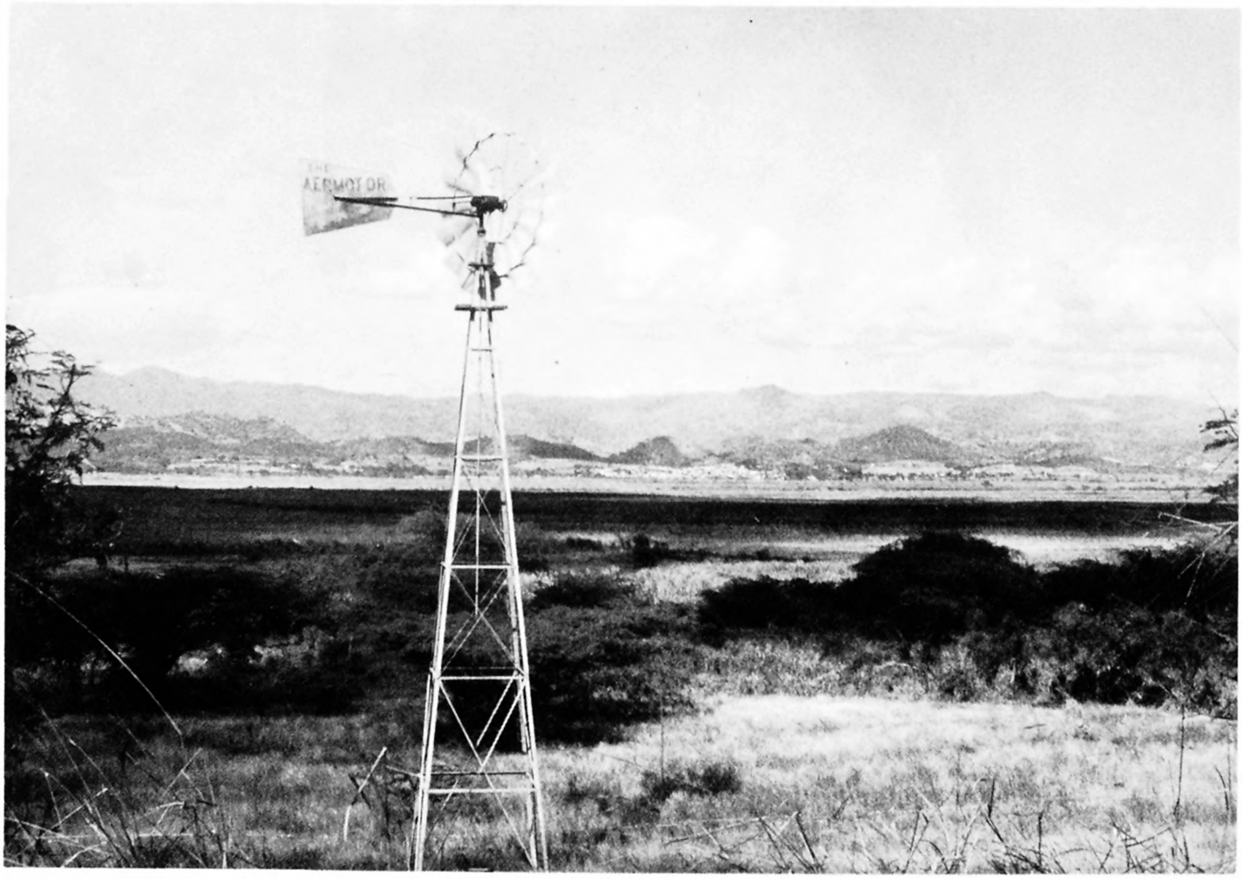
GROUND WATER IN THE LAJAS VALLEY, PUERTO RICO

U.S. GEOLOGICAL SURVEY
Water Resources Investigation 76-68



Prepared in cooperation with the
COMMONWEALTH OF PUERTO RICO

BIBLIOGRAPHIC DATA SHEET	1. Report No. USGS/WRD/WRI-77/039	2.	3. Recipient's Accession No

4. Title and Subtitle GROUND WATER IN THE LAJAS VALLEY, PUERTO RICO	5. Report Date March 1977 6.
7. Author(s) Henry R. Anderson	8. Performing Organization Report No. USGS/WRI 76-68
9. Performing Organization Name and Address U.S. Geological Survey, Water Resources Division P.O. Box 34168 Ft. Buchanan, Puerto Rico 00934	10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U.S. Geological Survey, Water Resources Division P.O. Box 34168 Ft. Buchanan, Puerto Rico 00934	13. Type of Report & Period Covered Final 14.

15. Suplementary Notes

16. Abstracts
Lajas Valley is plagued with salinity and waterlogging problems of the soils. Use of brackish (500 milligrams per liter) ground water for irrigation compounded the problem until an irrigation-drainage system was constructed in 1955.

Lajas Valley is an alluvium-filled trough between volcanic and limestone highlands. The alluvium, mostly clay and as much as 300 feet (90 meters) thick, contains brackish ground water except in the recharge areas located along the foothills. Artesian conditions exist in the eastern part of the valley where upward hydraulic gradients have increased due to the addition of irrigation water in the recharge areas.

Wells yield up to 200 gallons per minute (13 liters per second) from alluvial fan deposits in the recharge areas. Wells tapping the buried limestone aquifer in the northwest will yield as much as 2,000 gallons per minute (126 liters per second).

Results from a digital model show that a network of discharge wells could alleviate waterlogging of the soils in the artesian area.

17. Key Words and Document Analysis. 17a. Descriptors

*Aquifers, irrigation, alluvium, limestone, digital model, salinity, waterlogging.

17b. Identifiers/Open-Ended Terms

Lajas Valley

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Approved for NTIS by U.S. Geological Survey, WRD No restrictions on distribution	UNCLASSIFIED	52
	20. Security Class (This Page) UNCLASSIFIED	22. Price

GROUND WATER IN THE LAJAS VALLEY, PUERTO RICO

By Henry R. Anderson

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 76-68

Prepared in cooperation with the

Commonwealth of Puerto Rico

March 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

V.E. McKelvey, Director

For additional information write to:

U.S. Geological Survey, WRD
P.O. Box 34168
Ft. Buchanan, Puerto Rico 00934

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

CONVERSION TABLE

In most instances, area, volume, and flow values are shown in English and metric units in the text. The English units used in this report may be converted to metric units by multiplying the units given by the factors mentioned below:

Area

acres	4.047×10^{-1}	square hectometers (hm^2)
acres	4047	square meters (m^2)
square feet (ft^2)	9.29×10^{-2}	square meters (m^2)

Flow

cubic feet per second (ft^3/s)	28.32	liters per second (l/s)
gallons per minute (gal/min)	6.309×10^{-5}	cubic metres per second (m^3/s)
gallons per minute (gal/min)	6.309×10^{-2}	liters per second (l/s)
million gallons per day (10^6 gal/d)	4.381×10^{-2}	cubic meters per second (m^3/s)

Length

inches (in)	2.54	centimeters (cm)
inches (in)	2.54×10^{-2}	meters (m)
inches (in)	25.4	millimeters (mm)
feet (ft)	3.48×10^{-1}	meters (m)
miles (mi)	1.609	kilometers (km)

Specific Capacity

gallons per minute per foot [(gal/min)/ft]	2.07×10^{-1}	liters per second per meter [(l/s)/m]

Transmissivity

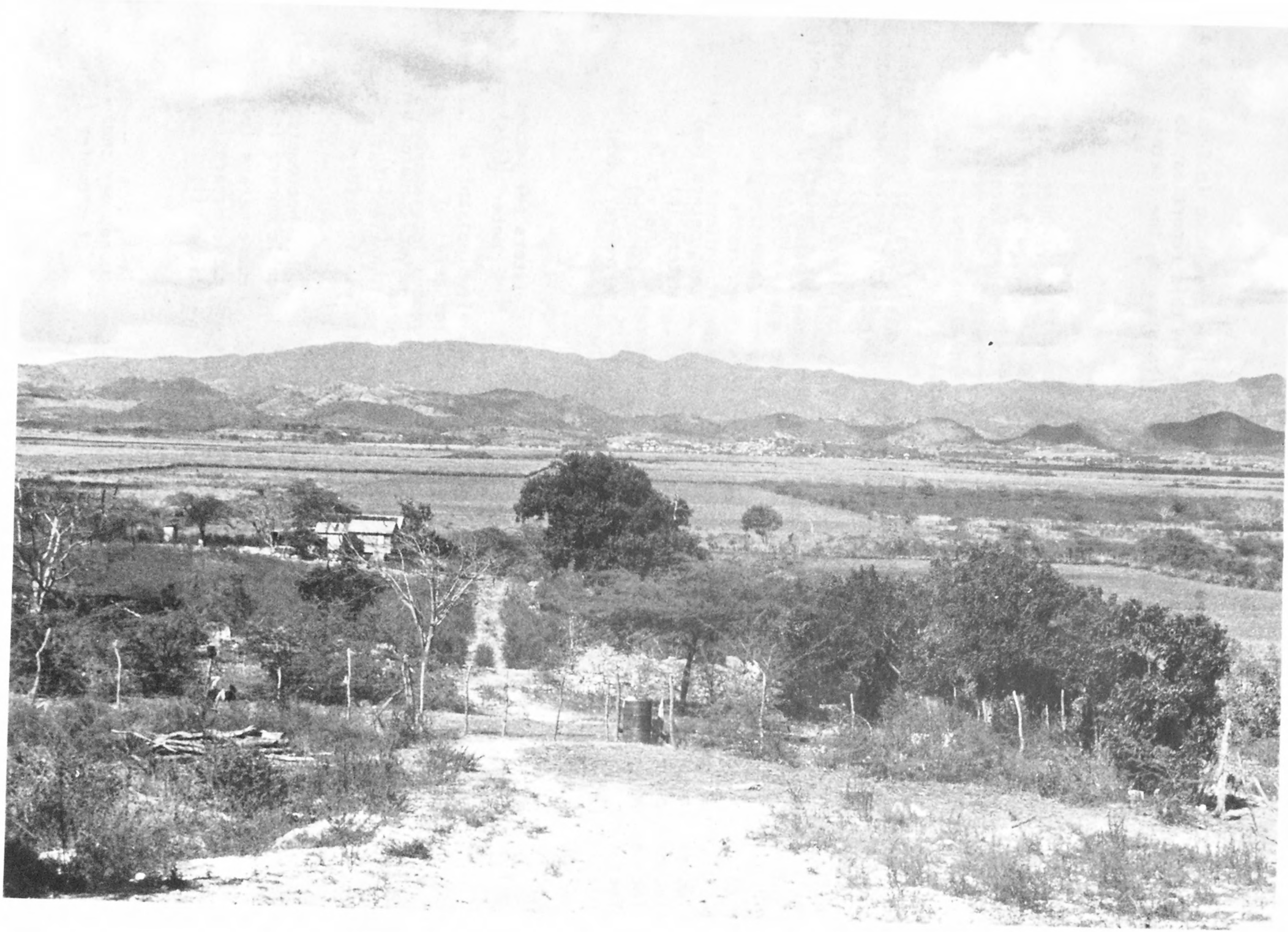
feet squared per day (ft^2/day)	9.29×10^{-2}	meters squared per day (m^2/day)

Volume

acre-feet (acre-ft)	1.233×10^{-3}	cubic hectometers (hm^3)
acre-feet (acre-ft)	1233	cubic meters (m^3)
cfs-day (ft^3/s)/day	2447	cubic meters (m^3)
cubic feet (ft^3)	2.832×10^{-2}	cubic meters (m^3)
gallons (gal)	3.785	liters (l)

Yield

tons per acre	2.222	tonnes per square hectometer (t/hm^2)



GROUND WATER IN THE LAJAS VALLEY,

PUERTO RICO

by Henry R. Anderson

ABSTRACT

Lajas Valley, an agricultural district in southwestern Puerto Rico, is plagued with salinity and waterlogging problems of the soils. Use of brackish ground water, averaging 500 milligrams per liter dissolved solids, for irrigation compounded the problem until a surface-water irrigation-drainage system was constructed in 1955.

Lajas Valley is an east-west trending fault basin that is 22 miles (35 kilometers) in length and 4 miles (6 kilometers) in width. Volcanic and limestone rocks of Cretaceous age form the highlands north and south of the trough. Alluvium, mostly clay, fills the basin to a maximum thickness of more than 300 feet (90 meters). Clay grades into coarser alluvial-fan deposits along the northern and southern foothills.

Rainfall in the valley averages about 34 inches (860 millimeters) annually, decreasing toward the south coast. Pan evaporation of 76 inches (1,930 millimeters) a year gives an evapotranspiration potential of about 50 inches (1,250 millimeters).

Areas of upward hydraulic gradients, in the eastern part of the basin, have increased due to irrigation water increasing the recharge to the alluvial fans. Ground water flows downgradient from recharge areas in the alluvial fans through the alluvium, discharges upward into the playa of the valley, and then is removed by evapotranspiration or seepage to drainage canals. Small-diameter windmill relief wells installed at random points help reduce local upward water gradients. Otherwise, ground-water withdrawals are insignificant. Brackish water occurs in most of the alluvial fill in the valley, whereas, freshwater occurs higher up in the recharge areas. Wells yield up to 200 gallons per minute (13 liters per second) from alluvial fan deposits in the recharge area.

Wells tapping the buried limestone aquifer in the northwest will yield as much as 2,000 gallons per minute (126 liters per second) of brackish water. At peak development in the 1940's, 18 wells in the valley pumped about 23 million gallons per day (1.1×10^6 cubic meters per second) for irrigation. The average specific capacity of the wells for an 8-hour period was about 30 gallons per minute per foot of drawdown (0.6 liter per second per meter). Transmissivity of the limestone aquifer is about 4,000-5,000 square feet (370-460 square meters) per day. Permeability is from solution holes and solution-enlarged fractures. Use of brackish ground water for irrigation was discontinued before the aqueduct from the Río Loco was completed in 1955.

Recharge to the limestone is principally by infiltration of rainfall and streamflow on the outcrop area of the limestone and the hydraulically connected alluvial fans on the northern side of the valley. Ground-water flow in the limestone aquifer is westward toward Bahía de Boquerón.

An aquifer, termed "rock sandstone" on driller's logs, occurs in the area east of the limestone near Lajas Arriba. The water-bearing unit may be a sandy transition of the Cotui Limestone Member of the San Germán Formation or possibly the basal limestone-volcanic conglomerate unit of the Jícara Formation. Yields of wells tapping the unit range from 200 to 500 gallons per minute (10 to 30 liters per second).

Results from a digital-model analysis of the valley show that a network of discharge wells could alleviate waterlogging in the eastern artesian area. The upward hydraulic gradients would be reduced by pumping, thereby easing drainage requirements.

INTRODUCTION

Purpose and Scope of the Investigation

This study was made from 1972 to 1974 to define ground-water conditions within the Lajas Valley, and relate water quality to the hydrologic system and to agricultural use of the land. The work was done by the U.S. Geological Survey in cooperation with the Puerto Rico Environmental Quality Board.

This report presents an assessment of the available ground-water supplies; a description of the geology and hydrology; data on the storage, recharge, discharge and yield of the aquifers, and quality of water; and suggestions for solution of the water-related problems. A digital model was made to simulate ground-water condtions in the eastern half of the valley as a means to study ways to reduce artesian pressure that causes waterlogging of the soils. Two simulated pumping conditions are discussed in this report. Additional data more fully describing the model study and the effects of discharge wells to reduce waterlogging, are on file in the office of the U.S. Geological Survey, San Juan, Puerto Rico.

Location, Area, and Water Problems

Lajas Valley is in the extreme southwestern part of Puerto Rico (fig. 1). The valley is a flat, narrow plain nestled between mountain ridges on the north and south. From the west at Bahía de Boquerón to the east where the valley connects with the Río Loco in the Guánica Valley, the alluvial plain is 18 mi (29 km) long and ranges from 1 to 2 mi (2 to 3 km) wide. The maximum altitude of the valley floor is about 80 ft (25 m). The maximum altitude of the mountains is 980 ft (300 m) in the northern range and 820 ft (250 m) in the Sierra Bermeja complex in the southern range.

Before construction of drainage canals the valley contained Laguna Cartagena, Laguna de Guánica and the Ciénaga El Anegado. The last two, drained by canals, are artesian ground-water discharge areas.

The valley has a population density of about 400 per square mile; about half that for Puerto Rico in general. In 1970 the population of Lajas Municipio was 16,500. The main towns are Lajas (3,400 population) and Boquerón (2,800 population), a small seaside resort. Also in the valley are the villages of Susúa and Lajas Arriba.

The chief agricultural problems in the valley are related to waterlogging and high salinity of the poorly permeable soil. For decades, before aqueducts were constructed, irrigation with brackish ground water from the high-yielding limestone aquifer, in the western and central parts of the valley, caused an increase in the salinity of the soils. Sugarcane, which prefers a Ca/Na (Calcium/Sodium) ratio of 15:1, was irrigated with water having a reverse ratio of Na/Ca of 3.7:1, a practice detrimental to both the soil and sugarcane (J.A. Bonnet and P. Tirado-Sulsona, 1950, p. 32). To counter the problem, ground-water use was curtailed before the aqueduct from the Río Loco dam was completed in 1955.

