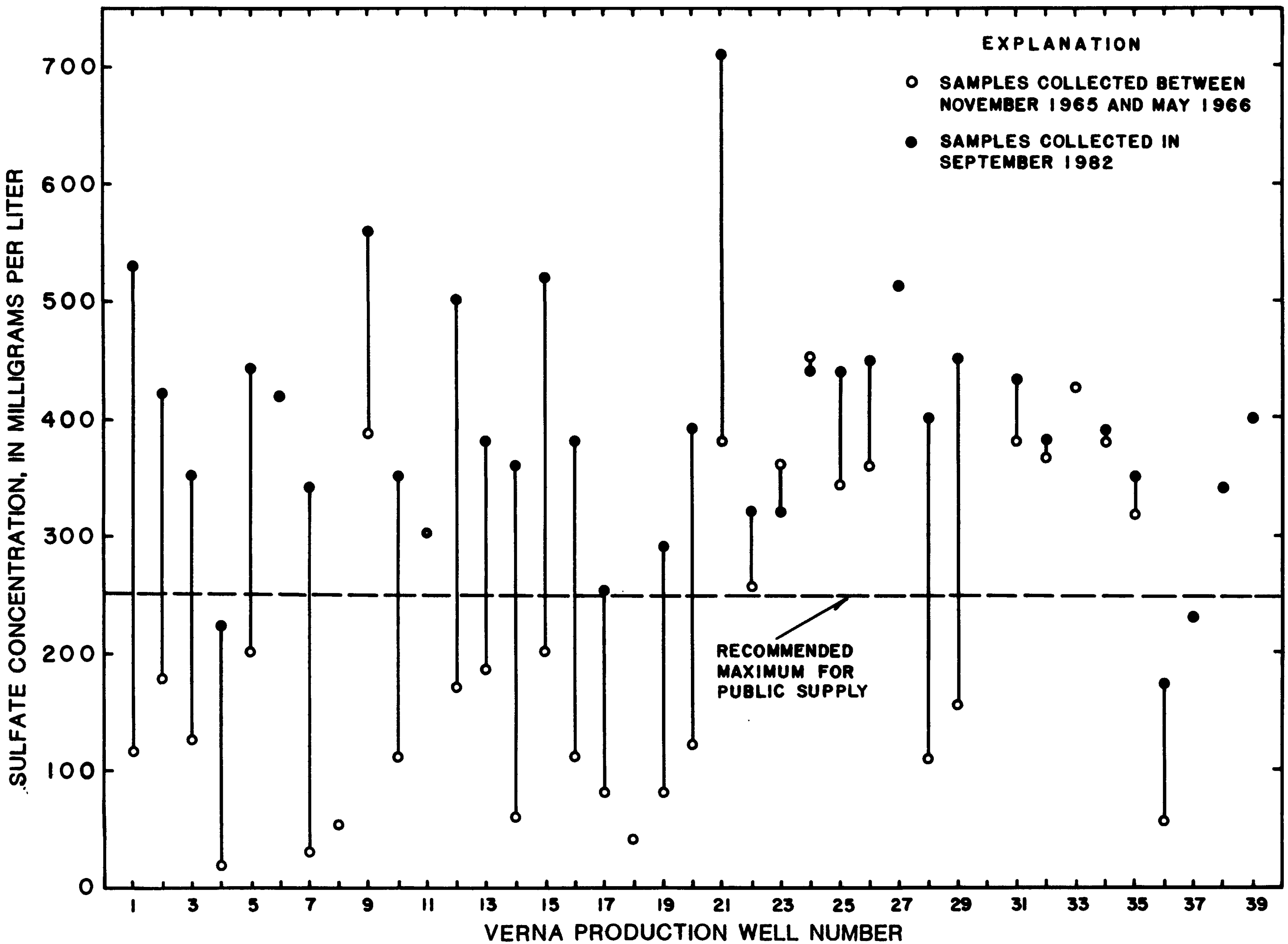


Figure 17.--Sulfate concentrations in water from production wells in 1965-66 and September 1982.

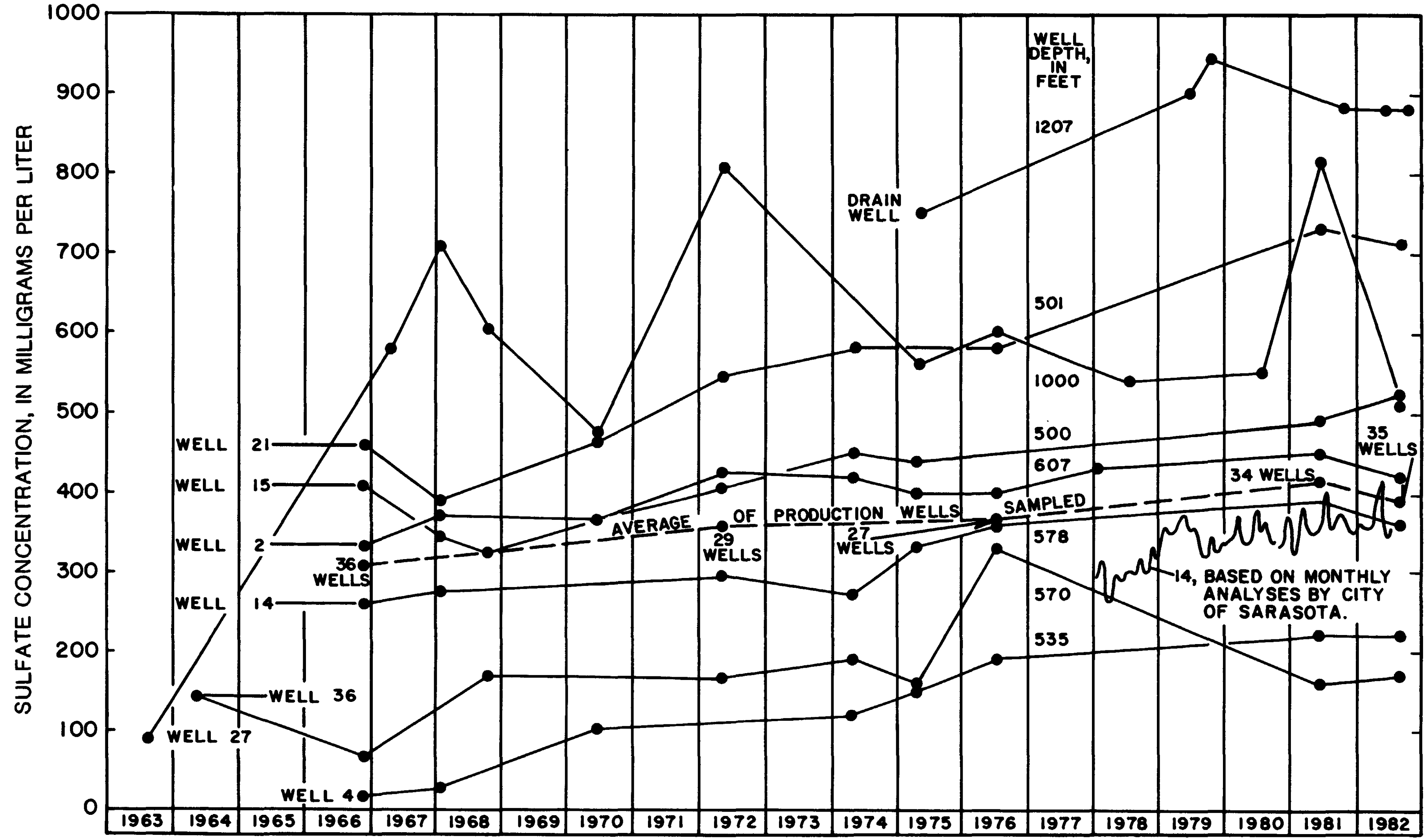


Figure 18.--Sulfate concentrations in water from production wells, 1963-82.

