80-60 EVALUATION OF A CAVITY-RIDDLED ZONE OF THE SHALLOW AQUIFER NEAR RIVIERA BEACH, PALM BEACH COUNTY, FLORIDA 80-60

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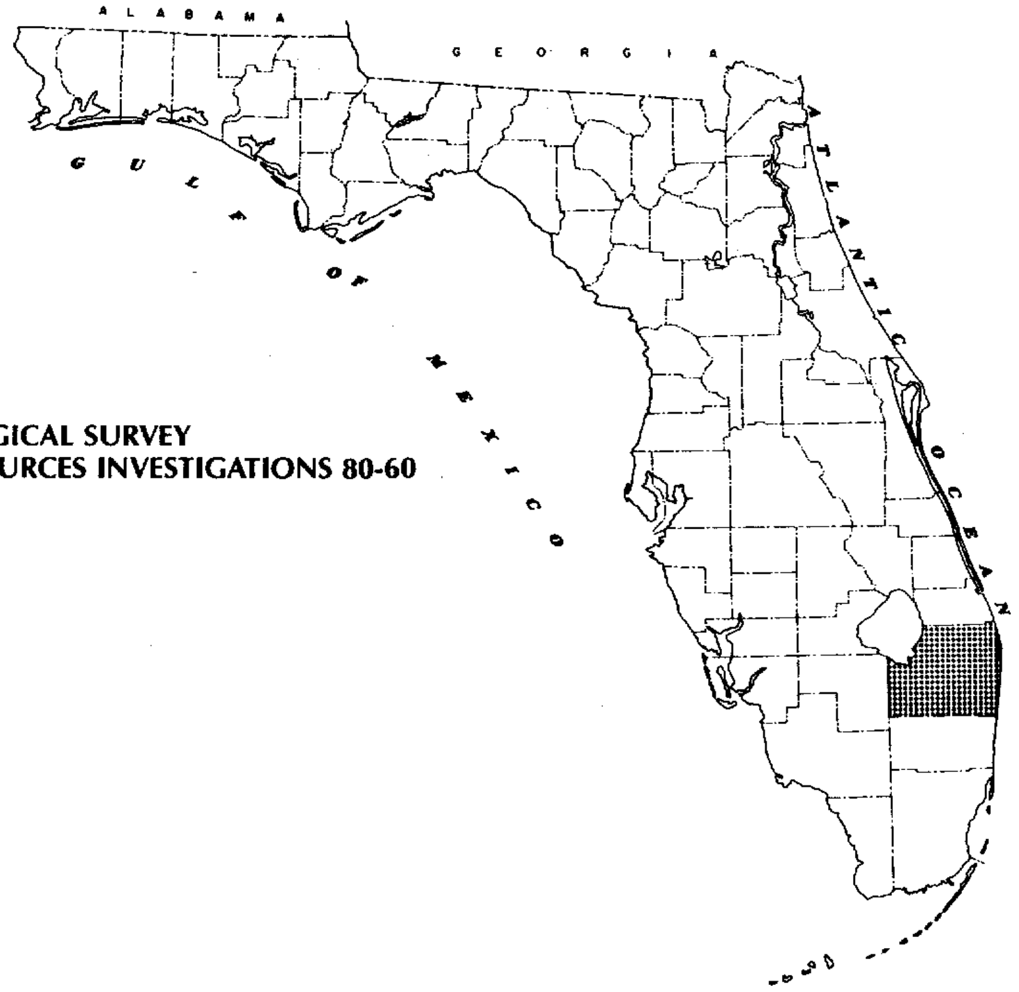

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS 80-60

Prepared in cooperation with

PALM BEACH COUNTY BOARD OF COMMISSIONERS
SOUTH FLORIDA WATER MANAGEMENT DISTRICT
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The shallow aquifer near Riviera Beach contains a cavity-riddled zone extending north and south about 5 miles inland from the Atlantic Ocean. The zone lies approximately 60 feet below land surface and varies from 15 to 50 feet in thickness. It is approximately 3 miles in width.

Aquifer material is calcareous quartz sandstone in the cavity zone, whereas the remainder of the consolidated aquifer material is primarily limestone. Most cavities are partly sand filled. The zone is overlain by several thin clay beds which provide varying degrees of confinement. The transmissivity of the cavity zone of the aquifer in the area of investigation is approximately 11,000 square feet per day. Water in the cavity zone is of suitable quality for public supply except in an area near a landfill where leachate has adversely affected water quality.

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1980

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

Page

Conversion factors-- v
Abstract-- 1
Introduction-- 1
    Purpose and scope------------------------------------- 2
    Acknowledgments--------------------------------------- 2
Previous investigations----------------------------------- 3
Area description-- 3
    Location-- 3
    Land use-- 3
    Climate--- 5
    Topography-- 5
    Geology--- 5
    General hydrology------------------------------------- 7
Aquifer evaluation-- 9
    Surface-resistivity and borehole geophysical data------ 9
    Aquifer description----------------------------------- 12
    Aquifer characteristics------------------------------- 22
    Water quality--- 29
Summary and conclusions----------------------------------- 37
References-- 38

ILLUSTRATIONS

Figure 1. Map of Palm Beach County, Florida showing area of investigation, surface-water features, and well PB-109-------------------------------- 4

2. Long-term hydrograph, well PB-109---------------- 8

3. Map showing surface-resistivity data collection sites-- 11

4. Map showing location of geologic test holes and sections------------------------------------- 13

5. Geologic section of the shallow aquifer from west to east (line A-A', figure 4) showing lithology and surface resistivity versus depth at an electrode spacing of 90 feet------------- 15

6. Geologic section of the shallow aquifer from north to south (line B-B', figure 4)----------- 16

7. Natural gamma log and lithology of test hole, PB-1026-- 19

ILLUSTRATIONS (Continued)

Page

Figure 8. East-west boundaries of the cavity zone---------- 21

9. Map showing aquifer test site and well locations-- 23

10. Aquifer test response curve---------------------- 27

11. Potentiometric contours, March 7, 1979----------- 28

12. Map showing water-quality sampling wells--------- 31

13. Map showing the specific conductance of ground water from cavity zone------------------------ 34

TABLES

Table 1. Geologic formations and water-bearing characteristics--------------------------------- 6

2. Water levels at Control no. 225, West Palm Beach catchment basin and in well PB-944-------------- 10

3. Test hole data------------------------------------- 14

4. Driller's log for test hole PB-1065--------------- 18

5. Aquifer test drawdown data for wells located 30 feet from the pumped well---------------------- 25

6. Water-quality data from observation wells--------- 32

7. Specific conductance, dissolved solids, and ammonia nitrogen from wells PB-940 through PB-943-- 35

CONVERSION FACTORS

For those readers who may prefer to use metric (SI) units rather than inch-pound units, the conversion factors for the terms used in the report are listed below:

Multiply inch-pound unit	By	To obtain metric (SI) unit
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.0929	square meter (m^2)
cubic foot (ft^3)	0.0283	cubic meter (m^3)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	0.003785	cubic meter (m^3)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
mean sea level (msl)	-------	National Geodetic Vertical Datum of 1929 (NGVD of 1929)

EVALUATION OF A CAVITY-RIDDLED ZONE OF THE SHALLOW AQUIFER NEAR RIVIERA BEACH, PALM BEACH COUNTY, FLORIDA

By John N. Fischer, Jr.

ABSTRACT

The shallow aquifer near Riviera Beach contains a cavity-riddled zone extending north and south about 5 miles inland from the Atlantic Ocean. The zone lies approximately 60 feet below land surface and varies in thickness from 15 to 50 feet. It is approximately 3 miles in width.

Aquifer material is calcareous quartz sandstone in the cavity zone, whereas the remainder of the consolidated aquifer material is primarily limestone. Most cavities are partly sand filled. The zone is overlain by several thin clay beds which provide varying degrees of confinement. The transmissivity of the cavity zone of the aquifer in the area of investigation is approximately 11,000 square feet per day. Water in the cavity zone is of suitable quality for public supply, except in an area adjacent to a landfill where leachate has adversely affected water quality.

INTRODUCTION

The population of Palm Beach County increased from 412,000 in 1971 to 557,000 in 1977, a growth of more than 35 percent (G. Hines, Palm Beach County, West Palm Beach, Florida, oral commun., January 23, 1980). Freshwater pumpage for municipal supplies over the same period increased by 32 percent (W. L. Miller, U.S. Geological Survey, Miami, Florida, oral commun., January 2, 1979). Similar trends are expected in the future. Coastal municipalities have met increased demands for freshwater in the past by augmenting pumping rates from existing well fields located near the coast. However, a recent report by the U.S. Geological Survey (Scott and others, 1977) stated that saltwater intrusion into the shallow aquifer is occurring near these well fields due in part to increased freshwater withdrawals. Therefore, the practice of increasing pumpage from coastal wells to meet rising demand is not a practical solution. Alternate sources of freshwater may exist farther inland where the threat of saltwater intrusion is reduced. This report discusses a zone within the shallow aquifer which may provide such a source.

National Geodetic Vertical Datum of 1929 (NGVD of 1929) is used as reference elevation in this report. For all intents and purposes, NGVD is equivalent to mean sea level (msl).

Purpose and Scope

The investigation of the shallow aquifer in Palm Beach County was prompted by the reports of Rodis and Land (1976) and Land (1977), both of which refer to a highly transmissive, cavity-riddled zone (henceforth referred to in this report as the "cavity zone") within the aquifer. Rodis and Land described the zone as offering "excellent potential for the development of future ground-water supplies." Because of saltwater intrusion problems into existing coastal well fields, this statement prompted the County Board of Commissioners, South Florida Water Management District, and Riviera Beach City Commission to enter into a joint program with the U.S. Geological Survey to evaluate the ground-water resources of the area. With this objective in mind, an investigation was designed to: (1) define the areal extent, thickness, and lithology of the cavity zone within the study area; (2) define the hydrologic characteristics of the zone; and (3) assess the impact of solid-waste disposal on ground-water quality within the zone. A subsidiary objective was to evaluate the application of surface-electrical resistivity data to hydrologic investigations in south Florida.

Acknowledgments

The interest and support of the Palm Beach County Board of Commissioners were vital to the success of this investigation and are gratefully acknowledged. Herbert Kahlert and Fred Singer, County Engineer and Assistant Engineer, respectively, contributed in many ways to the achievement of investigation goals. The County Road and Bridge Department, directed by Thomas Slider, provided equipment, material, and personnel for field tests during the investigation.

Abe Kreitman, Paul Jakob, and Michael Brown of the South Florida Water Management District, furnished important drilling and logging services to the investigation. The City Commission of Riviera Beach provided financial support for the investigation as well as field equipment for the aquifer test.

Many of the investigation data were obtained from wells, test holes, and canals located on private property. The cooperation of the owners and managers of these parcels, particularly Ted Climer and Elmer Holmgren, is appreciated.

PREVIOUS INVESTIGATIONS

Several U.S. Geological Survey reports with direct application to this investigation have been published as a result of investigations supported by Palm Beach County, South Florida Water Management District, the city of Riviera Beach, and the U.S. Geological Survey. A general appraisal of water resources of eastern Palm Beach County was completed by Land and others in 1973. A report on the hydraulic conductivity and water quality of the shallow aquifer in Palm Beach County was published by Scott (1976). In that report Scott refers to a calcareous sandstone with solution cavities in the eastern part of the county. Rodis and Land (1976) located a zone of high permeability in the shallow aquifer in the vicinity of Florida's Turnpike. Land (1977) reported a cavity zone west of Riviera Beach between Military Trail (State Road 809) and the east boundary of the West Palm Beach Water catchment area, 1 mile west of Florida's Turnpike (fig. 1). A map report by Scott and others (1977) showing the extent of saltwater intrusion in Palm Beach County was an important factor in the initiation of this investigation.

AREA DESCRIPTION

Location

Palm Beach County is located in southeastern Florida. Lake Okeechobee in the northwest corner of the county and the Atlantic Ocean, which forms the county's eastern boundary, are principal geographical features. The area of investigation occupies 9 mi^2 in the northeastern part of the county, 5 miles inland from the ocean (fig. 1). This site was selected because it lies within the area underlain by cavity-riddled material reported by Rodis and Land (1976); moveover, the U.S. Geological Survey has other ongoing investigations in the area from which useful data are available. Also, the area encompasses the Dyer Boulevard Sanitary Landfill, and therefore, provided an opportunity to assess the impact of solid-waste disposal on ground-water quality within the cavity zone.

Land Use

Land use in the eastern half of the investigation area consists of single-family housing, light industries, and a golf course. The Dyer Boulevard Sanitary Landfill occupies 160 acres in the center of the investigation area. The landfill is of particular interest because of its potential adverse effect on local ground-water quality. Land is vacant west of Florida's Turnpike. Small canals and ponds exist there, where shell beds have been excavated and sand has been dredged to provide cover for the landfill.