Though fresh water from the aqueduct tended to flush out salts in the soil, it did not solve the problem of waterlogging. Irrigation water not used by plants tended to waterlog the poorly permeable soils. Seepage through the unlined irrigation ditches also recharged the ground-water table and built up ground-water and soil-water pressures in the interior of the basin. The construction of the east and west main-drainage canals and the network of tributary canals has reportedly solved the worst of the waterlogging problems.

Land and Water Use

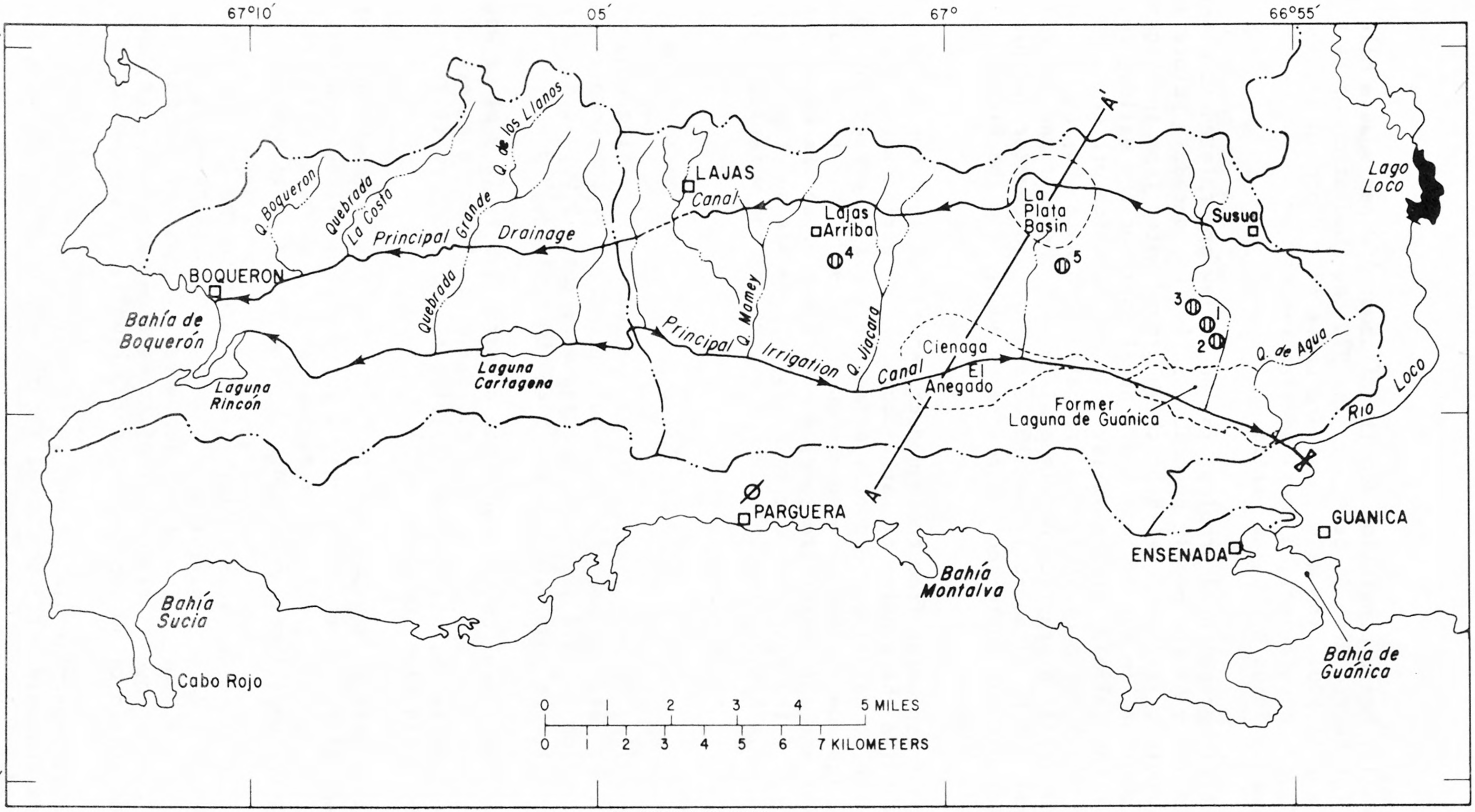
Lajas Valley is an agricultural belt dependent on raising sugarcane. The largest use of water in the valley is for irrigation of that crop. The land under irrigation in 1972 (table 1) totaled more than 19,000 acres (7,700 hm^2), an increase of more than 8,000 acres (3,200 hm^2) since 1959.

For optimum development, sugarcane requires 9.6 ft (2.9 m) of water for 12- to 14-month cane and 8.3 ft (2.5 m) for 10- to 12-month cane. Rainfall in the valley supplies 2.8 ft (0.8 m), leaving at least 5.5 ft (1.7 m) to be supplied by irrigation (Cordero, 1972).

In Lajas Valley, however, 4.0 ft (1.2 m) is the maximum amount of water allotted annually; nevertheless, only a third of this is being used. Overall average usage is only 1.4 ft (0.43 m) per year. Irrigation deliveries vary with climatic conditions. Peak months of demand are April and July.

Low cane yield in Lajas Valley is attributed to the low water consumption rate (Cordero, 1972). The average yield of cane in Lajas is 27 tons per acre (67 t/hm^2). The south coast irrigation district (east of the Lajas Valley), for example, uses over 3 ft (0.9 m) of irrigation water per year, and has an average cane yield of 40 tons per acre (99 t/hm^2).

The next important use of land in the valley is for dairy and beef cattle. Pastureland accounts for 3,545 acres (1,430 hm^2) of which 289 acres (117 hm^2) is irrigated.



SEE EXPLANATION BELOW

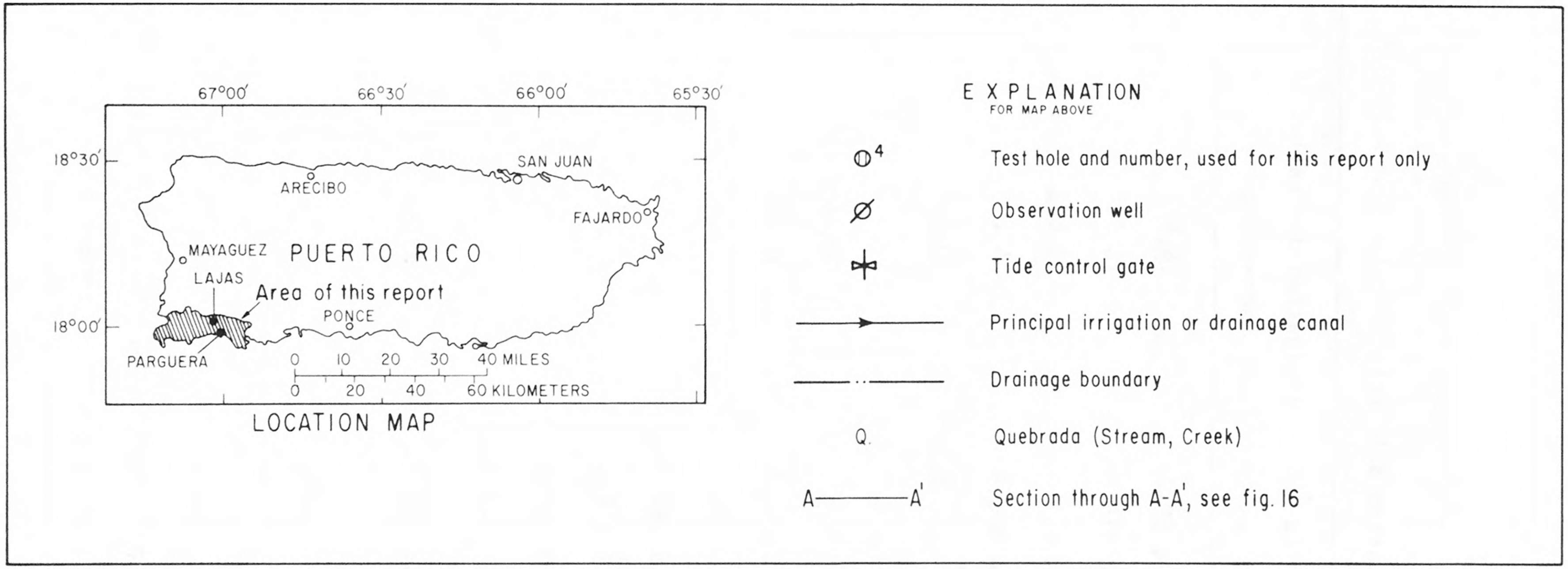


Figure 1.--Lajas Valley area showing principal features and wells.

Table 1.--Irrigation deliveries for the years 1959-72 in Lajas Valley

Year	Area 1/ acres	Irrigation deliveries 2/ acre-feet	Feet 3/ per year
1959-60	11,159.1	16,508	1.48
1960-61	12,415.4	16,644	1.34
1961-62	14,061.0	19,675	1.40
1962-63	14,806.5	24,895	1.68
1963-64	16,247.0	28,651	1.77
1964-65	17,073.3	24,253	1.42
1965-66	17,529.6	29,454	1.68
1966-67	18,143.8	37,753	2.08
1967-68	18,786.9	34,582	1.85
1968-69	18,947.7	24,270	1.28
1969-70	19,218.0	12,741	.66
1970-71	19,201.4	16,208	.85
1971-72	19,273.1	17,457	.91
Average	16,682	23,315	1.42

1/ Multiply acres by 4047 to obtain square meters.

2/ Multiply acre-feet by 1232 to obtain cubic meters.

3/ Multiply feet by 0.3048 to obtain meters.

The aqueduct system also supplies the towns of Lajas, Parguera, and Boquerón with water. Public water-supply use is small and averages 35 gal/d (92 l/d) per capita. Domestic water demand in 1970 for Lajas was 0.58×10^6 gal/d (0.03 m^3/s). Daily production of water for public supply during 1969-70 from the aqueduct averaged about 1×10^6 gal/d (0.04 m^3/s) or about 1,100 acre-feet (1.4 hm^3) per year.

Water use from wells is slight now (1974), though at one time it was considerable. The estimated pumpage of 18 irrigation wells in the 1940's was 16,000 gal/min (1.0 m^3/s) or 21,000 acre-feet (26 hm^3) over a 10-month period. With these wells abandoned, only a few windmill and small farm wells are in operation.

Irrigation and Drainage System

Construction of the Lajas irrigation canal and the east and west main drains was a result of more than 50 years of study and effort to establish an irrigation system in the valley. As part of the "Southwest Project," which is a multiple-purpose electricity, flood-control, and water-supply project, a concrete aqueduct was constructed from the Río Loco reservoir in the humid mountainous area of the Río Loco to the Lajas Valley as far west as Quebrada Boquerón. The main construction was completed in the mid-50's at a cost of 10 million dollars for the combined drainage and irrigation system. The irrigation canal, which is gravity-fed, is 23 mi (37 km) long and has 43 mi (69 km) of secondary canals that deliver water through 300 sluices to 236 properties in the valley (fig. 2).

In conjunction with the aqueduct, 64 mi (103 km) of drainage canals were constructed by 1955 to help alleviate waterlogging in the soils, to reclaim land under water, and to drain runoff and prevent flooding. Laguna de Guánica and Ciénaga El Anegado were drained by the east-main drain. A control on Río Loco prevents tidal water from coming into the canal.

The valley is separated by a drainage divide parallel with Highway 116 south of the town of Lajas. Surface flow is via the west-main drains to Bahía de Boquerón, and via the east-main drain to Bahía de Guánica.

Laguna Cartagena, 250 acres (101 hm^2), is preserved as a bird sanctuary. A weir maintains a water-surface altitude of 36 ft (11 m) in the lagoon, but due to seasonal lack of inflow and high evapotranspiration the water-surface fluctuates with the season and at times the lagoon will go dry. Average depth of the lagoon is about 3 ft (1 m), and storage averages 750 acre-feet (0.92 hm^3). In preaqueduct days, the lagoon was used for irrigation though the water may have had dissolved-solids concentrations as great as 1,300 mg/l (milligrams per liter).

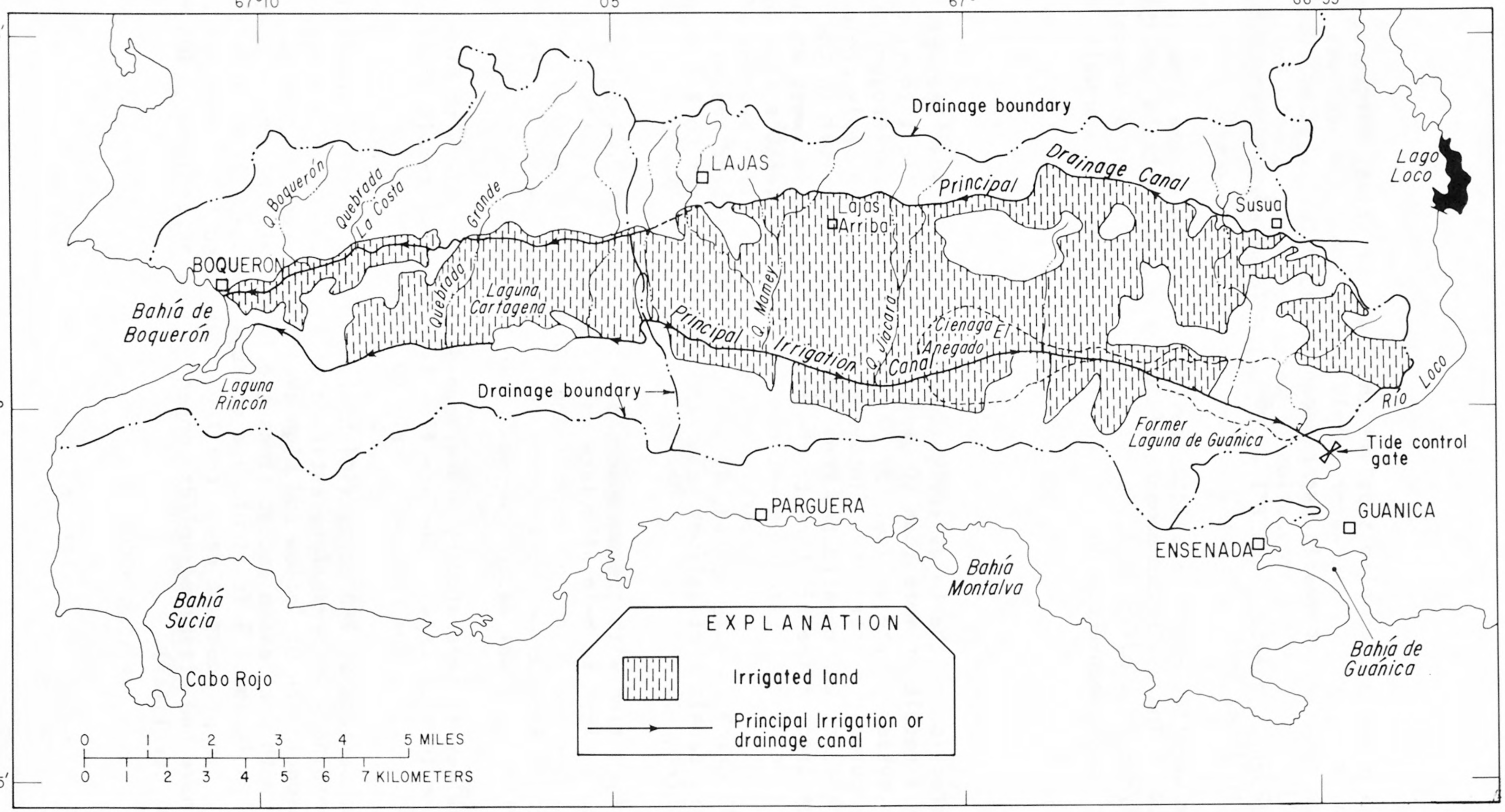


Figure 2.--Principal irrigation and drainage canals.

SOIL FORMATIONS

Associations

The distribution of soil types in the valley is related to ground-water recharge and discharge areas. Permeable soils exist in upland recharge areas and poorly permeable soils in the valley discharge area (fig. 3). A summary of the type, locations, and infiltration capacities of the soil association are given in table 2.

Salinity

Saline soils are typical of areas where rainfall is low, evaporation is high, and drainage is poor. In Lajas Valley, these conditions have created a sizeable acreage of saline and toxic soils; about 27 percent of the arable land. Early studies by Bonnet and Tirado-Sulsona (1950) showed a classification of soils into the following groups based on suitability for agriculture:

1.	Suitable for irrigation	25,294 acres
2.	Saline but reclaimable with water .	5,453
3.	Saline but reclaimable with sulfur and gypsum	5,028
4.	Rock with 24-in (610-mm) depth . .	2,944
5.	Water-table high 1 to 4 ft (0.3 to 1.2 m)	417
	Total . . .	39,136

Of the saline soils, the salt flats of Ciénaga El Anegado contained 1,931 acres (780 hm^2); Laguna de Guánica, 1,120 acres (450 hm^2); and Laguna Cartagena, 250 acres (100 hm^2). These depressions are ground-water discharge areas as well as topographic lows where surface runoff collects and evaporates, leaving a salt residue.