Radionuclides frequently occur in ground water in central and southwest Florida where uranium and radium are known to be associated with phosphate deposits. Of 161 water samples tested by Sutcliffe and Miller (1981, p. 1) in a reconnaissance of dissolved radionuclides in Sarasota County, 86 samples equaled or exceeded the 5 pCi/L (picocuries per liter) maximum level for radium-226 recommended by the U.S. Environmental Protection Agency (1979). Of eight samples tested from the producing zone in the Verna well-field area, four samples exceeded the maximum limit. The highest radium-226 level was 6.3 pCi/L detected in water from production well 14. Water from the treatment plant that consists of blended water from the Verna well field and reverse-osmosis plant contained a radium-226 level of 4.0 pCi/L.

Aquifer Yield

Pumpage at the Verna well field is derived from two zones, collectively called the producing zone. The upper zone comprises the intermediate aquifers and the lower zone is the uppermost part of the Floridan aquifer.

The first estimates of yields from various producing zones in Sarasota County were made by Stringfield (1933b) for wells at Palmer Farms about 8 miles southeast of the Verna well field (fig. 1). Borehole velocity determinations were made with a deep-well current meter in eight wells that ranged from 330 to 821 feet in depth. The velocities were taken at approximately 20- to 25-foot depth intervals as the wells flowed naturally. Discharge ranged from 3 gal/min in the deepest well to 140 gal/min in a 698-foot deep well. Stringfield (1933b, p. 220) concluded that the volocity data

> "... show that the principal supply of such wells comes from the Hawthorn Formation, and in some of the wells, the Ocala and Tampa Limestones yield little or no water. This fact is important, because it shows that the supply of artesian water is somewhat less in this area (Sarasota County) than in areas (mainly to the north) in which the Tampa and Ocala Limestones yield large supplies."

The 1933 report did differentiate between the upper and lower parts of the Hawthorn Formation, but not between the Suwannee Limestone and the Ocala Limestone, as delineated in table 1 of this report.

The percentage of water yielded to wells from each zone at the Verna well field was estimated from changes in water quality and specific capacity when eight production wells were deepened in 1966. The wells were pumped at rates that ranged from 72 to 634 gal/min (Sutcliffe and Buono, 1979, p. 119-121). It was assumed that water quality and specific capacity from the shallow depth were representative of the intermediate aquifers. Changes in water quality and specific capacity after the wells were deepened would be proportional to the contribution of water from the Floridan aquifer.

The relation between depth of well and specific capacity is shown in figure 19. The relation shows that the specific capacities of wells tapping only the intermediate aquifers are consistently near the average of 3.3 (gal/min)/ft of drawdown. When the wells are deepened into the Floridan aquifer to various depths between about 540 and 610 feet, the specific capacities increase, but are highly variable. Thus, deepening a well does not necessarily guarantee the

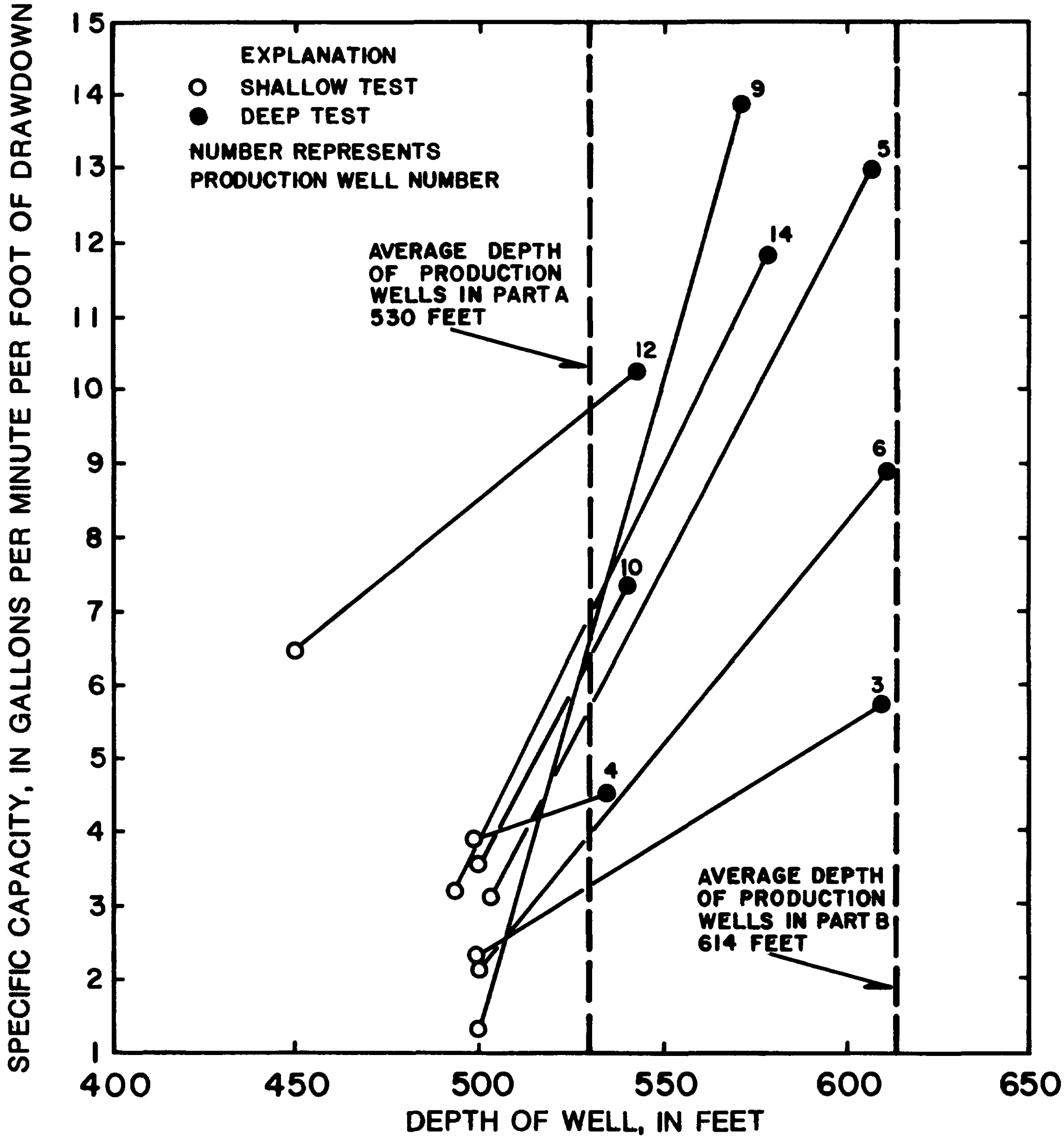


Figure 19.--Changes in specific capacity with depth. (Based on data in Sutcliffe and Buono, 1979.)

same proportion of increase in specific capacity that was observed in another well. The variability is probably related to the solution-riddled nature of the carbonates comprising the Floridan aquifer. If a well happens to penetrate a highly permeable zone associated with a cavity or faulting, then it will have a high specific capacity.

Results of testing at the Verna well field differ somewhat from the tests at Palmer Farms (Stringfield, 1933b). Tests at Verna indicate that the Tampa Limestone and underlying formations are relatively productive compared to the Hawthorn Formation, whereas the tests at Palmer Farms imply that the reverse is true. The Verna results were based on specific-capacity and water-quality data, whereas the Palmer Farms results were based on current-meter tests in flowing wells. The basic difference is that the pumping tests induced a much larger stress (drawdown) on the aquifers, thereby inducing movement of water from the deep zones. If the potentiometric surface of only the shallow zone was above the top of the well casing in a flow test, then upward flow through the well would be derived from that zone only. When the well is pumped, drawdown would occur in both zones, and a proportionately larger quantity of water might be derived from the lower zone if its specific capacity is relatively high. Results of the testing should not be misconstrued. The Palmer Farms test determined the yield of various zones to flowing wells, whereas the Verna tests indicated potential yields of each zone under pumping conditions.

