RECONNAISSANCE OF THE GROUND-WATER RESOURCES OF VIEQUES ISLAND, PUERTO RICO

By Sigfredo Torres-González

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CONVERSION FACTORS

Conversion factors for inch-pound units into metric units are listed below:

Multiply	By	To obtain metric unit
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot per day (ft^2/d)	0.09294	square meter per day (m^2/d)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic feet per second (ft^3/s)	0.02832	cubic meter per second(m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
gallon per minute per foot (gal/min/ft)	0.2070	liter per second per meter (L/s/m)
	Pressure	
pound per square foot (lb/ft^2)	4.88	kilogram per square meter (Kg/m^2)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter(Kg/m^3)
	Temperature	
degree Fahrenheit (°F)	5/9(°F-32)	degree Celsius (°C)
	Specific Conductance	
micromhos per centimeter at 25 degrees Celsius (umhos/cm at 25°C)	1.0	microsiemens per centimeter at 25 degrees Celsius (uS/cm at 25°C)

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ABSTRACT

A reconnaissance of the ground-water resources of the Island of Vieques was conducted during 1982-1984. The island, located about 9 miles southeast of Puerto Rico, is formed by volcanic and intrusive rocks overlain by thin alluvial deposits along portions of the north and south coasts. The Esperanza valley, in the south-central part, contains the principal alluvial aquifer. The area of the valley is about 10 square miles and the alluvial deposits are about 60 feet thick. Transmissivity of the aquifer ranges from 200 to 2,000 square feet per day. Previous to 1982, pumpage of as much as 400,000 gallons per day of water from the aquifer resulted in saline water intrusion throughout the coastal zone of the valley. Ground water withdrawals from the aquifer (1982 to 1985) were nearly zero. Most of the wells sampled (1982-1984) exhibited chloride ion concentrations of less than 100 milligrams per liter. However, sodium absorption ratios ranged from 2.9 to 4.8 units, indicating a potential salinity hazard for some crops.

Relatively important alluvial deposits also occur in Resolución valley, on the northwest coast, and near Playa Grande, to the southwest. Pumpage from the Resolución aquifer by the U.S. Navy through 1977 was as high as 200,000 gallons per day. In the Playa Grande area, as much as 50,000 gallons per day were pumped during 1965.

A 2-dimensional finite-difference model was developed and calibrated for the Esperanza alluvial aquifer. Digital model tests indicate that about 300,000 gallons per day of water can be withdrawn from the aquifer during the wet season before a reversal of the gradient of the water table occurs indicating potential saltwater encroachment. During the dry season, withdrawals would be limited to about 200,000 gallons per day.

(pg 3 follows)

INTRODUCTION

Vieques is the largest offshore island belonging to Puerto Rico, with a surface area of about 51 mi^2 (fig. 1). It is located about 7 mi east-southeast of Puerto Rico and has a population of 7,662 (1980 census). Water resources on the Island of Vieques are limited due to its relatively small basins which receive an average of about 45 inches per year of precipitation and experience high evapotranspiration. There are no perennial streams on the island, and the known aquifers common yield is usually less than 100 gal/min (Gómez-Gómez and Heisel, 1980). Well fields in the Esperanza and Resolución valleys were developed in the early 1960's, with total withdrawals of about 600,000 gal/d (written commun., Anderson, 1972). Ground-water withdrawals have been stopped in Resolución Valley, and operation of the well field in Esperanza Valley was discontinued in 1978 as a result of increasing salinity and maintenance problems. A pipeline was constructed in 1977 between eastern Puerto Rico and Vieques to provide water to supply the town of Isabel II and the Esperanza valley area. Currently about 500,000 gal/d of drinking water are pumped through the pipeline from the Río Blanco filtration plant to Vieques.

In 1982, ruptures in the pipeline reduced the amount of freshwater available to Vieques to less than 250,000 gal/day. Water had to be shipped by barge from Puerto Rico to supply the deficit. At the same time, plans for agricultural development of Esperanza Valley were drafted by the Puerto Rico Land Administration and the Puerto Rico Department of Agriculture. Although the pipeline was later repaired, the reliability of this supply system remains in question. The potential demands for agriculture greatly exceed the pipeline capacity.

The U.S. Geological Survey began an investigation in 1982 to define the ground-water resources of Vieques. The project was conducted in cooperation with the Puerto Rico Land Administration (PRLA), the Puerto Rico Department of Natural Resources (PRDNR), and the Puerto Rico Aqueduct and Sewer Authority (PRASA).

Purpose

The principal purposes of the investigation were as follows:

1. To describe the potential optimum yield and the occurrence, availability, and movement of water in the principal aquifers throughout the island of Vieques.

2. To define the areal and vertical extent of the Esperanza alluvial aquifer and the general characteristics of the Resolución aquifer.

3. To define the principal chemical and physical characteristics of ground water throughout Vieques.

4. To determine the effects of ground-water withdrawals on the Esperanza alluvial aquifer and the potential for saline-water intrusion.

5. To design, construct, and calibrate a two-dimensional ground-water flow model of the Esperanza alluvial aquifer.

Although the investigation included the entire island of Vieques, most efforts were concentrated in the Esperanza and Resolución valleys (fig. 2).

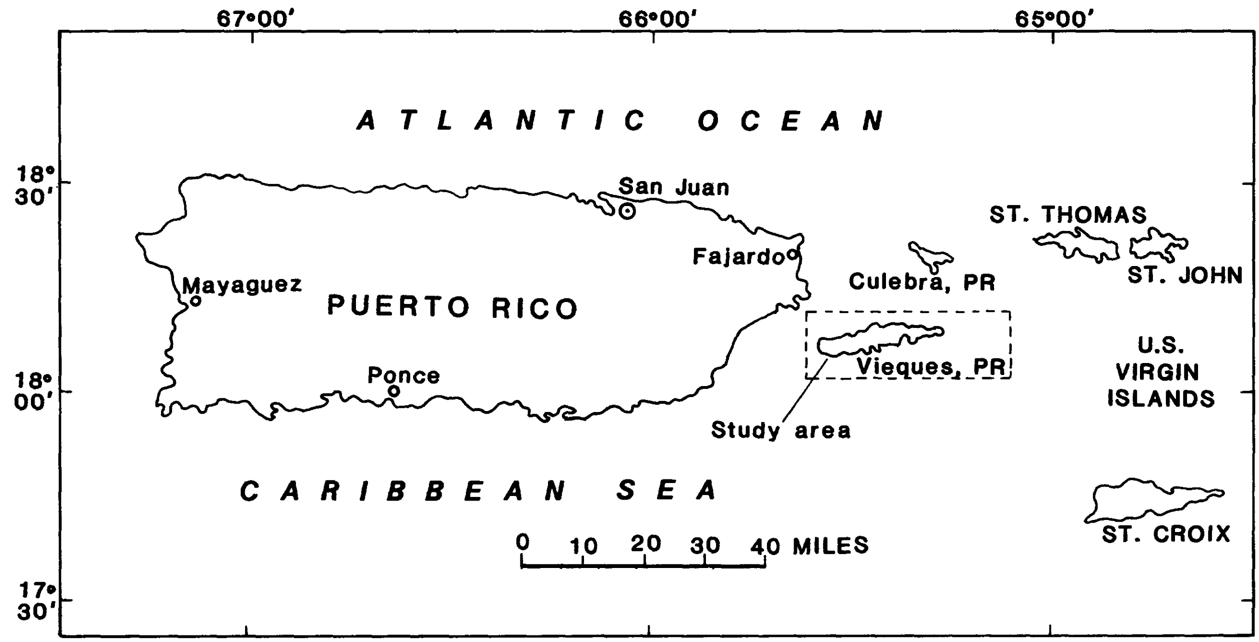


Figure 1.--Location of Vieques in relation to Puerto Rico and the U.S. Virgin Islands.

Approach

A literature review of previous investigations in Vieques was conducted, including an inventory of operational and abandoned wells. To supplement the available information, shallow test wells were drilled in the Esperanza Valley to define the potentiometric surface conditions, direction of ground-water flow, hydraulic characteristics of the aquifer, lithology, and depth to bedrock. Surface resistivity, borehole geophysics, and seismic refraction surveys were conducted to supplement the lithologic data and define the physical characteristics of the rocks. Interpretation of the resistivity and seismic surveys employed methods described by Zohdy (1973) and Scott and others (1972). Aquifer parameters, including transmissivity, storage coefficient, and leakance, were defined from aquifer tests conducted at pumping wells. Water samples were collected at key wells for determinations of specific conductance, pH, temperature, and concentrations of common ions, including chloride. Methods described by Brown and others (1970) were used for the collection and analyses of the samples.

The ground-water flow model for the Esperanza alluvial aquifer was designed and constructed in accordance with methods described by McDonald and Harbaugh (1984). The model utilizes a finite difference approach for the solution of the ground-water flow equation. The aquifer boundaries were defined from driller's logs of wells, aquifer test results, topographic maps, and surface geophysical data.

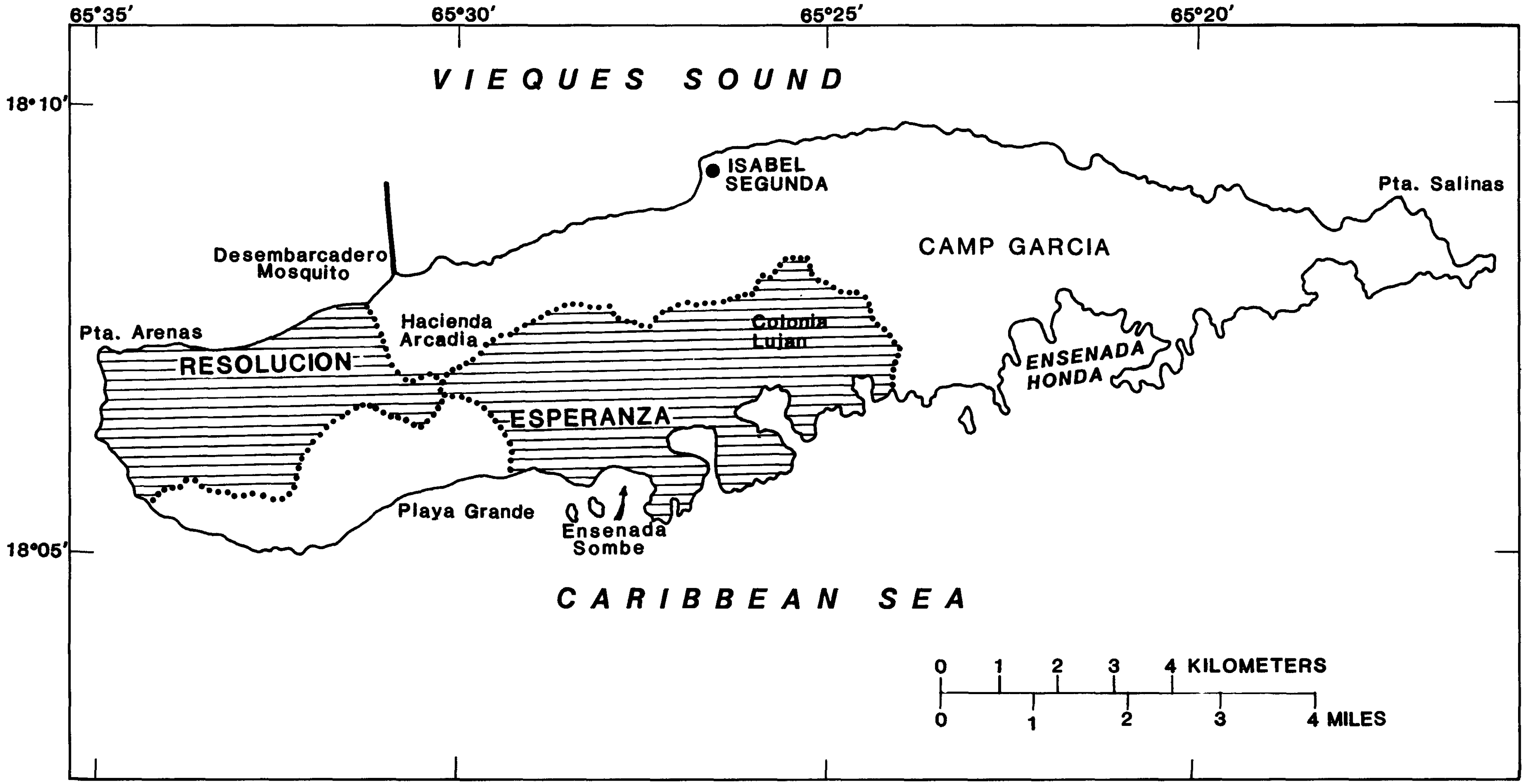


Figure 2.--Study area in Vieques, Puerto Rico.

Acknowledgement

We wish to acknowledge the support and cooperation of the U. S. Navy during the basic-data collection phase of the project. Mr. Wifredo Freytes, from PRASA, provided valuable support during the aquifer tests in the Esperanza valley. The PRASA staff in Vieques were invaluable in their support.

GENERAL FEATURES

Physiography and Land Use

The topography of Vieques is characterized by a series of low hills and small valleys (fig. 3). The most elevated areas occur along a west to east axis near the center of the island. The highest peak is Monte Pirata, on the western end, with an elevation of about 987 ft above mean sea level. Cerro Matias, with an elevation of about 450 ft is the highest peak in the eastern area. Slopes of the central mountains are steeper on the north coast than in the south.

Since 1943, the U.S. Navy has occupied nearly 76 percent of Vieques (fig. 4), using the land for a training area, including a practice bombing range. The land occupied by the civilian population is used mostly for cattle pastureland, minor agriculture, and urban development. Sugarcane was produced throughout most of the island prior to the U.S. Navy acquisitions.