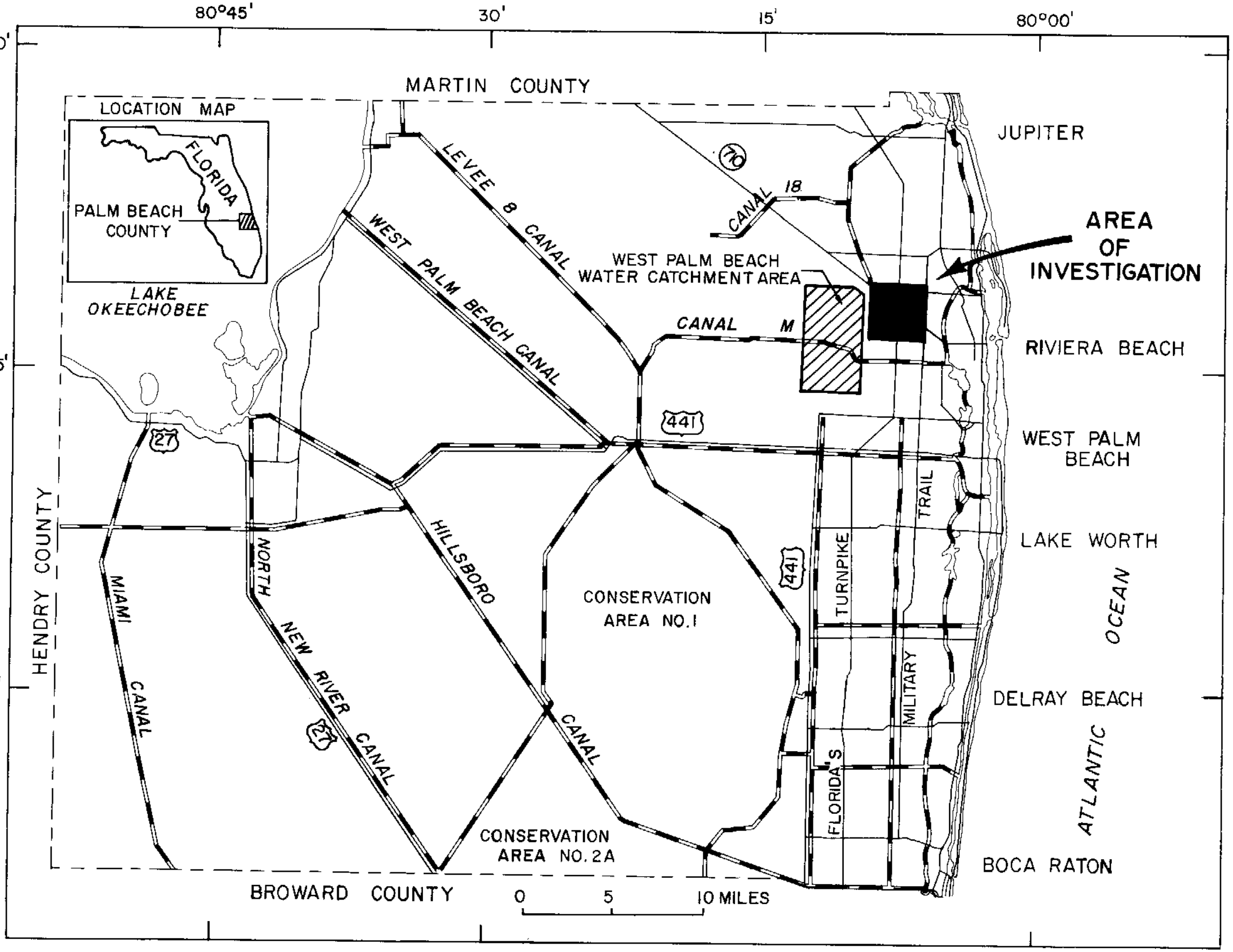

Figure 1.--Palm Beach County, Florida, showing area of investigations, surface-water features, and well PB-109.

Climate

The warm marine climate of Palm Beach County is due to its peninsular location at a semitropical latitude and the proximity of the Gulf Stream. A mean annual air temperature of 72°F (22°C), light but persistent winds, and an average annual rainfall of almost 60 inches characterize the climate. Rainfall is unevenly distributed in time, 70 percent occurring during May through October. An estimated annual average of 14 inches of water reaches the ground-water table; the remainder is lost to evapotranspiration and surface runoff (Land and others, 1973).

Topography

The area of investigation lies within the physiographic region of the Sandy Flatlands. As its name implies, this region is typified by little natural topographic relief. The elevation of the natural land surface ranges from 15 to 18 feet above NGVD of 1929.

Due to the lack of topographic relief, drainage of surface water is generally poor, causing flooding of large areas during the rainy season. Natural drainage patterns have been altered by drainage canals and elevated man-made features, such as major transportation arteries and the Dyer Boulevard Sanitary Landfill. Canal flow is south and east.

Geology

Geologic formations and their water-bearing characteristics within the area of investigation are shown on table 1. Gray to brown Pamlico Sand of Pleistocene age extends to about 12 feet below land surface. It is of medium texture and yields water to sand-point wells, even though small quantities of clay are intermixed.

Broken shells and partly consolidated gray sand underlie the Pamlico Sand and mark the top of the Anastasia Formation, also of Pleistocene age. The Anastasia Formation was formed in a marine environment largely as an offshore bar (Parker and others, 1955). It is composed primarily of gray and tan quartz sand and small marine shells which have been cemented to form a coquina or sandstone. Below 100 feet the formation grades into sandy limestone, interbedded with shells. The base of the Anastasia Formation is about 250 feet below land surface.

Table 1.--Geologic formations and water-bearing characteristics

Series	Formation	Depth	Lithology	Water-bearing characteristics
Pleistocene	Pamlico Sand	0-12	Fine quartz sand, gray to dark brown.	Yields water to small domestic wells.
Pleistocene	Anastasia Formation	12-250	Interbedded coquina, gray sand, calcareous sandstone and sand limestone. Cavity riddled in sections.	Primary local aquifer. Provides freshwater for both municipal and industrial use.
Pliocene	Tamiami Formation	250-330	Creamy-white limestone, greenish-gray clay, and marl.	Occasional yields from 10-30 gal/min in upper few feet.
Miocene	Hawthorn Formation	330-800	Sandy phosphatic marl, interbedded with clay, shell marl, silt, and sand.	Limited artesian water. Main confining bed of Floridan aquifer.
Miocene	Tampa Limestone	800-980	White to tan, soft to hard limestone. Generally recrystallized.	Limited artesian water. Top of Floridan aquifer.

In the area of investigation the Anastasia Formation is cavity riddled and highly permeable from about 60 to 100 feet below land surface. The cavities vary in size, with a probable average diameter of 1 to 2 inches and a maximum diameter of 1 foot. They are partly filled with fine, tan quartz sand. The cavity zone is overlain by beds of green clay, each less than 6 inches in thickness and separated by beds of light-gray quartz sand and sandstone which extend from about 45 to 55 feet below ground level. These beds are anisotropic and nonhomogeneous, and therefore, provide varying degrees of confinement. At about 100 feet below land surface, thin beds of white marl and limey sandstone mark the bottom of the cavity zone.

Directly underlying the Anastasia Formation in descending order are the Tamiami Formation of Pliocene age, and the Hawthorn Formation and Tampa Limestone of Miocene age (table 1). The Miocene sediments are low in permeability and serve as confining layers for the deeper artesian Floridan aquifer system, the top of which is approximately 980 feet below land surface (F. W. Meyer, U.S. Geological Survey, Miami, Florida, oral commun., October 31, 1978).

General Hydrology

Two aquifer systems exist in the investigation area. The first is the unconfined shallow aquifer which lies between land surface and approximately 250 feet, the bottom of the Anastasia Formation. The second is the artesian Floridan aquifer underlying the shallow aquifer and separated by about 730 feet of confining beds. Although the Floridan aquifer is a prime source of freshwater in central Florida, water from the aquifer is nonpotable in Palm Beach County due to high concentrations of chloride (over 900 mg/L) and other objectionable constituents (Parker and others, 1955).

Water levels in the shallow aquifer range annually from approximately land surface near the end of the rainy season in October to about 5 feet below the surface at the end of the dry season in April. In areas remote from pumping wells, water-level changes are caused primarily by recharge from precipitation and losses due to evapotranspiration. Water levels increase during the rainy season, even though evapotranspiration also increases during that period. Seasonal variations in water levels are illustrated in the long-term hydrograph for well PB-109 (fig. 2), 2 miles west of the investigation area. The well is open to the aquifer 14 feet below land surface.

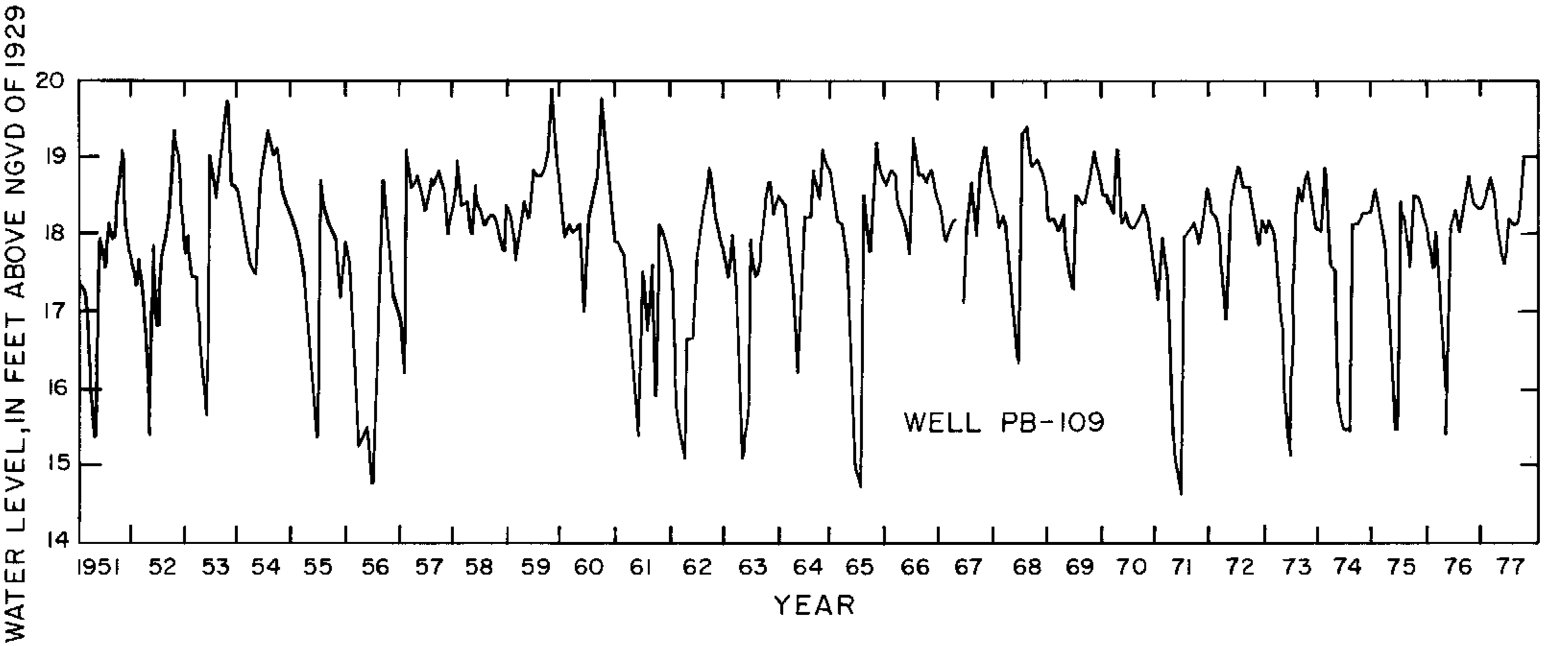

Figure 2.--Long-term hydrograph, well PB-109.

The city of West Palm Beach water catchment area is adjacent to and upgradient (west) of the investigation area (fig. 1). The catchment is supplied by rainfall and Canal M, which transports water from Lake Okeechobee. Water levels within the catchment area are artificially maintained higher than the surrounding area. Average monthly water levels at catchment control no. 225 in Canal M at the eastern edge of the catchment, 1 mile south of the investigation area (fig. 1), are compared to those in well PB-944 in the center of the investigation area on table 2. The average annual difference of more than 4 feet suggests that the catchment is a recharge area for the cavity zone. The general ground-water gradient in the area of investigation is eastward at approximately 1.3 ft/mi.

Surface-water bodies in Palm Beach County are shown in figure 1. In the investigation area, drainage ditches flow south and east. Because the ditches are shallow, flow rates seldom exceed 10 ft^3/s and they, therefore, have only a minimal effect on the ground-water system.