Based on the Verna specific-capacity tests, the relative percentages of water derived from the intermediate and Floridan aquifers can be approximated. Under the assumption that the specific capacity of the intermediate aquifers averages 3.3 (gal/min)/ft of drawdown, the ratio of this specific capacity to that observed in each completed production well is the fraction of water derived from the intermediate aquifers. Figure 20 shows this ratio plotted as a percentage against specific capacity of 28 production wells that were tested at rates between 205 gal/min and 818 gal/min (Sutcliffe and Buono, 1979, p. 119-121). Actual specific-capacity ratios of the eight additional production wells (3, 4, 5, 6, 9, 10, 12, and 14) that were used to compute average specific capacity of the intermediate aquifers were plotted to indicate the degree of scatter of points about the curve.

The graph of figure 20 was used to determine that about 38 percent of the total water from parts A and B is derived from the intermediate aquifers and 62 percent from the Floridan aquifer. Specific capacities of wells in part A are generally lower than in part B, which indicates proportionately more water is derived from the Floridan aquifer in part B. On the average, water pumped from the Floridan aquifer accounts for 57 percent of the production from part A and 80 percent from part B. If the anticipated long-term average pumping rate from the well field is 8 Mgal/d, about 3 Mgal/d would be derived from the intermediate aquifers and 5 Mgal/d from the Floridan aquifer. In part A, about 2.6 Mgal/d would be derived from the intermediate aquifers and 3.5 Mgal/d from the Floridan aquifer. In part B, about 0.4 Mgal/d would be derived from the intermediate aquifers and 1.5 Mgal/d from the Floridan aquifer.

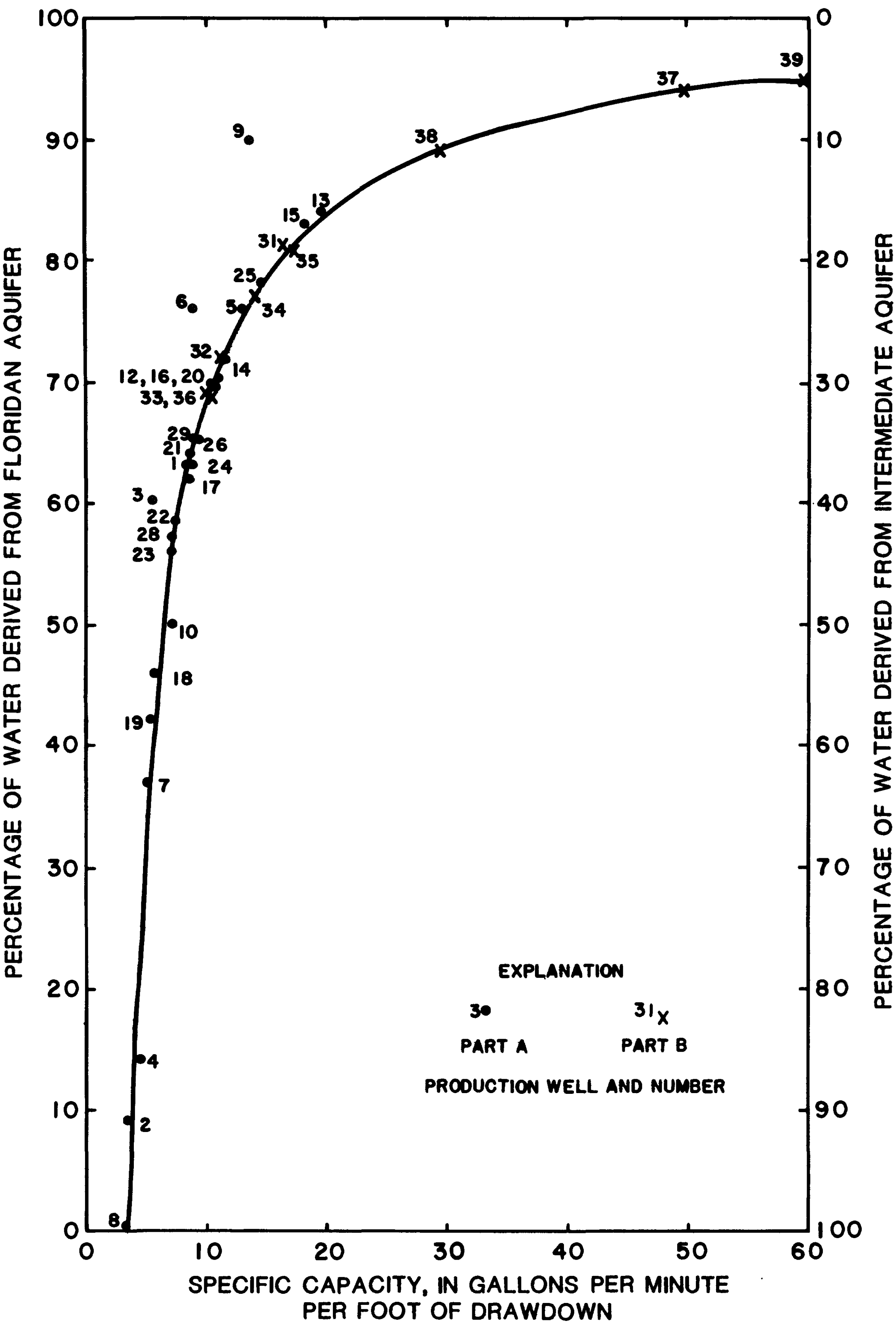


Figure 20.--Relation between percentage of water derived from the Floridan and intermediate aquifers and specific capacities of wells.

GENERALIZED CONCEPTUAL MODEL

Generalized hydrogeologic sections drawn from known and generalized data along nearly east-west lines through the Verna well field are shown in figures 21 and 22. The sections illustrate generalized hydrogeologic conditions that existed before and after development of the well field and surrounding area. Under steady-state predevelopment conditions, the vertical flow of water into or out of each aquifer depended upon relative water levels in the adjacent aquifers. Likewise, the quality of water is partly controlled by flow between aquifers; therefore, potability is head dependent and can be affected by pumping. The vertical scale in each hydrogeologic section is greatly exaggerated, and the vertical component of flow within the aquifers (flow paths represented by arrows) is likewise greatly exaggerated.

Under conditions prior to development, water moved downward from the surficial aquifer through the upper confining bed of the intermediate aquifers east of the Myakka River and within the Verna well field (fig. 21). Some water returned to the surface in topographically low areas, such as river valleys, or flowed laterally toward the Gulf. The remainder of the water continued to flow downward through the intermediate aquifers and confining beds to the Floridan aquifer where flow was generally westward toward the Gulf. North-south flow perpendicular to the section was sluggish under predevelopment conditions. As potable water moved into deep zones in the Floridan aquifer, it dissolved minerals in the rocks and became nonpotable. Along the coastal margins and in the Gulf and Tampa Bay, there was a reversal in relative hydraulic heads, and nonpotable water moved upward from the Floridan aquifer through the intermediate aquifers and confining beds to the surficial aquifer. This upwelling occurred along the Gulf Coast and near the Myakka River where the potentiometric surfaces of the confined aquifers rose above land surface (fig. 21).

Under pumping conditions, flow in the Floridan aquifer in the vicinity of the Verna well field is nearly perpendicular to that under nonpumping conditions (fig. 9). Much predevelopment gulfward flow is captured by pumping for irrigation and industrial supplies in Hillsborough and Manatee Counties. Upwelling of nonpotable water beneath the Myakka River has ceased. This should result in a general freshening of water in the surficial and intermediate aquifers as they now can accept downward leakage. The rate of such freshening has not been verified. Water that has leaked downward into the Floridan aquifer flows north and west toward Verna and the center of irrigation pumping in Hillsborough County. The water is derived from increased lateral inflow of nonpotable water and increased downward leakage of potable water. Pumping induces a rise of the interface between potable and nonpotable water and lateral movement of the interface from the south and west (fig. 22). Although upward movement of nonpotable water along the hydrogeologic sections is generally speculative, it has been documented at the Verna well field.