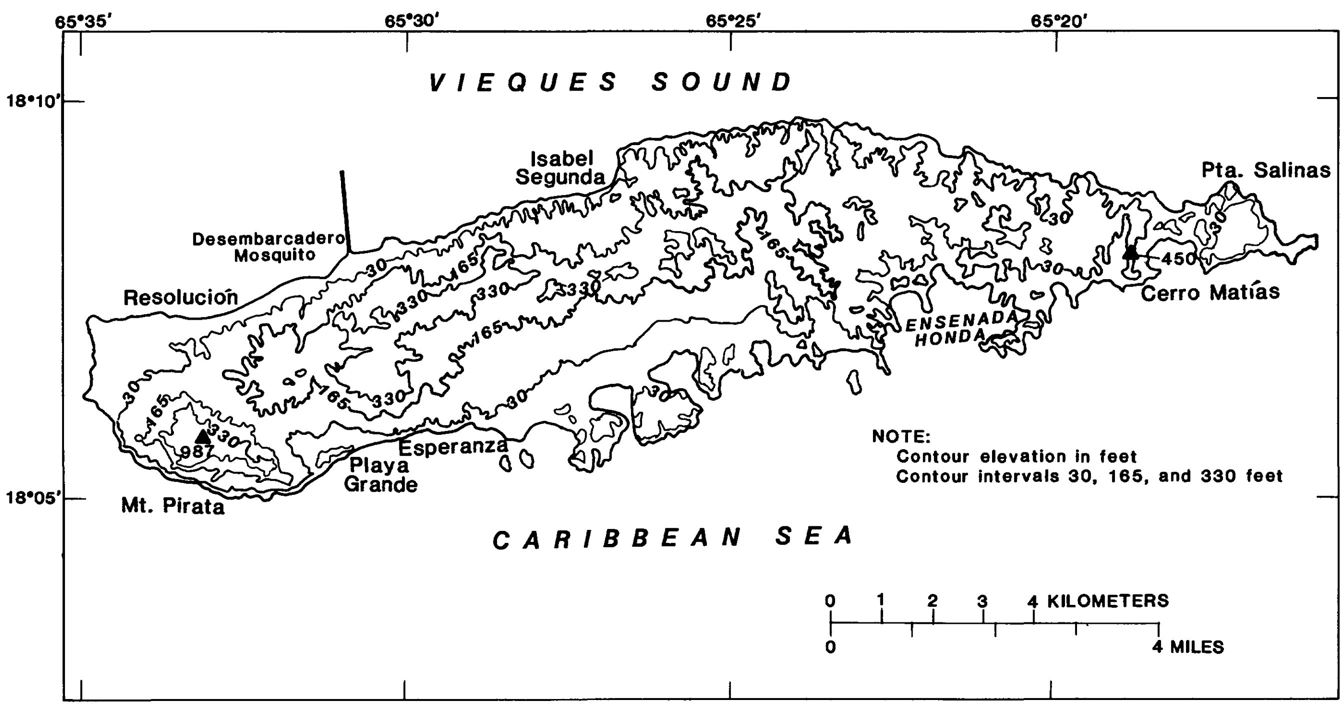


Figure 3.--Generalized topography of Vieques Island.

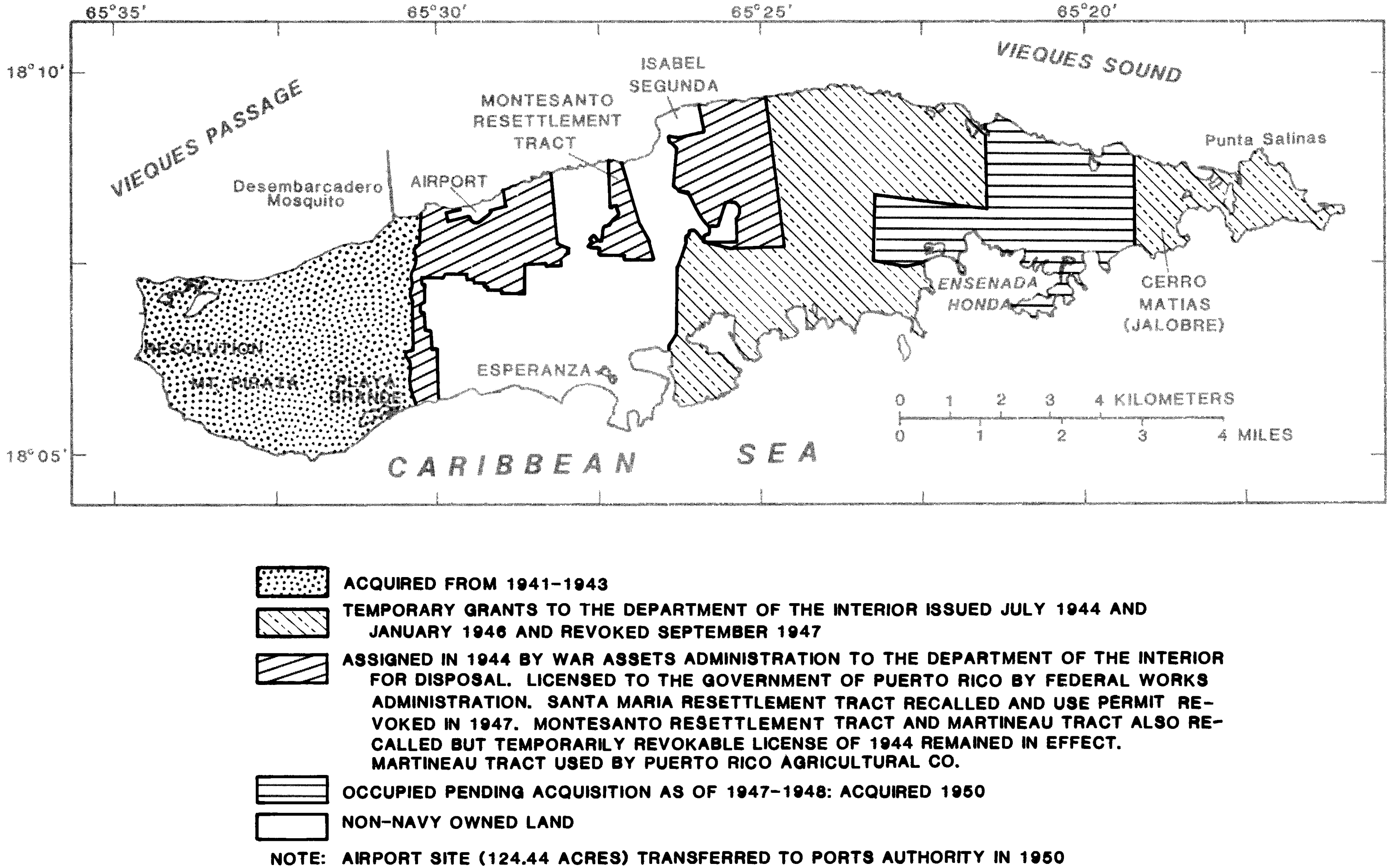


Figure 4.--Historic land ownership patterns.

Climate

The climate of Vieques is tropical-marine. Temperatures are nearly constant (fig. 5), with an annual average of about 79°F. August is the warmest month (82°F) and February the coolest (76°F). Vieques lies directly in the path of the prevailing easterly trade winds that regulate the climate of Puerto Rico (Calvesbert, 1974).

The easterly winds result in a rainfall pattern characterized by a dry season from December through July and a rainy season from August to November (fig. 6). However, localized thunderstorms can occur during May, June and July. Heavy precipitation may be induced by tropical storms in the Caribbean area from June to November. Showers are usually of short duration, less than 30 minutes, except those caused by tropical storms or low-pressure disturbances which are very common in the area.

Long-term annual precipitation data for Vieques ranges from a minimum of 26 inches in 1967 to a maximum of 73 inches in 1901 (National Weather Service data reports). The long-term annual average (78 years of record, 1899-1977) is about 45 inches. The eastern part of the island receives about 25 inches per year, while in the Resolución valley area the average is about 50 inches. Approximately fifty percent of the total-annual precipitation occurs during the rainy season (fig. 7). November is the rainiest month, with about fifteen percent of the annual total. April is usually the driest month, averaging less than 2 inches of rainfall.

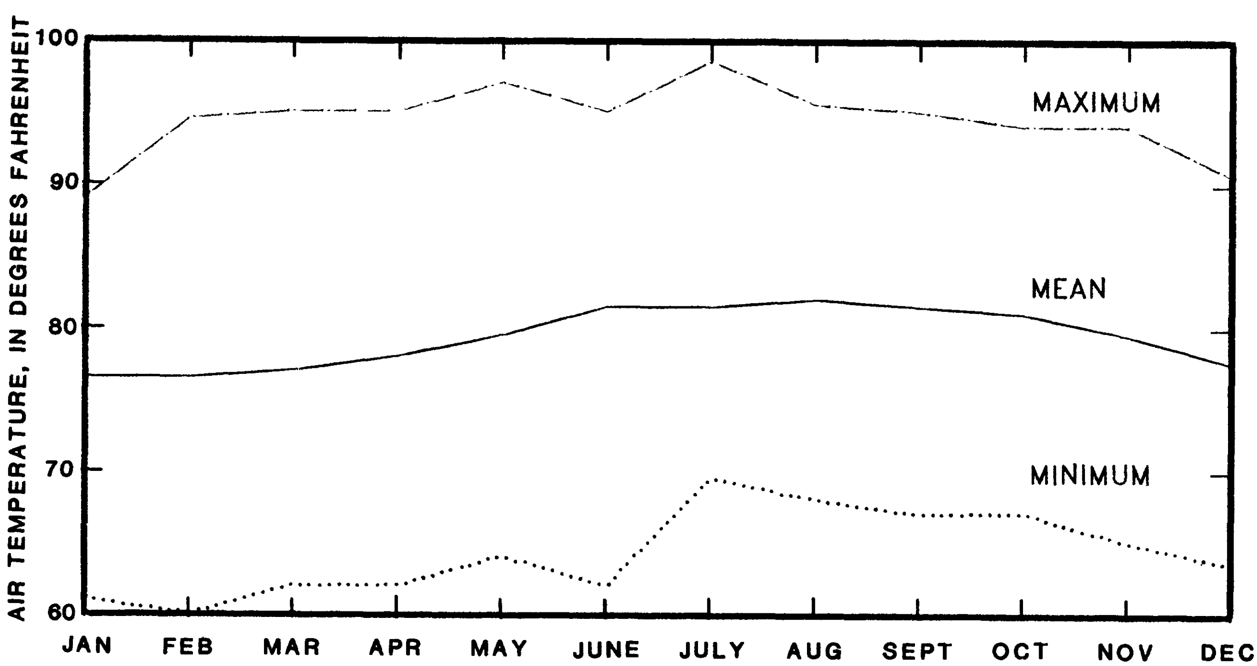


Figure 5.--Monthly mean and extreme temperature in degrees Farenheit at the Esperanza Valley.

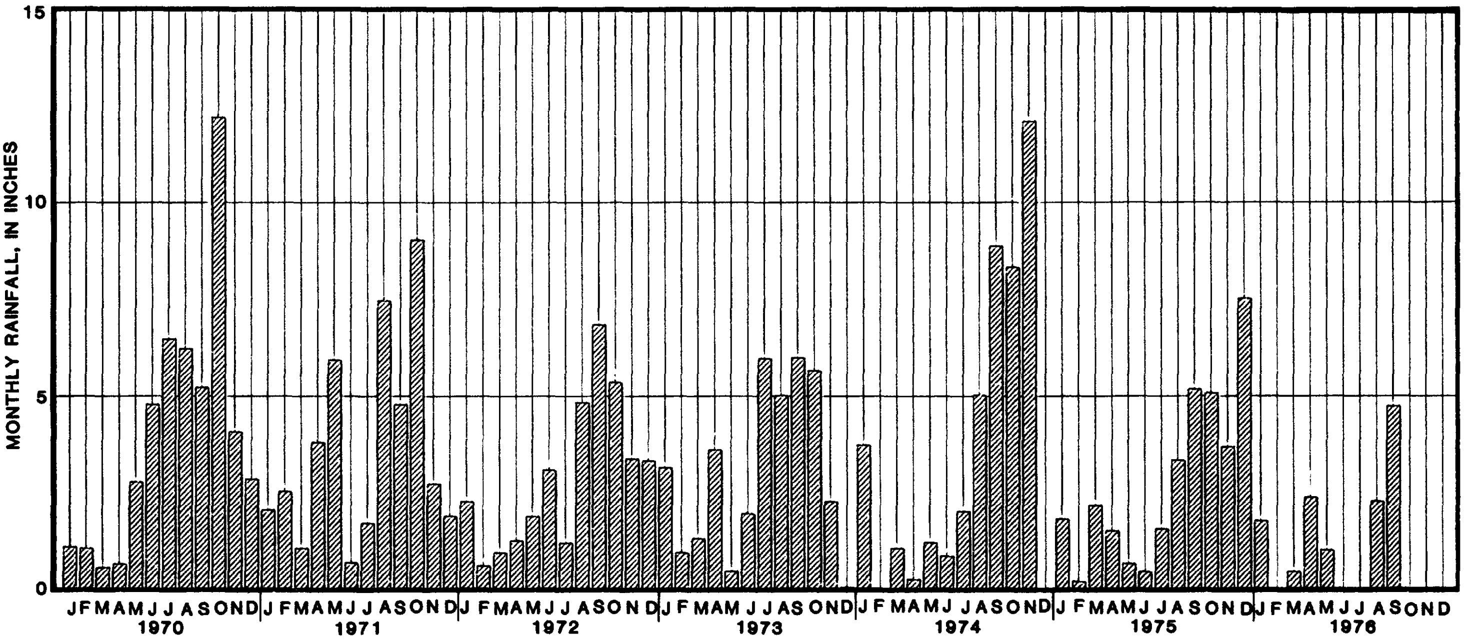


Figure 6.--Rainfall at Esperanza Valley from 1970 through 1976. (Data from Calvesbert (NOAA)).

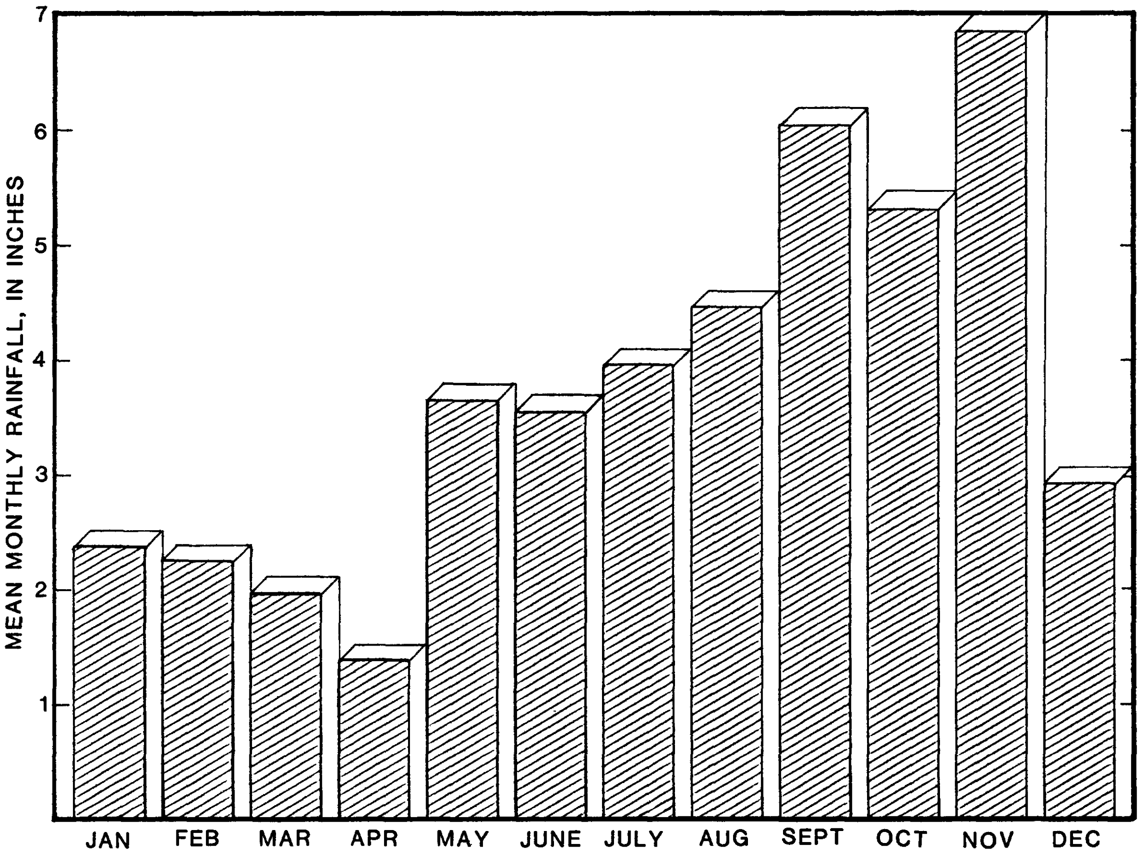


Figure 7.--Mean monthly rainfall distribution at Vieques, 1899-1970.