Studies show that salinity increases also with depth in the soils. Bonnet and Brenes (1958) sampled from 0 to 6 ft (0 to 2 m) at 1,534 locations covering 24,544 acres (9,930 hm^2) of Lajas Valley. The results showed 13 percent of the 0- to 8-in (0- to 200-mm) layer had a conductivity more than 4,000 micromhos per centimetre; 28 percent of the 8- to 24-in (200- to 600-mm) layer; 56 percent of the 24- to 48-in (600- to 1,200-mm) layer; and 66 percent of the 48- to 72-in (1,200- to 1,800-mm) layer.

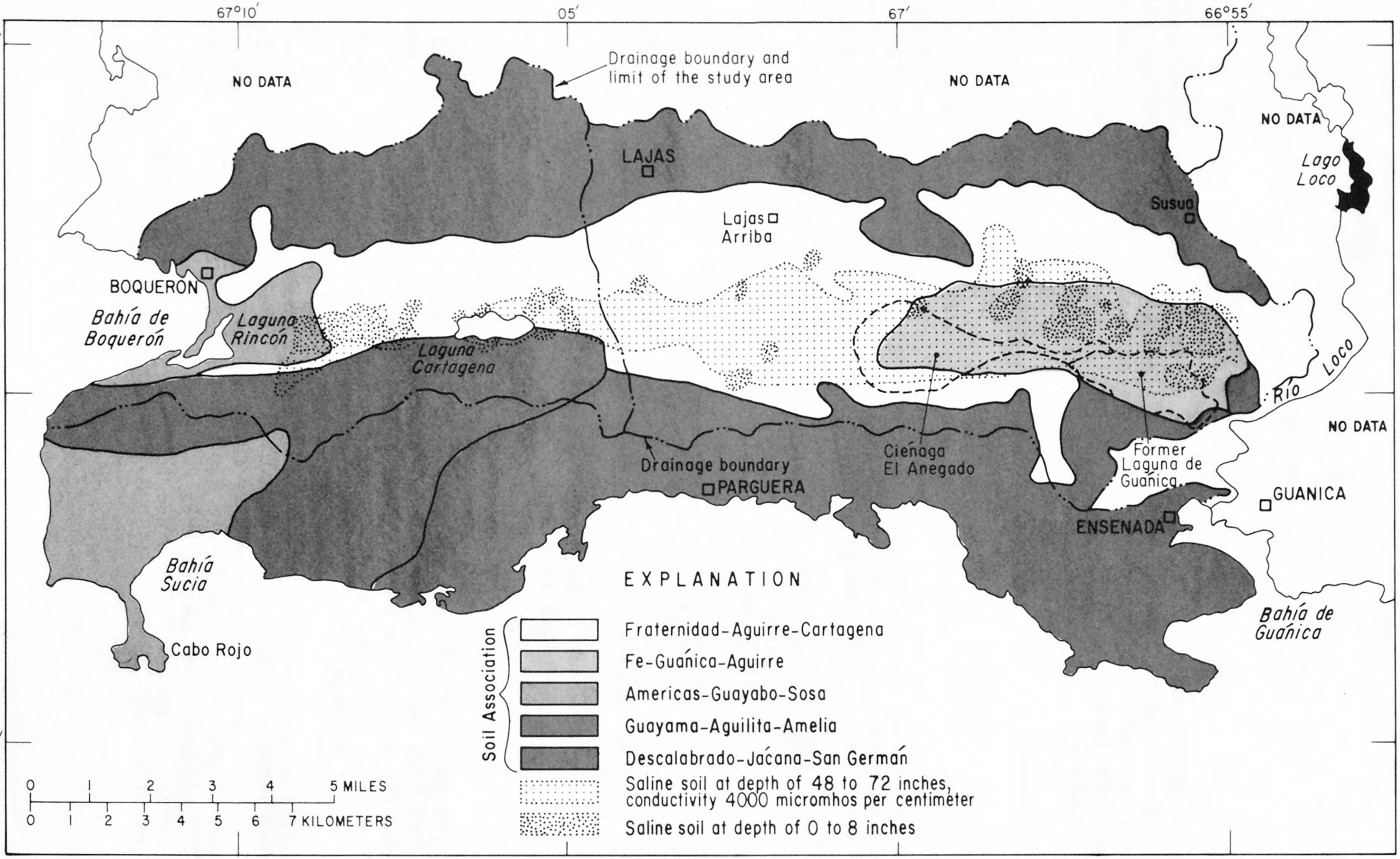


Figure 3.--Soil associations, well-drained, and waterlogged saline soils (after Bonnet and Tirado-Sulsona, 1950).

Table 2.--Summary of types, locations, and infiltration capacities of soil associations (after Bonnet and Tirado-Sulsona, 1950)

Name of soil association	Type	Location	Remarks	Infiltration capacities
1. Fraternidad-Aguirre-Cartagena	Calcareous and sticky clay	Lowlands on valley floor	Poorly drained. Slightly to moderately saline	Range from 7.40 inches of water per 1 hour infiltration into the soil to 0.24 inches per 8 hours
2. Fé-Guánica-Aguirre	Calcareous clay contains gypsum in substratum	Playa flats and edges of the pre-drainage wet areas	Poorly drained. About 25 percent is irrigated under sugarcane	
3. Americus-Guayabo-Sosa	Sandy	Coastal terraces	Discharge areas by evapotranspiration	
4. Guayama-Aguilita-Amelia	Sandy	Foothills and alluvial wash	Recharge areas	Range from 18.27 inches of water per 1 hour infiltration into the soil to 1.63 inches per 8 hours
5. Descalabrado-Jácana-San Germán	Cobbly volcanics	Steep, forested or pastured slopes	Recharge areas to underlying limestone	

GEOLOGY AND STRUCTURE

The basin and its bordering highlands, on the north and south, are underlain by consolidated igneous, metamorphic, and sedimentary rocks ranging in age from Late Cretaceous to Tertiary (fig. 4). The valley is a structural basin downfaulted on the south side (Garrison, Martin and Berryhill, 1972). The stratigraphic nomenclature used in this report was determined from several sources and may not necessarily follow the usage of the U.S. Geological Survey. The following sources were used: Mitchell, 1922; Slodowski, 1956; Kaye, 1957; Mattson, 1960; and Briggs and Akers, 1965. The formations are mostly volcanic andesite, basalt, or metamorphic rocks such as sepentinite. Limestones are interbedded with the crystalline rocks in the uplands and underlie the alluvium in the valley.

Table 3 describes the formations and their hydrologic properties. The geologic units in table 3 are used in the map explanation in figure 4.

Unconsolidated rocks in the valley consist mostly of clayey alluvium interspersed with sand stringers. Toward the northern highlands the fine material grades into coarser fan deposits, consisting of sand and gravel intermixed in clay. Intermittent streams have also sandy beds extending from the hills into the alluvial fans.

The maximum thickness of alluvium in the basin has not been determined (fig. 5). A well south of Lajas and east of Laguna Cartagena penetrated 300 ft (91 m) of clayey alluvium without reaching bedrock. Several holes have reportedly been drilled to a depth of 500 to 600 ft (150 to 180 m), west of Laguna Cartagena. These reportedly penetrated limestone (Pleistocene?) and ended in alluvium; however, the records could not be verified. The surficial deposits in the western end of the valley, as known, consist of 40 to 150 ft (12 to 46 m) of alluvial clay. In the eastern half of the valley, the clayey alluvium is more than 200 ft (60 m) thick in the vicinity of Ciénaga El Anegado.

The Cotui Limestone Member of the San Germán Formation is a microcoquina and pellet limestone that weathers to a roughly pitted surface, forms karst, and supports a thick vegetation. Capping hills on the northern side of the valley, the Cotui Limestone Member also extends under the alluvium as a discontinuous sheet (fig. 5). The limestone aquifer, consisting of the Cotui and possibly other undifferentiated limestones, is the most productive aquifer in the valley.

Borehole records indicate the limestone aquifer is located in a belt that extends from Lajas Arriba in the east to 1 mi (1.6 km) west of Laguna Cartagena. The thickness has been recorded as 160 ft (50 m), though the Cotui reaches 250 ft (75 m) in outcrops. Eastward, in the Ciénaga El Anegado and Laguna de Guánica areas, the formation is covered by tuff of the Jícara Formation (Slodowski, 1956). The tuff, in turn, is overlain by alluvium. The Cotui Limestone Member has not been tapped by wells in this area, except in the La Plata basin, because of its great depth. The Parguera Limestone (Mattson, 1960) is a water-table aquifer along the southern edge of the valley.

Possibly other Cretaceous limestones, the Melones and the Brujo Limestone, are aquifers beneath the alluvium in the valley. Data are not sufficient to determine if they are permeable where they underlie the alluvium in the southeastern part of the valley.

The basal part of the Jícara Formation consists of massive limestone and volcanic conglomerate. This may be an aquifer identified in drillers' logs as "sandstone" in the Lajas Arriba area. The Jícara crops out through the alluvium at various places in the eastern half of the valley.

HYDROLOGIC FEATURES

Rainfall and Runoff

Precipitation in Lajas Valley averages 34 in (860 mm) throughout the basin, but is greater than 40 in (1,020 mm) along the northern hills, and less than 30 in (760 mm) along the southern edge (fig. 6). About 50 percent of the rain falls during August-November, ranging from 4 to 6 in (100 to 150 mm) a month. In the drier months, January-March, about 2 in (50 mm) of rainfall is typical (fig. 7).

Average monthly temperatures in the valley range from 23°C (Celsius) in January to 26.5°C in July at the town of Lajas. The average annual temperature is 24.9°C.

Some of the precipitation is intercepted by vegetation and cultural structures. Intercepted water is mostly evaporated back into the atmosphere. Part of the precipitation infiltrates into the ground to restore soil moisture and the excess percolates to the water table and recharges the ground-water reservoir. Water left after evaporation and infiltration have occurred will flow overland as surface runoff to streams and ponds. Runoff is slight except after intense storms.

Natural streams flowing into the Lajas Valley are small. Along the drier southern side of the valley, streams are ephemeral, flowing in response to rainfall. Along the northern side of the valley, rainfall is higher and stream discharge more significant. A few streams have perennial reaches--such as Quebrada Boquerón and Quebrada de los Llanos. Flow of most of the streams heading in the mountains disappears in the alluvial fan deposits in the foothills, eventually recharging the ground water in the valley.

A partial record of gage heights was kept, in 1962-63, on the Lajas Valley drainage canal at the western end of the former Laguna de Guánica. Except during occasional floods, most of the flow was irrigation-water return and ground-water drainage.

Measurements of flow on the west-main drain are lacking. Several estimates are referred to in the report of Vázquez and Ortiz-Vélez (1967). In 1961 the average flow was 254 gal/min (0.016 m^3/s) and in 1964, 179 gal/min (0.011 m^3/s). These figures represented mostly surplus irrigation water overflow from Laguna Cartagena.

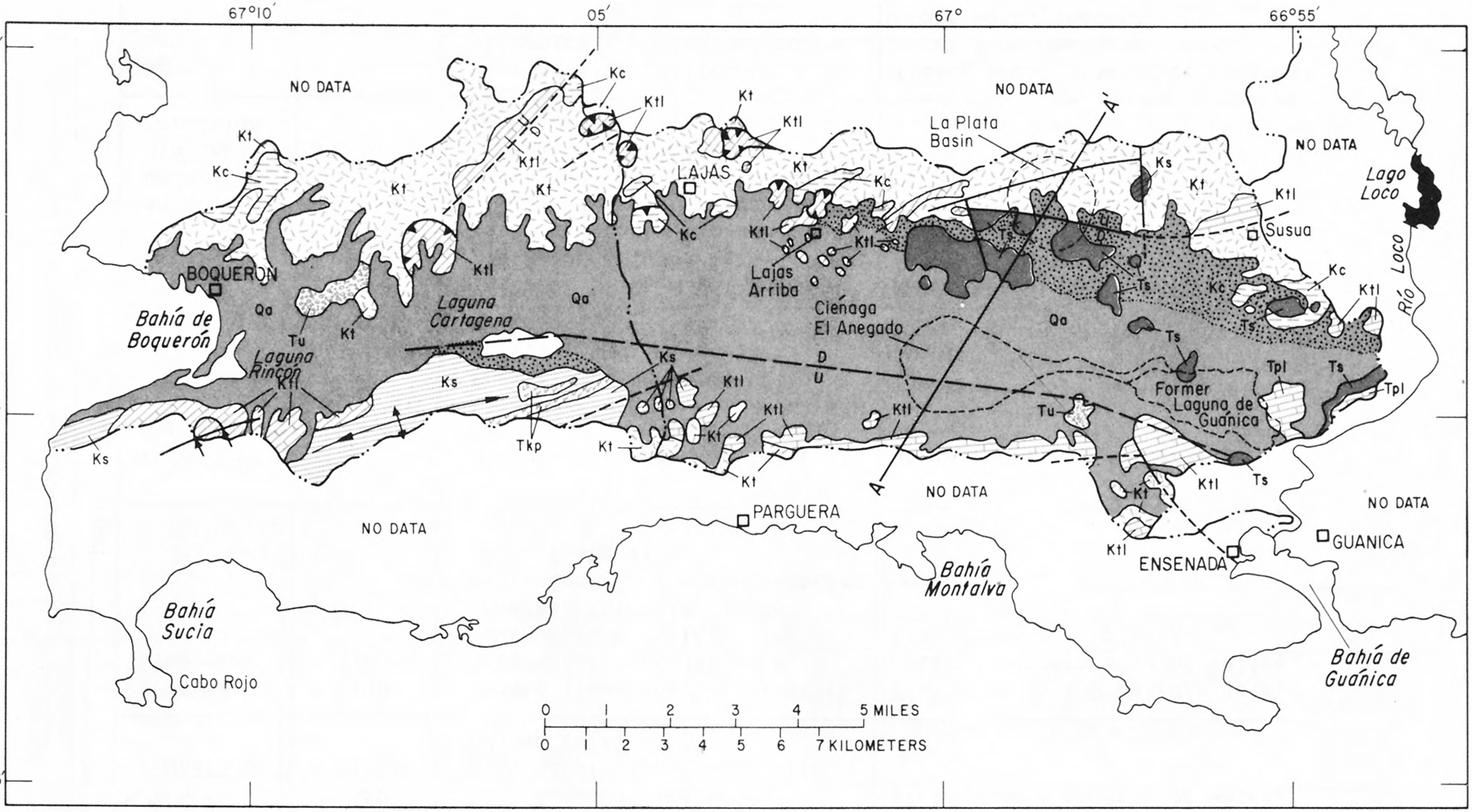
Table 3.--Physical and hydrologic properties of geologic units (adapted from Mattson, 1960).

System and Series	Geologic unit	Thickness ft (m)	Physical description	Hydrologic properties
Tertiary to Quaternary	Alluvium	0-300 (0-100)	Mostly silt and clay filling the valley. Sand and gravel fans in foothills. Includes swamp and marsh deposits.	Yields small quantitites of artesian brackish water at basin center. Moderate quantities of fresh water from alluvial fans in northern foothills.
Tertiary to Quaternary	Ponce Limestone	?	Pink, white fine limestone.	No well data. Generally above water table. May yield water where underlying alluvium.
Tertiary to Quaternary	Tertiary undifferentiated		Sandy limestone, red sandstone or clay with chert pebbles.	Yields meager amounts of brackish water near the town of Boquerón.
Tertiary to Quaternary	Jícara Formation	3300 (1000)	Fine-grained siliceous calcareous tuff. Limestone and volcanic conglomerate at base.	Chiefly nonwater-bearing. Basal member may be aquifer near Lajas Arriba. Yields to 500 gal/min fresh water.
	Plutonic rocks	?	Granodiorite and quartz diorite.	Small yields, less than 10 gal/min.
Cretaceous, Upper Cretaceous	San Germán Formation: Cotui Limestone Member	250 (75)	Microcoquina and pellet limestone. Caps hills, forms karst, supports thick vegetation north of valley.	Yields up to 2,000 gal/min of brackish water from limestone beneath valley fill, in western part of basin.
Cretaceous, Upper Cretaceous	San Germán Formation: Volcanic rocks	450 (150)	Andesite tuff, absent east of Lajas. Cabo Rojo Agglomerate Member at base, 150 ft (50 m) of boulders in andesite flow.	Slightly permeable, generally nonwater-bearing.

Table 3.--Physical and hydrologic properties of geologic units.--Continued

System and Series	Geologic unit		Thickness ft (m)	Physical description	Hydrologic properties
Cretaceous Upper Cretaceous	Mayaguez Group[1]	Melones Limestone	560 (175)	Argillaceous limestone, fragmental, lenticular with bonded tuff.	Yields small amounts of water.
		Parguera Limestone Ensenada Formation	2300 (780)	Bedded limestone, calcilutite, fragmental, wavy at base, southwestern valley. The Ensenada Formation is the equivalent in the southeastern part of the area.	Yields up to 100 gal/min salty water, southern edge of valley. Fresh water in uplands.
		Brujo Limestone	?	Massive microcoquina pellet limestone. Resembles Cotui Limestone Member of San Germán Formation. North of valley equivalent of Parguera Limestone.	No information. Generally above water table.
		Volcanic rocks Includes underlying Río Loco Formation	3300 (1000)	Includes El Rayo Volcanics--weathered olivine basalt. Yauco Mudstone, tuffaceous, 600 ft (200 m). Sabana Grande Andesite. Río Loco Formation--bronzite andesite lava, 900 ft (300 m).	Nonwater-bearing.
		Bermeja complex	?	Serpentinite, siliceous volcanics. Anticlinal cores.	Yields small amounts brackish water from weathered rock, slope wash, breccia.