IMPACT OF PUMPING

A quantitative assessment of the areal impact of pumping at the Verna well field is necessary for proper management and safeguarding of the water resources. Information on the impact of pumping is extremely useful in the planning and design of observation well networks and waste-disposal sites.

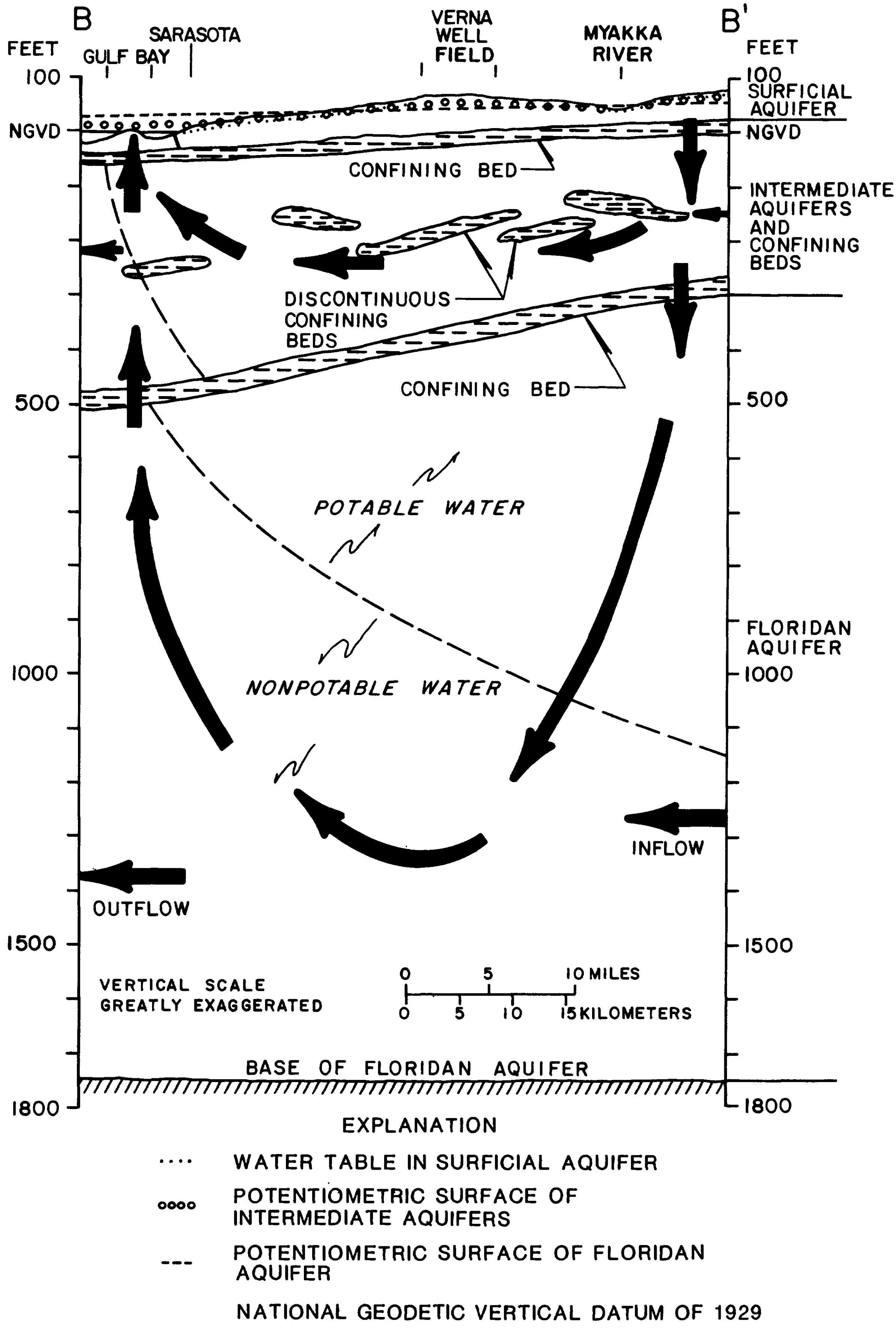


Figure 21.--Generalized hydrogeologic section showing steady-state ground-water flow conditions prior to development. (Line of section shown in figure 9.)

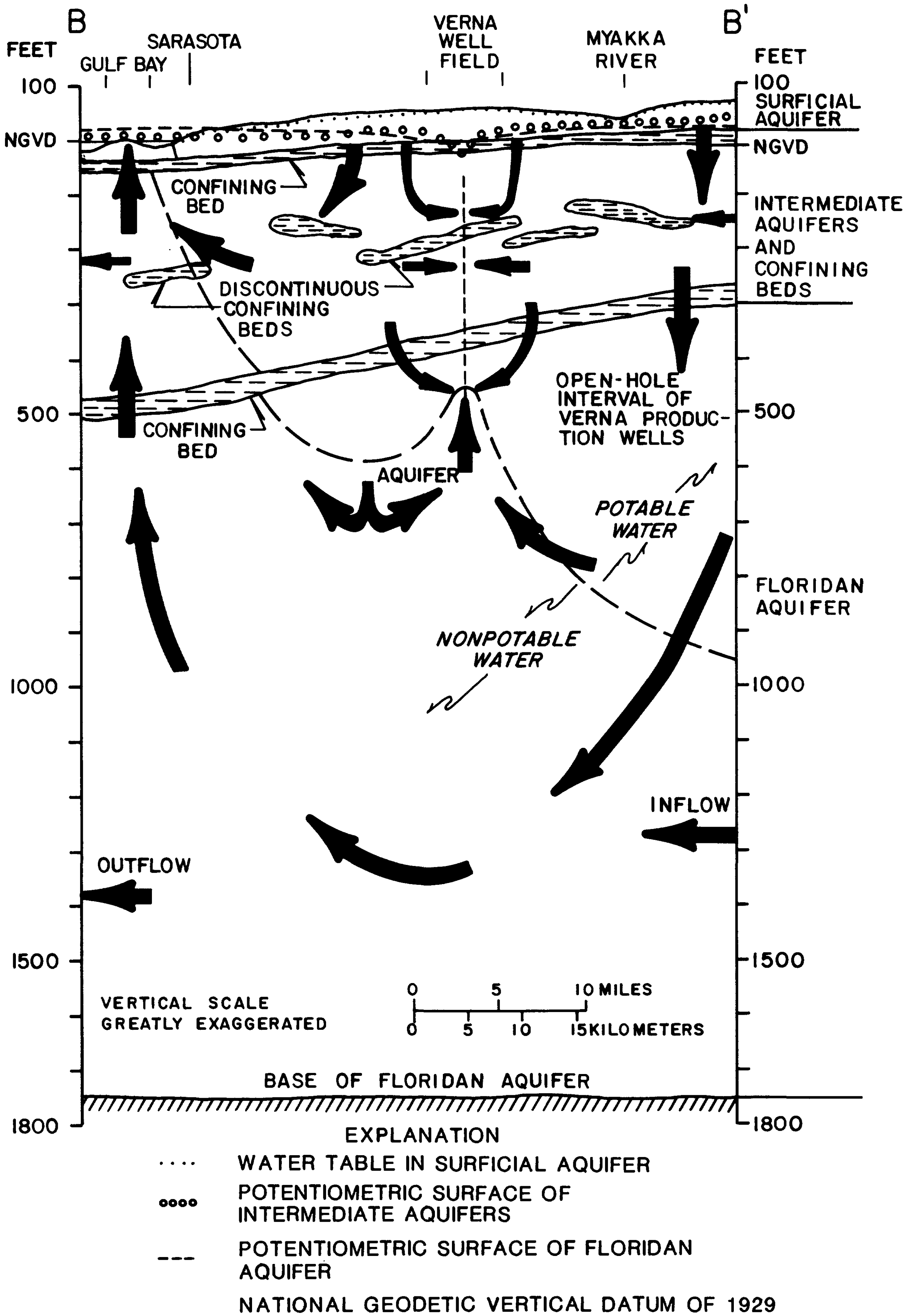


Figure 22.--Generalized hydrogeologic section showing steady-state ground-water flow under pumping conditions. (Line of section shown in figure 9.)