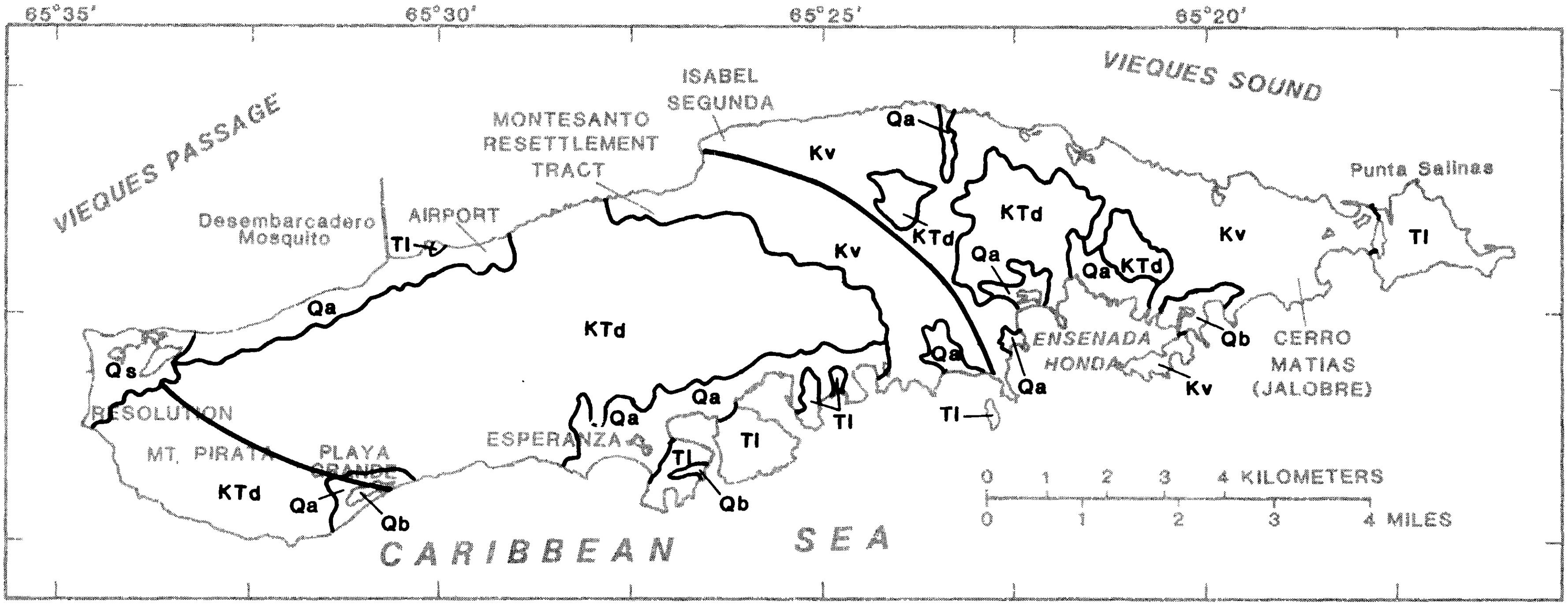
Geology

The geology of Vieques is characterized by volcanic rocks generally overlain by alluvial deposits and patches of limestone (fig. 8), and has been described in detail by Meyerhoff (1927). Volcanic andesites of Late Cretaceous age were deposited in a marine environment. Later in the Cretaceous a quartz-diorite plutonic complex intruded the andesites, and are exposed over a large percentage of the island. A gradual change in texture from coarse to fine-grained quartz-diorite has been observed from west to east (Kaye, 1959). Limestone of Tertiary age occurs in sectors of the north, south, and eastern parts of the island. The most extensive areas of limestone are found on the south coast peninsulas. The limestone is generally soft and yellowish, and well indurated where exposed to the atmosphere. The sedimentary deposits are generally of Quaternary age, consisting of a mixture of sand, silt, and clay. Most of the Esperanza and Resolución aquifers are formed by these sedimentary deposits. Seaward, the floodplains consist of beach and dune deposits formed by calcite, quartz, volcanic rock fragments and minor magnetite. Unconsolidated deposits of sand that are the direct result of stream erosion along major streams and along where the deposits enter the sea are carried along the coast. Unconsolidated deposits of sand are typically found in the northwestern part of the island, and to the south along Quebrada La Mina in the Esperanza valley.

Well logs and surface geophysical surveys indicate that the thickness of the sedimentary deposits range from 0 to about 90 feet in the Esperanza valley (figs. 9a and 9b). A basal clay bed, with a maximum thickness of 15 feet, overlies a granitic quartz-diorite. The clay is overlain by a interbedded sand and silt deposit with a maximum thickness of 60 feet. Aquifers in Vieques are generally semiconfined because of a series of interbedded clays. The uppermost unit is largely colluvium consisting of sand and silt, with sand predominating coastward.

SURFACE-WATER RESOURCES

The streams in Vieques are ephemeral. Although no streamflow data was collected during the investigation, Anderson (written commun.,1972) estimates that the total annual runoff is about 5,000 acre-ft. Field inspections during the rainy season showed that after a storm, streams flow only for a few days. There is no evidence that ground water discharges to the streams, except perhaps in response to heavy rainstorms. In the vicinity of streams, such as Quebrada La Mina in the Esperanza Valley, the elevation of the water table is generally lower than that of the streambed. Since Quebrada La Mina flows over the sedimentary deposits in the valley, it recharges the aquifer during rainy periods. Storm runoff could be used to augment recharge to the aquifer if retention could be optimized. Flow-retarding structures, such as retaining walls, could be constructed along the bed of the stream (Anderson, written commun., 1972). These impoundments would retain the runoff for a longer time period, allowing more recharge to the aquifer.



EXPLANATION

QUATERNARY
- **Qa** ALLUVIAL DEPOSITS, SAND, SILT, CLAY, GRAVEL FLOOD PLAIN, TERRACE DEPOSITS, AND PIEDMONT FAN DEPOSITS
- **Qb** BEACH AND DUNE DEPOSITS, LARGELY CALCITE, QUARTZ AND VOLCANIC ROCKS, AND FRAGMENT SAND WITH LOCAL MAGNETITE
- **Qs** SWAMP AND MARSH DEPOSITS, ORGANIC MUCK, SANDY OR SILTY, AND PEAT

TERTIARY
- **Tl** MARINE SEDIMENTARY ROCKS, UNDIVIDED

CRETACEOUS
- **Kv** SANDSTONE, SILTSTONE, CONGLOMERATE, LAVA, TUFF, AND TUFFACEOUS BRECCIA. LARGELY DEPOSITED IN MARINE ENVIRONMENT. EXTENSIVE DEEP WEATHERING. SOME LIMESTONE
- **KTd** PLUTONIC ROCKS, LARGELY GRANIDIORITE, AND QUARTZ DIORITE. LOCALLY DEEPLY WEATHERED

—— CONTACT

—— FAULT

Figure 8.--Generalized geology of Vieques Island. (Modified from Grove, 1972.)

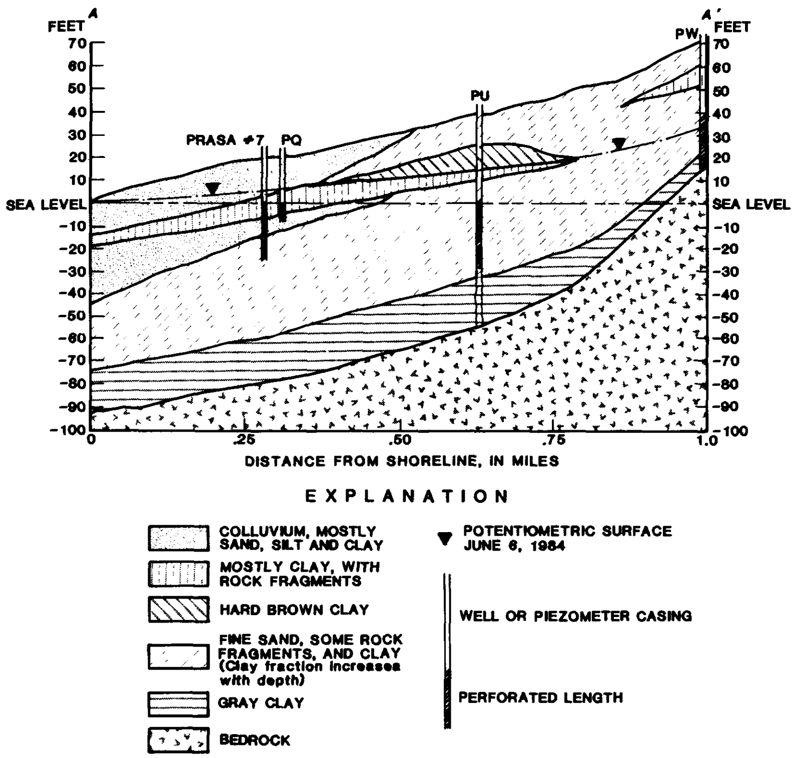


Figure 9a.--Hydrogeologic section of the aquifer of the Esperanza Valley.

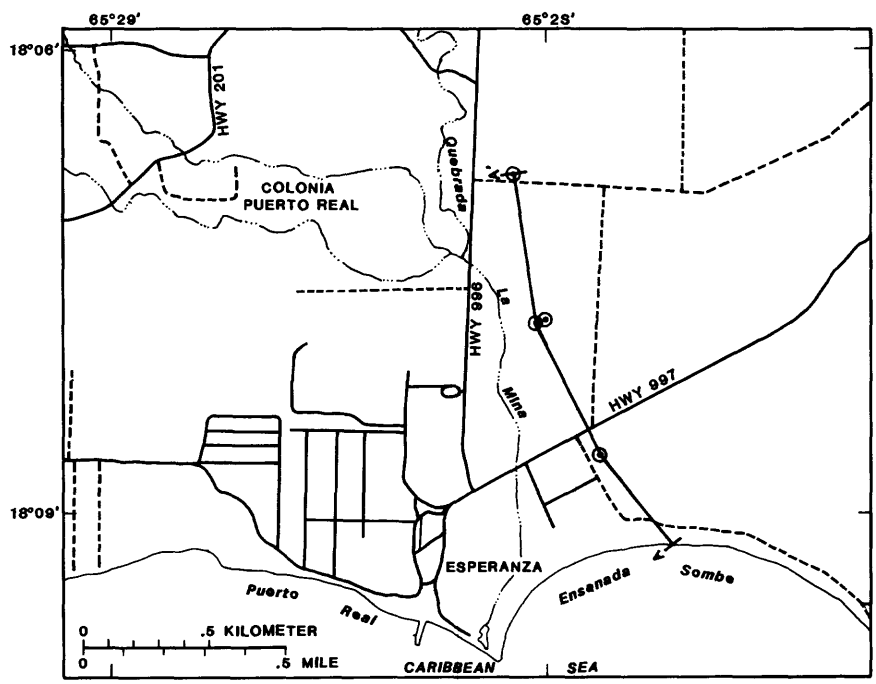


Figure 9b.--Map of Esperanza showing selected locations for hydrogeologic section A-A'.

WATER BUDGET

Precipitation in Vieques averages about 100,000 acre-ft/yr (on the basis of an average of 45 in/yr). There is no evapotranspiration (ET) data for the island, but estimates from data collected under similar climatic conditions in St. Thomas (fig. 1) suggest that about 90 percent of the precipitation or 90,000, acre-ft/yr is lost to ET. Runoff in Vieques was estimated at about 5,000 acre-ft/yr (Anderson, written commun., 1972). Recharge estimates indicate that about 3 to 5 percent of the rainfall is recharged to the aquifers (Jordan and Cosner, 1973). Accordingly, about 3,000 acre-ft/yr recharges the aquifers, which is equivalent to about 2.7 Mgal/d over the entire island. The maximum ground-water withdrawal from Esperanza and Resolución valleys was about 0.6 Mgal/d. The difference between the estimated recharge and withdrawals does not imply that 2.1 Mgal/d are available in Vieques. Most of the ground-water recharge in coastal areas is rapidly lost to the ocean. Some of the recharge occurring after heavy storms probably discharges to streams that flow for a few days.

GROUND-WATER RESOURCES

Esperanza Valley

The approximately 10 mi^2 Esperanza valley is the largest alluvial valley in Vieques. The alluvial deposits extend from the vicinity of Ensenada Sombe to Bahía Tapon in Camp Garcia. This area probably has the greatest potential for ground-water development in Vieques. Until 1978, PRASA operated a battery of 10 wells in the valley (fig. 10). The wells were generally 10 in. in diameter, about 40 to 60 ft deep, constructed of perforated casing and equipped with submersible pumps. Ground water withdrawals in the valley averaged about 425,000 gal/day (fig. 11). As pumpage increased with development of the well field, the salinity of the water increased.

The source of ground water in Esperanza valley is rainfall recharged to the aquifer from ephemeral streams or direct infiltration in the basin. The elevation of the water table in the lower valley ranges from 10 to 100 ft above mean sea level (fig. 12). Significant rises in ground-water potentiometric levels due to rainfall were monitored at observation wells in the valley (fig. 13), however long-term changes in potentiometric water levels were minimal and were related only to natural recharge and discharge, since there is no pumpage from the aquifer.