[1] Order of Mayaguez Group does not imply stratigraphic relationship



SEE EXPLANATION BELOW

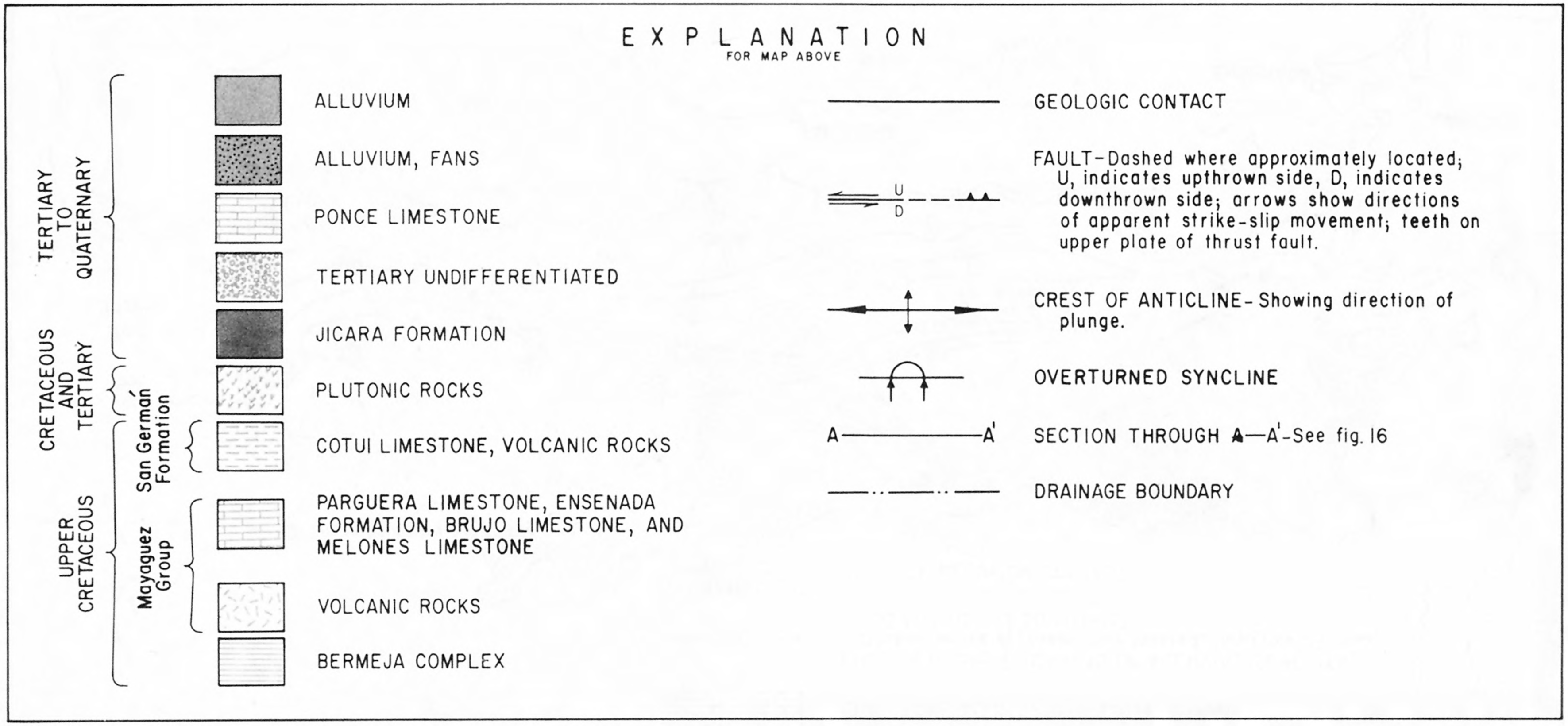


Figure 4.--Geologic map of Lajas Valley.

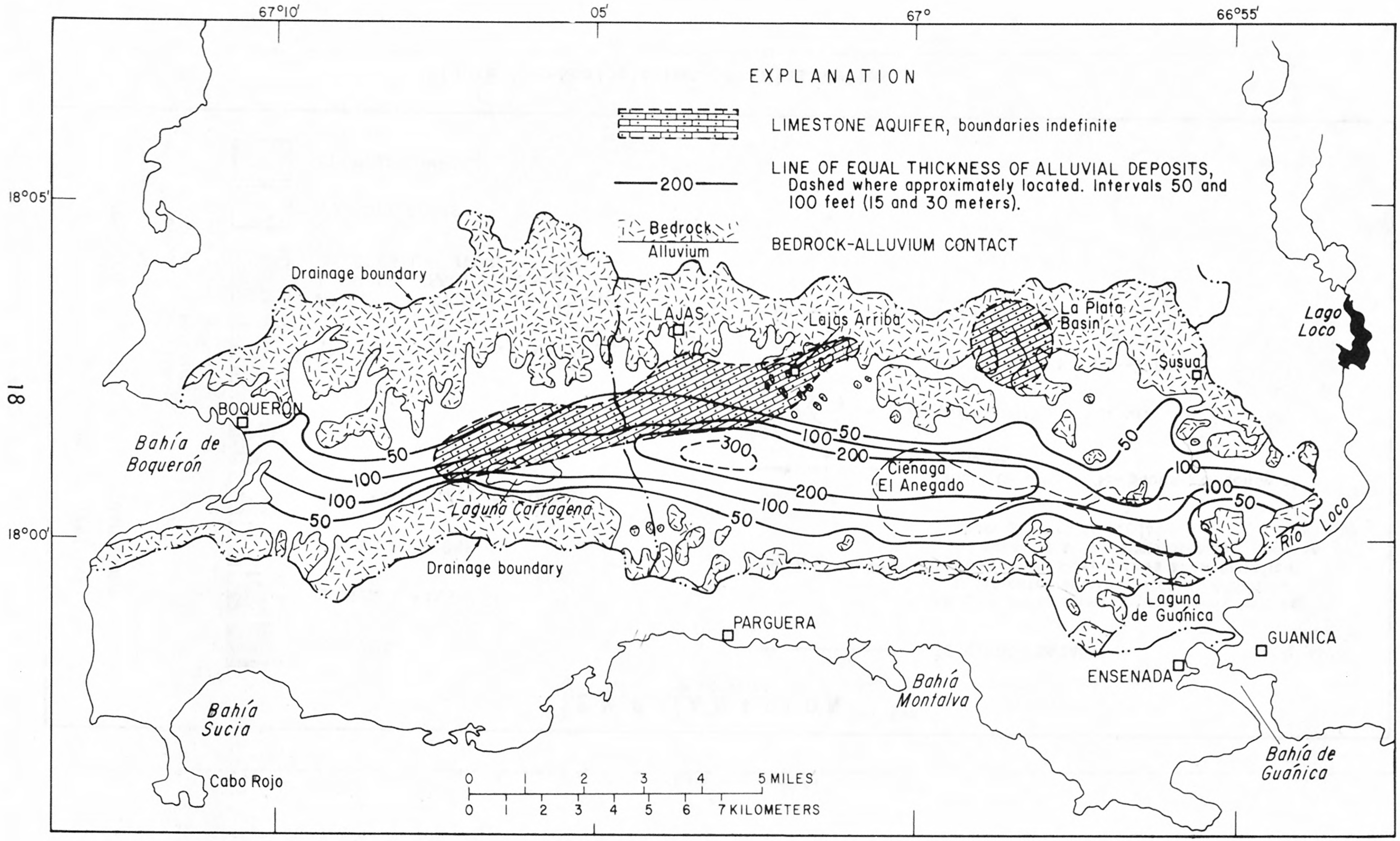


Figure 5.--Thickness of alluvium and area of limestone aquifers.

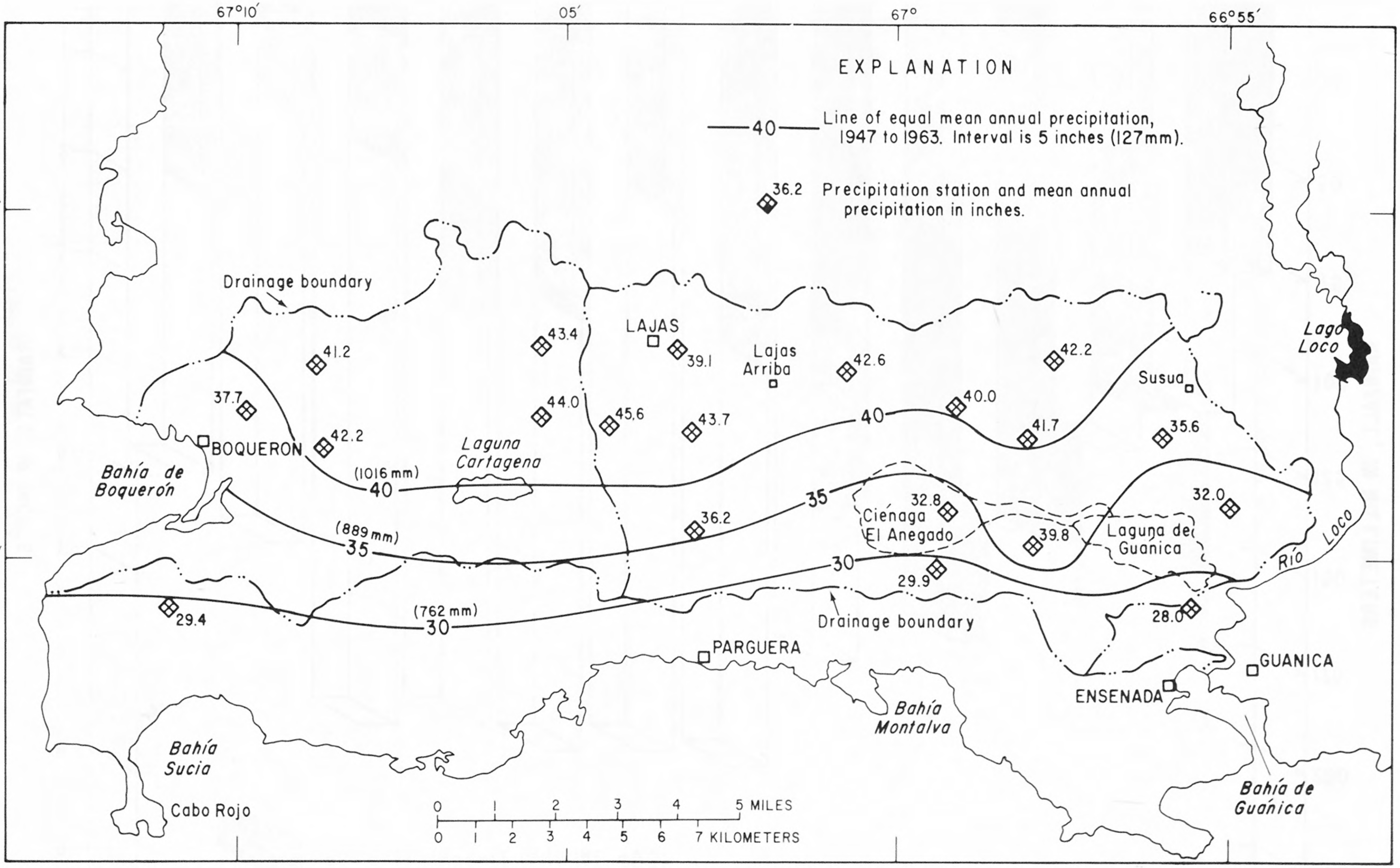


Figure 6.--Distribution of mean-annual rainfall (after Puerto Rico Water Resources Authority).

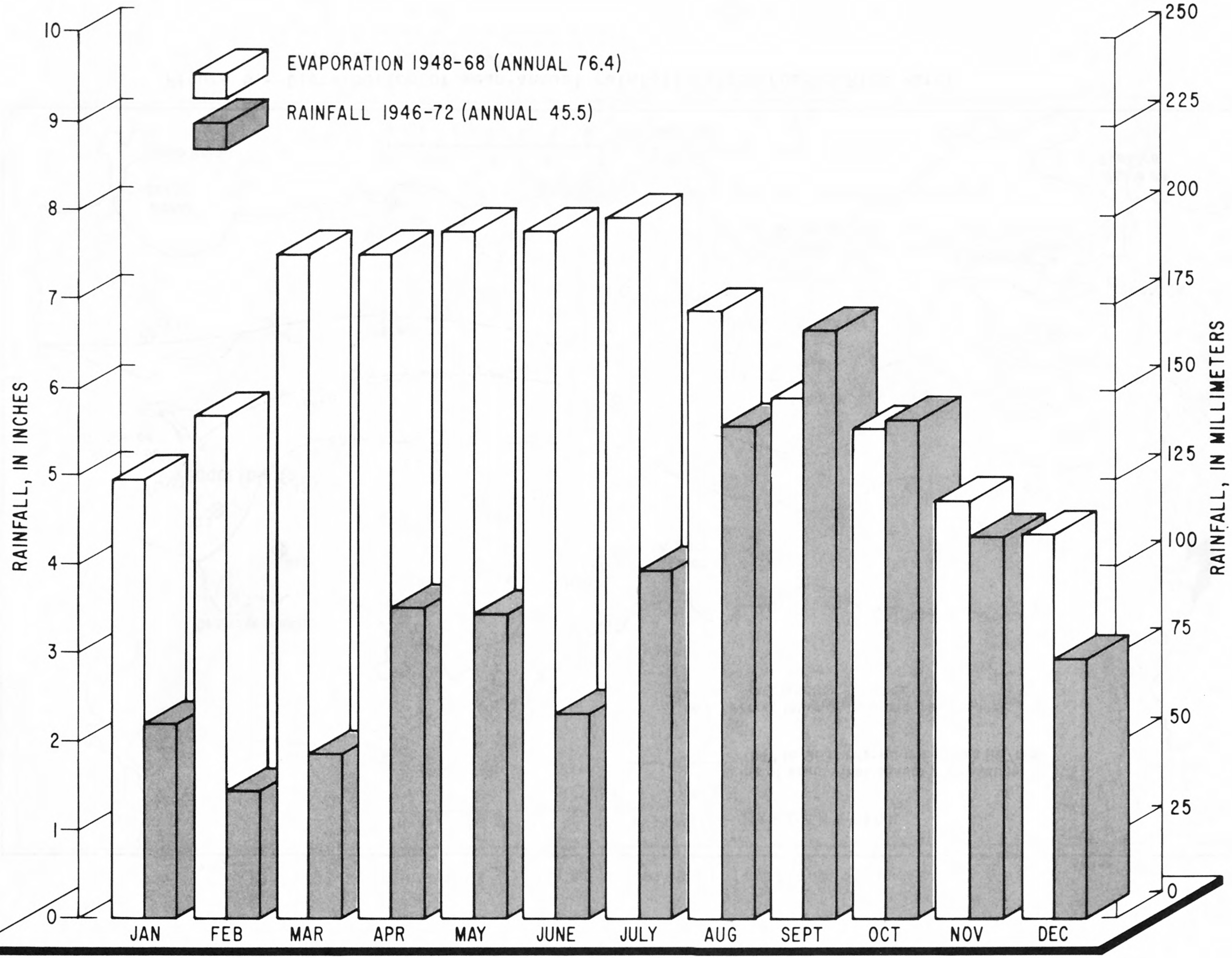


Figure 7.--Average monthly evaporation and rainfall, southwest of Lajas.