AQUIFER EVALUATION

Surface-Resistivity and Borehole Geophysical Data

One objective of selecting a 9 mi^2 section of the cavity zone for evaluation was to define an appropriate investigation methodology before proceeding with the evaluation of larger areas. Of secondary interest was the utilization of surface-resistivity methods, which to date have not been widely used in south Florida hydrogeologic investigations. Therefore, an assessment of surface electrical resistivity surveys was made to determine their usefulness in locating east-west extent, depth, and thickness of the cavity zone and to aid in selecting appropriate sites for exploratory drilling.

Surface-resistivity data were collected at sites shown in figure 3 using a portable field instrument and a Wenner electrode configuration. In making resistivity surveys, very low frequency current is introduced into the ground by way of two electrodes. The potential difference, measured between a second pair of electrodes, is a reflection of the earth material-water matrix from land surface to a depth proportional to the electrode spacing. It is affected by porosity, salinity, clays, and other physical characteristics of the aquifer (Zohdy and others, 1974). Resistivity soundings, indicating changes in resistivity of the earth material-water matrix with depth, were made at seven sites. Data were collected at 59 resistivity profile sites to ascertain areal resistivity changes.

Table 2.--Water levels at Control no. 225, West Palm Beach catchment basin and in well PB-944

Date	WATER LEVEL IN FEET	
	Control no. 225	PB-944
April 13, 1978	17.65	13.67
June 12, 1978	17.65	13.32
September 27, 1978	18.50	14.16
December 4, 1978	18.60	14.89
Average	18.10	14.01

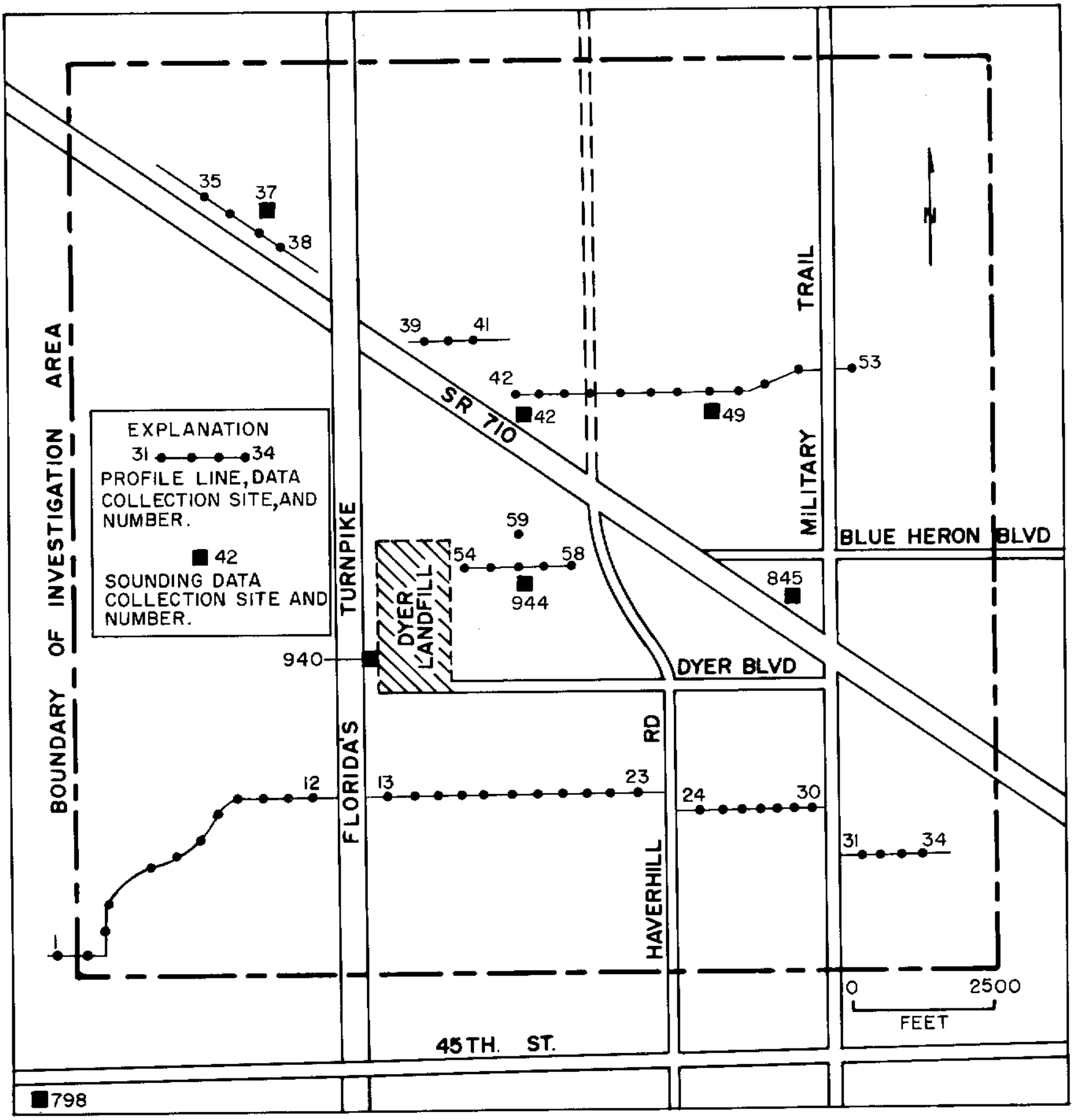

Figure 3.--Surface-resistivity data-collection sites.

Fifteen geologic test holes, in excess of 100 feet in depth, were drilled or cored for this investigation to supplement data from 11 existing test holes penetrating the cavity zone. Test hole locations are shown in figure 4. In addition to a driller's log collected for each hole, at least one borehole log was collected for each of the new test holes except the cored hole. A borehole log is obtained by first introducing a probe into the test hole. As the probe is raised or lowered in the hole, a signal is emitted into the earth material-water matrix. Part of the signal is absorbed in the matrix and part is reflected. The reflected part is received by the probe and transmitted to the surface where it is recorded. Variations in the return signal represent changes in the matrix penetrated by the borehole. Interpretations of these changes and of the absolute value of the returning signal, yield insights into water-quality, porosity, permeability, lithology, and other physical characteristics of the aquifer. Table 3 lists specific data collected in each hole.

Aquifer Description

Geologic information from section locations indicated in figure 4 is shown in figures 5 and 6. The sections are based upon interpretations of driller's logs and surface-resistivity and borehole geophysical data. In order to project test holes PB-655 and PB-798 to the east-west section line (A-A'), it was necessary to assume that aquifer materials are of similar lithology north and south of the line. The validity of this assumption is substantiated by the north-south section (fig. 6) which shows horizontal continuity in aquifer material in these directions. Because natural land-surface elevation varies only 3 feet in the area of investigation, the selection of land surface as datum for figures 5 and 6 does not introduce substantial error.

The zone of highest permeability in the aquifer lies from about 60 to 100 feet below land surface. In drilling between those depths, circulation was frequently lost and sudden 3 to 5 inch drops of the drilling bit were common. Both of these phenomena suggest the presence of cavities in the aquifer. In addition, about 25 percent of the cuttings from test holes in this depth interval were subrounded, such as might be expected of fill material in a zone of partly-filled cavities. The presence of calcite crystals in the cuttings further confirmed the existence of cavities because it is in such void spaces that calcite crystals form. Finally, a borehole televiewer lowered in test hole PB-1065, southeast of the Dyer Boulevard Sanitary Landfill, clearly showed cavities in the 60 to 100 foot depth interval.

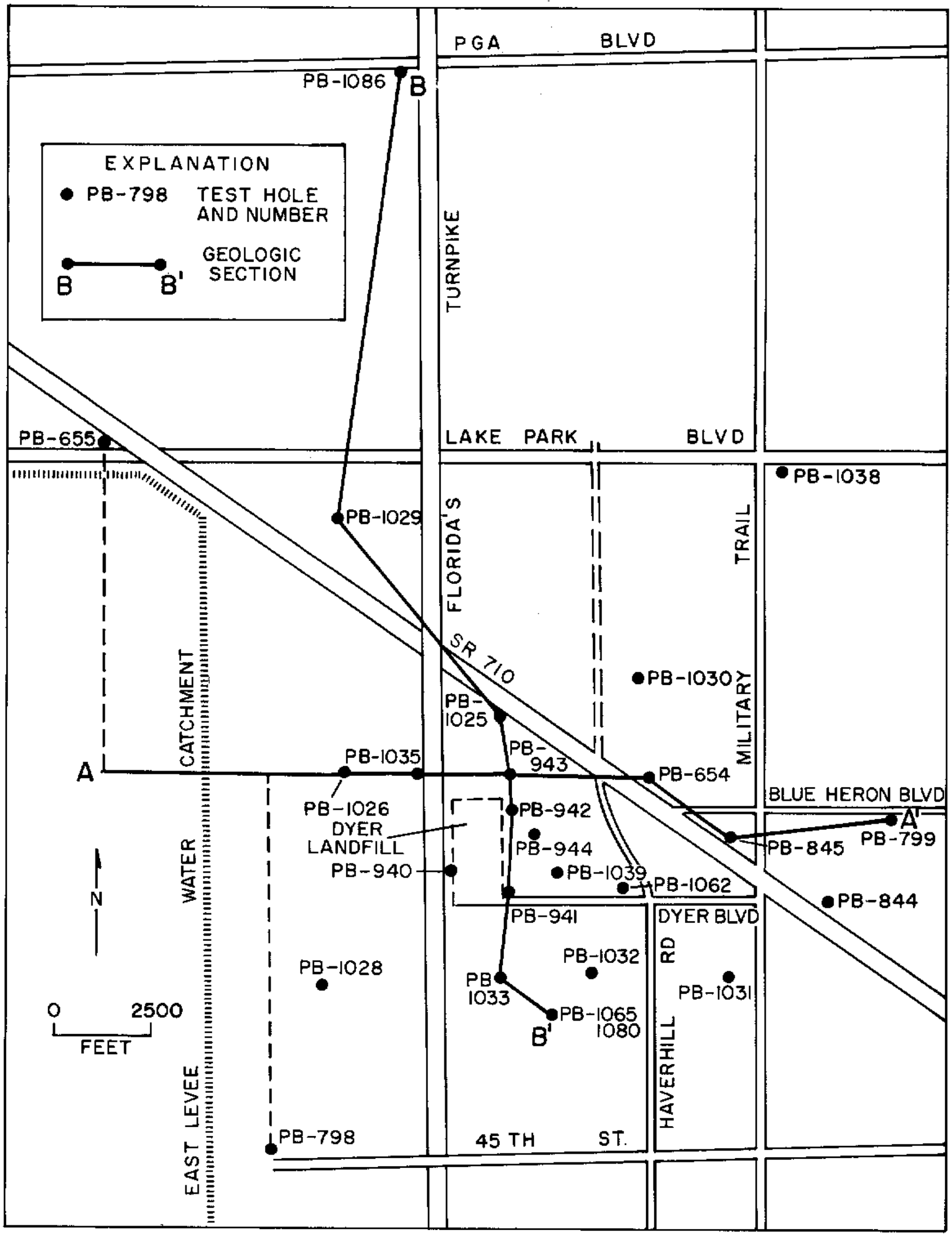

Figure 4.—Geologic test holes and sections.