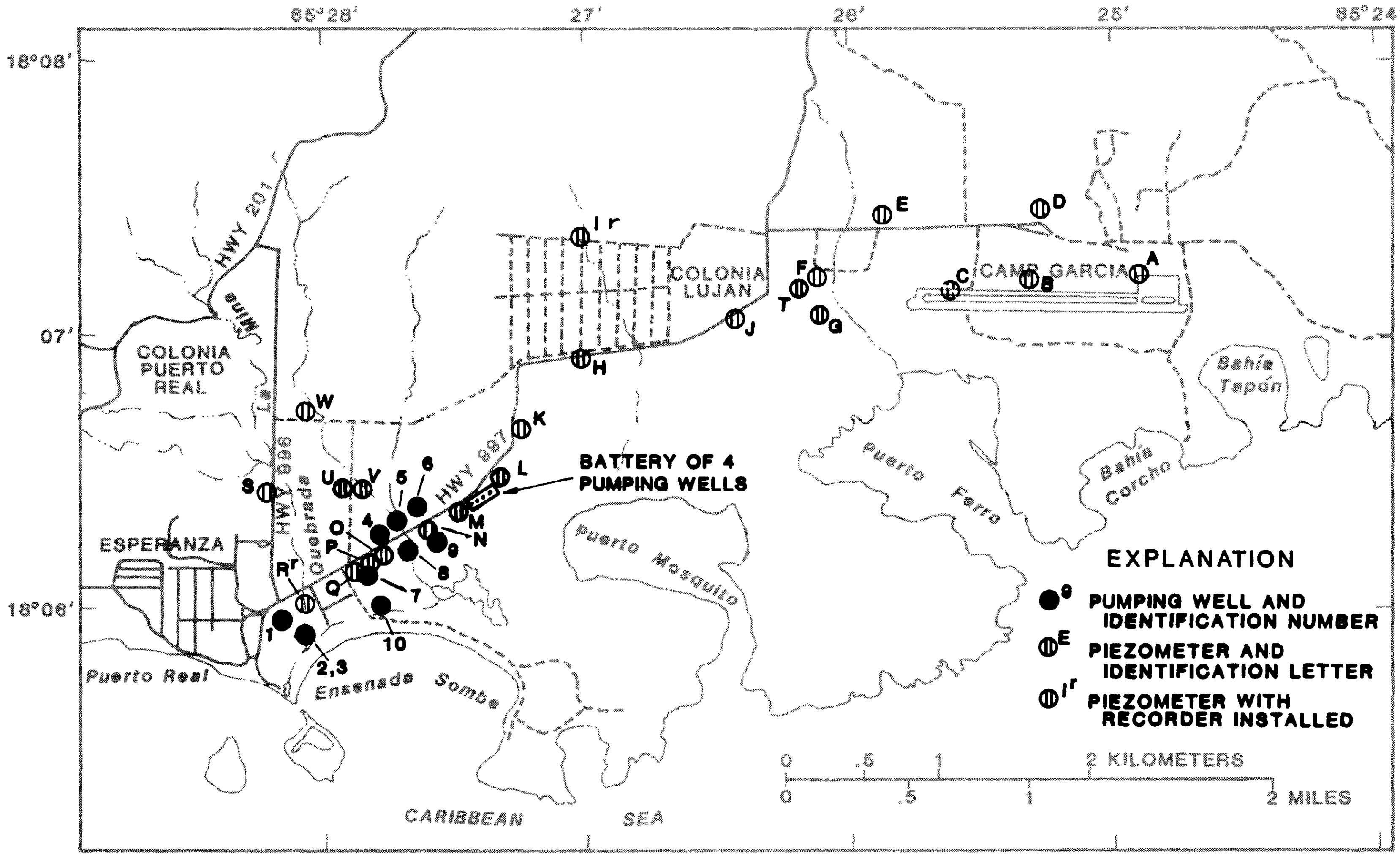


Figure 10.--Network of observation wells and piezometers in Esperanza Valley and Camp Garcia.

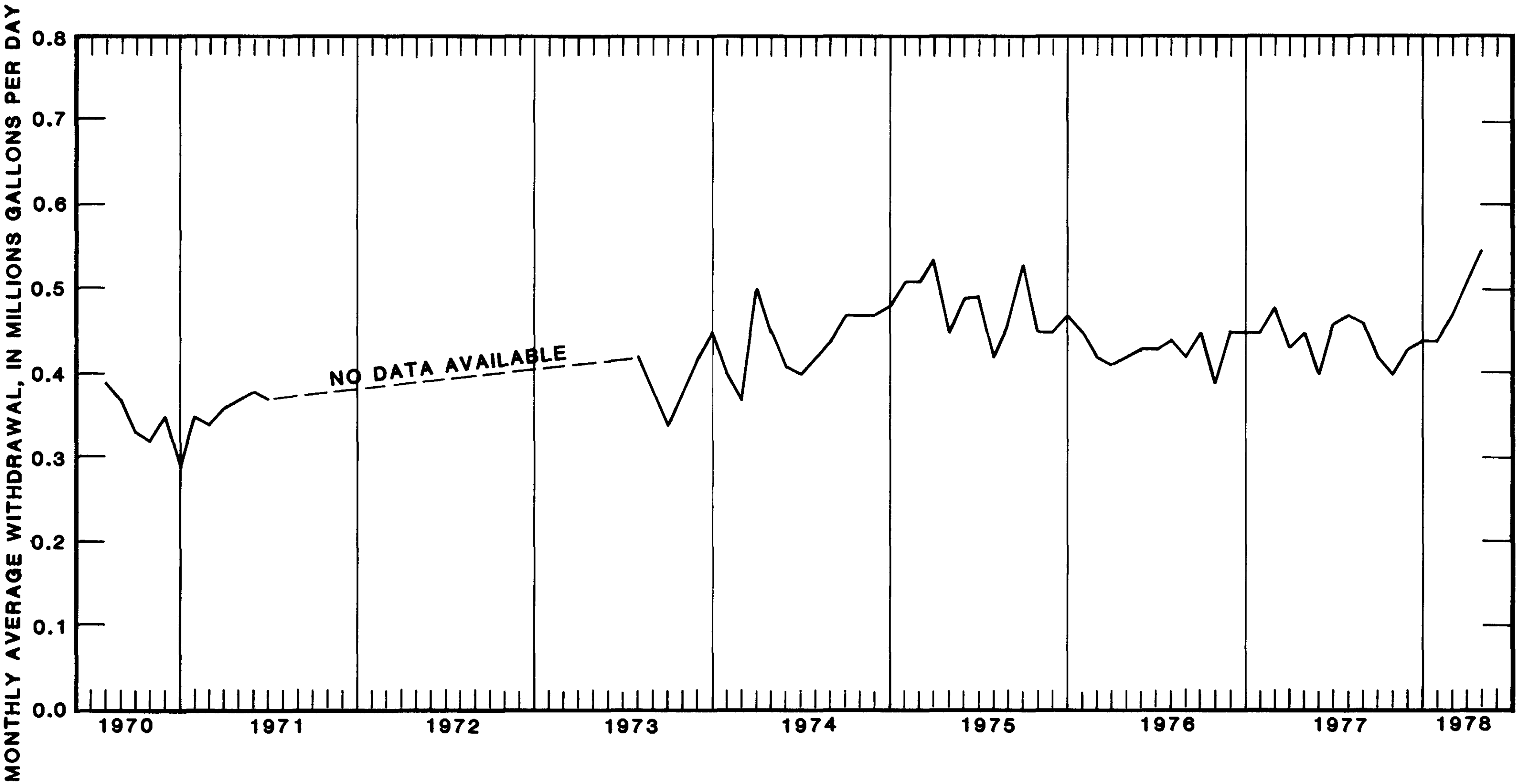


Figure 11.--Monthly average withdrawal in million gallons per day at the Esperanza alluvial aquifer from 1970 through 1977. (Data from PRASA records.)

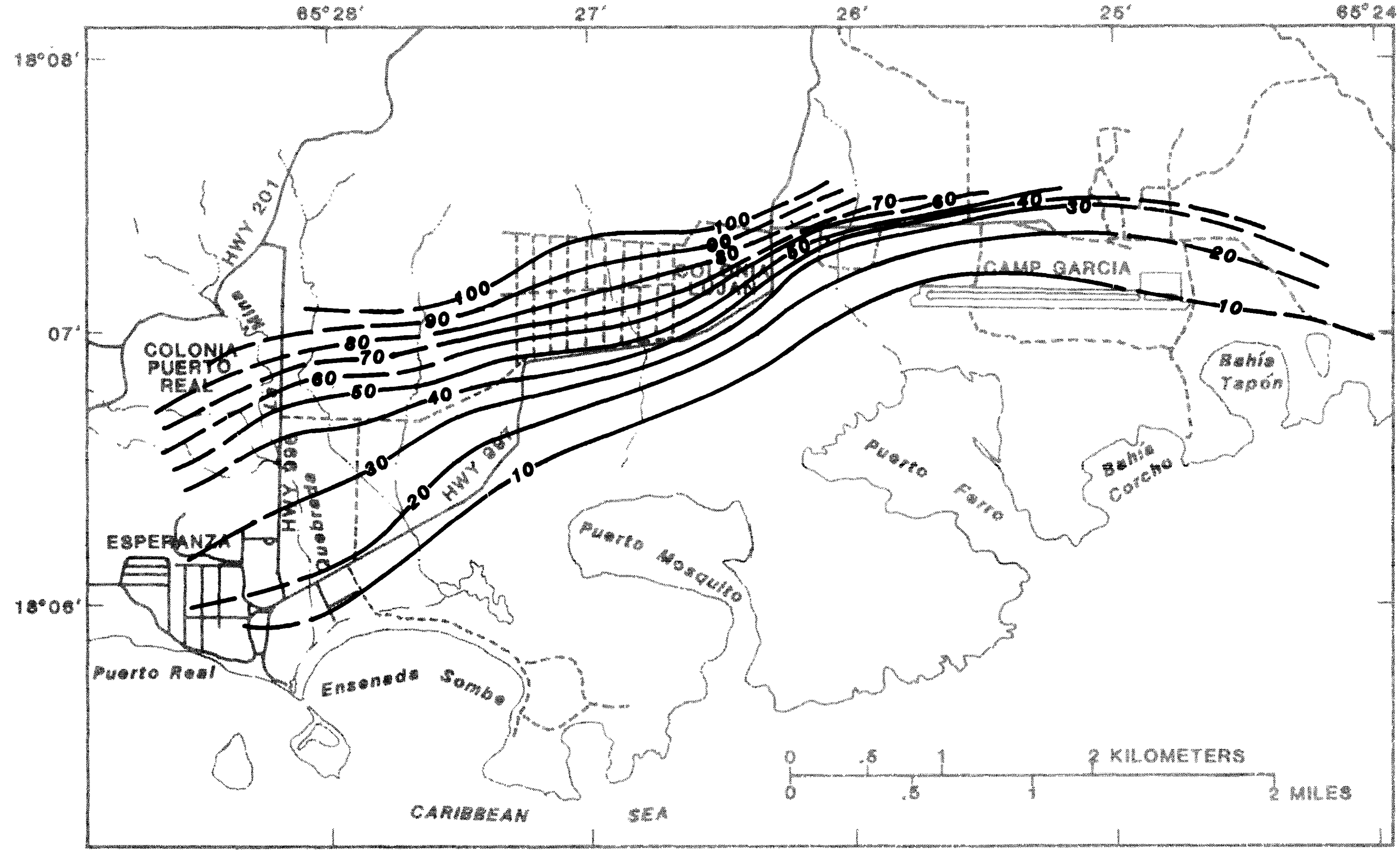


Figure 12.--Water-level contours in feet above MSL in the Esperanza alluvial aquifer during April 1983.

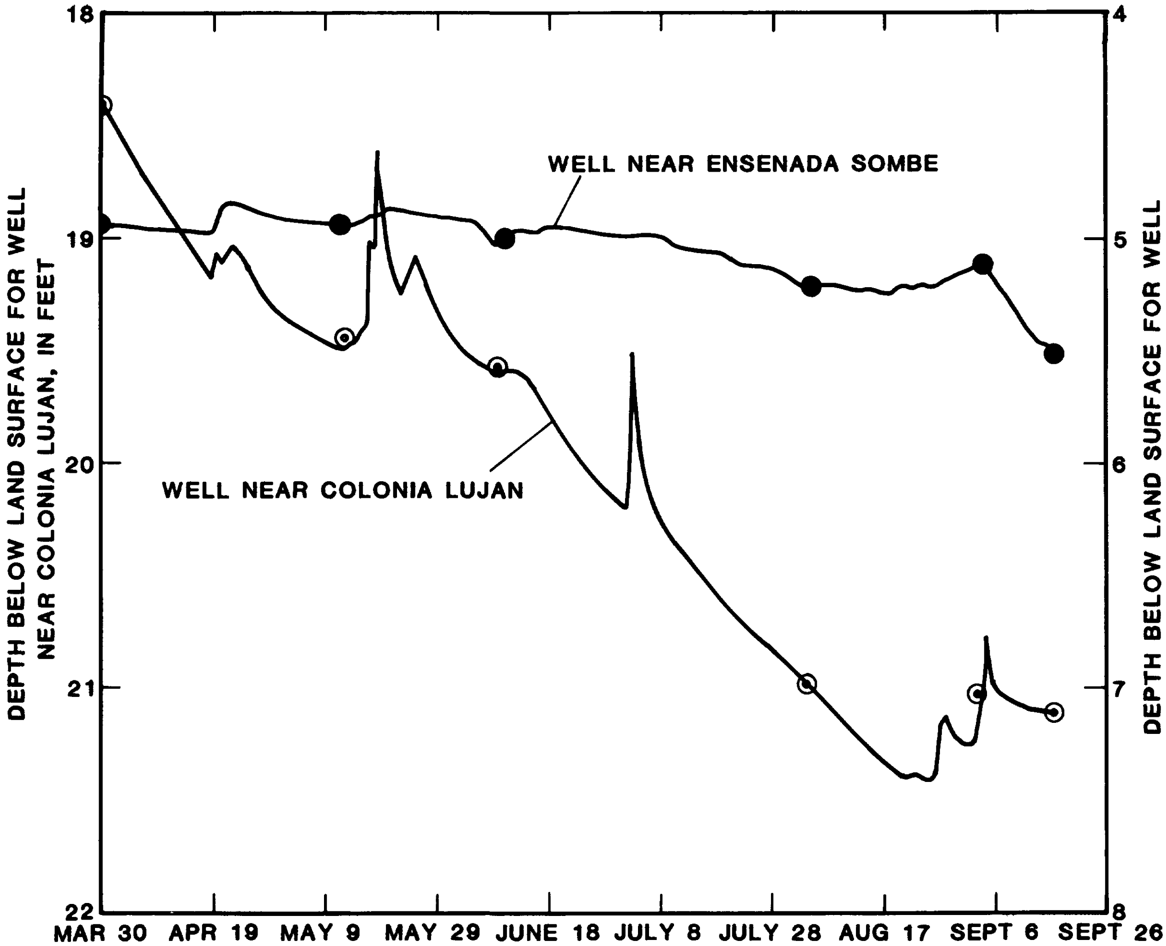


Figure 13.--Ground-water level fluctuations in wells in the Esperanza alluvial aquifer during 1983.