Water-level declines caused by pumping at the Verna well field are large. Because of the complexity of the hydrologic system, however, the effects of pumping are difficult to quantify. Areal and vertical distributions of head within each aquifer are not known. Production wells tap the intermediate aquifers and partially penetrate the Floridan aquifer. There is a regional variation of water levels in the Floridan aquifer of several feet in response to seasonal pumping for irrigation.

Pumpage is replenished by altering, with respect to background levels, inflow to or outflow from the producing zone. Although some lateral and upward movement of water from deep within the Floridan aquifer occurs, the pumped water is ultimately derived by increasing downward leakage and reducing upward leakage through the upper confining bed of the intermediate aquifers and confining beds. The area over which leakage changes is determined by the extent of the cone of depression around the pumping center. The change in leakage that is caused by the change in head results in a decline of the water table in the surficial aquifer. Because the surficial aquifer has remained nearly full with no long-term decline in the water table, leakage from the aquifer most likely is being replenished by increasing recharge to or reducing evapotranspiration from the water table. Under extreme conditions, these phenomena may be detected, in that increased recharge would result in reduced runoff, and reduced evapotranspiration would alter the vegetal cover.

Pumping impacts on the intermediate aquifers are most readily assessed by determining the shape of the cone of depression under anticipated long-term average pumping conditions. A mathematical assessment of the impact of pumping from the intermediate aquifers was made using the following assumptions:

1. The anticipated average daily pumpage is derived from changes in leakage.
2. Water levels in the underlying Floridan aquifer are drawn down in the pumping wells to about the same levels as those in the intermediate aquifers; therefore, leakage through the intervening confining bed is not significant.
3. The Verna well field contains three pumping centers; one in each half of part A and one in part B.
4. The well field contains 38 wells that tap the intermediate aquifers, and a 39th well that taps only the Floridan aquifer; 15 in the western half of part A, 14 in the eastern half of part A, and 9 in part B.
5. All wells produce 142 gal/min; however, wells in parts A and B derive 43 percent and 20 percent of their respective production water from the intermediate aquifers. Total production is 916 gal/min from part A west, 855 gal/min from part A east, and 256 gal/min from part B. When the well field is pumped at 8 Mgal/d, about 3 Mgal/d is derived from the intermediate aquifers.
6. Transmissivity of the intermediate aquifers is the total of that for the Tamiami-upper Hawthorn aquifer (825 ft^2/d) and the lower Hawthorn-upper Tampa aquifer (800 ft^2/d), or about 1,600 ft^2/d, and leakance coefficient of the upper confining bed is $2x10^{-5}$ (ft/d)/ft.
7. Steady-state conditions are represented with no further water-level declines or changes in ground-water storage.

8. Drawdown around each pumping center can be computed using a modified equation of Steggewentz and Van Ness (1939) for "steady-state radial flow in an isotropic leaky artesian aquifer with fully penetrating wells without water released from storage in aquitards and constant-discharge," by:

$$s = \frac{Q}{2 T} K_o \, (r/B) \qquad (1)$$

where $r/B = \frac{r}{T/(k'/b')}$;

s = drawdown, in feet;

r = distance from pumped well to observation point, in feet;

Q = discharge, in cubic feet per day;

T = transmissivity, in feet squared per day;

k'/b' = leakance coefficient, in feet per day per foot;

K_o = the modified Bessel function of the second kind of zero order.

Values of $K_o(r/B)$ in terms of the practical range of r/B are presented in Hantush (1956).

The cone of depression that would develop in the intermediate aquifers under the above conditions is shown in figure 23. Drawdown would be more than 1 foot over a 90-mi^2 area and more than 20 feet over a 6-mi^2 area. The computed change in leakage rate averages 0.6 in/yr over the 90-mi^2 area, but would be much higher within the well field. The computed drawdown near the western boundary of the well field is about 20 feet. The actual average drawdown observed in exploration test well E2 (fig. 5), represented by the difference in average water level between 1966 and 1981, is about 20 feet. However, this well taps both the intermediate aquifers and the Floridan aquifer, so it is not truly representative of the intermediate aquifers. The computed drawdown in the center of the well field is about 30 feet. The average observed water level in observation well 0-3 during a period when pumping averaged about 8 Mgal/d (fig. 6) is about 5 feet above sea level, which represents a drawdown of about 30 feet. Well 0-3 also taps the Floridan aquifer. The reasonably close match between computed and observed water-level declines verifies the combination of regional values of transmissivity and leakance coefficient of the intermediate aquifers. Although the computed water levels correspond to field observations, errors could result from using observation wells open to multiple aquifers for comparison purposes.

The map of drawdown shown in figure 23 can be used to evaluate regional impact, such as the areal spread of the cone of depression. Local impact may also be evaluated. For example, a well located 3 miles north of the well field could expect a 10-foot drawdown due to pumping at Verna.

The impact of pumping from the Floridan aquifer at the Verna well field was not evaluated. Too little is known of the hydraulics of the Floridan aquifer at the site. The production wells tap only the upper 100 to 200 feet of a 1,300-foot thick anisotropic aquifer, which contains much nonpotable water. There is probably a large vertical component of flow caused by partial penetration of the aquifer that cannot be computed. Drawdown in the Floridan aquifer is similar to