Table 3.--Test hole data

Test hole	BOREHOLE LOGS									
	Driller's	Spontaneous potential	Natural gamma	Neutron	16 inches and 64 inches normal resistivity	6 feet lateral resistivity	Single point resistivity	Caliper	Televiewer	Geologic core
PB-654	X									
PB-655	X		X				X			
PB-798	X		X							
PB-799	X		X							
PB-844	X		X							
PB-845	X		X							
PB-940	X	X					X			
PB-941	X	X					X			
PB-942	X	X					X			
PB-943	X	X					X			
PB-944	X	X					X			
PB-1025	X		X		X	X				
PB-1026	X	X	X		X	X				
PB-1028	X	X	X		X	X				
PB-1029	X	X	X		X	X				
PB-1030	X	X	X		X	X				
PB-1031	X		X		X			X		
PB-1032	X	X	X	X	X					
PB-1033	X	X	X	X	X	X				
PB-1035	X	X	X	X	X	X				
PB-1038	X	X	X	X	X					
PB-1039	X	X	X	X	X	X				
PB-1062	X	X	X	X	X	X				
PB-1065	X	X	X	X	X				X	
PB-1080	X									X
PB-1086	X	X	X	X	X					

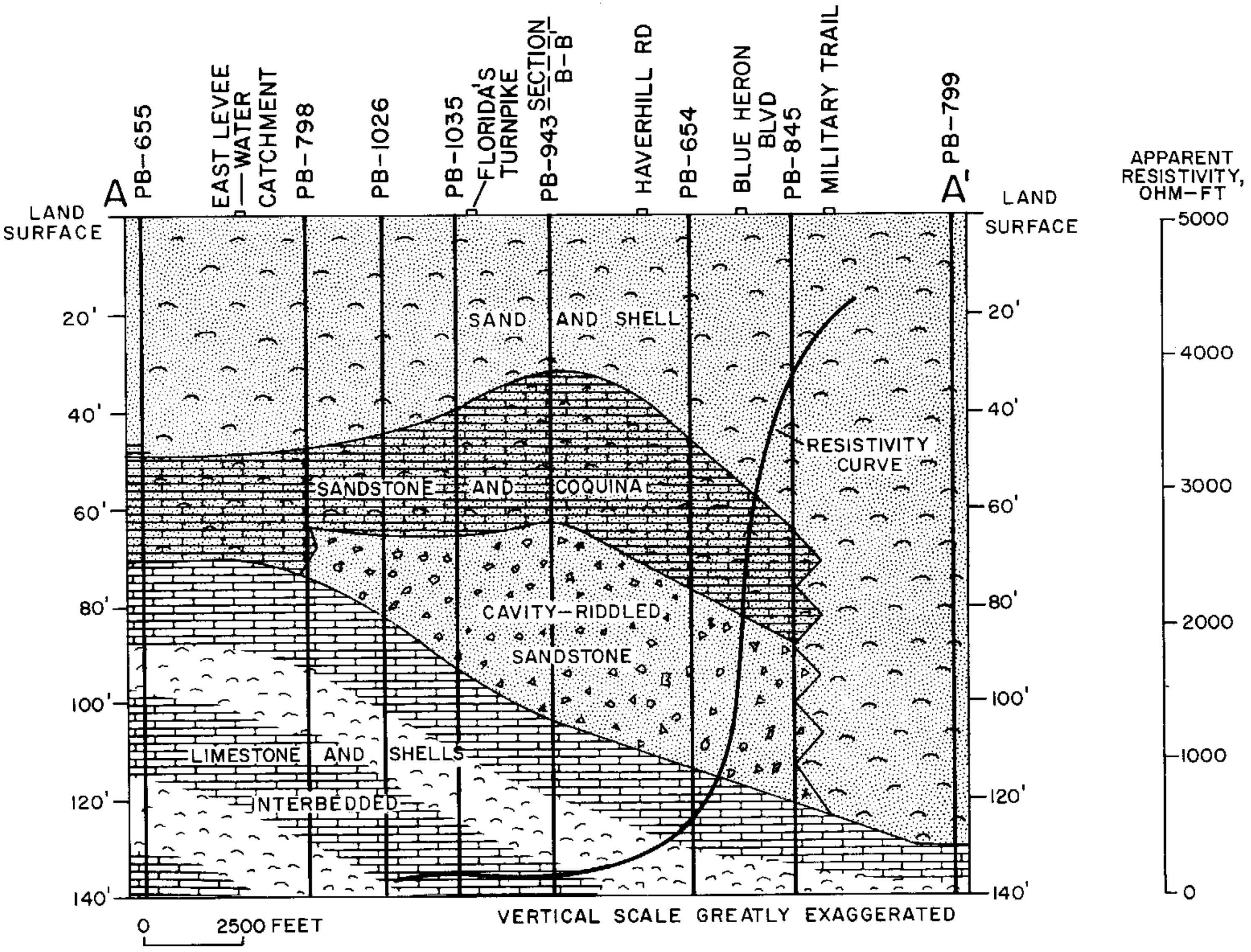

Figure 5.--Geologic section of the shallow aquifer from west to east (line A-A', figure 4) showing lithology and surface resistivity versus depth at an electrode spacing of 90 feet.

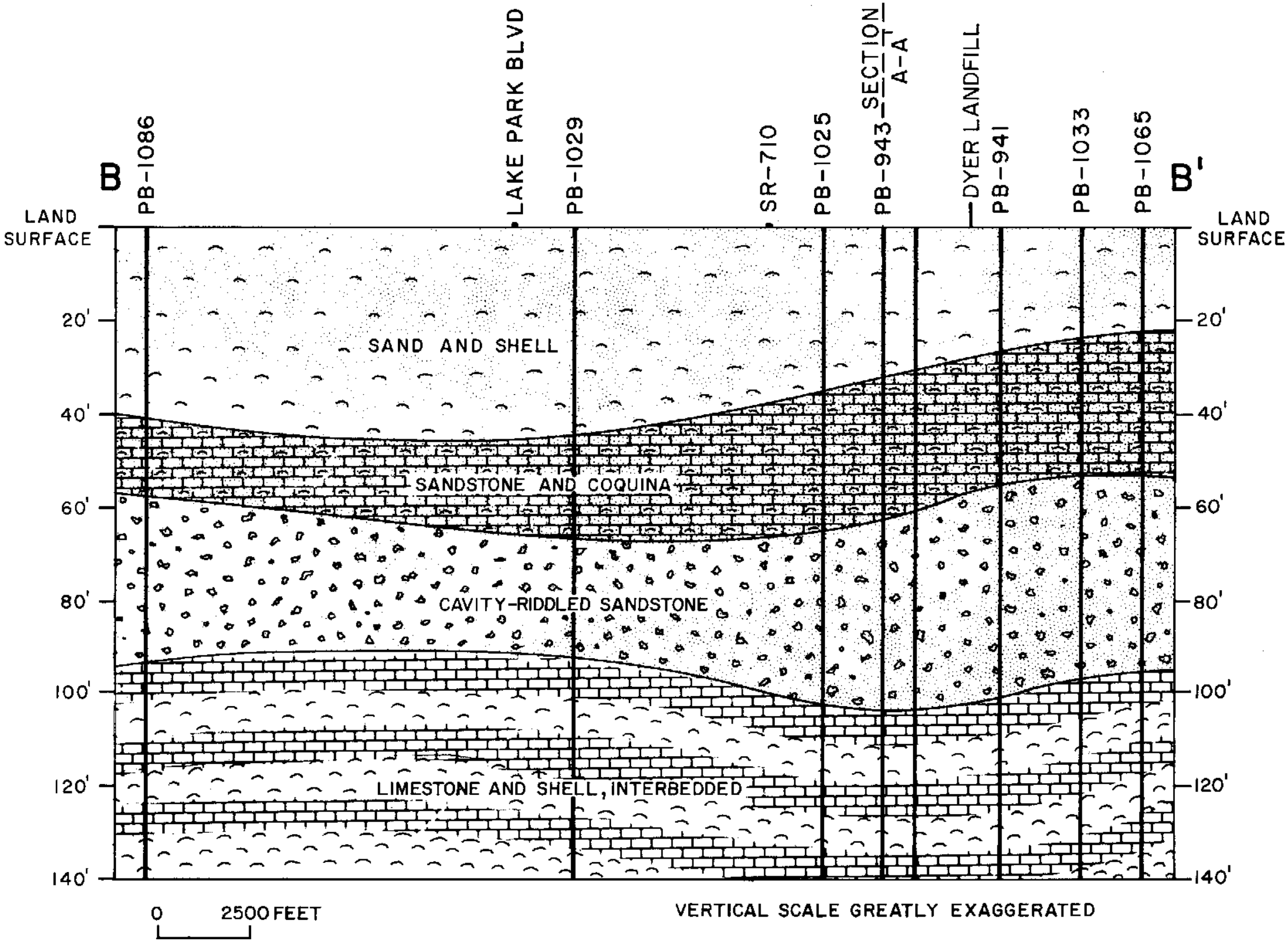

Figure 6.--Geologic section of shallow aquifer from north to south (line B-B', figure 4).

The driller's log for test hole PB-1065 is listed on table 4. The term "circulation loss" at 57 to 68 and 74 to 86 feet refers to the nonreturn to the surface of drilling fluid. Such losses are commonly associated with high permeability of formation material. Based upon references to fine-grained sands and sandstone in that and other logs from test holes in the cavity zone, it is probable that the cavities are at least partly sandfilled. This phenomena, as it relates to aquifers in south Florida, was first reported by Parker and others (1955, p. 107).

A geologic core, 2 inches in diameter, extracted from test hole PB-1080 revealed aquifer material containing three separate lithologic features in the cavity zone. The most common core component is gray calcareous quartz sandstone, cavity riddled to such an extent that it was extracted in approximately 1 in^3 round-edged fragments. The fragments show no evidence of recent fractures indicating that they existed in nature as extracted and were not fragmented in the coring process. The second most common feature is calcareous quartz sandstone that despite having numerous cavities and canals, has not lost its original structure. The interconnected nature of these features suggests their formation was due to the breakdown of aquifer cementing material and not to dissolution of shells or other marine organisms. Numerous calcite crystals occur within irregular cavities throughout these sections. The third feature in the core is gray sandstone nodules, slightly smaller than golf balls, and composed entirely of uniform gray quartz sand. Throughout the coring process, circulating mud returned large amounts of very fine sand to the surface, confirming that the cavities are at least partly sand filled by sand left behind when the sandstone and coquina were broken down.

The cavity zone is overlain by 5 to 7 feet of thin beds of green clay, fine gray sand, and weakly consolidated gray calcareous sandstone. The clay beds are nonuniform and discontinuous, and therefore, provide varying degrees of confinement. A thin layer of hard sandstone lies immediately below the clay beds and directly above the cavity zone. The thin clay beds and hard sandstone layer identify the top of the cavity zone throughout the area of investigation. The bottom of the zone is bounded by beds of sandy limestone with streaks of white marl.

A natural gamma log from well PB-1026, located in the west-central part of the area of investigation, is shown in figure 7. A depiction of material described in the driller's log is also included. The peak in gamma radiation at 5 feet is due to clays mixed with surficial sands. At 40 and 90 feet, radiation peaks occur due to the presence of clay and marl, respectively. The cavity zone is composed of calcareous quartz sandstone. At 57 and

Table 4.--Driller's log for test hole PB-1065

Depth feet	Thickness feet	Hardness	Description of formation
0-3	3	Soft	Sand, fine to medium, light gray.
3-5	2	Medium soft	Sand, fine to medium, dark brown.
5-8	3	Soft	Sand, fine to medium, tan.
8-12	4	Medium soft	Sand and shell, dark brown.
12-28	16	Medium soft	Sandstone, fine to medium, light gray.
28-29	1	Soft	Shells, fine, broken, white.
29-47	18	Hard	Sandstone, fine to medium, light gray, cuttings angular.
47-49	2	Hard	Same as above with greenish-gray clay.
49-54	5	Medium soft	Clay and sandstone layered, gray-green; no sand.
54-57	3	Very hard	Sandstone, light gray, with fine broken white shells.
57-68	11	Very hard	Sandstone, fine grained, gray circulation losses.
68-74	6	Very hard	Sandstone, white to dark gray, sandy, bit action irregular.
74-86	12	Hard	Sandstone and some shell, cemented, calcite crystals, few nodular sandstone cuttings, most angular, momentary circulation loss at 75-77 feet.
86-96	10	Very hard	Sandstone and shells, thin white marly streaks, gray, and calcite cemented.
96-110	14	Medium	Limestone, gray to buff with fine broken shell and white marl.
110-115	5	Medium	Limestone and shell, gray to buff, shell small and broken.