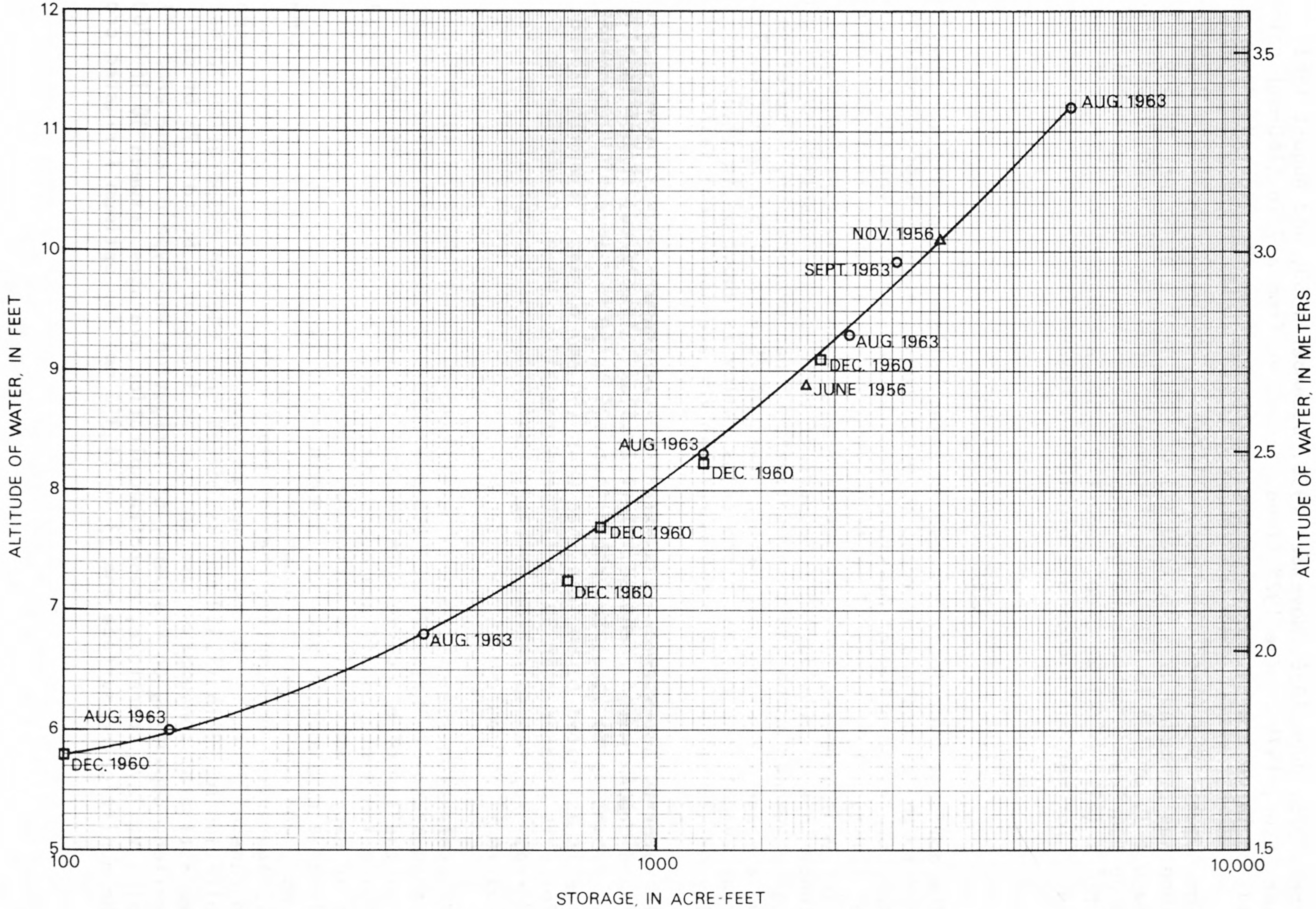


Figure 8.--Stage-capacity relation of Laguna de Guánica.

Floods have hit the eastern part of the valley on at least five occasions: September 1928, June 1956, November 1956, December 1960, and August 1963 (Johnson, K.G., 1974). The 1928 flood, resulting from a 7-in (180-mm) rainfall, covered the largest area. Most of the runoff was from the Quebrada Mamey.

The August 1963 flood, the second largest, was more completely documented. The flood was preceded by 4 in (100 mm) of rain over a 5-day period and a final day, August 3, of 7.6 in (193 mm). Floodwater from the Río Loco flowed into Laguna de Guánica. Peak discharge from the Lajas Valley drainage canal was 1,460 ft^3/s (41.3 m^3/s) at 0400, August 3. Stage-capacity relations of Laguna de Guánica for various floods are plotted in figure 8.

Evapotranspiration

The dominant hydrologic process in Lajas Valley is the rainfall that is returned to the atmosphere by means of evapotranspiration. Evapotranspiration includes both evaporation of moisture from exposed surfaces and the transpiration of moisture by plants. Potential evapotranspiration is that portion of total (or pan) evapotration that actually occurs as a result of moisture deficiency in the soils during some part of each year. Potential evaporation is usually assumed to be about seven-tenths of pan evaporation. Therefore, with an average annual pan evaporation rate of 75.4 in (1,915 mm)--fig. 7--potential evapotranspiration in the Lajas Valley is about 53 in (1,350 mm) annually or almost 20 in (510 mm) more than the average annual rainfall.

In water-budget studies, evapotranspiration equals annual rainfall minus runoff and ground-water recharge. In the Lajas Valley area, runoff is slight, usually amounting to about an inch or two (25 or 50 mm) a year. Ground-water recharge is estimated to be less than 2 in (50 mm) a year. Evapotranspiration, therefore, is greater than 30 in (760 mm) annually. When irrigation is considered, evapotranspiration probably approaches the potential annual rate of about 53 in (1,350 mm).

Transpiration rates have been determined by experiments on water consumption of sugarcane in Lajas Valley (Vázquez, 1970). Consumptive use was calculated as the sum of effective rainfall, or the rainfall usable by plants (precipitation minus runoff and evaporation) and irrigation water extracted by plants in experimental plots. From April 1965 to May 1966, Vázquez (1970) calculated a consumptive use for 13-month plant cane of 55 to 65 in (1,390 to 1,650 mm), and for 12-month ratoon cane from 48 to 56 in (1,220 to 1,420 mm). The average annual consumptive use for plant cane of 54 in (1,370 mm), and for ratoon cane of 51 in (1,300 mm) compares favorably with the potential evapotranspiration of 53 in (1,350 mm) estimated from the pan evaporation rates. Vázquez estimated consumptive use to have an index of 0.60 to 0.76 of pan evaporation, depending on frequency of irrigation and type of cane crop. In the Lajas Valley, therefore, evapotranspiration averages between 30 in (760 mm) for the nonirrigated surface and 53 in (1,350 mm) for optimum irrigated crops.

Ground Water

Occurrence

Except for greater rainfall, Lajas Valley has many distinct features comparable to a closed desert basin or bolson of the southwestern United States. The Lajas basin itself is downfaulted in relation to the surrounding mountains. Ciénaga El Anegado compares with the playa of the basin, and the alluvium with the basin fill. Fine-grained alluvium of relatively low permeability in the playa, grades into coarser material of the coalescing alluvial fans in the foothills. Recharge comes mainly at irregular intervals from small, intermittent or ephemeral streams that head in surrounding mountains. Unsaturated alluvial fans absorb most of the streamflow. Floodflow may reach the playa, pond up and evaporate, leaving behind salt residue. Where cultivation has not altered the vegetation, phreatophytes grow in the playa areas of the basin.

Hydrologic boundaries of Lajas Valley often transgress the consolidated and unconsolidated rocks. In some areas, permeable consolidated rocks such as limestone are hydraulically continuous with unconsolidated alluvial fan deposits. Conversely, consolidated rocks such as the volcanics may form a nearly impermeable boundary as does the clay alluvium. Thus, Lajas Valley is not simply a porous-basin fill surrounded by an impermeable liner of consolidated rocks.

In the Lajas Valley, ground water occurs under both unconfined and confined conditions. Unconfined or water-table conditions occur when the surface of the zone of saturation is at atmospheric pressure, generally along the foot hills and mountain areas bordering the northern and southern edges of the valley. Aquifers are consolidated limestone, sandstone or unconsolidated alluvial-fan deposits.

Confined, or artesian conditions, occur when water is under hydrostatic pressure; where the water level in a well rises above the top of the aquifer or the base of a confining layer. A confining layer essentially preserves the pressure head originating from the recharge area. Confined conditions occur in the eastern center of the valley (fig. 9). In the Ciénaga El Anegado-Laguna de Guánica area, wells have pressure heads above land surface and therefore flow. The aquifer is a slightly permeable clayey alluvium. In La Plata basin wells tapping limestone overlain by less permeable alluvium also flow.

In the western part of the valley, the Laguna Cartagena area, the major aquifer is a buried limestone. This highly permeable aquifer is generally considered unconfined though the water surface in places rises above the top of the aquifer. The water surface is near sea level, many feet below the perched water surface in the overlying soil zone (fig. 10). Soil water drains down to the limestone. Waterlogged soil could be drained by hydraulic connector wells to the limestone.

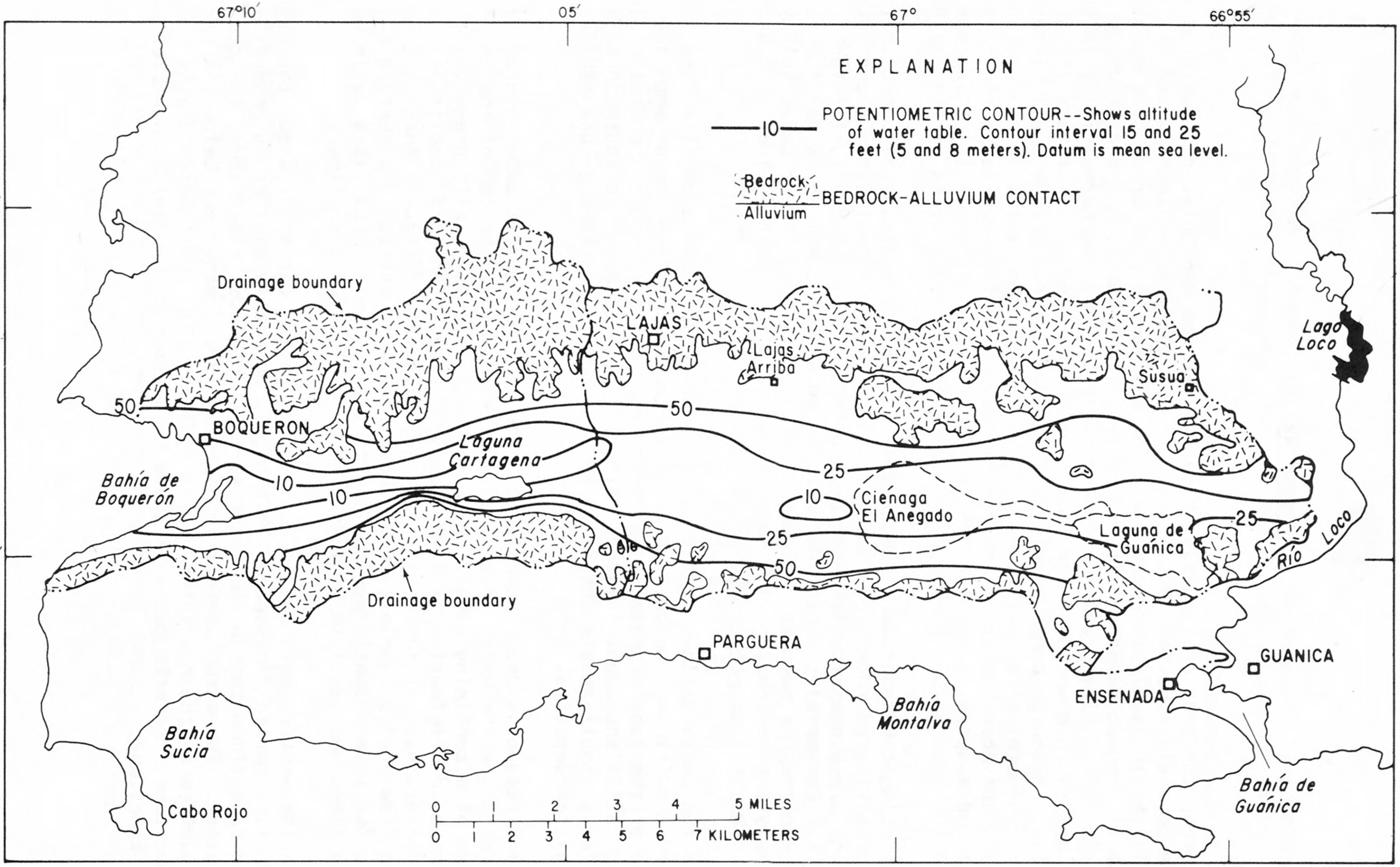


Figure 9.--Configuration of the potentiometric surface in March 1965.

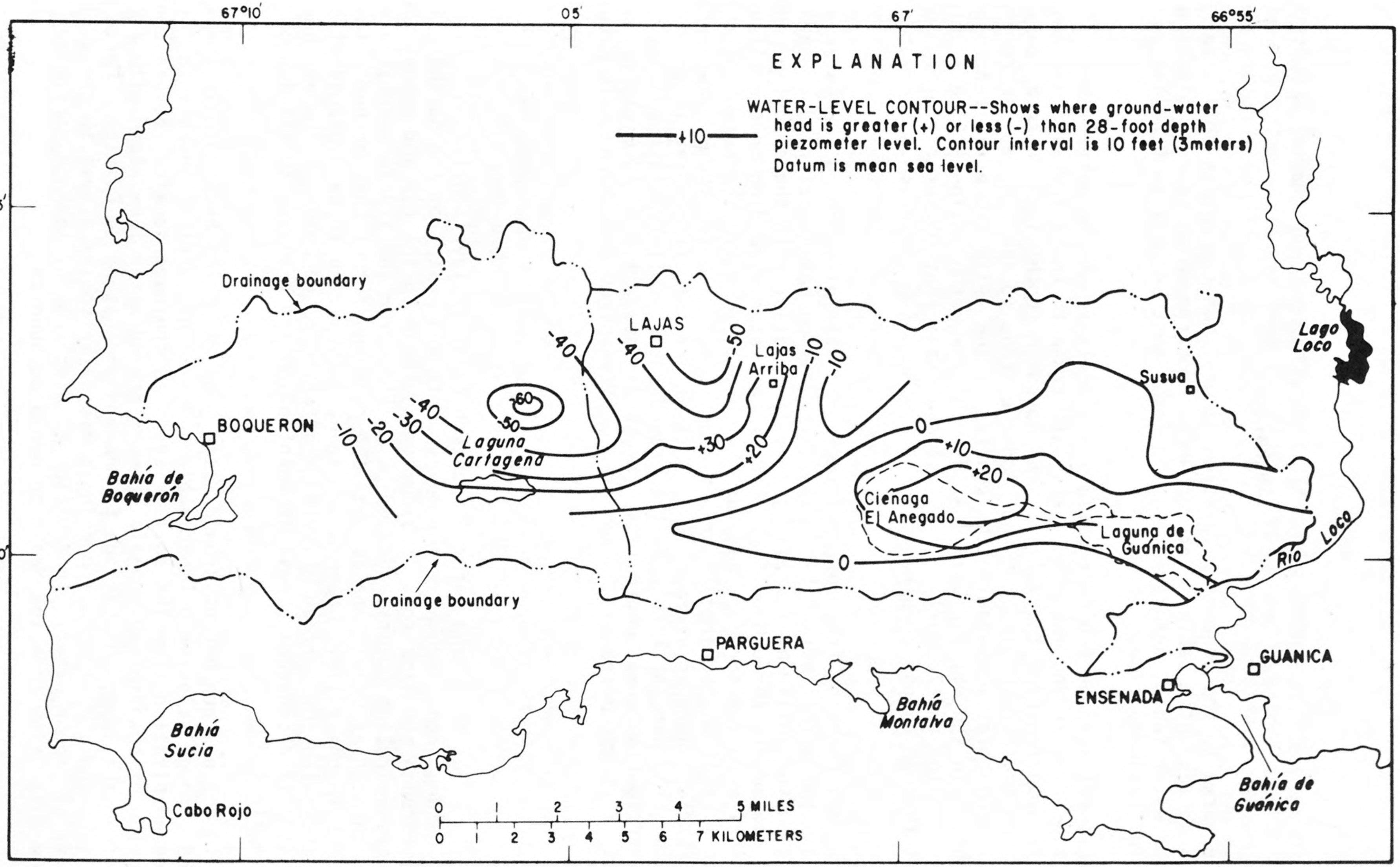


Figure 10.--Difference between ground-water surface and the 28-foot depth piezometer level in March 1965.

Recharge

Recharge to the zone of saturation occurs when the excess soil water percolates to the water table. Net recharge, recharge which exceeds discharge from the water table, occurs during the rainy months--July to December causing the water table to rise.

Influent seepage from streamflow also replenishes the water table. Streams heading in the mountain areas infiltrate to the alluvial and limestone aquifers upon reaching the valley. The northern foothills, and to a lesser degree the southern hills, are the recharge areas to the aquifers in the valley. The total recharge to the aquifer in the valley is estimated to be less than 2 in (50 mm) per year. A salt-balance method using 400 mg/l chloride in ground water and 20 mg/l in rainfall indicates that 95 percent of the water is lost through evapotranspiration; about 1.8 in (46 mm) reaches the water table.

Besides recharge from losing streams and rainfall, irrigation water also recharges the water table. Since 1955, irrigation has contributed to waterlogging in the soils and increasing artesian pressures in the alluvium. Most of the leakage is through unlined ditches and water spreading on the alluvial fan deposits on the northern edge of the basin. However, the extent of the current irrigation recharge is probably not large. In the south coast irrigation district where an average of 3 ft (1 m) of irrigation water is applied, about 20 to 30 percent recharges the ground-water aquifer. In the Lajas Valley irrigation area, where less irrigation water, 1.4 ft (0.5 m), is applied, a larger percentage evaporated or transpired and recharge is naturally less.

Discharge

Discharge of ground water in western Lajas Valley is principally toward Bahía de Boquerón. Ground water moves south and west from the northern foothills through the limestone or alluvium aquifers to the bay and swamps where evapotranspiration occurs. Ground-water flow from the Sierra Bermeja area is north through alluvial fans to the limestone aquifer or the perched alluvial aquifers in the valley. Laguna Cartagena is believed to be hydraulically connected with the perched alluvial aquifer. Ground water in the perched zone generally is discharged as evapotranspiration and drainage to the lagoon or to the canals.

In the eastern basin, ground-water under artesian head, slowly leaks upward through relatively impermeable soils. The vertical leakage is lost to evapotranspiration from the soil or seeps to drainage canals. Before construction of the drainage canals, upward ground-water flow along with flooding sustained the swamps of Ciénaga El Anegado and Laguna de Guánica. Large trees that forested the areas surrounding these water bodies attest to the availability of ground water. In addition to discharge by leakage, there may be ground-water flow from the basin to Bahía de Guánica.