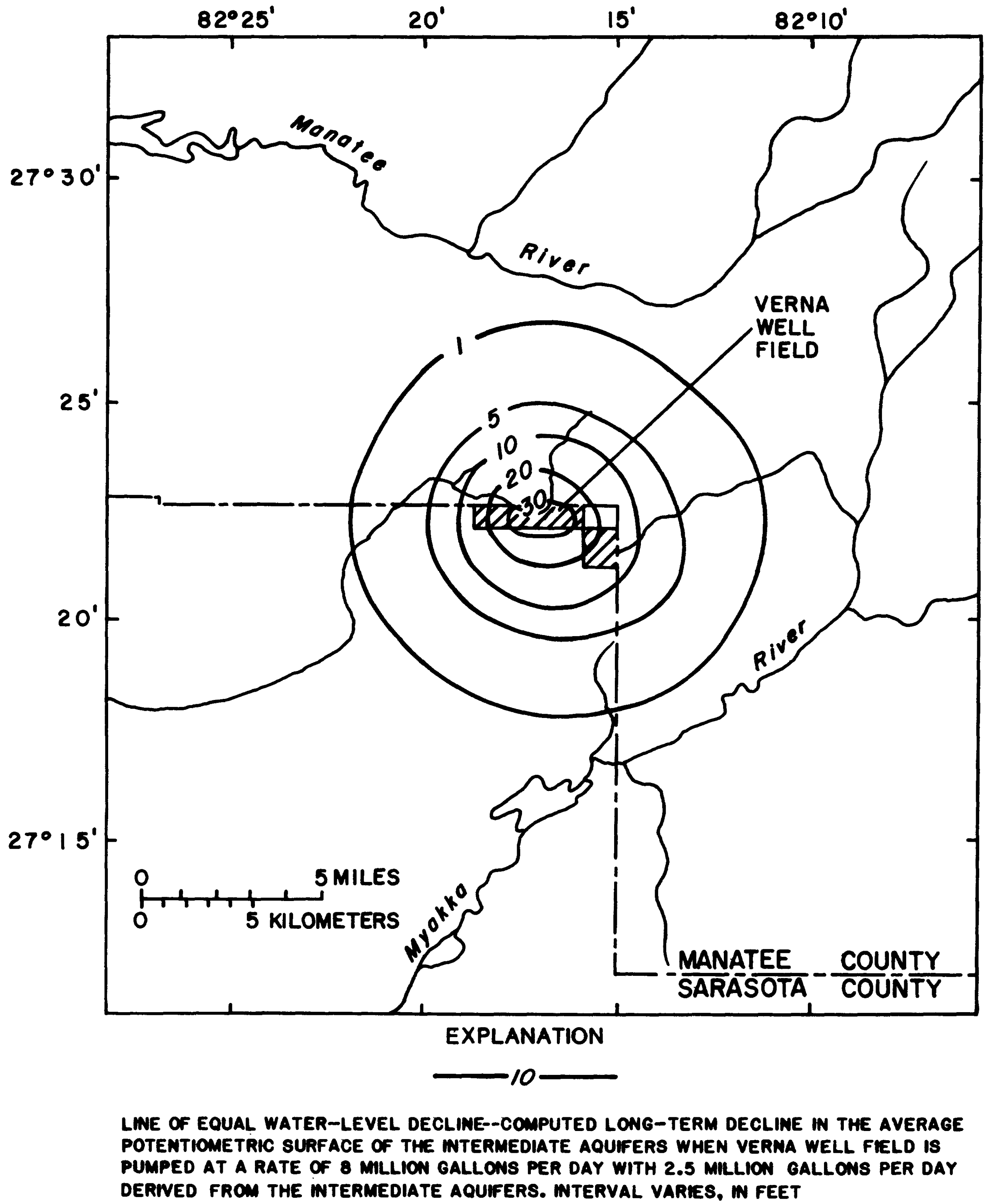


Figure 23.--Computed drawdown in the intermediate aquifers due to pumping the Verna well field at the anticipated long-term average rate.

drawdown in the intermediate aquifers. This similarity is reflected by water levels in the drain well and observation well 0-3 (fig. 6). It should be noted, however, that observation well 0-3 taps multiple aquifers and that water levels in the Floridan aquifer are influenced by regional pumping for irrigation in addition to pumping at the Verna well field.

GROUND-WATER MANAGEMENT

Rainfall averages 56 in/yr, yet little of this water seeps into the producing aquifers. With an evapotranspiration rate of about 39 in/yr and runoff of 15 in/yr, only about 2 inches leaks downward. If the pumping rate is 8 Mgal/d, this amounts to 56 in/yr of water over the 3-mi^2 well field. Clearly, all the rainfall cannot be captured by pumping, so there must be a resultant impact on water resources adjacent to and in the well field.

Development of additional supplies from the intermediate aquifers and Floridan aquifer would further increase the deficit between leakage and pumpage within the well-field boundaries. Increased pumping would result in additional drawdown beyond the well-field boundaries, greater interference between production wells, and further degradation of water quality. A feasible method is needed for managing runoff and evapotranspiration.

Thoughtfully planned water management can salvage runoff and evapotranspiration, minimize drawdown at the boundaries of the well field, increase the supply, and improve water quality. Management alternatives considered here include:

1. Constructing a network of connector wells that would allow water captured from runoff and evapotranspiration to drain by gravity from the surficial aquifer into the producing zone.
2. Developing computer models of ground-water flow and solute transport to optimize the yield and quality of water from the well field.
3. Constructing monitoring wells that can be utilized for model development or direct management of the resources.

Probable Impacts of Connector Wells

Pumping from the Verna well field has a significant effect on the hydrologic system. Deep, extensive cones of depression have developed in the intermediate aquifers and Floridan aquifer, and sulfate-rich water has moved upward into the producing zone. The surficial aquifer is not significantly affected by pumping and is an untapped source of water supply that has excellent quality. If the water table could be systematically lowered, conceivably 25 percent of the runoff (4 in/yr) plus the residual between actual and minimum evapotranspiration (4 to 14 in/yr) could be salvaged for public use. If 10 in/yr could be salvaged, this would total about 1.4 Mgal/d. Because the transmissivity of the surficial aquifer is low, many production wells would be required to pump small quantities of water, which would be impractical. Connector wells may be a feasible means for conveying these waters to the intermediate aquifers and Floridan aquifer to increase the yield of the well field through the existing production wells and reduce drawdown in the producing zone.

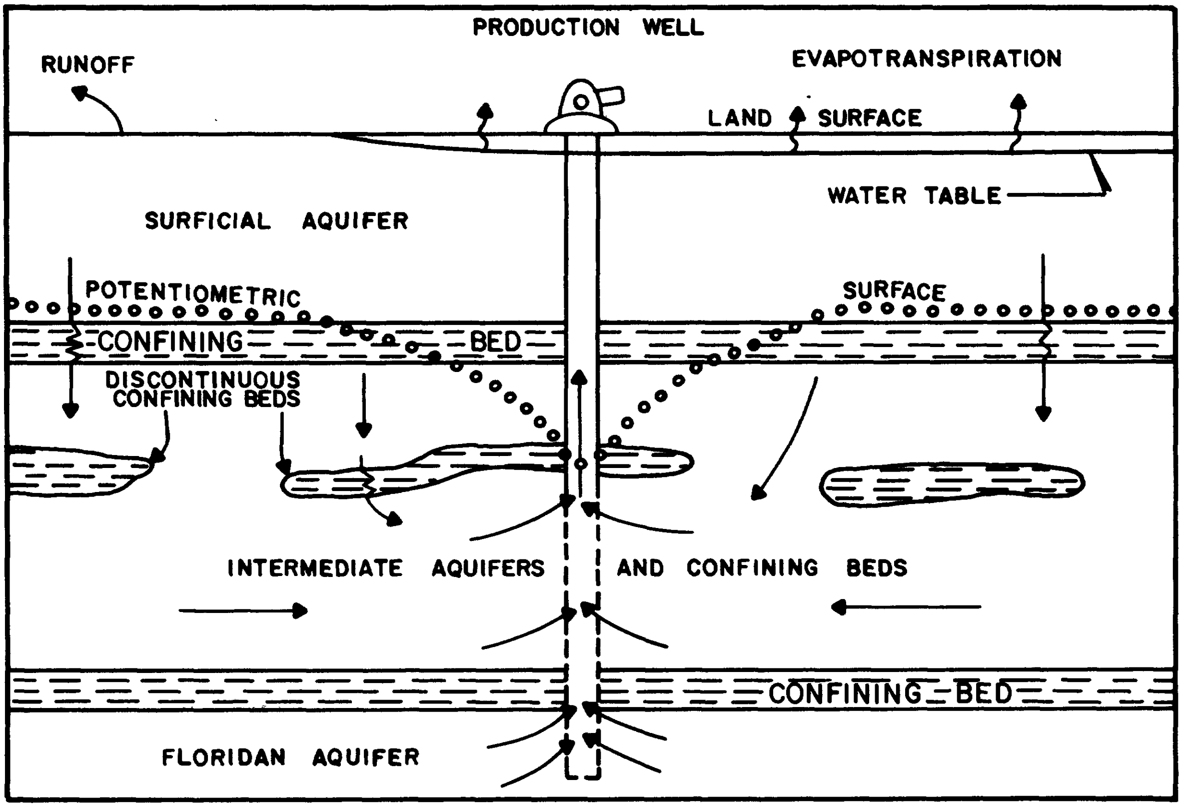
Aquifer recharge through connector wells became a common practice in the central Florida phosphate area during the 1970's. The Verna well-field area has a similar hydrogeologic setting; therefore, it is a potentially favorable site for installing connector wells. The concept involves drilling wells that are open to the surficial aquifer and the intermediate aquifers, thereby providing a direct hydraulic connection between them (fig. 24). Because a positive head difference exists between the surficial and intermediate aquifers, water would drain by gravity from the surficial aquifer into the permeable zones below. The purpose for installing such wells is threefold: (1) connector wells would introduce water of excellent quality into the producing zone and lower the dissolved solids of pumped water, (2) more water could be pumped, and (3) drawdown in the intermediate aquifers and Floridan aquifer caused by pumping at current rates would be reduced.