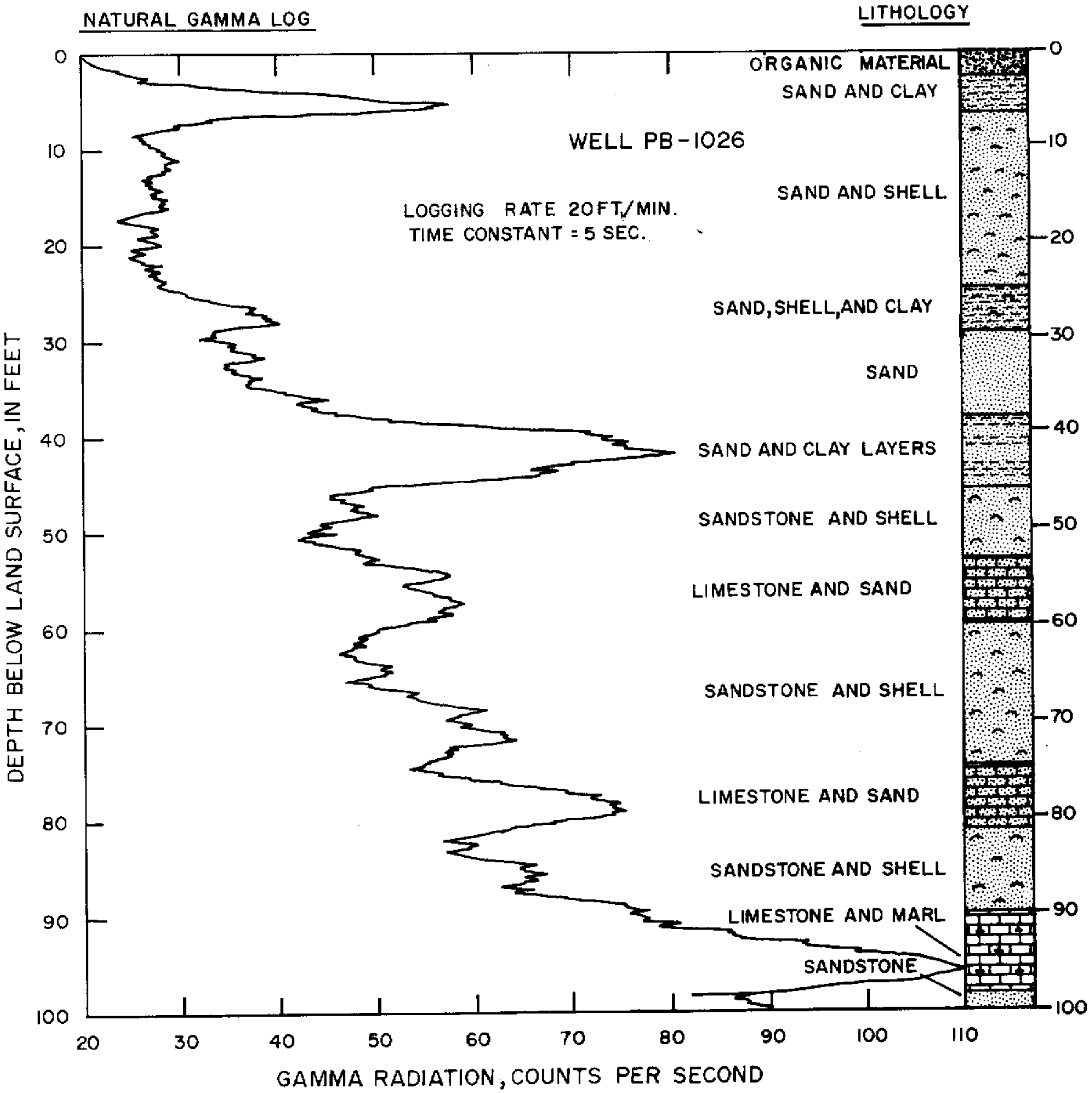

Figure 7.--Natural gamma log and lithology of test hole, PB-1026.

77 feet, however, sandy limestone is interbedded with the sandstone, causing increases in gamma radiation. The presence of limestone in the sandstone matrix illustrates the coastal origin of the Anastasia Formation, in which facies changes from calcareous sandstone to coquina to sandy limestone are common. The overall increasing trend of gamma radiation with depth is due to the settling of drilling mud in the borehole.

Aquifer materials between 100 and 150 feet are interbedded with sandy limestone and shells. Although the limestone is not cavity-riddled, this section is quite permeable because the shell beds are composed of large and sometimes unbroken shells. It is possible that the permeability of this deeper material may approach that of the cavity zone in some areas of the shallow aquifer, particularly where the percentage of fine sand in the cavities is high.

Locations of the top and bottom of the cavity zone were established at approximately 60 and 100 feet, respectively, based upon interpretations of borehole and driller's logs and the geologic core. Surface-resistivity data proved inconclusive in identifying these levels due to a probable combination of several factors including water-quality changes within the aquifer, the lack of an interface to which the data were sensitive, variations in aquifer porosity, and instrument limitations.

The eastern boundary of the cavity zone is located on a north-south line slightly west of Military Trail. A first approximation of the boundary was obtained from surface-resistivity profiles which show a pronounced decline in resistivity of aquifer materials in that area. Figure 5 shows the profile obtained from data points 35 to 53 (fig. 3) superimposed on the east-west lithologic section. Electrode spacing was 90 feet for the curve shown. At this spacing resistivity data is representative of approximately the first 70 feet of aquifer material. The trend of decreasing resistivity, west of Military Trail, is typical of a traverse from well-sorted sand to porous sandstone. However, an increase in dissolved solids in water in the aquifer could cause a similar resistivity change. Therefore, test holes were drilled in the vicinity of Military Trail to confirm the boundary location. East of Military Trail, driller's logs show aquifer material to be unconsolidated to a depth of at least 65 feet, and in most cases 100 feet below land surface. In contrast aquifer material to the west of Military Trail becomes consolidated at a depth of approximately 15 feet below land surface, and cavities are evident beginning at 60 feet. These findings were confirmed by test holes drilled by the city of Riviera Beach near the intersection of Military Trail and Dyer Boulevard (fig. 3) as part of a well field exploration program (Angel, 1979). Because the quality of water in wells PB-844 and PB-845 (fig. 8) is similar, the change in surface resistivity near Military Trail can be attributed to the lithologic change.

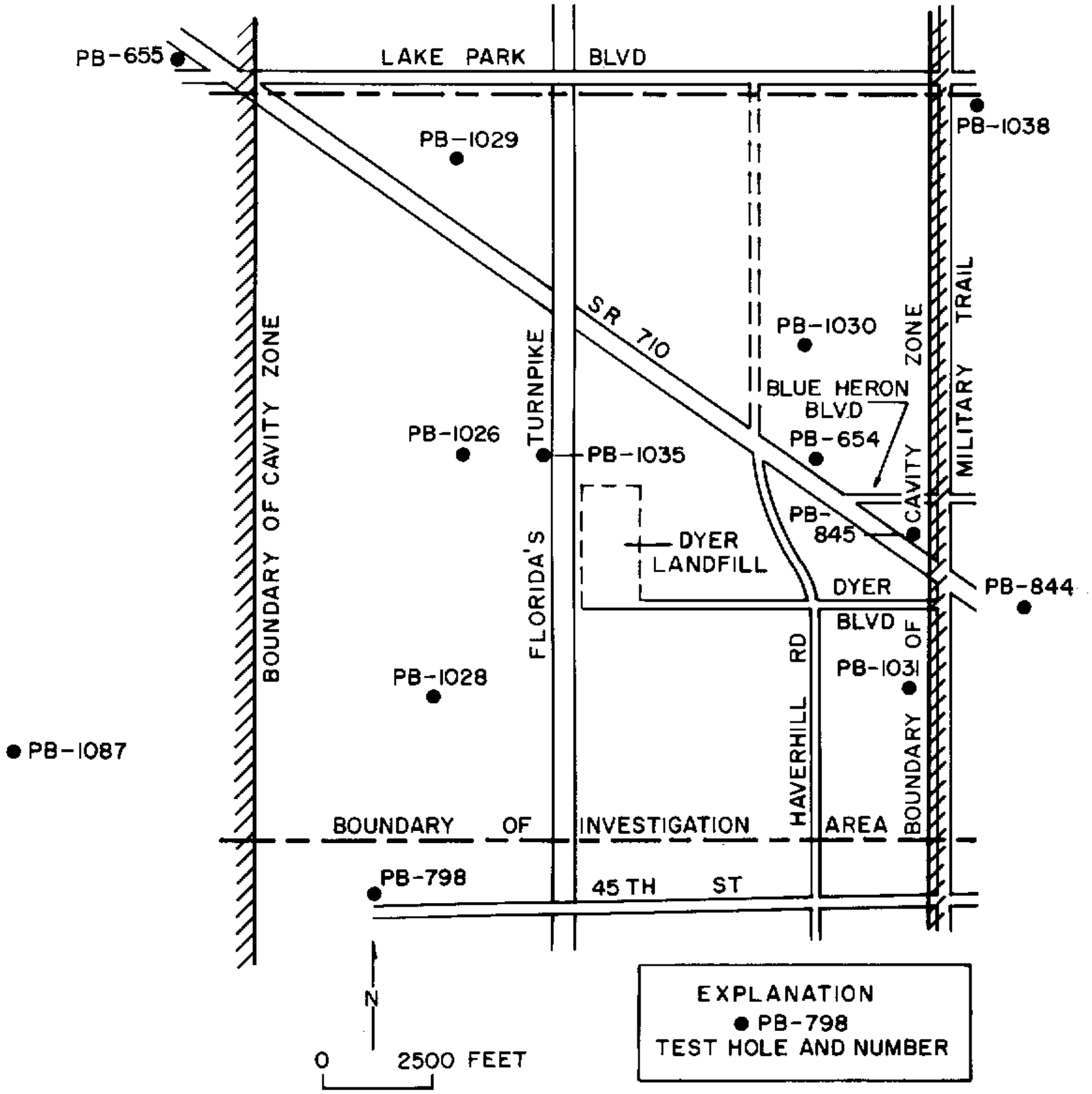

Figure 8.--East-west boundaries of the cavity zone.

The western boundary of the cavity zone is not as clearly defined. Surface-resistivity data did not show abrupt changes in resistivity, such as were apparent in eastern traverses, although this may have been due as much to an insufficient extension of the western profile as to the data. Each test hole showed at least some lithological features associated with the cavity zone, such as thin green clay beds at 45 to 55 feet below land surface, hard layers just beneath the clay, bit drops, and losses of circulation while drilling. However, these features are either less distinct or not of the magnitude of holes farther east; neither does each hole show all features. It is probable, therefore, that cavities decrease in number and size west of Florida's Turnpike. A thinning of the zone is also apparent in figure 5. Because a transition zone is indicated in the west part of the area, the boundary location there is slightly arbitrary. The boundary delineation in figure 8 represents the best estimate.

Based upon scattered data from other areas of the county, it is possible that the cavity zone extends at least 6 miles north and 20 miles south of the investigation area (Rodis and Land, 1976). There are, in fact, similarities in cavity zone hydrogeology and that of the Biscayne aquifer in southern Palm Beach and northern Broward Counties (Tarver, 1964; McCoy and Hardee, 1970; and Sherwood and others, 1973).

Data analyses suggest that the aquifer material in which the cavity zone lies was formed as a shallow marine depositional feature. Cementation gradually occurred, bonding sand grains and sand-sized shell fragments into a sandstone-coquina matrix. As time passed, water levels rose and fell, alternately exposing and submerging the material. During these cycles the cavity zone may have existed for extended periods at or above sea level, subject to cyclic tidal and water-table fluctuations. Over long periods of time, such water action could have caused dissolution of cementing material and shell fragments until the first cavities began to appear. At about this time the cavity zone was overlain by additional sand and shell which later consolidated. Finally Pamlico Sand was deposited over the sand and shell. The cavities, once established, have continued to enlarge over time through the process of solution stimulated by ground-water flow until the present average diameter or approximately 1 to 2 inches was achieved.

Aquifer Characteristics

An aquifer test was conducted May 3-5, 1978, at the site shown in figure 9. Water was pumped from a production well fully penetrating the cavity zone from 55 to 95 feet. The effect of the withdrawal on water levels at different depths in the aquifer, and different distances from the pumped well was monitored in observation wells. Three 2-inch observation wells, drilled to 95 feet

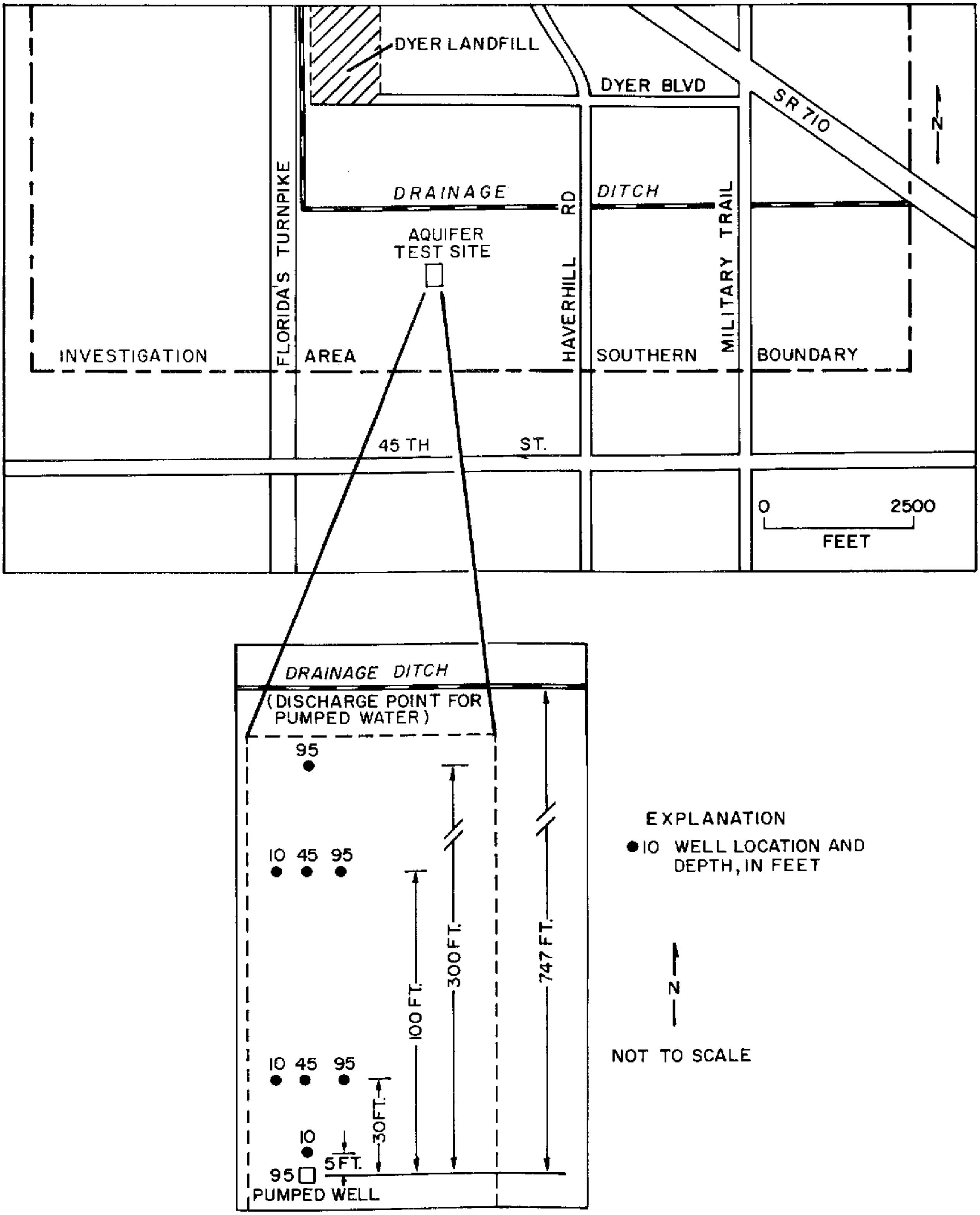

Figure 9.--Aquifer test site and well locations.