Discharge through pumping wells is slight now, though at one time it was considerable. The estimated pumpage of 18 wells in the limestone aquifer of the western basin was 16,000 gal/min (1 m^3/s) or 21,300 acre-feet (26 hm^3) over a 10-month irrigation period in the 1940's. Presently (1974), with the wells abandoned, only a few windmill and small farm wells exist. These are used to relieve artesian pressure and to provide water for stock. Discharge is probably in the tens of thousand gallons per day.

Water-Level Fluctuations

Shallow wells.--Water-level fluctuations recorded for the shallow water in the alluvium involve, to a large extent, unsaturated flow in the soils. Vázquez and Ortiz-Velez (1967) studied the shallow, 5.5 to 28 ft (1.7 to 7.9 m), water-level changes brought about with the introduction of surface water for irrigation and of drainage structures in the valley. During their studies, they observed water-level fluctuations in 146 soil piezometer installations from 1955 to 1965. Their results show that in 60 piezometers water levels remained constant; in 46 the water level rose; in 19 water levels fell; 9 experienced a rise and a fall; 12 fell, then rose (fig. 11). The proportion of land with rising water levels increased slightly from 69 percent in 1958 to almost 74 percent in 1965.

Increases in vertical hydraulic gradient, symptomatic of an increase in artesian ground-water pressure, have caused water to reach the land surface in areas of the most intense pressure gradient. This is evident from soil tumors (mud boils) emerging around the former northern shore of Laguna de Guánica (Acevedo, Lubo-López, and Ortiz-Vélez, 1959).

Deep wells.--Water levels in the deeper drilled wells indicate the status of the ground-water supply in the zone of saturation. The hydrograph of figure 12 shows water-level fluctuations for the Parguera well (1960-64). The low level for the year usually occurs in July, which normally corresponds to the end of the dry season. Highest ground-water level may be reached any time between September and December, the end of the rainy season. The hydrograph shows a gradual decline of water level during October 1961 to July 1963. Rainfall during that period was 14 in (360 mm) below the average. Not until monthly rainfall exceeds 2.5 in (60 mm) do water levels tend to level off or rise slightly. Normally, it takes rains of this magnitude or more, distributed throughout the month, to satisfy soil moisture deficiency, transpiration requirements, and runoff before recharge to the water table takes place.

Two severe storm periods were examined to determine response of the water table to rainfall. In December 1960, 7 in (180 mm) of rain fell in a 3-day period (fig. 13), and the water level rose more than 2 ft (0.6 m) over a 3-week period.

In August 1963, 7 in (180 mm) of rain was recorded at the Lajas weather station in 3 days. There was only a slight rise in water level in the observation well at Parguera on August 2 from 1.5 in (40 mm) of rain, but there was an overall rise of 2 ft (0.6 m) after 5.3 in (130 mm) of August 3.

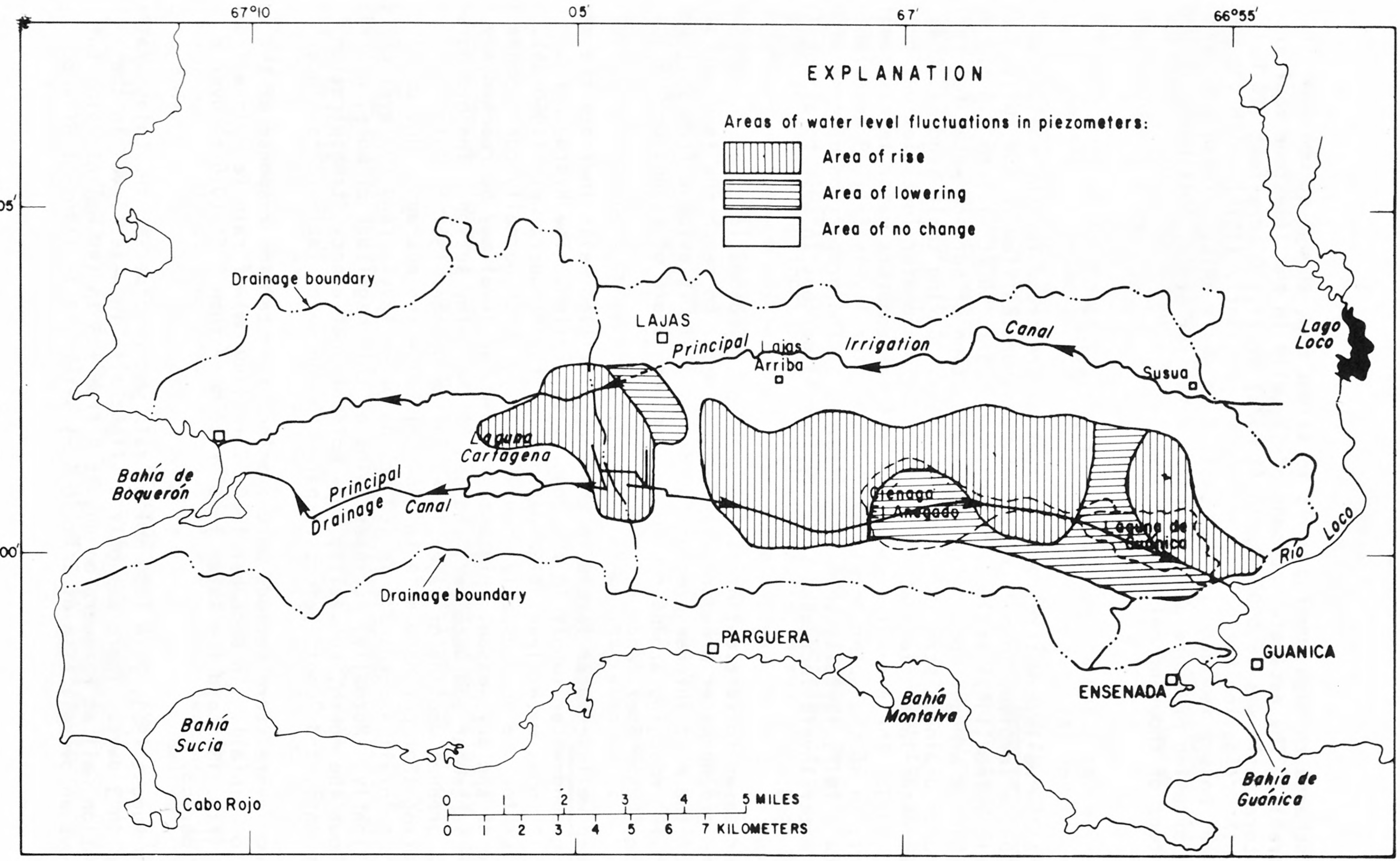


Figure 11.--Changes in shallow water levels, 1955-65 (after Vázquez and Ortiz-Vélez, 1967).

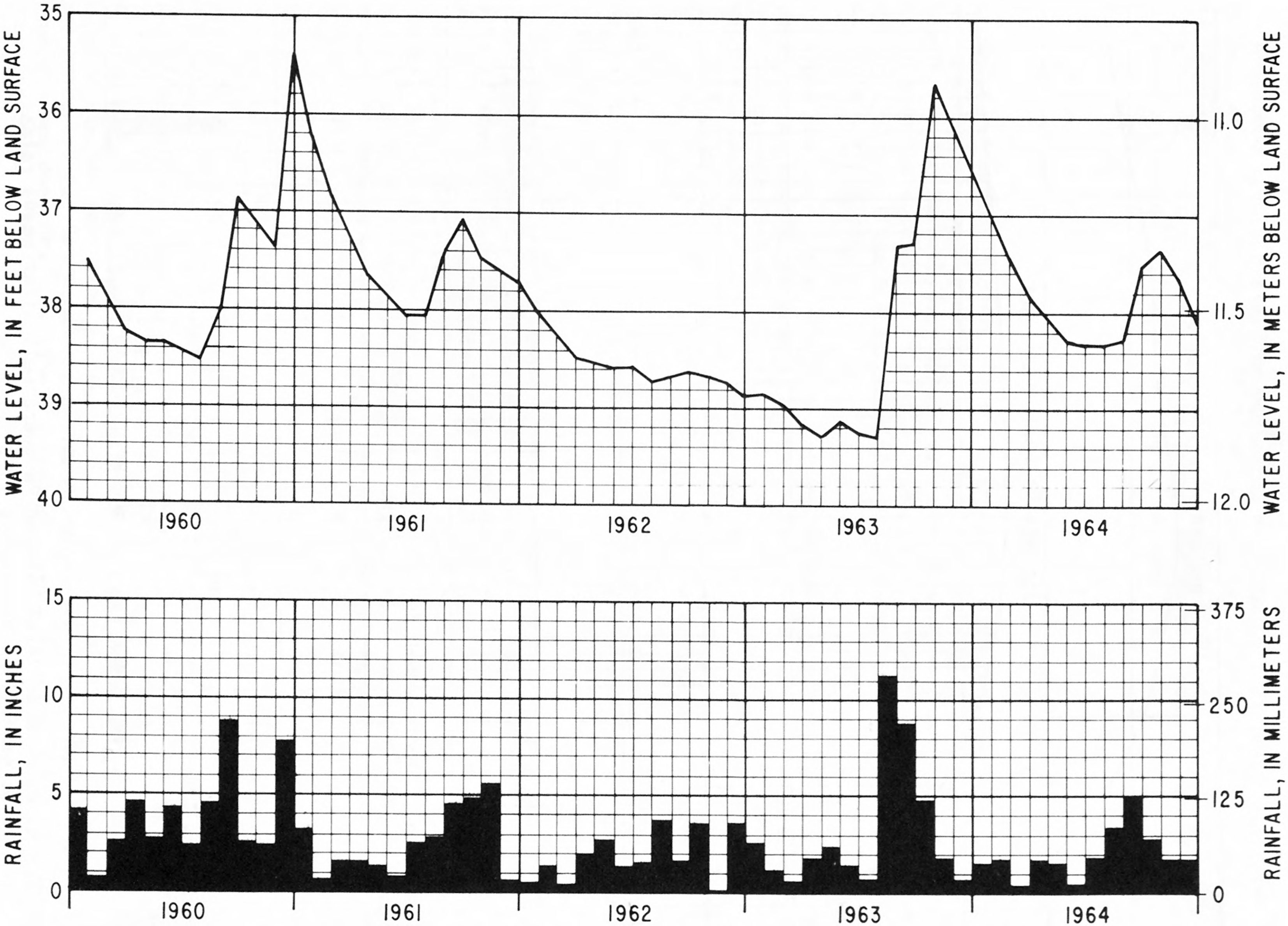


Figure 12.--Water levels in the Parguera well, 1960-64, and monthly precipitation.

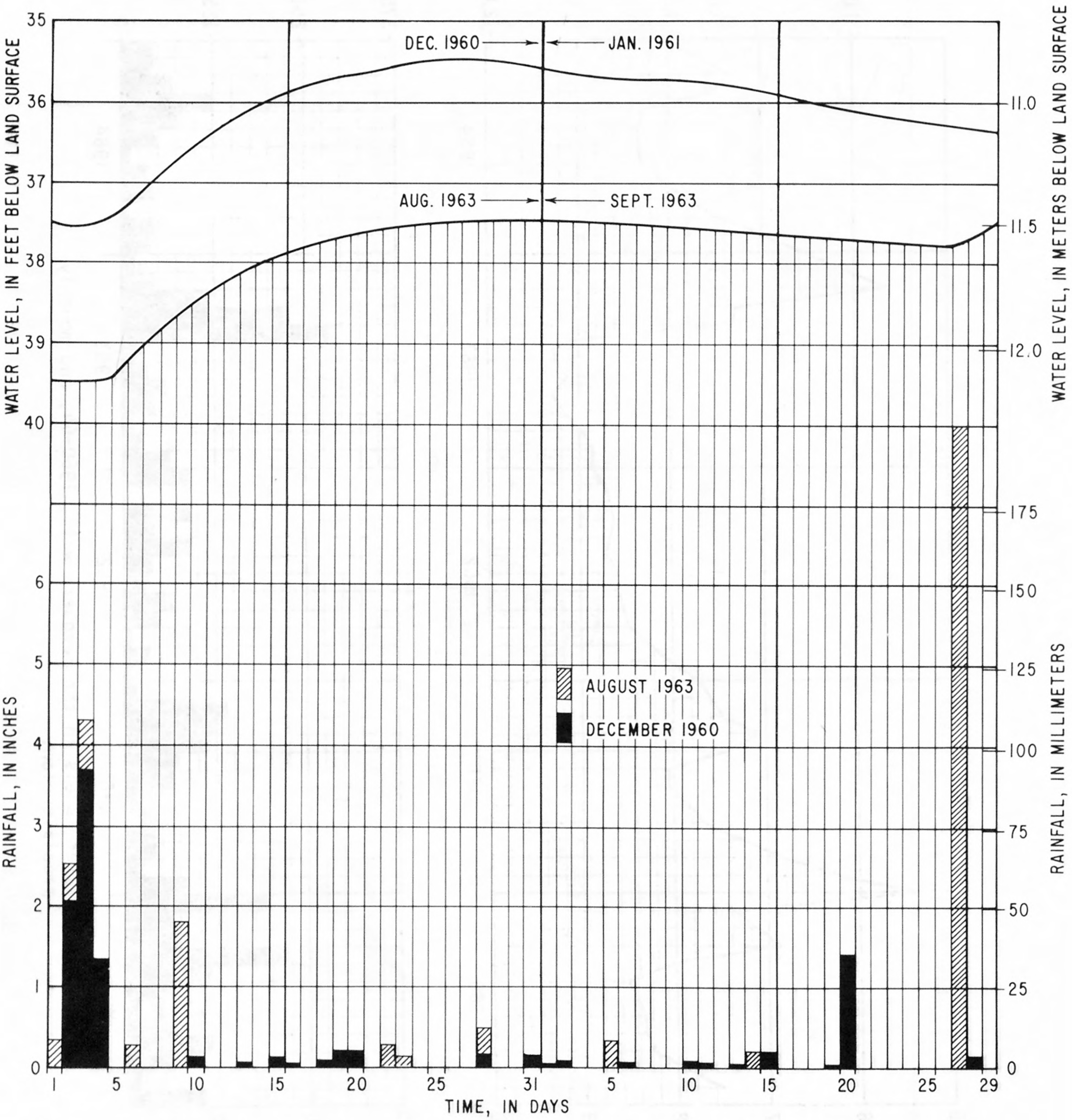


Figure 13.--Rise in water levels in the Parguera well after heavy rains in December 1960 and August 1963.

A maximum specific yield is estimated by assuming that rainfall, 7 in (180 mm); minus runoff, 5.2 in (130 mm); was recharged to the water table. Soil moisture was presumed saturated. The Parguera well rose 24 in (610 mm) apparently from 1.8 in (45 mm) of recharge, the storage coefficient of the aquifer was computed to be 1.8 divided by 24, which equals 0.08.

Water-Bearing Formations

Consolidated Rocks

Aquifers in consolidated rocks are primarily limestone and sandstone. Limestone rims the valley cropping out on hills and slopes among predominantly volcanic rocks. Permeability is developed in limestones from cracks and fractures in the rock which in places develops solution openings. Well data indicate that the limestone has greater hydraulic conductivity than volcanic rocks in outcrop areas.

Along the southern edge of the valley, windmill-pumped wells are used for watering stock. A few farm wells in this area tapping Parguera Limestone yield up to 100 gal/min (6 l/s). Unlike the freshwater situation on the northern edge of the valley, ground water in the south is saline containing as much as 4,100 mg/l chloride. In this part of the basin, rainfall is low, evaporation high, and salts tend to accumulate in the soil and ground water. Contributing to this condition may be the presence of connate seawater entrapped in the buried limestone aquifer during deposition. Seawater encroachment in the area is not likely because of the impermeable nature of the volcanic rocks separating the southern edge of the valley from the sea.

Yields of wells tapping the undifferentiated igneous rocks depend on several factors--the type of parent rock, thickness, and permeability of the weathered zone. In the hilly areas the water table is below the weathered zone and dry holes in bedrock often result. However, on the valley slopes along the northern and southern valley margins, successful low-yield wells are obtained. A typical well in consolidated rock is 100 ft (30 m) deep, penetrating 40 to 50 ft (12 to 15 m) of weathered rock in addition to dense rock below. The well casing is perforated in the weathered zone (although the zone normally is above the water table) and below that is open hole. The water level, about 60 ft (10 m) below land surface, may draw down to 90 ft (27 m) below land surface while pumping 10 to 25 gal/min (0.6 to 1.6 l/s).

The buried limestone in the western Lajas Valley is the most permeable aquifer in the basin. The formation has a recorded thickness of as much as 150 ft (46 m), and is covered by 40 to 50 ft (12 to 15 m) of clayey alluvium. The aquifer, thus far defined, extends in a band from west of Laguna Cartagena to an area between Lajas and Lajas Arriba. Outcrops of Cretaceous limestone in this area suggest a continuation with, and an area of recharge to, the buried limestone aquifer under the valley. The aquifer is probably the Cotui Limestone Member of the San Germán Formation, though parts of the Melones Limestone, Parguera Limestone, Brujo Limestone, and undifferentiated Tertiary limestone may be included.

The potentiometric surface in the limestone is flat and near sea level, reflecting the high permeability of the aquifer. Depth to water averages 40 to 50 ft (12 to 15 m) below land surface. Porosity is from cracks, fractures, and solution openings in the limestone. Ground-water quality is generally mineralized; more than 300 mg/l chloride concentration. Overlying the water table in the limestone is a shallow perched water table in the alluvium.