As water from the surficial aquifer flows downward through the connector well, the water table declines. This decline reduces evapotranspiration and creates additional storage in the aquifer allowing a greater volume of water to infiltrate, thus capturing water that would have run off or been lost to evapotranspiration. For this to occur, the water table under natural conditions must be at or near land surface so that at least part of the evapotranspiration loss represents water withdrawn from the saturated zone, and also, so that at least part of the runoff represents water that could not infiltrate the ground because the surficial aquifer was full. If the water table is always several feet below land surface, the lowering of the water table by artificial means would nocrease infiltration--and, hence, would not reduce overland runoff--and probably would cause little or no reduction in evapotranspiration. Under such conditions, capture would occur mostly or entirely in the form of a decrease in ground-water discharge into streams.

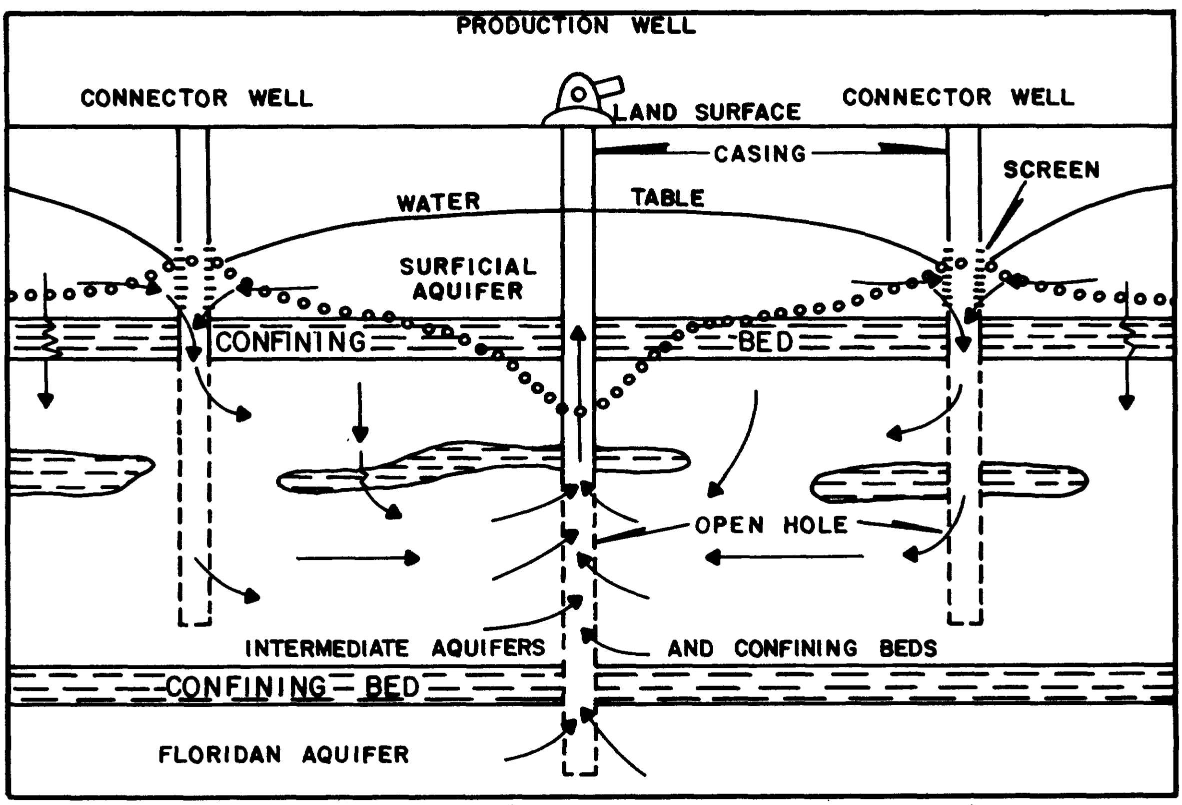
The water table is near land surface based on all measurements of water levels in wells in the surficial aquifer. During the dry spring months, the water table is at its lowest level, about 8 feet below land surface. During the wet summer months, the aquifer becomes fully saturated and the water table is at or just below land surface. Thus, a wide-scale lowering of the water table by use of wells that tap the surficial aquifer offers potential for capturing water by reducing evapotranspiration and overland runoff and by decreasing the amount of ground-water discharge to streams.

For the 3-mi^2 Verna well-field area, the quantity of water represented by capture of 10 in/yr would equal about 1.4 Mgal/d, about 20 percent of the anticipated long-term average pumping rate from the well field. On an annual basis, this represents 5 percent of the 10 billion gallons stored in the surficial aquifer. By blending 1.4 Mgal/d of water from the surficial aquifer (dissolved-solids concentration of 150 mg/L) with 6.6 Mgal/d of water from the producing zone (dissolved-solids concentration of 820 mg/L), the average dissolved-solids concentration of the product water should decrease from 820 to about 700 mg/L. Further improvement in quality and quantity of water could be obtained by installing connector wells adjacent to the well field. Development of a surficial aquifer-intermediate aquifers connector-well network could alleviate pumping stresses on the Floridan aquifer and improve quality of the pumped water.

An assessment of the feasibility of a connector-well network at the Verna well field would require broad-scope investigations that would: (1) establish how overland runoff and evapotranspiration vary with depth to the water table;



PUMPING WITHOUT CONNECTOR WELLS



PUMPING WITH CONNECTOR WELLS

Figure 24.--Generalized hydrogeologic section showing ground-water conditions without and with connector wells.

(2) determine where and how long the water table is close enough to land surface so that a reduction in overland flow and evapotranspiration could be expected to result from a lowering of the water table; (3) define more accurately the natural leakage of shallow ground water into the intermediate aquifers and the extent that natural leakage would be reduced by decreasing the vertical head gradient across the upper confining bed and, hence, establish whether artifically recharging the intermediate aquifers with shallow ground water could produce a significant gain in recharge; (4) evaluate environmental impacts at various levels of withdrawal of shallow ground water; and (5) assess the cost effectiveness of the network. Prior to installing the connector-well network, tests need to be made of the water quality in the surficial aquifer and drainage ditch. Based on the tests, an assessment can be made of the potential for degradation of the community water supply by trace metals, pesticides, microbiological contaminants, and radionuclides.

A practical method for evaluating the effectiveness of connector wells is to install a network and observe the response of the aquifers. Various spacing could be tested, or the test limited to only part of the well field. One feasible plan might be to install a network of several wells spaced 1,500 feet apart. The capture of runoff and evapotranspiration could be computed from measurements of recharge rate and effective drawdown using analytical techniques developed by Papadopulos and Cooper (in Knochenmus, 1975, p. 24-28). Installation of a network of connector wells at the Verna well field would determine if:

1. The concentration of dissolved solids in water in the producing zone would be reduced.

2. There would be less drawdown around the well field.

3. Hypotheses concerning the feasibility of a connector-well network could be substantiated.

Computer Modeling

Improved management of ground-water resources in the Verna well-field area might be attained through utilization of digital computer models of ground-water flow and solute transport. A model of ground-water flow could be used by water managers to:

1. Optimize pumping distributions to minimize drawdown at the well-field boundary.

2. Assess the effects of projected increases in regional irrigation and industrial pumpage from the deep Floridan aquifer on the shallower resources at Verna.