below land surface, were screened from 55 to 95 feet. Five additional 2-inch observation wells were installed with depths of 10 and 45 feet to determine the confining nature of clay at two depth intervals - 5 to 12 and 47 to 54 feet. Each of these wells was screened in the final 5 feet of depth.

The aquifer test was designed to determine values for transmissivity and the storage coefficient, hydrologic parameters which together, describe the potential of an aquifer to yield water to wells. Transmissivity is a measure of the volume of water that can move through a section of the aquifer per unit width over its entire saturated thickness under a hydraulic gradient of one per unit time. The storage coefficient is the volume of water taken into or released from storage per unit area of the aquifer per unit change in head (Lohman, 1972).

The 6-inch well was pumped at a rate of 220 gal/min for 24 hours. Water-level drawdown and recovery were measured in all observation wells. Drawdown data for observation wells located 30 feet from the production well are shown on table 5. Water levels in wells 5 feet, 100 feet, and 300 feet from the pumped well reacted similarly to the wells of equivalent depth at a distance of 30 feet.

Water-level changes in wells of 10 and 45 feet in depth were virtually the same. This is evidence that the clayey sand, 5 to 12 feet below land surface, did not significantly influence the vertical movement of ground water. Comparisons of drawdown in wells open to the aquifer from 40 to 45 feet below land surface to those open from 55 to 95 feet, however, showed significant differences. For example, after 12.5 hours of pumping, drawdown in the suite of wells 30 feet from the production well was 1.12 feet in the 195-foot well, but only 0.12 feet in the well screened at 40-45 feet. Similar differences existed in other pairs of observation wells. The difference in drawdowns was probably due to intervening thin-bedded clays which retard vertical water movement.

The shallow aquifer in Palm Beach County is generally regarded as an unconfined system. However, data on table 5 show substantial differences between drawdown in the pumped (cavity zone) and that in overlying material. This is a response common in semi-confined aquifers and reflects the fact that the pumping well is screened only in the cavity zone, and that zone is separated from the overlying aquifer materials (0 to 47 feet) by a zone several feet in thickness having a relatively low hydraulic conductivity. Because the aquifer responded in a semi-confined manner to test conditions, the Hantush equations (Lohman, 1972) which assume a semi-confined, leaky aquifer were used in data analysis.

Table 5.--Aquifer test drawdown data for wells located 30 feet from the pumped well

Elapsed time, in minutes	DRAWDOWN IN FEET		
	Well Depth = 10 feet	Well Depth = 45 feet	Well Depth = 95 feet
1	0	0	0.27
10	0.02	0.01	0.48
21	0.04	0.02	0.57
60	0.06	0.04	0.75
90	0.07	0.04	0.81
150	0.08	0.06	0.89
210	0.09	0.08	0.94
270	0.10	0.08	0.98
330	0.11	0.09	0.99
390	0.11	0.09	1.01
450	0.12	0.10	1.03
510	0.12	0.11	1.05
570	0.12	0.12	1.06
630	0.13	0.11	1.09
750	0.13	0.12	1.12
1000	0.13	0.12	1.12

The Hantush analysis yielded a transmissivity of 11,000 ft^2/d. The value applies to the cavity zone only (55 to 95 feet below land surface) and must be considered approximate because of a lack of data regarding aquifer characteristics of the shallow aquifer between 0 to 47 and 95 to 250 feet. The calculated transmissivity is lower than that commonly associated with wells penetrating Pleistocene Formations in Broward and Dade Counties because of larger quantities of fine sand in the cavities and thinner sections of highly permeable aquifers in Palm Beach County. Data were insufficient to determine the storage coefficient. Response curves and match points for the test analysis are shown in figure 10. Data points within the first minute of the test were not utilized in drawing the curve because their position is distorted due to the pumping rate which varied early in the test before stabilizing.

Potentiometric contours in the cavity zone are shown in figure 11. The contours are based upon data collected March 7, 1979, near the beginning of the wet season. Historical data show an increase in water levels of several feet by October, the end of the wet season. The eastward gradient shown in figure 11 remains essentially the same throughout the year. The water-level gradient in the aquifer above the cavity zone is similar to the contours shown in figure 11, except it is somewhat distorted near the landfill. This is due to the elevation of the landfill, which is 30 feet above natural land surface and to the addition of water to the northern landfill area in the process of transporting sand slurry for cover operations.

Ground-water velocity is estimated (Lohman, 1972, p. 10-11) by the equation:

$$V = \frac{KI}{\theta} \tag{1}$$

where:

V is average pore velocity in feet per day in a lateral direction;

K is lateral hydraulic conductivity in feet per day, equal to transmissivity divided by the saturated thickness of the aquifer;

I is hydraulic gradient in feet per feet; and

θ is porosity of aquifer material in cubic feet per cubic feet.

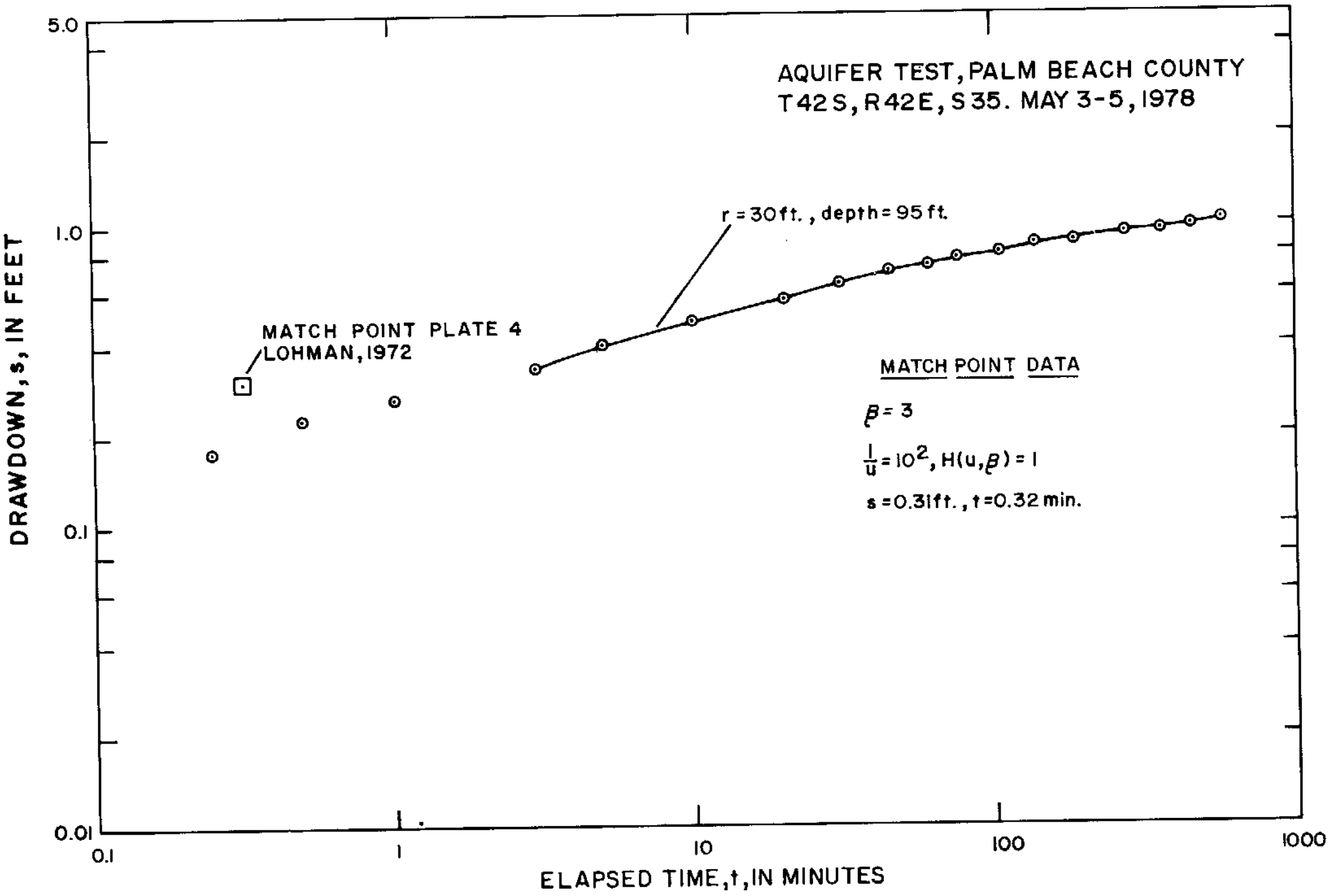

Figure 10.—Aquifer test response curve.

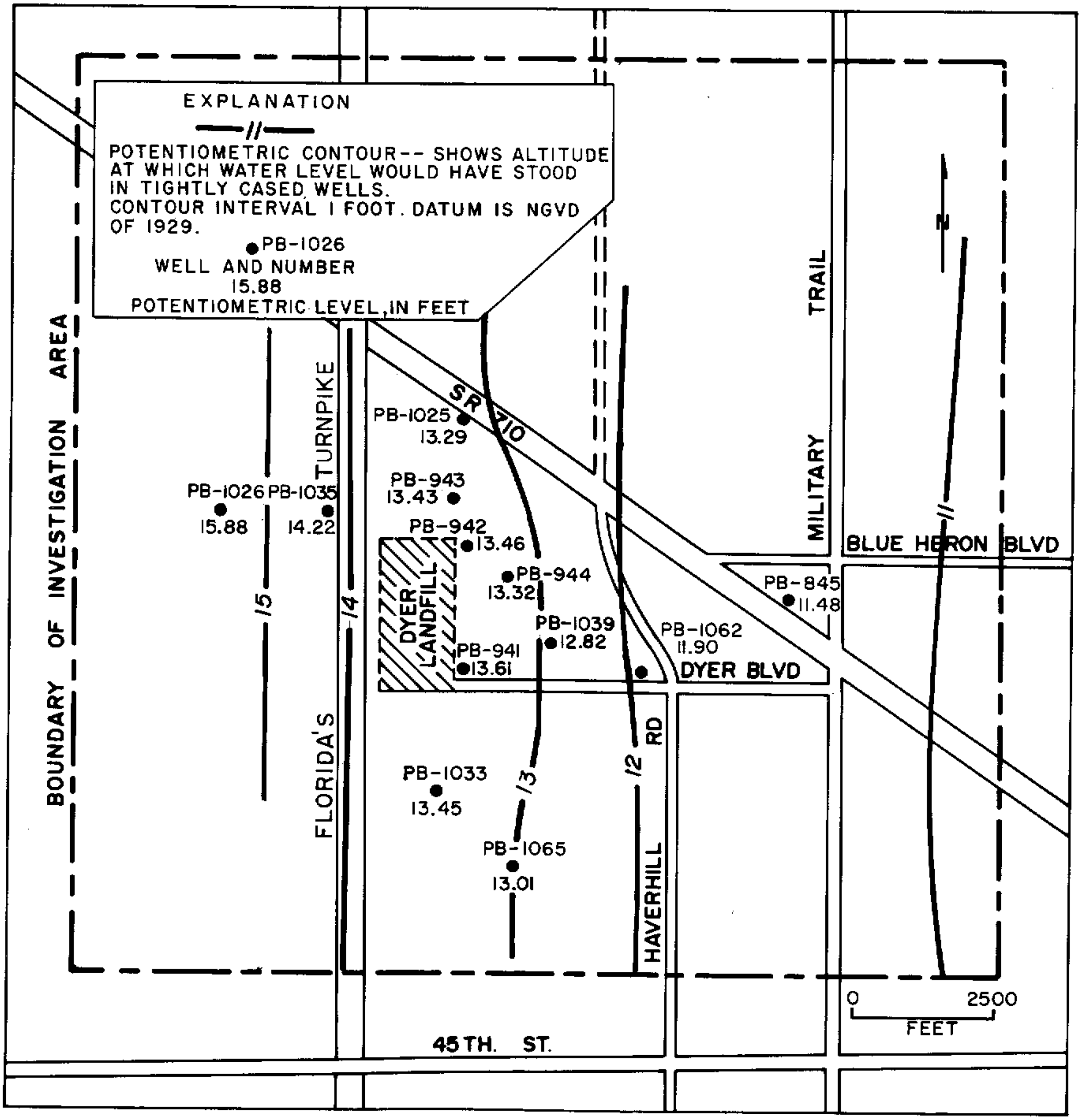

Figure 11.—Potentiometric contours, March 7, 1979.