Wells were drilled in the 1920's and 30's for irrigation; however, they have since been abandoned because of the toxic effects of mineralized water on soil and crops. Originally, the 18 limestone wells yielded from 500 to 2,000 gal/min (30 to 130 l/s) and averaged 1,000 gal/min (60 l/s). Well construction was 12- or 16-in (300- or 400-mm) in diameter with slotted casing. Specific capacities averaged 30 (gal/min)/ft or 0.6 (l/s)/m of drawdown. Transmissivity computed from average specific capacity is about 4,000 to 5,000 ft^2/day (370 to 460 m^2/day).

A second permeable water-bearing unit is in the area east of the limestone near Lajas Arriba. The aquifer is termed "rock (sandstone)" on drillers' logs but may be a sandy transition of the Cotui Limestone Member or possibly the limestone conglomerate unit of the Jícara Formation. Wells tapping this unit have hields of 200 to 500 gal/min (10 to 30 l/s) and specific capacities of 10 gal/min)/ft or 2 (l/s)/m.

Unconsolidated Rocks

Alluvial fan.--On the northeastern side of the valley from Lajas Arriba to Susúa, the water-bearing materials are alluvial fan deposits, some in hydraulic connection with limestone or sandstone of the borderlands. A few wells and well batteries obtain moderate yields from alluvial fan deposits, typically less than 300 gal/min (20 l/s).

A particularly permeable zone is the pocket basin of La Plata. One well there yielded 1,000 gal/min (60 l/s) with less than 8 ft (2.4 m) of drawdown from a static level of 20 ft (6 m) below the land surface. In the rainy season, the well often flows 200 gal/min (10 l/s). Though records are incomplete, these wells are thought to tap both alluvium and the underlying Cotui Limestone Member. The limestone may be the principal aquifer.

To the extreme eastern end of Lajas Valley, north of the former Laguna de Guánica, the alluvium is finer grained and well yields are less than 100 gal/min (6 l/s). Generally, this area is one of upward artesian pressure and flowing conditions prevail.

Valley fill.--The alluvial-fan deposits on the northern edge of the valley serve as the recharge areas for the fine-grained alluvium in the interior of the basin. Ground-water flows from alluvial-fan intake areas downgradient into the valley and discharges by evapotranspiration from the playa.

Water-bearing layers in the alluvium of the Lajas basin consist of slightly permeable sand-silt stringers confined by clay. Ground water is under confined conditions. The deepest wells have penetrated about 300 ft (90 m) of the alluvium. Yields are a few gallons a minute of brackish water, having pressure heads as high as 15 ft (4.6 m) above land.

Some wells in the eastern part of the basin are pumped to reduce upward hydraulic gradients in the soil and thereby alleviate waterlogging. About 50 small-diameter windmill and flowing wells drain small volumes of water from the alluvium. Many wells are nonoperating; only 13 were under continuous operation in a survey made in May 1964 (Quiñones, 1964). The estimated pumpage or flow is less than 50,000 gal/d (2 l/s).

An unknown factor in the eastern part of the basin is the amount of water leaving as underflow to the Guánica outlet. Underflow through alluvium is believed small because of the low permeability; however, underflow through gravel or limestone formations that may be present beneath clayey alluvium could be significant.

Test holes to 200 ft (60 m) in the center of the basin show that ground-water salinity decreases and head increases with depth. The deeper layers are recharged at higher altitudes, areas where the ground water is fresher. Such evidence suggests the need for deep test drilling to determine if additional ground-water reserves are present at depth.

Hydrologic Properties

In the 1950's and 60's, tests were conducted in the eastern part of the valley to determine the feasibility of using drainage wells to relieve upward hydraulic gradients in the soil (Willardson, 1958; Vázquez and Ortiz-Vélez, 1967). The success of these tests was limited by low permeability of the alluvium which, in turn, limits the yield of the well and increases the cone of influence.

For this report, the records of the drainage-well tests in eastern Lajas Valley were used to estimate transmissivity and hydraulic conductivity. A summary of the results of the tests follows, along with the estimates of transmissivity and storage coefficients (table 4). Locations of the test sites are shown in figure 1.

The hydraulic situation in the alluvium, overlying limestone in western Lajas Valley, is somewhat reversed. The water table in the limestone is about 40 ft (12 m) below the perched water in the alluvium. Pumping the limestone will not affect the perched water. However, hydraulic connector wells may be practical; gravity wells would drain water from the alluvium into the limestone below.

Drainage well tests in western Lajas Valley were inadequate to determine hydraulic coefficients for the limestone aquifer, because observation wells were in shallow alluvium and the pumping well tapped the underlying limestone.

However, transmissivities were computed from specific-capacity data collected during drillers' drawdown tests. For the limestone aquifer, transmissivities range from about 2,000 to 30,000 ft /day (200 to 3,000 m^2/day). The lowest transmissivities are near Lajas, and the highest are in the center of the valley, north of Laguna Cartagena.

RESULTS OF DIGITAL-MODEL SIMULATION

To determine if the use of discharge wells could alleviate waterlogging of the soils by reducing artesian pressure in the valley, the geohydrologic conditions were simulated on a digital computer. A grid of 1,260 nodes spaced to represent 1,650 ft (0.5 km) in the field, was superimposed on a map of the Lajas Valley area. For each node, values of the hydraulic conductivity, specific yield, and thickness of the aquifer area were punched on cards in the program. In addition the altitudes of land surface, water table and bottom of aquifer were added to the cards.

The model solves the ground-water flow equation:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T} \left[\frac{\partial h}{\partial t}\right]$$

by reducing it to a geometric problem, using finite differences.

In the above equation,

h = water-level head;

x,y = horizontal, orthogonal directions;

T = the transmissivity of the aquifer;

S = the storage coefficients;

t = time increment;

$\frac{\partial^2 h}{\partial x^2}$ = the rate of water-level gradient change in the x direction;

$\frac{\partial^2 h}{\partial y^2}$ = the rate of water-level gradient change in the y direction; and

$\frac{\partial h}{\partial t}$ = the change in water level with time.

Rates of recharge and discharge (evapotranspiration and pumpage) are applied to the model. The model and the computer are used to solve the equations and to determine heads and drawdowns for each selected time period.

In the case of Lajas Valley, the basin was simplified as a water-table aquifer. Though heads above land surface were applied in the eastern part of the basin to simulate original swampy and upgradient conditions in the soil, the initial evapotranspiration rates reflect lowering of the water surface below land.

A simulated 2-year run of the model was made to determine the hydrologic balance for steady-state conditions. A recharge rate of 1.34 in (34 mm) per year (basinwide) was applied to the highland recharge areas north and south of the valley. At the end of 4 months, evapotranspiration rates from the aquifers were high, 2.98 in (76 mm) per year, as water levels were depressed to the evapotranspiration cutoff level of 6-ft (1.8-m) depth. Evapotranspiration is at a maximum of 50 in (1,270 mm) per year at land surface and declines linearly to zero at the 6-ft (1.8-m) depth in the soil. After 1 year, the evapotranspiration rate dropped to 1.95 in (50 mm) per year. Upward vertical leakage in the eastern alluvial basin could not keep pace with evapotranspiration rates; and 0.60 in (15 mm) per year was removed from storage and 1.35 in (34.3 mm) per year came from recharge. After 2 years, evapotranspiration of 1.32 in (3.5 mm) per year declined below the recharge rate and storage increased slightly to 0.03 in (1 mm) per year.

Flow to constant-head boundaries about equalled inflow from Bahía de Boquerón, with 0.05 in (1 mm) per year throughout the run.

Had the model simulated impervious soil layers, evapotranspiration losses would be less and more water would flow to the bay.

To reduce water pressures in the eastern basin, several runs were made with 35 discharge wells pumping 50 gal/min (3.2 l/s), with 2.5 Mgal/d (0.11 m^3/s total. For this simulation a recharge rate of 2.14 in (54 mm) per year was applied. Evapotranspiration accounted for 1.80 in (46 mm) per year and pumping wells for 0.46 in (12 mm) per year.

The amount of water diverted from evapotranspiration by pumping wells was 0.30 in (7.6 mm) per year or 1.6 Mgal/d (0.07 m^3/s).

Figure 14 shows the area of the cone of depression and lines of equal drawdown for 1- and 5-year periods. The cone of depression was still expanding after 5 years of pumping and water levels had been lowered 10 ft (3 m) or more over an area of 13 mi^2 (34 km^2) with a maximum drawdown of 46 ft (14 m). Results of the model runs indicate that waterlogging would be reduced over an area of several square miles after 1 year of pumping and virtually eliminated over a much larger area after 5 years of pumping. However, the lowered water levels may increase saltwater intrusion from the west.

Ground water available to wells from storage was computed for the 74,000 acres (30,000 hm^2) represented by the model. The volume was 500,000 acre-feet (620 hm^3), which is about 7 ft (2.1 m) of water spread over the Lajas Valley area.

Table 4.--Results of drainage-well tests[1/] (see fig. 1 for location)

Wells	Location	Aquifer, geologic unit	Well depth	Yield and drawdown
Willardson Well No. 1 Map number 1	East end of valley, north of Ciénaga Guánica.	"Semicemented granular rock" underlain by artesian Jícara Formation.	100 ft (30 m)	53 gal/min (3.3 l/s) for 73 ft (22 m) drawdown.
Willardson Well No. 2 Map number 2	2,000 ft (610 m) from Willardson Well No. 1.	Heavy clay layers of alluvium and Jícara Formation.	140 ft (43 m)	37 gal/min (2.3 l/s) with 74 ft (23 m) of drawdown.
Antongiorgi Well Map number 3	Site 3, a cluster of five wells north of Ciénaga Lagoon.	Alluvium.	--	300 gal/min (19 l/s) and drawdown from 9 ft (2.7 m) to 5 ft (1.5 m) above land surface.
Well No. 21 Map number 4	Site 4 along northern edge of valley where limestone aquifer and the "sandstone" aquifer merge.	Alluvium and limestone, sandstone.	85 ft (26 m)	409 gal/min (25.8 l/s) with 20 ft (6 m) of drawdown.
Delfín Rodríguez Carlos Well W 10 Map number 5	One of four in drainage valley (Quebrada La Plata) on the north side of the valley.	Clay-sand alluvium and "tosca" of the Jícara Formation.	90 ft (27 m)	300 gal/min (19 l/s) 54 ft (16 m) drawdown.

1/ Data from Willardson, 1958.

Table 4.--Results of drainage-well tests[1] (see fig. 1 for location)--Continued

Wells	Transmissivity[3]	Storage coefficient[3]	Results
Willardson Well No. 1 Map number 1	350 ft^2/day (32 m^2/day)	2.2×10^{-3}	"The effect of pumping was measurable in the 27-ft (8.2-m) deep piezometer 1,270 ft (387 m) from the well. The area in which the water pressure was lowered below 6 ft (1.8 m) was only 130 ft (90 m) from the well." [2]
Willardson Well No. 2 Map number 2	720 ft^2/day (67 m^2/day)	24×10^{-2}	
Antongiorgi Well Map number 3	3,500 ft^2/day (325 m^2/day)	2×10^{-4}	Pumped for 10 days. Drawdown observed in a well 2,800 ft (850 m) to the south. High value of T due to thicker and probably coarser-grained alluvial cover. Permeability increases southward.
Well No. 21 Map number 4	2,600 ft^2/day (242 m^2/day)	0.5×10^{-2}	Yield diminished to 225 gal/min (14 l/s) with 60 ft (18 m) of drawdown at end of 6 months. Well 21 and nearby well pumped at 700 gal/min (44 l/s) caused drawdowns 3,000 ft (914 m) away.
Delfín Rodríguez Carlos Well W 10 Map number 5	2,000 ft^2/day (186 m^2/day)	3×10^{-2}	Three wells have specific capacities of 1.5 to 5.2 (gal/min)/ft or 0.09 to 0.3 (l/s)/m; and one well has 33 (gal/min)/ft or 6.8 (l/s)/m.

[1] Data from Willardson, 1958. [2] Page 22, Willardson, 1958. [3] Estimated.

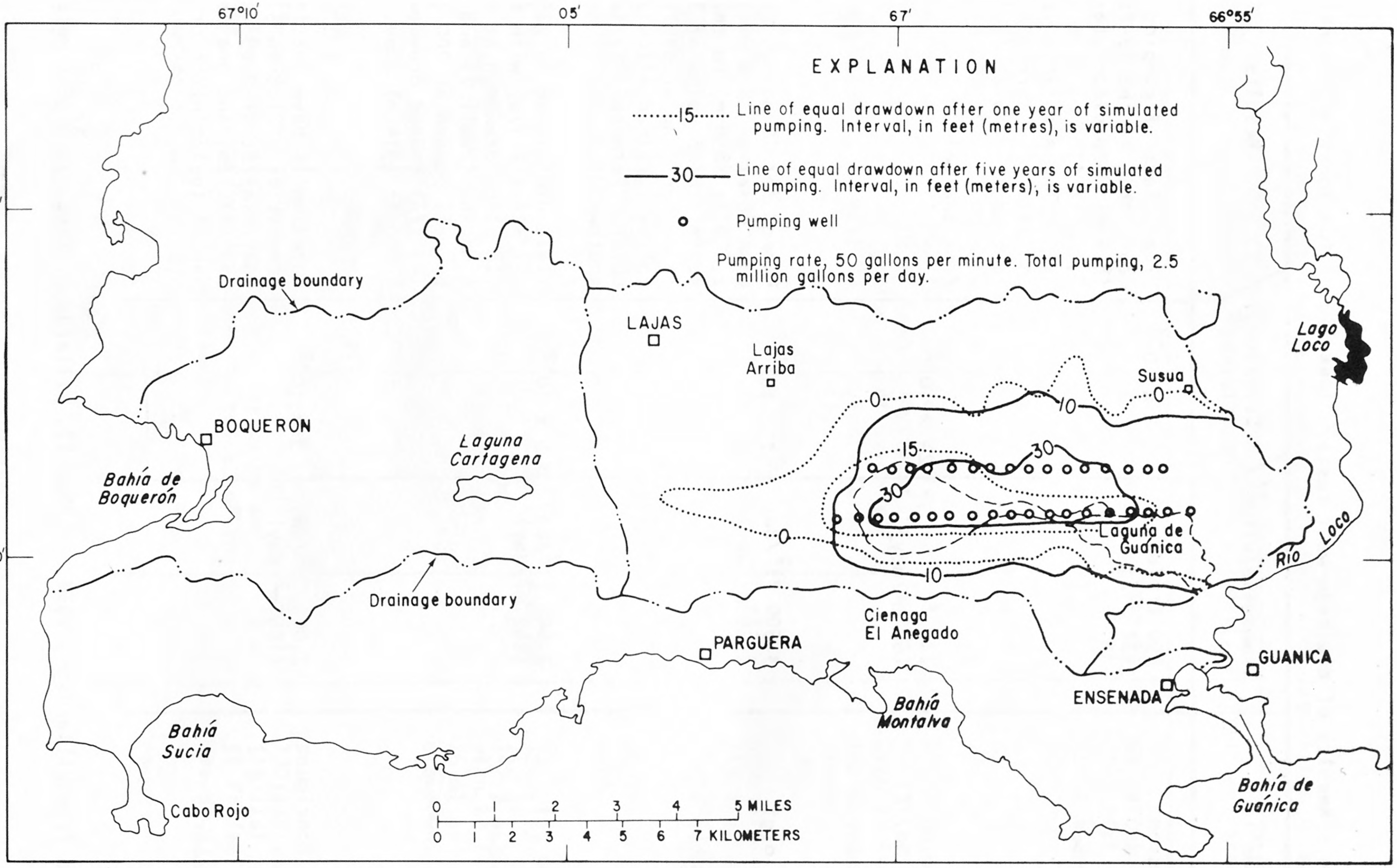


Figure 14.--Drawdowns after 1 and 5 years of simulated pumping.

QUALITY OF GROUND WATER

Ground water in more than half of Lajas Valley is too salty for drinking, irrigation, and most industrial uses. The concentration of salts apparently increases as ground water moves from recharge to discharge areas, from highland areas of high rainfall and low evapotranspiration to lowland areas of low rainfall and evapotranspiration. Evaporation from the water table increases the mineral concentration as the ground water moves downgradient. In addition, the water redissolves salts precipitated in the soil, further increasing salinity downgradient. Freshwater (less than 250 mg/l chloride concentration) is found along the northern fringe of the valley; the recharge areas where rainfall is high and evaporation is low (fig. 15). Ground water in the remainder of the valley is either brackish (250 to 1,000 mg/l chloride concentration) or saline (greater than 1,000 mg/l chloride concentration), as shown in figure 15. Saltwater in the limestone aquifer near Bahía de Boquerón is probably a seawater mix.