3. Calculate hydrologic budgets of inflow to and outflows from aquifers under natural (nonpumping) and stressed (pumping) conditions.

A ground-water flow model requires accurate determinations of head and pumping rates from each aquifer, hydraulic parameters for each aquifer and confining bed, and a knowledge of boundary conditions.

A model of solute transport contains the same elements as a flow model, but also requires information on the vertical, areal, and temporal distribution of water-quality parameters. Such a model could be used to estimate future changes in water quality that result from upconing of sulfate-rich water when the well field is pumped at various rates.

The impact of expanding the Verna well field could be evaluated using flow and transport models. The well field already contains many closely spaced wells and the water quality is deteriorating; therefore, the long-term outlook for developing large additional quantities of water from the existing property is not very promising. Development and testing of a model and the associated data collection would be costly. One of its main applications would be to optimize the distribution of pumping so that yield is maximized and mineralization is minimized. This might result in a reduction in pumping rates at the well field when nearby irrigation and industrial withdrawal rates are increased. Typically, this occurs during the dry season when maximum quantities of water are required for all uses. Optimization of pumping may be achieved more practically through maintenance of a monitoring network that would physically detect changes in water levels and quality in each aquifer under various distributions of pumping.

Monitoring Network

A well-designed ground-water monitoring network could supply the needed data base for developing a model of the Verna well-field area or for direct management of ground-water resources. As of 1982, monitoring consisted of:

1. Semiannual water-level measurements in all wells and nonpumping production wells shown in figure 2.
2. Continuous water-level recorders on the Tamiami-upper Hawthorn aquifer test well S14; exploration test wells E2, E10, E11, and E13; water-table well W9; the drain well; and observation wells 1A, 0-1, 0-2, 0-3, and 0-4.
3. Bimonthly water-level measurements on water-table wells W2 and W11.
4. Biannual water-quality samples from the drain well and all pumping production wells.
5. Monthly water levels and water-quality samples from production wells 1, 7, 14, 19, 24, 29, 35, and 37.

The existing network adequately monitors conditions in the producing zone where water levels and water quality represent composite values from multiaquifer systems. There are not any wells that measure head or quality of water solely from the lower Hawthorn-upper Tampa aquifer. The way in which water levels and quality change with depth to the base of the Floridan aquifer is also unknown.

An ideal monitoring network would consist of clusters of closely spaced wells spread evenly in and around the well field. Each well in the cluster would tap a single zone--the surficial aquifer, Tamiami-upper Hawthorn aquifer, lower Hawthorn-upper Tampa aquifer, upper part of the Floridan aquifer, and lower part of the Floridan aquifer. Head and water-quality data obtained from such a network could be used to develop ground-water flow or solute-transport models. The network would be useful from a water-management standpoint in that observed changes in head could be used to optimize the distribution of pumping to minimize energy requirements. It would act as an early-warning system for detecting upward movement of poor quality water from the lower part of the Floridan aquifer.

CONCLUSIONS

The appraisal of ground-water resources and management alternatives at the Verna well field has been directed toward the following questions:

1. <u>What are the hydrogeologic conditions in the Verna well-field area?</u>--The Verna area has a 60-foot thick layer of fine sand that forms a low-yielding surficial aquifer. Underlying the surficial aquifer is a 360-foot thick series of moderately transmissive sandy limestone aquifers that are separated by discontinuous confining beds, referred to as the intermediate aquifers and confining beds. Underlying the intermediate aquifers and confining beds is the Floridan aquifer, a highly transmissive section of limestone and dolomite that is about 1,300 feet thick.

   The Verna well field contains 39 production wells, one of which taps only the Floridan aquifer. The other 38 wells tap the lower two-thirds of the intermediate aquifers and the upper 100 to 200 feet of the Floridan aquifer. The anticipated long-term average pumping rate from the well field is 8 Mgal/d, of which about 3 Mgal/d is from the intermediate aquifers and 5 Mgal/d from the Floridan aquifer.

   Head relations indicate that water percolates downward from the surficial aquifer to the intermediate aquifers. In the Floridan aquifer, sulfate-rich water moves laterally and upward toward the zone tapped by the production wells. In addition to stresses imposed by pumping the Verna well field, the Floridan aquifer is also affected by large seasonal withdrawals of water for irrigation in the region around the well field.

2. <u>What effect has the Verna Well field had on ground-water levels and quality?</u>--Pumping from the Verna well field has resulted in water-level declines and changes in water quality. Based on hydrograph analysis, pumping has had little effect on the water table in the surficial aquifer. In 1964, prior to construction of the well field, the composite potentiometric surface of the producing zone was about 30 feet above sea level. In May 1982, the potentiometric surface was below sea level over most of the well field. This level reflected the effects of local pumping and regional pumping for irrigation.

   Computed declines in the potentiometric surface of the intermediate aquifers, based on a pumping rate of 8 Mgal/d, are more than 1 foot over a 90-mi^2 area and more than 20 feet over a 6-mi^2 area. The reasonably close match between computed and observed water-level declines verifies the combination of values for the hydraulic properties of the intermediate aquifers. The impact of pumping from the Floridan aquifer was not evaluated because of uncertainties associated with partial penetration of the 1,300-foot thick, anisotropic aquifer by the production wells.

The sulfate concentration of water in the producing zone in part A of the well field has increased from an average background level of about 200 mg/L in 1965-66 to about 400 mg/L in 1982. In part B, the sulfate concentration increased from about 300 mg/L in 1965-66 to 350 mg/L in 1982. This indicates sulfate-rich water is being drawn upward from the lower part of the Floridan aquifer by the production wells in both parts of the well field. The trend of increasing sulfate concentrations roughly parallels increases in pumping rates from 5 Mgal/d in 1966 to 8 Mgal/d in 1982.

3. What are some feasible water-resources management alternatives for improving yield and quality of water from the well field?--Water-management techniques can be employed to salvage runoff and evapotranspiration, minimize drawdown at the boundaries of the well field, increase the supply, and improve water quality. Methods evaluated in this report include installing a network of wells that connect the surficial aquifer and intermediate aquifers, modeling of ground-water flow and solute transport, and maintenance of a ground-water monitoring network.

A network of connector wells open to the surficial aquifer and intermediate aquifers would allow water to drain by gravity from the surficial aquifer into the intermediate aquifers. The network would effectively increase recharge to the producing zone, thereby reducing drawdown (and ultimately, the size of the cone of depression) and improving water quality. It was estimated that if 1.4 Mgal/d of good quality water could be salvaged from runoff and evapotranspiration and be recharged through a network of connector wells, the dissolved-solids concentration of the product water would decrease from about 820 to 700 mg/L.

Computer models of ground-water flow and solute transport could be developed for the Verna well-field area. Ideally, models could be used to optimize the distribution of pumping in order that the desired amount of water is obtained with the lowest mineralization. Conversely, if specific water-quality criteria are to be met, models could be used to determine the distribution of pumping that maximizes yield yet still meets the quality requirements. Models can be used as tools for assessing how nearby irrigation pumping affects the well field and the effects of developing large additional quantities of water from the existing property. The outlook for such development is not very promising though because pumping already has resulted in large cones of depression and degradation of water quality. Additional data on hydrologic characteristics of the Tamiami-upper Hawthorn aquifer and the Floridan aquifer would be needed to develop models capable of these tasks.

The existing monitor-well network is suitable for observing conditions in the producing zone. A revised network could be used to detect vertical, areal, and temporal changes in water levels and water quality in each aquifer. It could be used to signal adverse impacts of pumping, such as increases in sulfate concentrations. Information gained through an improved monitoring network could serve as a useful data base for developing models for managing ground-water resources.

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