Esperanza Valley (Continued)

Recharge to the alluvial aquifer occurs primarily throughout the island's along the central volcanic contact. Along the south-central shoreline, recharge through outcrops of limestone rock is limited by the low permeability of the indurated and weathered limestone surface. The limestone unit, however, is uncommon elsewhere in Vieques, except along the southern shore in the deepest sections of the Esperanza alluvial aquifer. North of the limestone outcrops, the aquifer consists of alluvial deposits. A clay layer averaging 5 feet thick was found consistently across the aquifer (fig. 9a) at a depth of 25 feet or less. This clay layer hydraulically isolates the alluvial sediments, limiting recharge to the aquifer; a common condition throughout Vieques. However, the hydraulic relationship between the sand and silt deposits and the clay layers within the alluvial aquifer is more complex. Far from the shoreline, the entire aquifer sequence behaves as one aquifer under water-table conditions. However, where the clay layers are well developed, near the southern shoreline, the aquifer behaves as if semi-confined. Such conditions occur near the coast where aquifer tests indicate that saturated sediment of the upper unit behaves as a strongly anisotropic water-table aquifer, but the sand and silt of the lower unit behave as an artesian aquifer (fig. 9a). Water is released from storage in the clay layer when the aquifer is pumped. With time, the clay tends to transmit water from the overlying alluvium as well as provide water from storage. Definition of the true hydrologic characteristics of each unit requires aquifer tests that would account for leakage, anisotropy, and a wide range of specific-storage values. Aquifer tests of this nature were beyond the scope of this investigation.

Aquifer tests in the Esperanza alluvial aquifer indicate transmissivity values ranging from 200 ft^2/d near Camp Garcia to as much as 2,000 ft^2/d east of Ensenada Sombe. Transmissivity is affected by: (1) the thickness of the surficial deposits, and (2) the hydraulic conductivity of the sediments. The hydraulic conductivity of the alluvium increases toward the coast where the amount of sand in the deposits increases. Alluvium thickness increases toward the sea from 0 to about 90 ft (fig. 9a), decreasing toward the east where depth to the bedrock is about 30 ft. Hydraulic conductivity values for the alluvium were estimated as less than 1 ft/d along the north-central hills in the valley to as much as 35 ft/d near the coast. Storage coefficient values were assumed to be about 0.1 in the water-table zone and computed at about 0.006 in the semi-confined layer. The aquifer tests showed that the overlying clayey deposits release water in response to pumping from the alluvium.

Additional data about the hydrogeology and the stratigraphy of the Esperanza alluvial aquifer was obtained from surface geophysical surveys. Electrical resistivity tests defined the bottom of the unconsolidated deposits at about 60 ft below the land surface where the alluvial deposits are thickest (north of Ensenada Sombe).

Resolución Valley

The Resolución valley, in northwestern Vieques, is the second largest valley on the island (fig. 2). The valley slopes from Monte Pirata toward the Vieques passage, with an area of about 8 mi^2. The slopes in the valley are gentle except in the upper reaches. Although there are no perennial streams in the valley, Monte Pirata induces orographic effects resulting in higher precipitation in this area than in any other area of Vieques.

The Resolución valley water resources investigation was limited to geophysical surveys, inventory of existing and abandoned wells, collection of water samples for chemical analyses, and interpretation of previous data, including well logs.

The geology of Resolución valley is similar to the Esperanza area, except that sedimentary deposits here overlie a saprolite derived from the plutonic rocks; whereas in the Esperanza area, sedimentary deposits overlie volcanic and limestone rock. The geophysical surveys and data from abandoned wells show that the alluvial deposits average about 30 ft thick. Seismic refraction surveys indicate the presence of a compacted clay layer about 20 to 30 ft below the surface, similar to the conditions in the Esperanza valley. A geologic lineament, possibly a block fault, occurs within the Resolución valley north of Hacienda Arcadia (fig. 2). A rectangular regional drainage pattern is formed in the area, probably indicative of jointing as a result of faulting. Fractured or broken Cretaceous age igneous rocks may yield considerable quantities of water.

Most of the wells in the Resolución valley are abandoned or could not be reached. Future investigations in the area will require a comprehensive drilling program to further evaluate the aquifer characteristics and its full water-yielding potential. Past experience and data from previous investigators show that, with adequate management, it may be feasible to pump as much as 200,000 gal/d from the alluvial aquifer.

Playa Grande Area

The Playa Grande drainage area (5.5 mi^2), south of Resolución valley, yielded as much as 50,000 gal/d of water through 1965 (Anderson, written commun., 1972). Seismic refraction and electrical resistivity tests did not reveal the existence of a confining layer above the alluvial deposits. This suggests that water-table conditions prevail throughout the aquifer. Additional investigations, including test drilling, will be required to better define the aquifer characteristics in the Playa Grande area.

Camp Garcia

Camp Garcia, located east of Esperanza valley (fig. 2), includes about 5 mi^2 of the U.S. Navy controlled land in Vieques. Bedrock in the Camp Garcia area is predominantly unweathered, highly impermeable granodiorite (U.S. Department of Defense, 1980); the porosity is very low, and the potential for ground-water development is limited. Toward the coast, clayey alluvium overlies the granodiorite. Samples from wells in the Camp Garcia area show mostly saline water in the clayey alluvium. Historical data collected by Anderson (written commun., 1972) show that prior to the development of the well field in Esperanza valley in 1945, ground-water levels in the Camp Garcia area were about 10 ft below land surface. A continuous decline in the water levels has occurred. From 1961 to 1965, declines from 2 to 20 ft were recorded in three wells in the area. Well yields also declined from about 35 to 10 gal/min. This data suggests that ground water in Camp Garcia was originally withdrawn from the alluvial zone, whereas now it originates from the unweathered granodiorites. At present, six (6) storage tanks with a capacity of 42,000 gallons are used in the Camp. The tanks are filled gradually to limit pumpage from the wells to about 25 gal/min.

Aquifer characteristics in the Camp Garcia area were estimated by Davis and Deweist (1966). The porosity was estimated at 0.02-0.05, while transmissivity values averaged 300 ft^2/d. Current ground-water withdrawals from Camp Garcia are about 2,000 gal/d.

SALTWATER INTRUSION

The maintenance of potable ground water in Vieques island depends upon the quantity of water pumped and the location of wells. During the initial development stages of the Esperanza and Resolución well fields, ground-water quality was generally good, with chloride ion concentration seldom exceeding 100 mg/L. However, as uncontrolled development and pumpage proceeded, saline water intruded into the alluvial aquifers, with chloride concentration exceeding 200 mg/L. As water quality deteriorated, complaints from the residents prompted the construction of the Vieques pipeline, which became operational in 1977.

Historical water-quality data from PRASA show the effects of saline water intrusion in the Esperanza alluvial aquifer (figs. 14a - 14d). From 1973 to 1977, the chloride concentration at six of the wells increased from a background concentration of 100 mg/L to about 250 mg/L. At well no. 10 (fig. 14d), chloride concentrations increased from about 100 to about 300 mg/L.

Saline water contamination usually occurs by upconing or intrusion. In areas where wells are located too close to the saline-freshwater interface, "upconing" of saline water can occur. The upconing occurs as the well is pumped, with a gradual "lifting" of a "dome" of saline water into the area of the well screen (Zack, 1988). When the well is idled, the dome of saline water may slowly recede, freshwater may be produced from the well once the pump is re-started, until the dome is again lifted. Horizontal intrusion of saline water is a more common phenomena: saline water advances inland into an aquifer as the head of freshwater over the saline water interface is reduced due to pumpage.

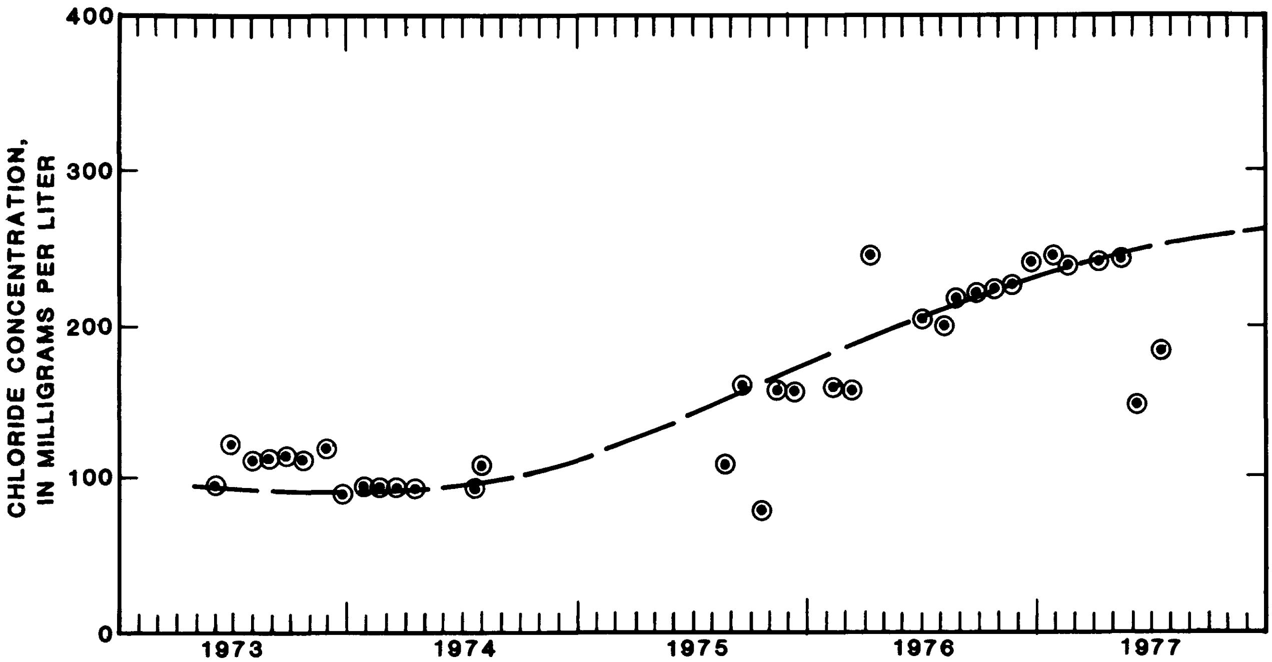


Figure 14a.--Chloride concentrations in water at well 1 at Esperanza alluvial aquifer. (Refer to fig. 10 for site location.)

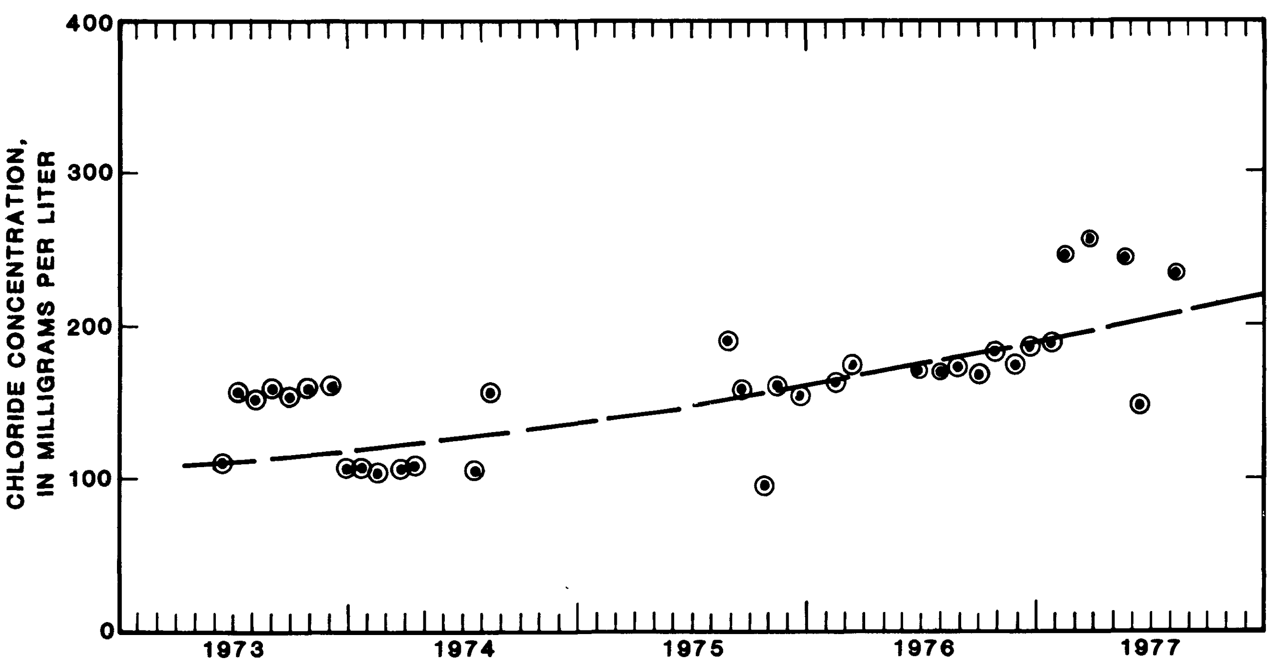


Figure 14b.--Chloride concentrations in water at well 3 at Esperanza alluvial aquifer. (Refer to fig. 10 for site location.)

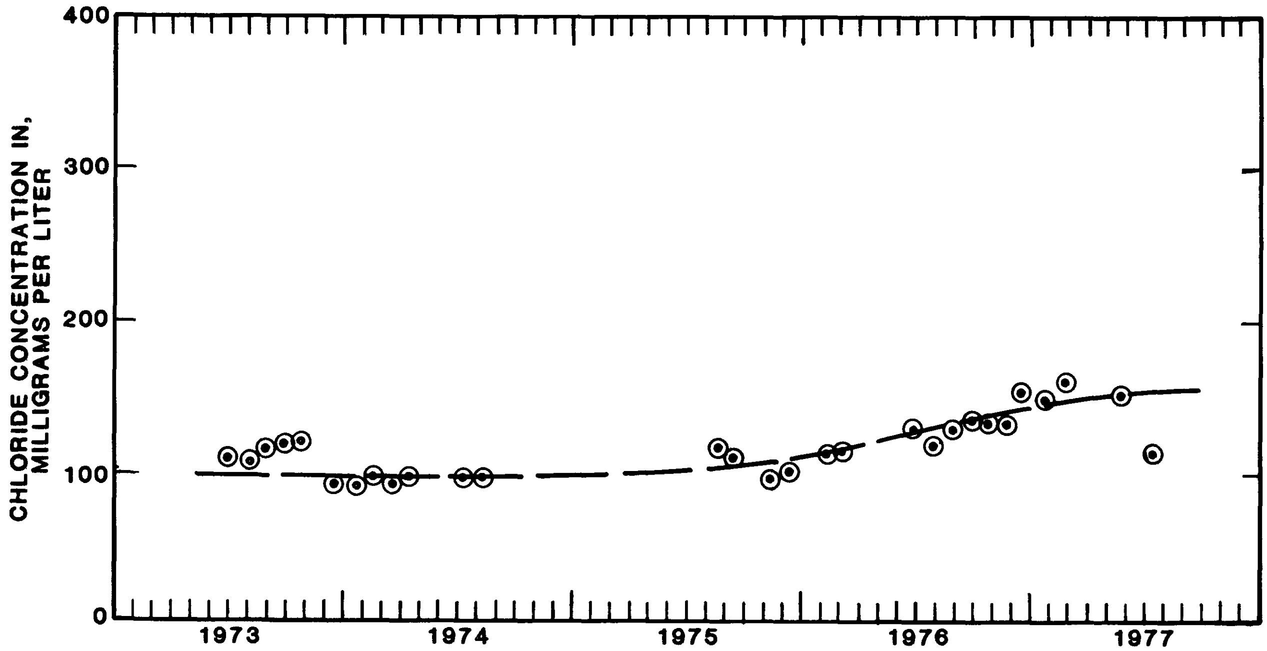


Figure 14c.--Chloride concentrations in water at well 5 at Esperanza alluvial aquifer. (Refer to fig. 10 for site location.)