The salinity of ground water in the artesian area, in the eastern part of the basin, was found to decrease with depth (fig. 16). In one drainage experiment (Willardson, 1958), the Puerto Rico Water Resources Authority made a test boring in the Ciénaga El Anegado depression to 200 ft (60 m), sampling and analyzing changes in salinity of the water with depth. The uppermost water was saline and the ground-water level was depressed below sea level by the intense evaporation and transpiration. Water in deeper layers, however, was progressively fresher. The test hole ended in a confined zone that had water rising 4 ft (1.2 m) above land surface. The clay material showed these conductances (in micromhos):

4,600 at 10 ft (3.0 m)

6,000 at 20 ft (6.1 m)

5,000 at 25 ft (7.6 m)

2,600 at 115 ft (35.1 m)

3,700 at 158 ft (48.2 m)

1,000 at 197 ft (60.0 m)

The possible decrease in ground-water salinity with depth may be due to the folllowing conditions. Shallow ground-water flow originates in the lower slopes of the foothills where evapotranspiration intensifies the mineralization of ground water. Deeper ground-water flow lines originate in higher areas of the foothills, where evapotranspiration and, consequently, the mineralization of the ground water is less. Willardson (1958), suggests that the salt in the soil may be pushed to the surface by fresh water under pressure at lower depths.

The saltiest ground water is along the southern edge of the valley, where the chloride concentration is as much as 4,100 mg/l.

The quality of the ground water can be attributed to several factors: saltwater encroachment from the sea, concentration of the mineral content of the water through evapotranspiration, and a seldom considered factor of bulk fallout.

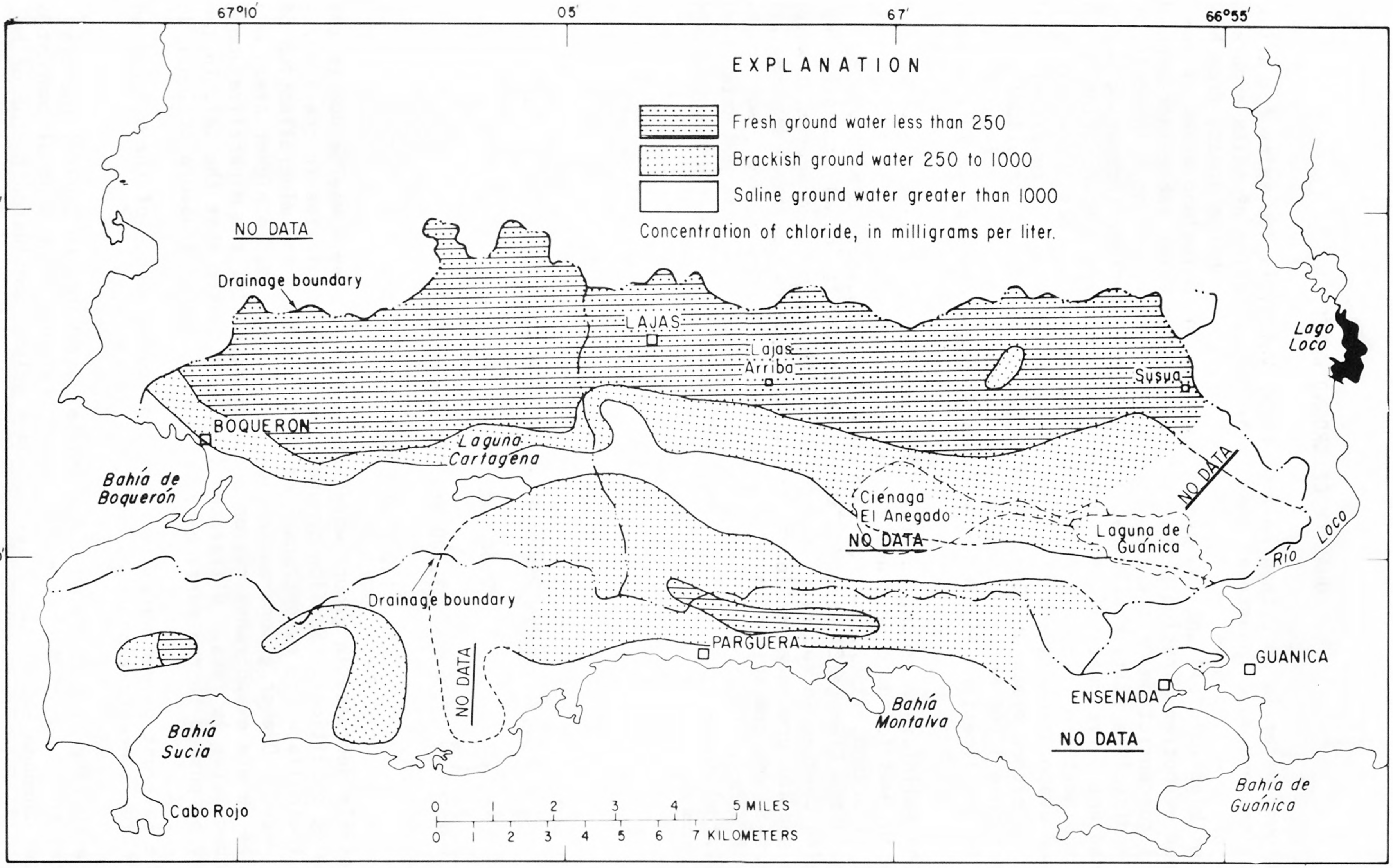


Figure 15.--Chloride concentration in ground water, Lajas Valley area.

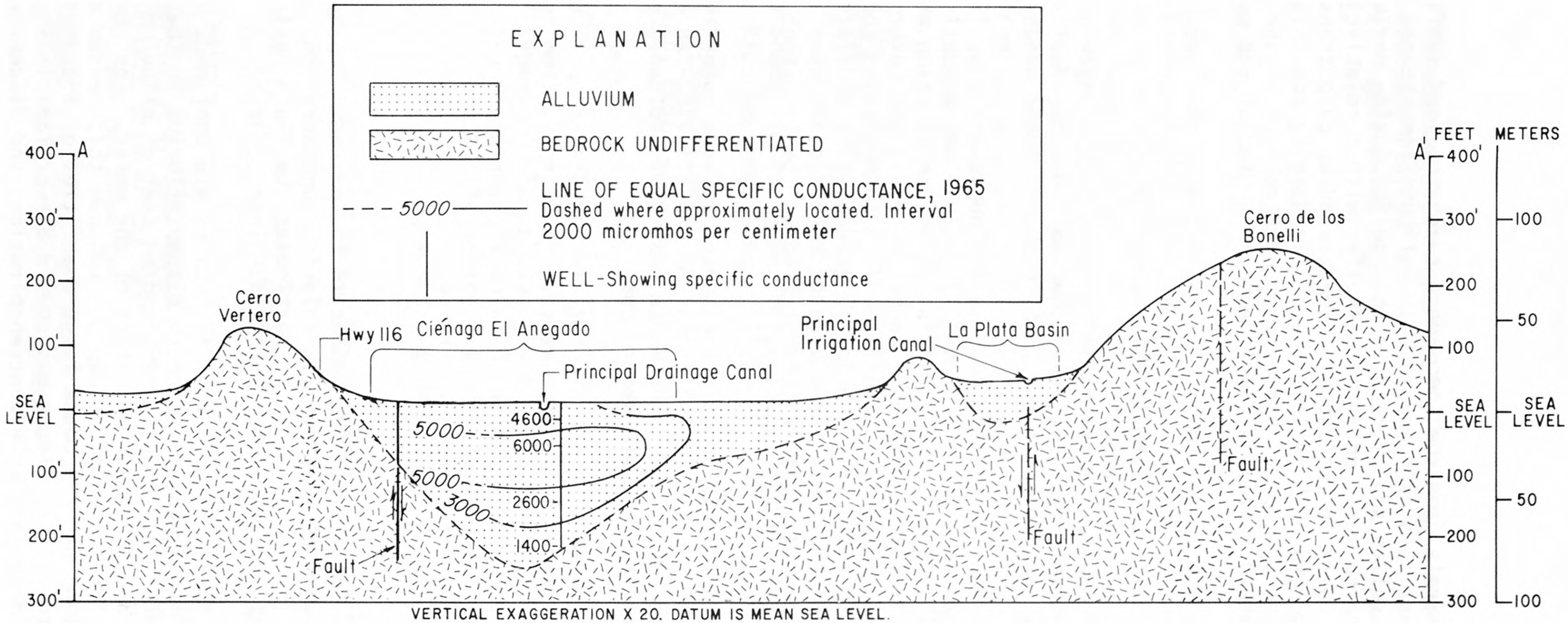


Figure 16.--Schematic section showing changes in specific conductance of ground water with depth.

Airborne minerals from the atmosphere reach the land surface dissolved in rainfall or as dust. In arid areas, bulk fallout from the sea and dust from salt flats is dissolved and carried to the aquifer during periods of recharge. As a result, recharge water enters the aquifer with a relatively high initial mineral content, where it is further concentrated by evapotranspiration. Evapotranspiration and bulk fallout are believed to be the chief causes of the high mineralization in ground water in the eastern part of the basin. Seawater intrusion is an added factor in the limestone aquifer of the western part of the valley.

SUMMARY AND CONCLUSIONS

A bolson for the most part, Lajas Valley is essentially a closed drainage basin where evapotranspiration exceeds the available rainfall supply. As a consequence, salts are concentrated both in the soil and ground water.

Rainfall averages 34 in (860 mm) a year supplemented by irrigation from imported surface water of an additional 17 in (430 mm) annually. Pan evaporation is 76.4 in (1,935 mm), and potential evapotranspiration about 53 in (1,320 mm). Except for flash floods, runoff is small and intermittent, amounting to a few inches per year. Streams heading in mountains soon disappear in the valley flats to recharge the brackish ground-water aquifers (250 to 1,000 mg/l chloride concentration). Ground-water recharge averages 1 to 2 in (25 to 50 mm) valleywide, but is concentrated in the limestone terrane and alluvial fan deposits of the foothills.

The northern highlands contain freshwater in some quantity in the Cotui Limestone Member of the San Germán Formation and alluvial-fan deposits. Yields of several hundred gallons per minute are possible. Volcanic rocks yield up to 50 gal/min (3 l/s) from the weathered zone.

The buried limestone aquifer (Cotui) in the western part of the valley yields large quantities of brackish water. Porosity is from solution holes and solution-widened fractures. Though well yields are substantial, as much as 2,000 gal/min (126 l/s), the water contains a chloride concentration of more than 400 mg/l and is unsuitable for irrigation of the poorly permeable soil, except for salt-tolerant crops. Thirty years ago the aquifer was the main source for irrigation but pumpage was discontinued because salts toxified the soil.

Areas of the Cotui Limestone Member in the northern foothills could supply locally large amounts of water of low chloride concentration (150 mg/l) for agricultural and industrial use. In particular, La Plata basin and possibly the Susua area require additional subsurface investigation.

Aquifers in the eastern part of the valley are confined. Coarser alluvial fans in the northern foothills grade to clayey alluvium in the valley. Development of ground water in the upper few hundred feet of alluvium is limited by low permeability and the brackish nature of the water. Test holes to 200 ft (60 mm) indicate fresher water at depth. Unknown thicknesses of alluvium and underlying limestone might produce large quantities of freshwater at depth. Ground water in the valley discharges upward by vertical leakage to the playa deposits and ultimate loss to evapotranspiration, and discharge to drainage canals.

Ground water in the southern highlands is from the Parguera Limestone. The water is brackish and limited in quantity--yields to wells are less than 100 gal/min (6 l/s). Most wells in this area are windmill powered and are used for watering stock.

The digita simulation of the valley indicated that a hydrologic balance is maintained with the recharge rate about equaling the evapotranspiration rate from the water table of 1.34 in (34 mm) per year.

The digital model was used to determine if discharge wells would effectively reduce artesian pressures and waterlogging of soil in the eastern part of the valley. A system of 35 wells pumping 50 gal/min (3.2 l/s) was imposed on the model. After 5 years of simulated pumping the water levels were reduced 10 ft (3 m) or more over an area of 13 mi^2 (34 km^2). Maximum drawdown was 46 ft (14 m) and the cone of influence continued to expand after 5 years. There is a possibility that continuous pumping would cause an increase in salt-water intrusion from the west.

SELECTED REFERENCES

Acevedo, G., Lubo-López, M.A., and Ortiz-Vélez, J., 1959, Occurrence of soil tumors northeast of the Guánica Lagoon, Lajas Valley, Puerto Rico: Univ. Puerto Rico Agr. Expt. Sta. Jour., v. XLIII, no. 2, p. 103-115.

Bonnet, J.A., and Brenes, E.J., 1958, Detailed salinity survey of Lajas Valley: Univ. Puerto Rico Agr. Expt. Sta. Bull. 141, 114 p.

Bonnet, J.A., and Tirado-Sulsona, P., 1950, Soil studies in Lajas Valley: Univ. Puerto Rico Agr. Expt. Sta. Bull. 86, 64 p.

Briggs, R.P., and Akers, J.P., 1965, Hydrogeologic map of Puerto Rico and adjacent islands: U.S. Geol. Survey Hydrol. Inv. Atlas HA-197.

Carter, O.R., 1965, Soil survey, Lajas Valley area Puerto Rico: U.S. Dept. Agr. Soil Conserv., in coop. with Univ. Puerto Rico Agr. Expt. Sta. Series 1961, no. 23, 170 p.

Cordero, I.A., 1972, A study of the costs and effects of irrigation in the planning and implementation of the Lajas Valley Agricultural Development Programme: Water Resources Research Inst., Univ. Puerto Rico Project A-024-PR for Office of Water Resources Research, U.S. Dept. Interior, Washington, D.C., 143 p.

Gahagan Overseas Dredging Co., 1956, Report on the geophysical survey of the Lajas Valley site for the Puerto Rico Water Resources Authority: Geophys. Survey Div., Gahagan Overseas Dredging Co., New York, N.Y., 2 p.

Garrison, L.E., Martin, P.G., and Berryhill, H.L., 1972, Preliminary tectonic map of the eastern Greater Antilles Region: U.S. Geol. Survey, in coop. with Dept. Navy and the Commonwealth of Puerto Rico, Misc. Geol. Inv. Map I-732.

Gordon, W.A., 1961, Miocene foraminifera from the Lajas Valley, southwest Puerto Rico: Jour. Paleontology, v. 35, no. 3, p. 610-619.

Israelson, O.W., 1954, Drainage and reclamation problems in Lajas Valley, Puerto Rico: Univ. Puerto Rico Agr. Expt. Sta. Bull., 48 p.

Johnson, K.G., 1974, Floods in eastern Lajas Valley and the lower Río Loco basin, southwestern Puerto Rico: U.S. Geol. Survey Hydrol. Inv. Atlas HA-532.

Kaye, C.A. 1957, Notes on the structural geology of Puerto Rico: Geol. Soc. Am. Bull.,v. 68, p. 103-118.

Lobeck, A.K., 1922, The physiography of Porto Rico: New York Acad. Sci., Sci. Survey of Porto Rico and the Virgin Islands, v.1, p. 301-379.

Mattson, P.H., 1960, Geology of the Mayaguez area, Puerto Rico: Geol. Soc. Am. Bull., v. 71, p. 319-362.

_______ 1973, Middle Cretaceous Nappe structures in Puerto Rican ophiolites and their relation to the tectonic history of the Greater Antilles: Geol. Soc. Am. Bull., v. 84, p. 21-38, 9 figs.

Mitchell, G.J., 1922, Scientific survey of Porto Rico and Virgin Islands: New York Acad. Sci., v. 1, 249 p.

Mitchell, R.C., 1954, A survey of the geology of Puerto Rico: Univ. Puerto Rico Agr. Expt. Sta., Tech. Paper 13, 167 p.

Puerto Rico Water Resources Authority, 1944, Report on the water resources of southwestern Puerto Rico, their development and utilization: Puerto Rico Water Resources Authority Eng. and Construction Div., 170 p.

_______ 1948, Report on the southwestern Puerto Rico Project: Puerto Rico Water Resources Authority Eng. and Construction Div., 107 p.

Quiñones, M.A., y Asociados, 1964, Salinity and drainage problems of the Lajas Valley: M.A. Quiñones y Asoc. for Puerto Rico Water Resources Authority, 45 p.

Reeve, R.C., 1955, Review of the drainage and salinity problems in the Lajas Valley, Puerto Rico, Special report, July 14-22, 1955: Univ. Puerto Rico Agr. Expt. Sta., 9 p.

_______ 1956, Review of experimental drainage and reclamation program for the Lajas Valley, Puerto Rico Special Report, June 17-July 2, 1956: Univ. Puerto Rico Agr. Expt. Sta., 19 p.

Slodowski, T.R., 1956, Geology of the Yauco area, Puerto Rico: Princeton Univ. Ph. D. thesis, 130 p.

University of Puerto Rico, 1954, Survey of saline and alkaline soils in the Lajas Valley irrigation area: Special rept., Univ. Puerto Rico Agr. Expt. Sta., October 1954.

Vázquez, Roberto, and Ortiz-Vélez, J., 1967, Drainage and ground-water research in Lajas Valley, Puerto Rico: Univ. Puerto Rico Agr. Expt. Sta. Bull. no. 206, 36 p.

Vázquez, Roberto, 1970, Water requirements of sugarcane under irrigation in Lajas Valley, Puerto Rico: Univ. Puerto Rico Agr. Expt. Sta. Bull. no. 224, 36 p.

Ward, J.S., and Associates, 1970, Report of preliminary soils and foundation investigation for proposed international airport southwest Puerto Rico: J.S. Ward and Assoc. Construction Eng., Caldwell, N.J., 15 p.

Willardson, L.S., 1958, Lajas Valley drainage problems: Univ. Puerto Rico Agr. Expt. Sta. Bull. no. 143, 64 p.