Solving this relationship, utilizing the average lateral hydraulic gradient shown in figure 11, and assuming effective thickness of the cavity zone and porosity to be 40 feet and 0.35, respectively, yield an average pore velocity equal to:

$$V = \frac{1.1 \times 10^4 \ \frac{\text{ft}^2}{\text{d}} \times \frac{4 \text{ ft}}{11{,}500 \text{ ft}}}{40 \text{ ft} \times 0.35} = 0.27 \text{ feet per day}$$

This figure represents flow velocity in the cavity zone. Based upon relative permeability estimates made from driller's logs, geophysical logs, and geologic core samples, it is probable that flow velocities in the intervals from 0 to 55 feet and from 95 to 250 feet below land surface are substantially less. However, estimates of those velocities must await independent information on the conductivities of those zones.

In addition to the approximation introduced into the velocity calculation by estimating the thickness of the flow zone, the derivation of the equation itself is based upon several simplifying assumptions including uniform aquifer thickness, homogeneity of aquifer materials, and constant hydraulic gradient, none of which is wholly satisfied in nature. Moreover, the equation is sensitive to the value of porosity (θ), which for this calculation was estimated based upon work by Schmoker and others (1979).

Wells pumping water from an aquifer alter regional ground-water flow and induce gradients toward the wells, so that water entering the system within the radius of influence is eventually drawn toward and discharged through the well. Equation (1) shows that the velocity at which this water travels is directly proportional to the gradient. This relationship has important implications for areas surrounding sanitary landfills, such as the Dyer Boulevard site, because of contaminants generally associated with landfill leachates. Specifically, if the hydraulic gradient in the landfill area is increased, such as could occur due to ground-water withdrawals from wells, the velocity of leachate movement would also be increased.

Water Quality

The quality of water at a point downgradient from another location cannot be predicted accurately simply by knowing ground-water velocity and initial water quality. As water moves through the ground, it is altered in quality by dilution, dispersion, solution of soils and organic matter, colloidal attraction, filtering, and other natural phenomena. More complicated analysis techniques involving the use of digital computers and solute transport models have been developed to simulate the effects of these phenomena on travel time and solute concentration. Because of the complexity of water chemistry near most sanitary landfills, however, even these more sophisticated methods may not accurately simulate actual conditions.

Water-quality data in the area of investigation were collected at sites shown in figure 12. Analyses results are listed on table 6. Specific conductance, a measure of the ability of water to conduct a current, is proportional to the ionic concentration of the water and was used extensively, therefore, in evaluations of water quality.

The data on table 6 indicate substantial variations in water quality in the area of investigation. Some of the variation is due to natural phenomena. A comparison of water quality from wells at the same site, but different depths such as PB-1026/PB-1027 and PB-1067/PB-1069, for example, show an increase in specific conductance with depth. The increase is probably due to the saline nature of connate water which over time has been diluted by precipitation nearer to land surface than at depth. Substantial natural areal variation in water quality within the cavity zone is also apparent. For example, the specific conductance of water in wells PB-799, PB-844, PB-845, PB-1026, and PB-1069 ranges from 610 to 860 micromhos. Wells PB-1026 and PB-1069 were chosen as control wells, because they were the most remote from human activity.

The specific conductance of water samples taken from the cavity zone is shown in figure 13. Samples from several cavity zone wells near the landfill show that constituent concentrations exceed 1,000 micromhos. Water-quality data on table 6 show that the specific conductance of water from wells above the cavity zone, such as PB-1012 and PB-1016, also exceeds 1,000 micromhos. These values are in contrast with the average background level of 765 micromhos (PB-1026 and PB-1069). The most probable cause of these water-quality differences is landfill leachate.

The specific conductance of water from well PB-942, near the landfill and open to the cavity zone, also exceeds background. A similar contrast exists in the more definitive tracer of landfill leachate, ammonia nitrogen. Moreover, a sample collected on August 2, 1978, from well PB-941 contained concentrations of manganese (30 mg/L), zinc (420 mg/L), and phenol (1 mg/L) constituents not present in background wells. Because water-quality data prior to landfill operation are unavailable, it is not possible to show a direct cause-and-effect relationship between the landfill and inferior water quality in wells PB-941 and PB-942. However, given the location of the wells adjacent to the landfill and the nature of the contaminants, it is highly probable that landfill leachate is the contaminant source. Because both wells are open to the cavity zone, it follows that leachate has entered the zone.

Results of analyses for specific conductance, dissolved solids, and ammonia nitrogen in samples collected over a 2-year period from wells directly adjacent to the landfill and open to the cavity zone are given on table 7. No definite trends in the data are apparent.

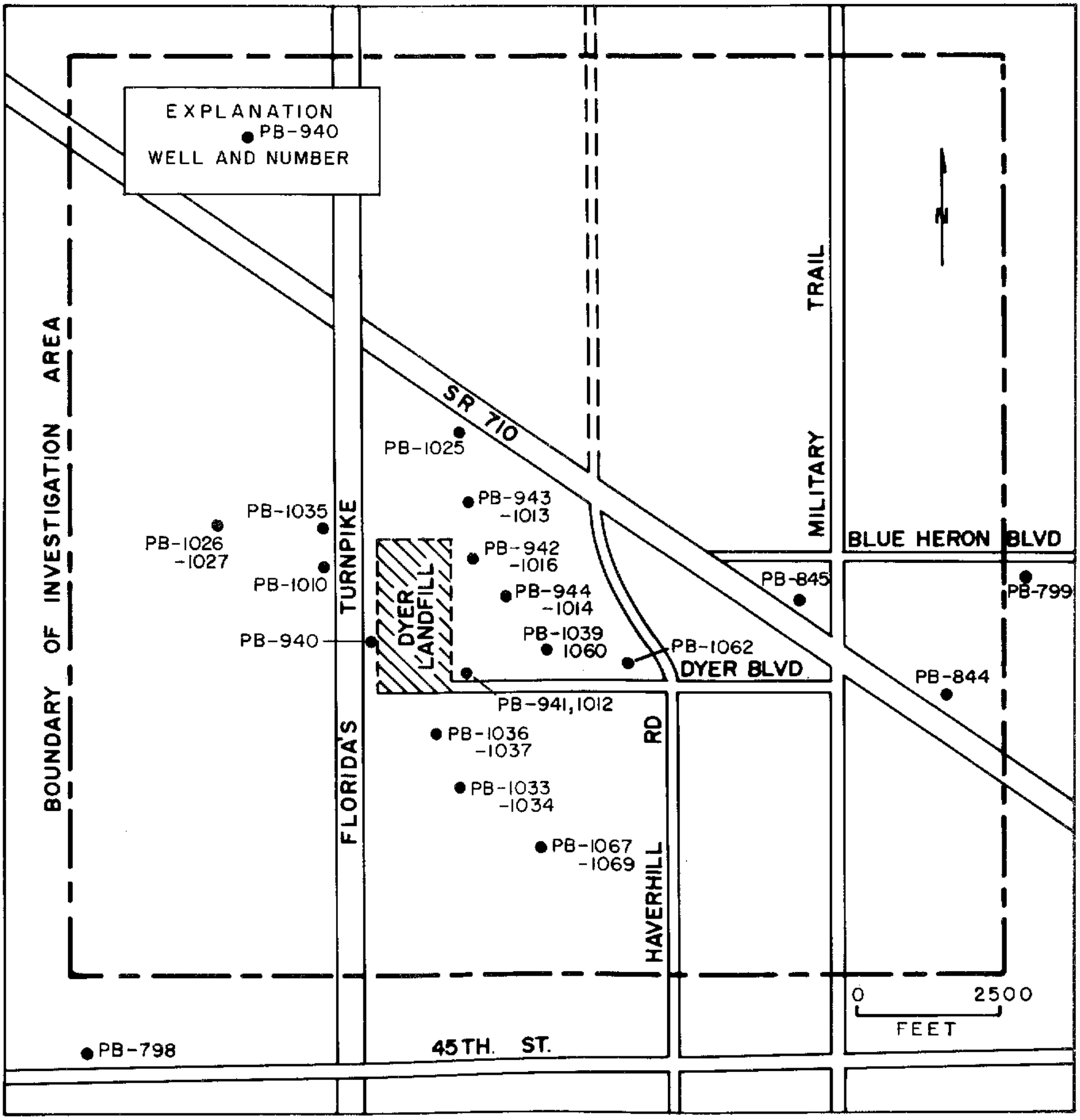

Figure 12.--Water-quality sampling wells.

Table 6.--Water-quality data from observation wells

[Values in mg/L, except where indicated]

Local well No.	Collection date	Sampling depth (feet)	Specific conductance in micromhos at 25°C	Dissolved chloride	Temperature in Degrees C	pH	Color platinum-cobalt units	Alkalinity
PB-798	6/78	87	1,060	-	25.5	6.8	-	-
PB-799	6/78	151	700	-	27.0	-	-	-
PB-844	6/78	110	860	90	25.5	6.8	150	320
PB-845	6/78	88	610	35	25.0	6.8	70	260
PB-940	4/78	65	835	70	25.5	7.0	50	367
PB-941	12/77	80	916	60	27.0	7.0	55	400
PB-942	12/77	60	1,840	-	27.0	6.7	35	740
PB-943	12/77	65	1,420	130	26.5	6.9	80	480
PB-944	12/77	75	555	35	26.0	7.1	65	230
PB-1010	4/77	18	650	50	24.0	7.1	20	310
PB-1012	12/77	32	6,400	-	27.0	6.9	-	2,480
PB-1013	12/77	15	500	32	26.5	7.3	60	190
PB-1014	12/77	17	320	10	26.5	7.4	100	160
PB-1016	12/77	22	2,670	260	28.0	6.6	80	1,160
PB-1025	4/78	80	890	72	25.0	7.0	40	407
PB-1026	4/78	76	750	25	24.5	6.9	20	404
PB-1027	4/78	37	660	23	24.0	7.1	50	374
PB-1033	4/78	107	970	42	25.5	6.9	10	420
PB-1034	4/78	37	770	65	25.5	7.0	80	341
PB-1035	12/77	78	1,370	120	26.0	7.0	28	480
PB-1036	4/78	42	600	33	26.0	7.0	80	289
PB-1037	4/78	20	345	22	24.0	7.4	50	131
PB-1039	4/78	89	640	51	26.0	7.1	25	315
PB-1060	12/77	37	610	42	26.0	7.2	35	270
PB-1062	4/78	78	550	47	24.5	7.1	50	282
PB-1067	6/78	12	625	20	24.0	6.8	180	280
PB-1069	6/78	55	780	58	25.0	6.8	75	370

Table 6.--Water-quality data from observation wells (Continued)

[Values in mg/L, except where indicated]