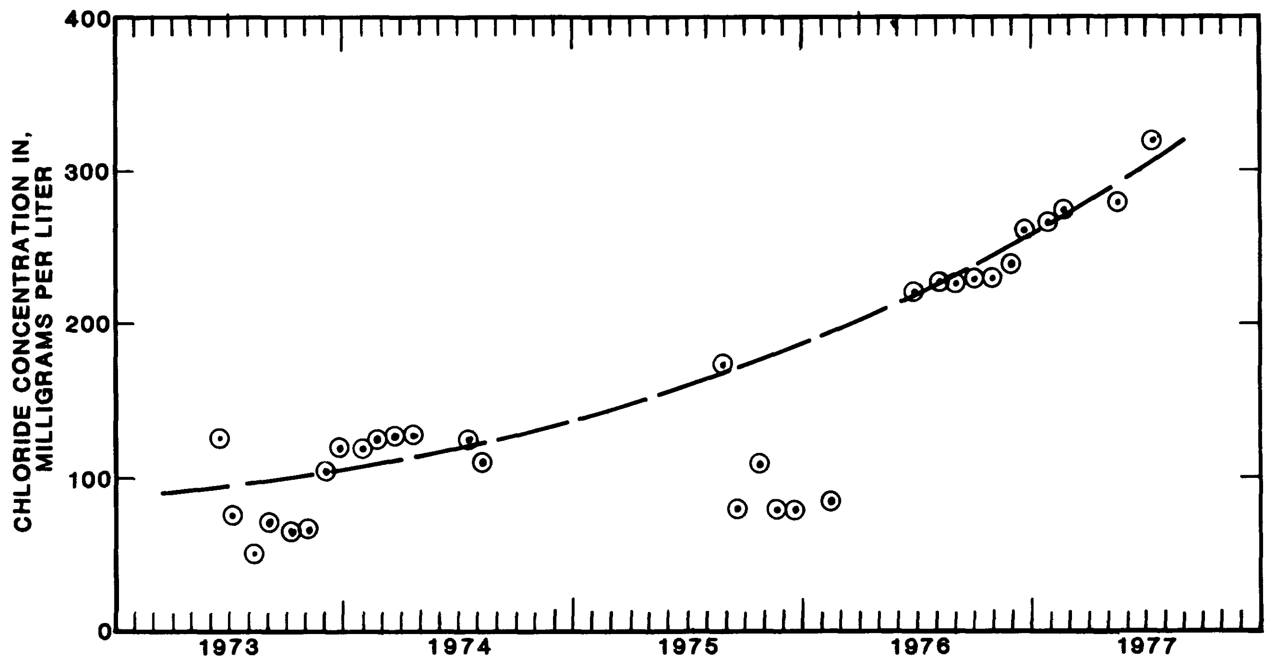


Figure 14d.--Chloride concentrations in water at well 11 at Esperanza alluvial aquifer. (Refer to fig. 10 for site location.)

SALTWATER INTRUSION (Continued)

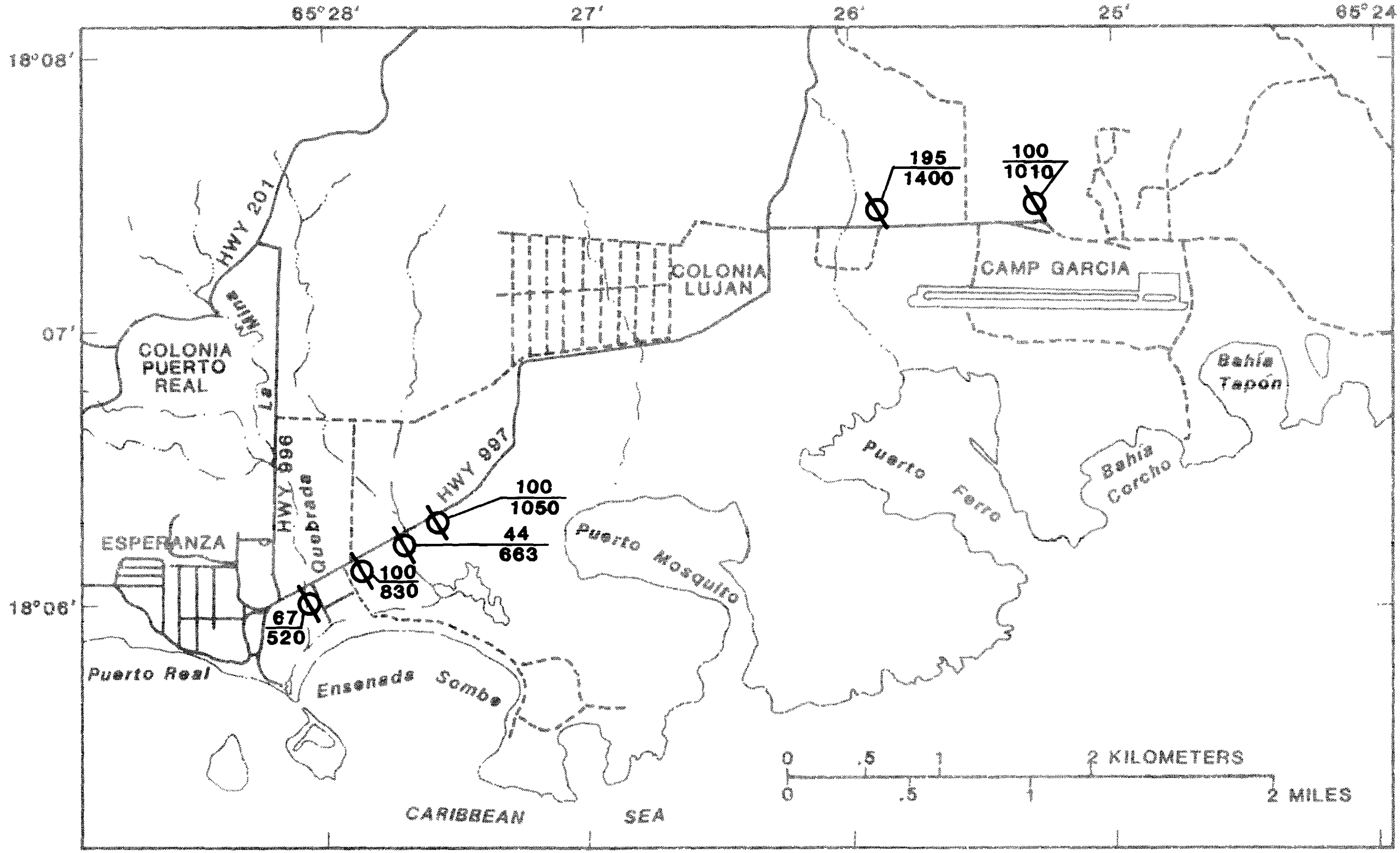
Water-quality data for Vieques indicate that in the Esperanza valley, saline water intrusion occurred throughout most of the alluvial aquifer as a result of overpumpage and reduction of the elevation of the freshwater lens. Chloride concentrations as depicted in figures 14a to 14d, increased. If upconing had occurred instead of intrusion, the chloride concentration would have reacted to changes in pumpage and would not show a continuosly increasing concentration. Changes in chloride-ion concentration shown in figure 14 probably were caused by pumpage patterns (fig. 11) as the well batteries were never pumped simultaneously.

Data collected during this investigation show that the aquifer has nearly recovered to pre-developed conditions. Freshwater has recharged the aquifer, replacing the intruded saline water. Physical and chemical anlayses of samples collected at key wells show chloride concentrations do not exceed 100 mg/L at Esperanza valley (fig. 15, table 1) and 130 mg/L at the U.S. Naval Ammunition Facility in Resolución (table 1). At the Camp Garcia wells, the chloride concentration does not exceed 200 mg/L. The water from all wells meets U.S. Environmental Protection Agency Drinking Water Standards for maximum chloride concentration of 250 mg/L (1972).

In spite of the observed improvements in the quality of the ground water in Vieques, its use may be limited for agricultural purposes. The data in table 1 show relatively high sodium concentrations and sodium-adsortion ratios (SAR). The SAR is an indication of the ability of the water to exchange ions with the soils (U.S. Department of Agriculture, 1954). Under current conditions, with no pumpage since 1977, SAR ratios for samples collected in the area approach a medium to high salinity hazard level of 4.8 units for irrigation water.

Table 1. Chemical analysis for typical well at Ensenada Sun Bay public beach during 1982

WELL NAME AND LOCATION	pH	SPECIFIC CONDUCTANCE	ALKALINITY, TOTAL AS $CaCO_3$	CALCIUM	CHLORIDE	FLUORIDE	HARDNESS, TOTAL	MAGNESIUM	SILICA	SULFATE	SODIUM	SODIUM ADSORPTION RATIO (SAR)	DATE SAMPLE COLLECTED
	Units (field)	Micro-siemens (uS)	Milligrams per liter										
PRASA #5, ESPERANZA	7.3	663	197	32	44	0.7	140	15	36	73	72	2.9	8/18/82
PRASA D1, ESPERANZA	7.8	1050	276	41	100	0.6	200	24	47	96	140	4.6	8/17/82
PRASA D2, ESPERANZA	7.8	830	229	58	95	0.5	260	27	46	55	110	3.3	8/19/82
CAMP GARCIA G1	7.6	1010	277	—	100	0.3	--	—	—	42	—	—	8/18/82
NAF, RESOLUCION	7.1	982	287	41	130	0.3	210	26	35	22	120	4.0	8/18/82



EXPLANATION

OBSERVATION WELL OR PIEZOMETER

$\frac{100}{1010}$ CHLORIDE CONCENTRATION / SPECIFIC CONDUCTANCE

Figure 15.--Chloride ion concentration (milligrams per liter) and specific conductance (mirosiemens per squared centimeter) of ground water from key wells in the Esperanza Vallley and Camp Garcia, 1982.

DIGITAL SIMULATION OF GROUND-WATER FLOW IN THE ESPERANZA ALLUVIAL AQUIFER

Model Design

A digital model simulating ground-water flow in an aquifer is a mathematical representation of the hydrogeologic characteristics of the aquifer and can accurately simulate changes in water levels as a result of pumpage and/or recharge. A model is designed, constructed, and calibrated on basis of field data and aquifer para-meters, as well as test runs against known values of water levels in wells. In the calibration process, the model parameters are adjusted to obtain a satisfactory match with the field values.

Ground-water flow in the Esperanza alluvial aquifer was simulated using the modular finite-difference model of McDonald and Harbaugh (1984). The model solves the ground water flow equation through a series of finite-difference approximations. Although the model can be used to simulate steady state (equilibrium) and transient conditions in the aquifer, the calibration in Esperanza valley was limited to steady-state. Limited data precluded transient approximations. Several assumptions pertain to the model calibration:

1. Precision of response is related to the accuracy and appropriateness of the input data.

2. The model does not take into account changes in the location of the saline-freshwater interface.

3. The computation assumes that the wells fully penetrate the simulated aquifer and are 100 percent efficient.

4. Evapotranspiration was considered negligible except near the coast, where water levels are less that 10 ft below the land surface.

Model Construction

A finite-difference grid of the study area was constructed (fig. 16). It consists of rectangular cells ranging in size from 200 to 1,000 ft along each edge with the smaller cells located near the areas where most of the wells are located. The grid covers an area of about 9 mi^2 and consists of 23 rows and 42 columns.

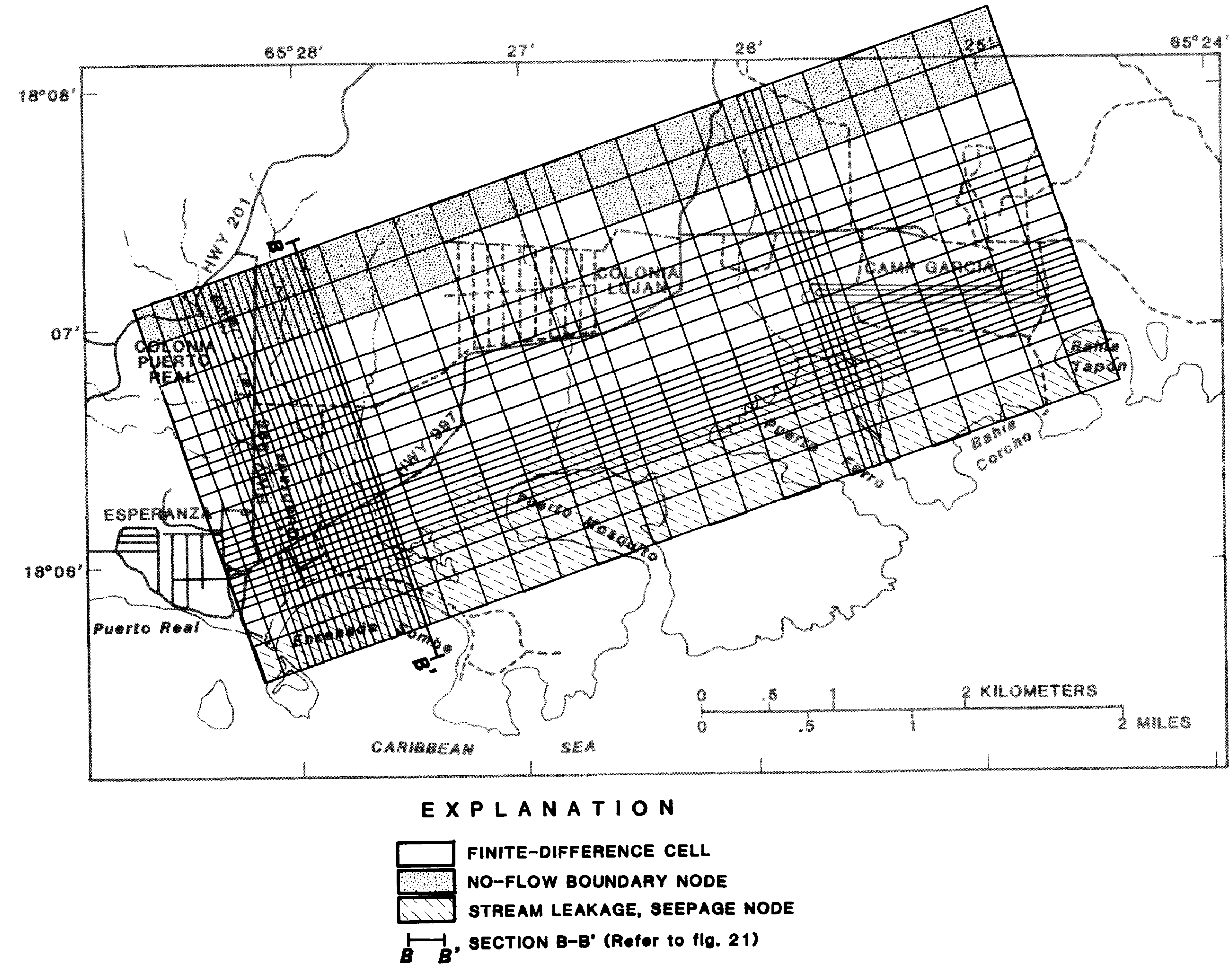


Figure 16.--Finite-difference grid and boundary conditions used in the Esperanza alluvial aquifer model.