Local well No.	Collection date	Bicarbonate	Dissolved calcium	Hardness	Dissolved solids residue at 180°F	Dissolved fluoride	Dissolved potassium	Dissolved sodium	Total ammonia nitrogen
PB-798	6/78	588	-	-	-	-	-	-	-
PB-799	6/78	-	-	-	-	-	-	-	-
PB-844	6/78	392	130	27	531	0.2	1.2	62	0.8
PB-845	6/78	316	100	6	386	0.3	0.6	23	0.7
PB-940	4/78	448	140	380	528	0.2	1.4	41	1.7
PB-941	12/77	490	140	380	469	0.3	1.0	33	0.95
PB-942	12/77	904	210	580	1,290	0.2	6.6	85	33.0
PB-943	12/77	590	140	430	717	0.2	2.8	80	1.0
PB-944	12/77	286	100	260	340	0.1	0.8	17	1.1
PB-1010	4/77	376	100	290	404	0.2	2.3	33	0.72
PB-1012	12/77	3,024	370	1,100	2,870	0.2	200.0	540	330.0
PB-1013	12/77	232	65	170	307	0.1	2.0	45	0.29
PB-1014	12/77	192	66	170	215	0.0	0.4	5.3	0.34
PB-1016	12/77	1,420	410	1,100	1,650	0.1	9.7	160	12.0
PB-1025	4/78	496	-	-	590	-	1.7	42	0.61
PB-1026	4/78	492	-	-	516	-	1.0	21	0.75
PB-1027	4/78	456	-	-	470	-	9.0	20	1.30
PB-1033	4/78	512	-	-	634	-	2.0	61	0.68
PB-1034	4/78	416	-	-	512	-	0.5	39	0.89
PB-1035	12/77	584	150	460	684	0.2	5.2	80	0.89
PB-1036	4/78	352	-	-	412	-	0.3	19	-
PB-1037	4/78	160	-	-	254	-	0.2	18	0.65
PB-1039	4/78	384	-	-	446	-	0.8	30	0.75
PB-1060	12/77	328	100	260	382	0.2	0.6	23	0.72
PB-1062	4/78	344	-	-	406	-	0.5	26	0.61
PB-1067	6/78	316	110	290	449	0.2	4.5	16	0.35
PB-1069	6/78	452	140	370	511	0.2	0.9	31	0.92

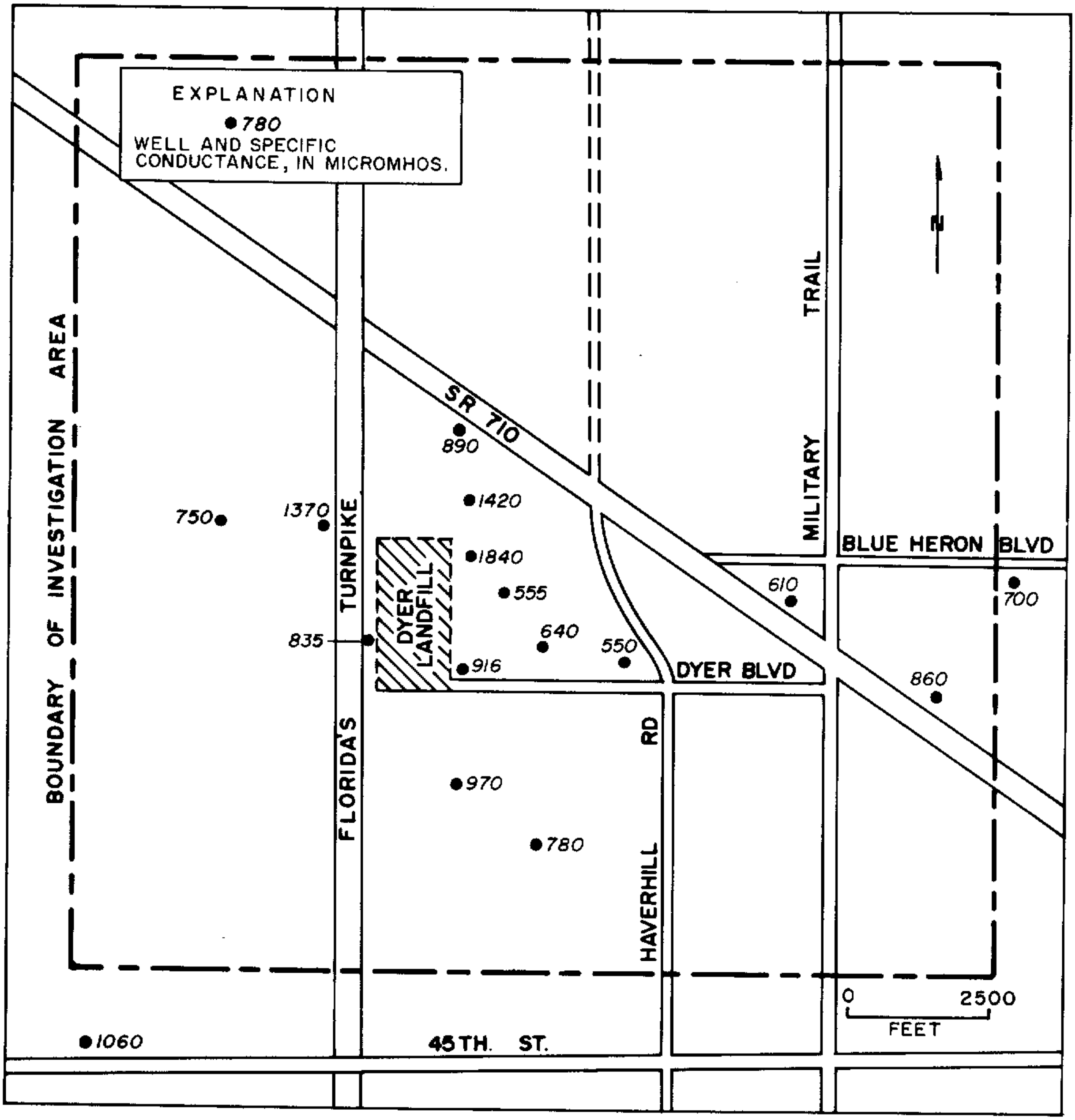

Figure 13.—Specific conductance of ground water from cavity zone.

Table 7.--Specific conductance, dissolved solids, and ammonia nitrogen from wells PB-940 through PB-943

[Values in mg/L, except where indicated]

Well No.	Depth	Sample month	Specific[1/] conductance	Dissolved solids	Ammonia nitrogen
PB-940	65	4/77	830	495	1.70
PB-941	80	4/77	740	464	0.86
PB-942	60	4/77	1,210	730	9.70
PB-943	65	4/77	1,240	727	1.00
PB-940	65	8/77	880	510	1.70
PB-941	80	8/77	800	496	0.80
PB-942	60	8/77	1,600	816	28.0
PB-943	65	8/77	1,200	512	0.89
PB-940	65	12/77	870	517	1.90
PB-941	80	12/77	916	469	0.95
PB-942	60	12/77	1,840	1,290	33.0
PB-943	65	12/77	1,420	717	1.00
PB-940	65	4/78	835	528	1.70
PB-941	80	4/78	--	--	--
PB-942	60	4/78	--	--	--
PB-943	65	4/78	--	--	--
PB-940	65	8/78	890	539	1.60
PB-941	80	8/78	790	511	0.82
PB-942	60	8/78	1,470	796	26.0
PB-943	65	8/78	1,220	701	0.87
PB-940	65	12/78	--	--	--
PB-941	80	12/78	--	--	--
PB-942	60	12/78	--	--	--
PB-943	65	12/78	510	332	0.56
PB-940	65	4/79	890	--	1.80
PB-941	80	4/79	750	480	1.30
PB-942	60	4/79	1,230	704	18.0
PB-943	65	4/79	--	696	0.92

1/ Specific conductance values are in micromhos.

Samples collected north and west of the landfill in cavity-zone wells PB-943 and PB-1035, respectively, have values of specific conductance and dissolved solids (table 6) which exceed background, suggesting possible leachate contamination. The presence of leachate in these wells is contrary to what might be expected based upon the eastward direction of ground-water flow shown in figure 11. Examination of control points PB-942, PB-943, and PB-1025, however, reveals a small northern gradient in the cavity zone which could cause leachate to move into the direction of PB-943. The contours do not clearly illustrate this fact due to the limited area in which the control points are located.

In addition to high values for specific conductance and dissolved solids, the sample from PB-1035 also contained 10 ug/L of dissolved zinc, 18 ug/L of dissolved lead, 30 ug/L of dissolved manganese, and other heavy metals. This is clear evidence that leachate has reached the cavity zone at this site. The appearance of leachate at a site upgradient from the generalized direction of flow (fig. 11) suggests either a highly complex local ground-water flow system beneath the northwestern section of the landfill or the existence of a period of time after the commencement of landfill operations during which ground-water gradient was reversed. A reversal may, in fact, have occurred during recent excavation operations in the vicinity of PB-1035, at which time substantial amounts of sand slurry were pumped from the west side of the turnpike to the east.

Evidence of a complex flow system is indicated in water-level measurements made in shallow wells on the same day that the control points for figure 11 were measured. While measurements at north control points in the cavity zone (PB-942, PB-943, and PB-1025) showed a northern flow direction, shallow wells at two of the same sites (PB-1013 and PB-1016, fig. 12) indicated a southerly flow. This explains why samples from shallow wells PB-1010 and PB-1013, at or near the sites of the deep contaminated wells PB-1035 and PB-943, respectively (fig. 12), do not show leachate influence.

There are two general paths that leachate may follow in its flow from the landfill. First, if it is assumed that, because of higher dissolved solids content, leachate is more dense than native ground water, then it (leachate) may migrate vertically through overlying material and leak through clay layers (at 47 to 54 feet below land surface) into the cavity zone. It then could move horizontally through that more permeable zone. A worst-case estimate of horizontal movement would result from assuming rapid vertical migration. Then, using the previously estimated velocity of ground water in the cavity zone (0.27 ft/d), leachate from the landfill would have traveled eastward approximately 1,100 feet in the 11 years of landfill operation. Cavity-zone wells PB-941 and

PB-942, located 20 feet east of the landfill, produce water clearly showing the presence of leachate (table 6). However, samples from well PB-944, located in the cavity zone and 1,000 feet east of the landfill, do not show any indication of leachate. Therefore, the eastern edge of the leachate plume in the cavity zone must be located between wells PB-941/PB-942 and PB-944. If the general path of leachate movement is indeed primarily vertical then horizontal, then the fact that leachate has not traveled horizontally 1,100 feet as estimated by the velocity calculation is due to delays in leachate arrival in the cavity zone. Such delays would be caused by slow migration through overlying, lower permeability material.

The second possible general path of leachate movement is horizontal through the sand and sandstone which make up the aquifer overlying the cavity zone. Samples from wells in this layer, such as PB-1012 and PB-1016, located within 20 feet of the eastern boundary of the landfill, show the presence of leachate (table 6). Well PB-1014, 1,000 feet downgradient, however, yields samples free from contamination. Therefore, the assumption that the movement of leachate is primarily horizontal through the shallow part of the aquifer (0 to 47 feet below land surface) results in the same conclusion as was drawn in assuming that leachate movement was primarily in the cavity zone, that is, leachate has moved eastwardly (downgradient) more than 20 feet but less than 1,000 feet in the 11 years of landfill operation.

The range of the possible distance to the eastern (leading) edge of the leachate plume (20 to 1,000 feet) implies an effective velocity of leachate over the first 11 years of landfill operation to have been between 0.005 to 0.25 ft/d. The actual velocity and subsequent location of the leading edge of the plume is dependent upon which of the flow paths discussed was predominant over that period of time. However, in view of the fact that leachate has been detected in the cavity zone, the calculated flow velocity in that zone (0.27 ft/d) would appear to be the appropriate figure to use in future calculations of leachate movement from its present position in the cavity zone for comparable hydraulic gradients. Any such calculation, however, would produce only an estimate of leachate advance because of the unknown effects of previously mentioned natural phenomena such as dilution, collodial attraction, filtration, etc.

SUMMARY AND CONCLUSIONS

Surface-resistivity data and test-hole logs show that a cavity-riddled, permeable zone of calcareous quartz sandstone occurs within the shallow aquifer, about 5 miles west of Riviera Beach. The zone extends approximately 3 miles in the east-west direction and may extend 25 miles or more north to south. It lies from about 60 to 100 feet below land surface and is directly overlain by 8 to 10 feet of sandy clay interbedded with sandstone. The cavities are partly filled with fine sand. The bottom of the zone is marked by thin beds of marl interbedded with sandy limestone.

The cavity-riddled zone of the shallow aquifer has a transmissivity of about 11,000 ft^2/d. Water samples from wells in the cavity zone in areas remote from human activity have a specific conductance of approximately 780 micromhos. Samples from wells near the Dyer Boulevard Sanitary Landfill, both above and within the cavity zone have specific conductances exceeding 1,000 micromhos. Although variations in water quality, due to natural causes, exist in the area of investigation, higher-than-background levels of specific conductance, total ammonia nitrogen, and heavy metals in wells adjacent to the landfill indicate that leachate has entered the shallow aquifer and migrated to the cavity zone.

Surface-resistivity data were useful in determining the eastern boundary of the cavity zone and in selecting appropriate drilling sites. In locating the vertical boundaries of the zone, resistivity data were less useful due primarily to complexities in aquifer hydrogeology.

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