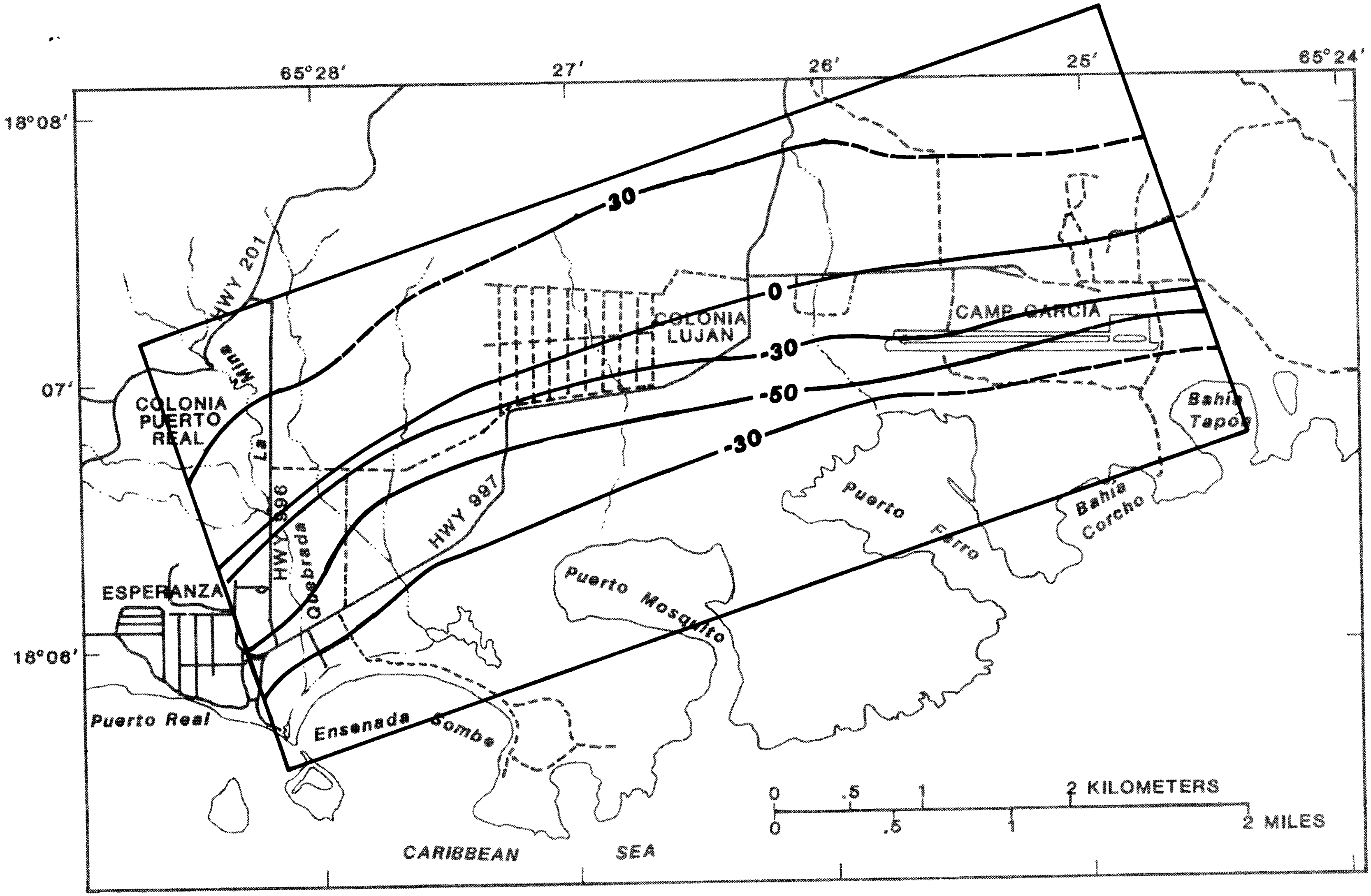
Model Construction (Continued)

The model utilizes no-flow and stream-cell boundaries. No-flow boundaries represent impermeable zones (igneous rock). The stream-cell boundaries represent areas where water flows out of the model boundaries. The lateral boundaries of the model were chosen to coincide with volcanic rock outcrops, where the transmissivity would be greatly reduced and little or no flow would be introduced into the aquifer through pumping. The headwaters of the surface-drainage area of the basin were selected as the northern boundary. The lateral boundaries were initially considered active (permeable) with hydraulic conductivities similar to the nearby alluvial deposits. It was later determined that there is no flow across the lateral boundaries. The northern area was considered a no flow boundary because the rocks are nearly impermeable volcanic formations. The coastal lagoons and the shoreline were selected as the southern boundary representing the discharge point for the freshwater flow. In this area, (stream-cell boundaries) a hydraulic conductivity of 1 ft/d was assumed to account for the nearly impermeable layer of clayey material that overlies the sand and silt deposits.

Other parameters adjusted in the calibration of the model included the aquifer thickness, hydraulic conductivity, conductance of riverbed recharge, and evapotranspiration rates (ET). During the field investigation these values were either measured or estimated. The altitude of the base of the alluvial aquifer (fig. 17) was determined from well logs and the geophysical tests, generalized to include the modeled area. Aquifer tests, geologic data, and values of specific capacity of wells were used to estimate the hydraulic conductivity (fig. 18). Recharge values (fig. 19) were estimated from precipitation data and other studies in which recharge rates have been estimated from surface-drainage-runoff studies (Jordan and Fisher, 1977).

Model Calibration

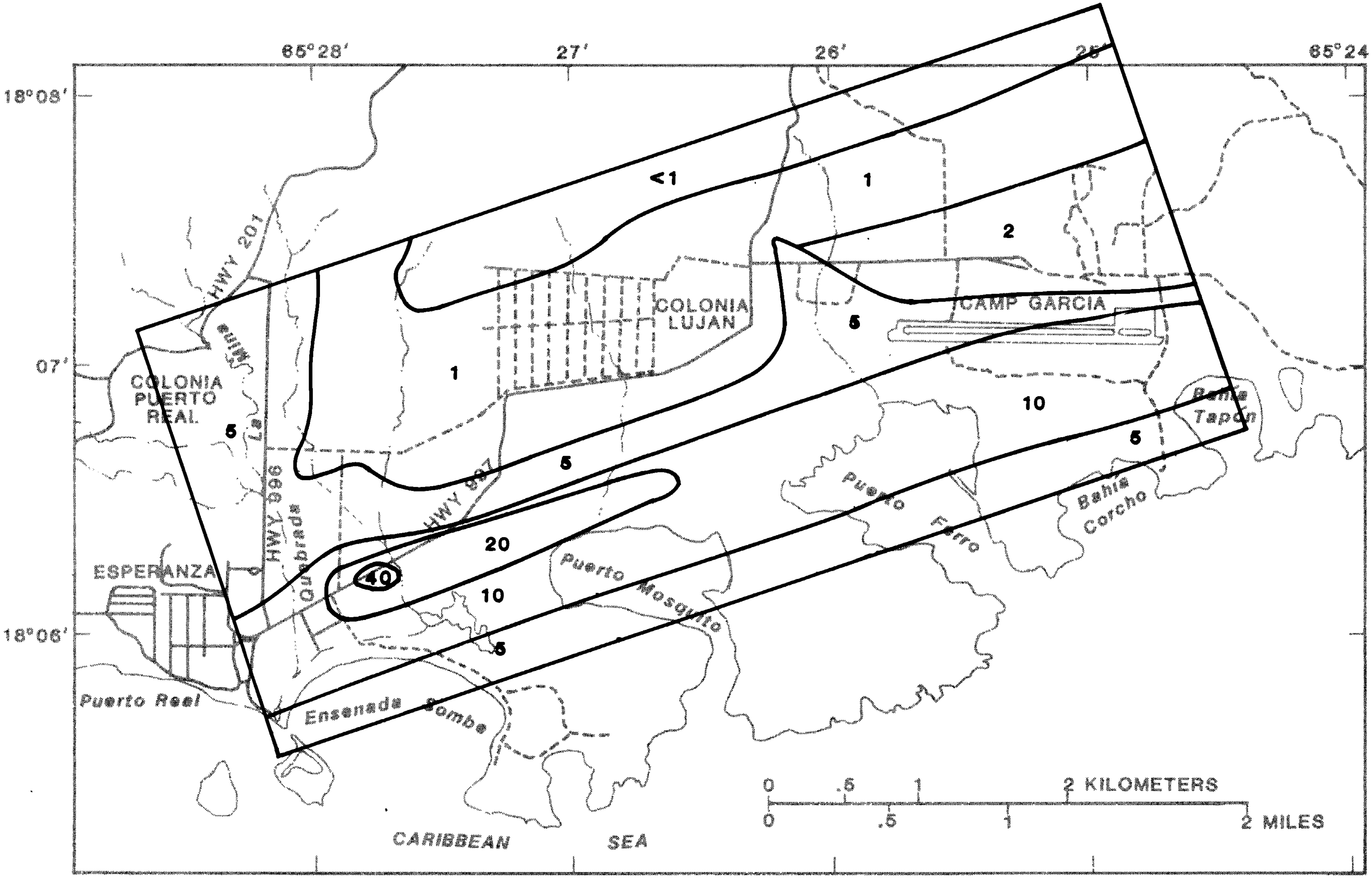
The calibration of a ground-water flow model is performed through an iterative computational process. The hydrogeologic parameters of the model (hydraulic conductivity, riverbed conductance, recharge, thickness, ET) are adjusted within reasonable limits to match the observed and simulated water levels. In the calibration of a ground-water flow model, differences between the computed and observed levels always occur. The observed water levels represent a point measurement, while the model elevations represent the estimated altitude of the potentiometric surface based on the areal hydrogeologic modeled properties for the cell. Although head at a cell may meet the calibration limits, it may differ several feet from the point value.



EXPLANATION

—— -30 —— STRUCTURE CONTOUR--Shows altitude of base of the alluvial aquifer in feet. Interval variable. Datum is mean sea level.

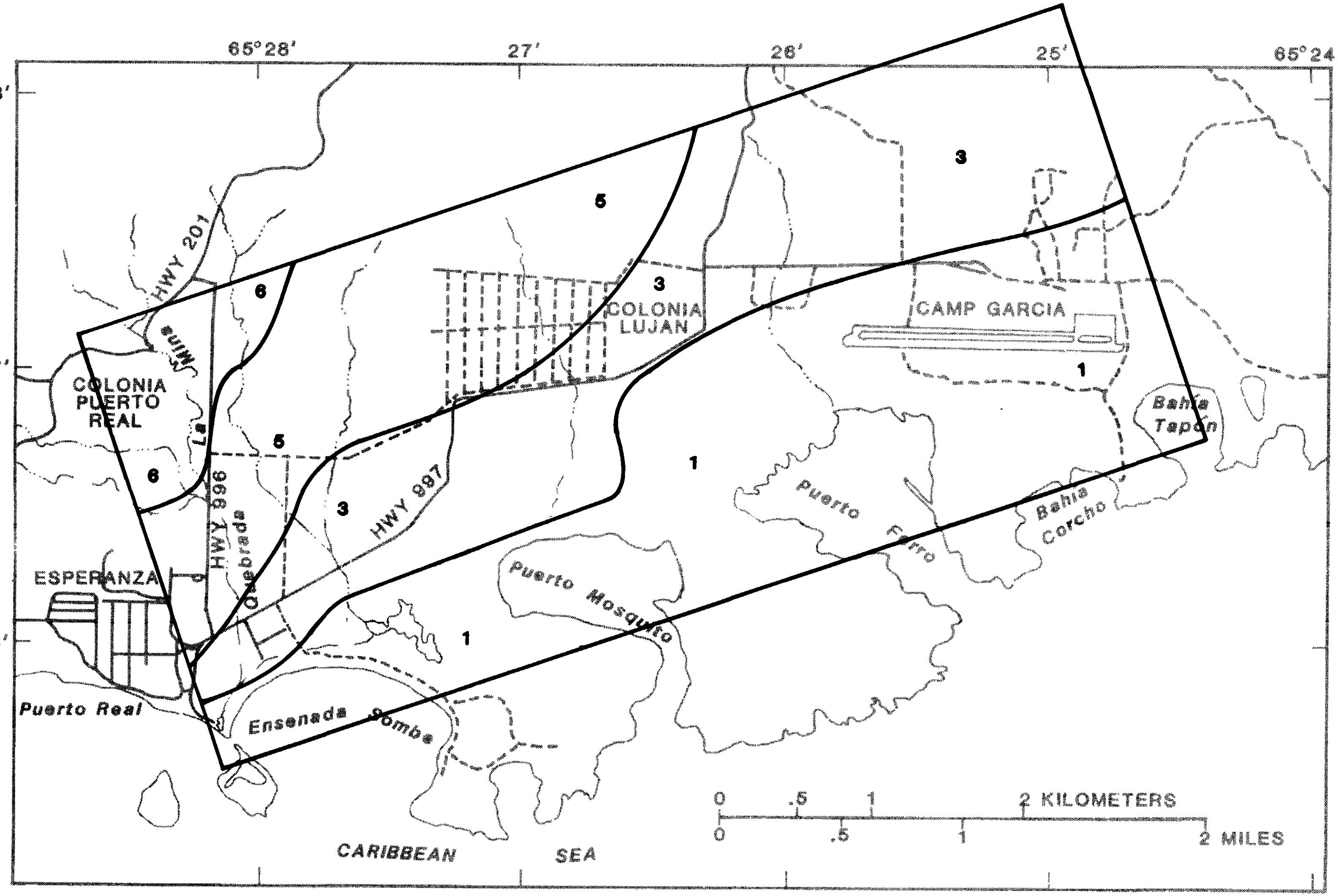
Figure 17.--Altitude of base of the Esperanza alluvial aquifer.



EXPLANATION

20	AREAS OF EQUAL HYDRAULIC CONDUCTIVITY, IN FEET PER DAY

Figure 18.--Simulated values of hydraulic conductivity in the Esperanza alluvial aquifer model.



EXPLANATION

1	AREAS OF ANNUAL RECHARGE, IN INCHES

Figure 19.--Simulated values of recharge in the Esperanza alluvial aquifer model.

Model Calibration (Continued)

A steady-state calibration of a ground-water flow model occurs when the potentiometric surface remains constant with time. In an idealized steady-state system an eventual equilibrium is attained when the amount of water entering and leaving the system are equal with no changes in storage. The potentiometric surface as of June 1983 was used as a base to be matched by the model. Since no effective pumpage was occurring in the area, outputs were equaled to ET and seepage flows into the lagoons and ocean.

The steady-state calibration produced a good match between the observed and simulated water levels (fig. 20). In the matching process, the following steps were taken:

1. After the first run, the difference between the observed and simulated water levels ranged from 0 to 20 ft.

2. The values of hydraulic conductivities (K) and recharge (R) were adjusted until a better match was obtained. The K values were adjusted by areal patterns in the valley. In the area north of Ensenada Sombe, the K values were adjusted from 30 to 45 ft/d. West of Camp Garcia airfield, K values were varied from 1 to 5 ft/d. The adjustments were justified because of the low permeability of the aquifer and overlying soils which results in lower infiltration rates. In the upper reaches of Quebrada La Mina, a K value of 5 ft/d was used because the bed material is more permeable than the clayey layer that predominates in most of the area.

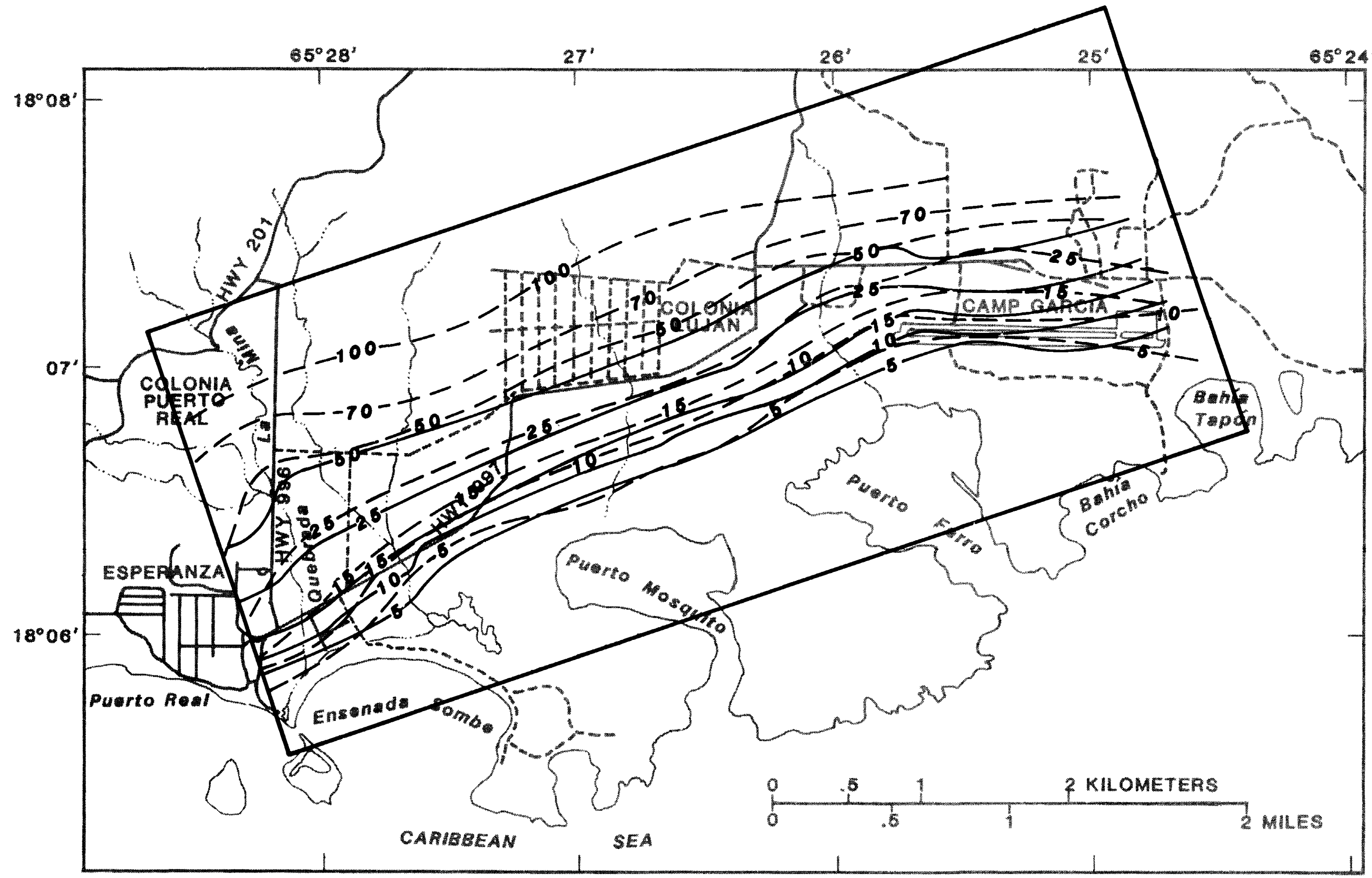
3. The recharge (R) distribution was estimated on the basis of the precipitation data and recharge values for similar climatic environments in the U.S. Virgin Islands (Jordan and Fisher, 1977).

4. The final adjustments in the values of K and R produced head matches within five (5) ft of observed and computed water levels. Eighteen of 28 wells and piezometers matched within two (2) ft.

5. The ET rates and ground water levels were then adjusted until a satisfactory seepage value along the boundary was obtained.

6. Finally, the conductance of the riverbed used along the southern boundary was adjusted to correct the heads in the aquifer next to the sea. A close match between the observed and simulated water levels confirmed that the procedure was satisfactory.

A chloride-ion mass balance was applied in the Esperanza alluvial aquifer to complement the water budget utilized in the steady-state calibration. Initial concentrations of 100 mg/L of chloride were observed in some Esperanza wells prior to 1973. Prior to the closure of the wells in 1977, most of them had chloride concentrations ranging from 250 to 300 mg/L. It was assumed that the difference between the original and final chloride concentrations was due to saline water encroachment. This assumption can be supported by a steady-state simulation of the existing wells pumping at between 20-30 gal/min each (approximately 360,000 gal/d) which resulted in a reversal of the hydraulic gradient of the potentiometric surface between the well field and the sea. This reversal would induce seawater encroachment into the alluvial aquifer.



EXPLANATION

— 50 —	POTENTIOMETRIC SURFACE– Shows altitude of potentiometric surface as of June 1983. Interval variable in feet. Datum is mean sea level.
— 50 —	SIMULATED POTENTIOMETRIC SURFACE– Shows altitude of simulated surface as of June 1983. Interval variable in feet. Datum is mean sea level.

Figure 20.--Observed and simulated steady-state potentiometric surface in the Esperanza alluvial aquifer model, June 1983.

Sensitivity Analyses

The model is calibrated by making changes in the hydrologic parameters within reasonable limits. The response of the model to these changes is a measure of the sensitivity as well as possible errors in the calibration. The sensitivity of the digital model of the Esperanza alluvial aquifer was tested by varying the hydraulic conductivity (K) recharge (R), and evapotransporation (ET) by +/- 50 percent. Normally, where evapotranspiration is significant, sensitivity tests are also conducted for this parameter, however, ground-water level changes are negligible when testing the ET sensitivity of the digital model.

Results of the sensitivity analyses showed that the model is highly sensitive to changes in recharge and hydraulic conductivity. The sensitivity of the model was tested along cross section B-B' perpendicular to the grid length and running almost parallel to Quebrada La Mina (fig. 21). This area is probably the most representative of the modeled grid. Changes of 50 percent in recharge resulted in differences of as much as 20 ft between the steady-state calibrated (middle line in fig. 21a) and recharge-adjusted water levels. Changes of 50 percent in hydraulic conductivity also resulted in differences of as much as 20 ft between the calibrated and adjusted water levels (fig. 21b). Changes of 50 percent in maximum evapotranspiration rate resulted in differences of only 2 ft or less between the calibrated and adjusted water levels (fig. 21c).

Simulation of Ground-Water Withdrawals in the Esperanza Alluvial Aquifer

The principal objective in the development and calibration of the Esperanza alluvial aquifer model was to evaluate responses of the system (in terms of changes in water levels) to stresses such as pumpage. A series of simulations were performed involving different pumping scenarios at the existing PRASA wells in the valley. The simulations included equal pumping rates at each of the ten wells at rates ranging from 10 gal/min to 25 gal/min (total withdrawals from the valley ranging from 144,000 to 360,000 gal/d).

The results of steady-state simulations show that as much as 20 gal/min from each well (a total of 288,000 gal/d) result in drawdowns that will not significantly affect well performance or induce saltwater encroachment in the aquifer (table 2). The maximum drawdown with this pumpage (33.66 ft at well "R") is within the observed values during actual field tests. When the model is stressed to a rate of 25 gal/min at each well (a total of 360,000 gal/d), drawdowns exceed the maximum available water column at some of the wells. The simulation suggests that no more than 200,000 gal/d should be pumped during the dry season.

Although the simulations suggest that about 360,000 gal/d could be withdrawn from the aquifer, additional testing would be required to ascertain that this is a "safe" yield value. As previously indicated, the model was not calibrated for a transient response, where storage changes may affect the drawdown rates. In a transient response, changes in recharge may also affect the model response. The transient calibration would require a long-term data collection program to develop a better data base, including rainfall, ET rate, accurate storage coefficient values, and water levels.

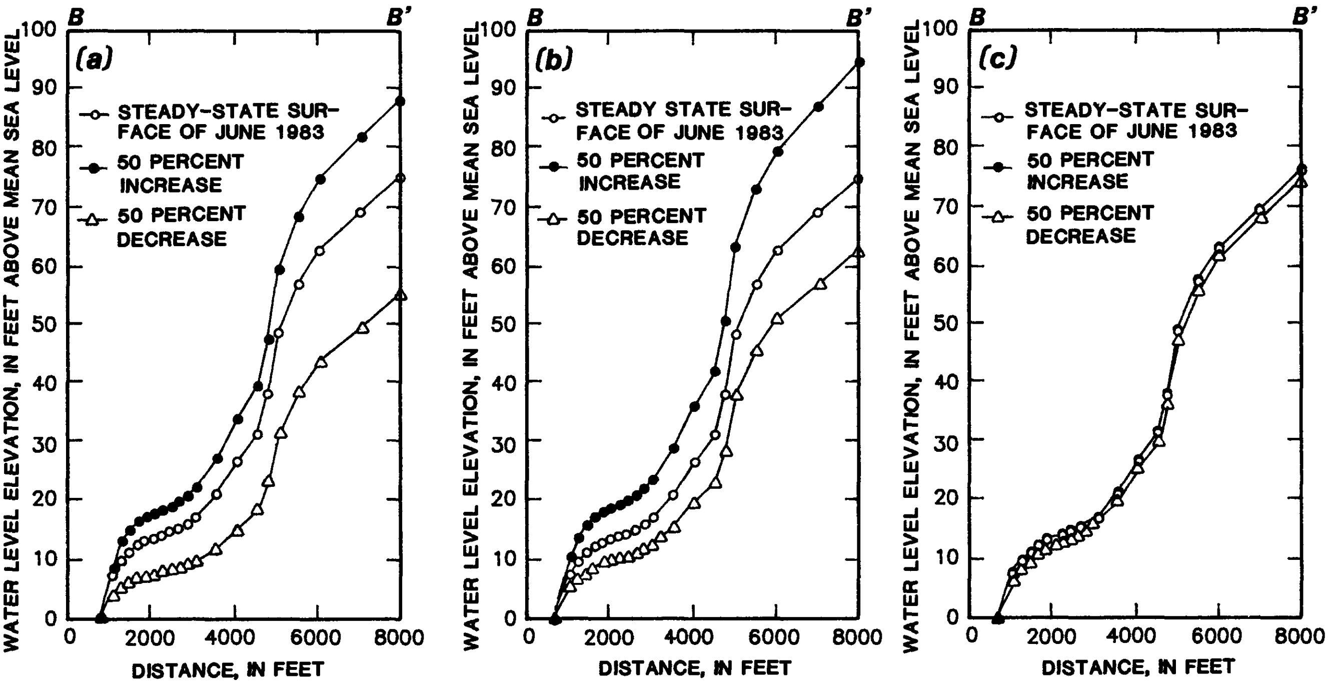


Figure 21.--Results of sensitivity analyses along cross-section B-B' for (a) recharge, (b) hydraulic conductivity, and (c) evapotranspiration in the steady-state model.

Table 2. Simulation of varied ground-water withdrawals from existing wells in the Esperanza alluvial aquifer

PRASA* well no. and/or piezometer ID	Well and/or piezometer location in model grid matrix** row	column	Final simulated drawdown, in feet — Withdrawal rate gallons per minute 10	15	20	25
4	15	14	9.56	15.57	23.05	#
5	15	15	9.45	15.40	22.88	#
6	15	16	9.16	14.92	22.14	#
7	17	11	10.89	18.03	27.69	#
8	16	12	10.08	16.50	24.68	#
9	15	17	8.95	15.60	21.76	#
P	17	10	11.55	19.21	29.84	#
Q	16	8	11.16	18.29	27.40	#
R	17	3	12.91	21.53	33.66	#
10	18	5	11.98	19.89	30.81	#

*PRASA - Puerto Rico Acueduct and Sewer Authority.
** - See figure 10 for well location and 16 for grid matrix.
# - Digital model does not converge to a solution.

SUMMARY AND CONCLUSIONS

A 2-year investigation of the principal aquifers in Vieques Island was conducted beginning in 1982. The principal findings of the investigation were as follows:

1. The principal aquifers in Vieques occur in alluvial deposits within the Esperanza and Resolución valleys. Important unexplored alluvial deposits also occur in the Playa Grande area, on the southwestern part of the island. A less productive aquifer occurs within the Camp Garcia area.

2. In the Esperanza valley, the alluvial aquifer extends over an area of about 10 mi^2. The alluvium varies in thickness from 90 ft near the coast to 0 ft in the north near the volcanic rock contact.

3. Ground water in the Esperanza alluvial aquifer occurs under unconfined and semi-confined conditions. Depth to the water table varies from 10 to 100 ft above mean sea level, depending on the distance from the sea.

4. The aquifer tests in the Esperanza alluvial deposits show transmissivity values ranging from 200 ft^2/d near Camp Garcia to 2,000 ft^2/d east of Ensenada Sombe Bay.

5. Yields from wells in Esperanza valley range from 5 to 60 gallons per minute. Pumpage from the area totaled as much as 450,000 gal/d through 1977. At present, pumpage is nearly zero because practically all of the water used in Vieques is pumped from eastern Puerto Rico through a sub-marine pipeline.

6. In the Resolución valley, alluvial deposits average 30 ft in thickness extending over an area of about 8 mi^2. A clay layer 20 to 30 ft deep overlying the alluvium appears to induce semi-confined conditions. Limited data from the area indicates that as much as 200,000 gal/d were withdrawn from the aquifer through 1977.

7. Ground water throughout Vieques generally contains high concentrations of sodium and chloride ions. The sodium-absorption ratio in samples from wells in Esperanza valley, Resolución area, and Camp Garcia approach values considered hazardous for agricultural use.

8. Simulations using a 2-dimensional ground-water flow model of the Esperanza alluvial aquifer show that withdrawals in excess of about 0.40 Mgal/d could induce saline water intrusion. During a drought, saline water intrusion could occur at pumpages as low as 0.20 Mgal/d.

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