WATER RESOURCES OF THE MAUNABO VALLEY, PUERTO RICO

U.S. GEOLOGICAL SURVEY
Water Resources Investigation 115-76

Prepared in cooperation with the
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16. Abstracts The Maunabo Valley, in southeastern Puerto Rico, consists of a 3.5-square mile (9.1 square kilometer) alluvial plain surrounded by hills of metavolcanic and igneous intrusive rocks. The principal source of ground water in the basin is a shallow unconfined aquifer in the valley alluvium. Continuous pumping of the shallow aquifer has caused the chloride concentration to increase to 540 milligrams per liter in the lower part of the valley. Hydraulic conductivities of the aquifer materials are less than 1 foot per day (0.3 meters per day) for the metavolcanic and igneous rocks and from 10 to 100 feet per day (3 to 30 meters per day) for the alluvium. The average transmissivity of the alluvial aquifer is 4,000 feet squared per day (370 meters squared per day) and the average specific capacity is 10 gallons per minute per foot (2 liters per second per meter). Data gathered in the field suggest that development of the water needs could be supplemented by construction of surface-water control sutructures in addition to moderate capacity wells. Simulation from a digital model suggests locating the wells in the upper reaches of the alluvial aquifer where a yield of 3,000 gallons per minute (192 liters per second) exists.

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By D.G. Adolphson, M.A. Seijo, and T.M. Robison

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May 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

Cecil Andrus, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

For additional information write to:

U.S. Geological Survey
P.O. Box 34168; Building 652
Ft. Buchanan, Puerto Rico 00934

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CONVERSION TABLE

For those readers interested in using the metric system metric equivalents of English units of measurement are given in the text (in parenthesis). 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	.4047	hectares (ha)
square miles (mi^2)	2.590	square kilometers (km^2)
	Flow	
cubic feet per second (ft^3/s)	28.32	cubic meters per second (m^3/s)
gallons per day (gal/d)	3.785×10^3	cubic meters per day (m^3/d)
gallons per minute (gal/min)	.06309	liters per second (l/s)
inches per day per foot [(in/d)/ft]	84.62	millimeters per day per meter [(mm/d)/m]
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
	Hydraulic Conductivity	
feet per day (ft/d)	.3048	meters per day (m/d)
	Length	
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
feet per mile (ft/mi)	.1894	meters per kilometer (m/km)
miles (mi)	1.609	kilometers (km)
	Specific Capacity	
gallons per minute per foot [(gal/min)/ft]	.207	liters per second per meter [(l/s)/m]
	Transmissivity	
feet squared per day (ft^2/d)	.0929	meters squared per day (m^2/d)
	Volume	
acre-feet (acre-ft)	1233	cubic meters (m^3)
billion gallons (10^9 gal)	3.785×10^6	cubic meters (m^3)

Puerto Rico Aqueduct and Sewer Authority public water supply well near the town of Maunabo (1975).

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ABSTRACT

The Maunabo Valley, in southeastern Puerto Rico, consists of a 3.5-square-mile (9.1-square-kilometer) alluvial plain surrounded by hills of metavolcanic and igneous intrusive rocks. The principal source of ground water in the basin is a shallow unconfined aquifer in the valley alluvium, although the bedrock probably has some water in storage.

Future development in the valley depends upon the quantity of high-quality water available. Continuous pumping of the shallow aquifer has induced the flow of saltwater and has caused the chloride concentration to increase from about 30 to 540 milligrams per liter in the lower part of the valley.

A study from January 1971 to December 1974 indicated that the hydraulic conductivities of the aquifer materials, in the basin, are less than 1 foot per day (0.3 meter per day) for the metavolcanic and igneous rocks. Estimated conductivities range from 10 to 100 feet per day (3 to 30 meters per day) for the alluvium. The average transmissivity of the alluvial aquifer is estimated to be 4,000 feet squared per day (370 meters squared per day) and the average specific capacity is 20 gallons per minute per foot (4.1 liters per second per meter) of drawdown. In December 1974, the alluvial aquifer contained an estimated 10,000 acre-feet or 3.3 billion gallons (12.3 million cubic meters) of water in recoverable storage.

The data suggest that water supplies to meet future needs could be supplemented by the construction of surface-water-control structures and additional wells. Analysis of a digital simulation model suggests that wells be located in the upper reaches of the alluvial aquifer where a sustained yield of 3,000 gallons per minute (189 liters per second) could be obtained.

INTRODUCTION

A hydrogeologic study was made from January 1971 to December 1974 of the Maunabo drainage basin, under a cooperative agreement between the U.S. Geological Survey and the Commonwealth of Puerto Rico. The cooperating Commonwealth agencies were the Puerto Rico Aqueduct and Sewer Authority and the Puerto Rico Department of Natural Resources. The Maunabo Valley, which is located in southeastern Puerto Rico (fig. 1), is in a relatively unpopulated part of the island.

The objectives of the study were: (1) to estimate the water budget for the valley, with emphasis on the alluvial aquifer in the lower part of the valley; (2) to estimate the sustained yield of the alluvial aquifer; (3) to provide information for future dam storage studies; and (4) to provide a dam predevelopment data baseline so that postdevelopment hydrologic changes can be determined.

The hydrogeologic investigations in the basin consisted of studying the published results of investigations and unpublished records of the Commonwealth and Federal agencies. In addition, data were collected and analyses made using the following field and laboratory methods: (1) delineating areas of water-bearing alluvial deposits; (2) making an inventory of wells as an aid in determining areas of greatest ground-water potential; (3) examining samples from test holes to determine the thickness, extent, and character of water-bearing deposits; (4) determining the altitudes of selected test holes and wells; (5) collecting and analyzing water samples to determine the chemical character of water; and (6) testing aquifers to determine the hydraulic properties of the water-bearing deposits.

The existing data were used in developing a digital hydrologic model of the alluvial aquifer. The model was used to plan the ground-water exploration program, to make a preliminary water budget, and to estimate the potential of the aquifer for further development.

GROUND-WATER RESOURCES

Geologic Setting

The Río Maunabo drainage basin rises in the Cordillera Central and extends to the Mar Caribe (Caribbean Sea) on the south coast. Nearly all of the 18.5 mi^2 (47.9 km^2) basin is underlain by diorite and granodiorite rock of the San Lorenzo batholith. There is a small area of metavolcanic rocks in the southwestern corner of the basin adjacent to the sea.

The upper part of the Río Maunabo follows the strike of a major fault (fig. 2) that bisects the length of the basin (Kaye, 1957). There is extensive jointing perpendicular to this fault, causing a trellis-type drainage pattern. Much differential weathering takes place along joint planes which cause the joint blocks to weather into large subangular to well-rounded boulders.

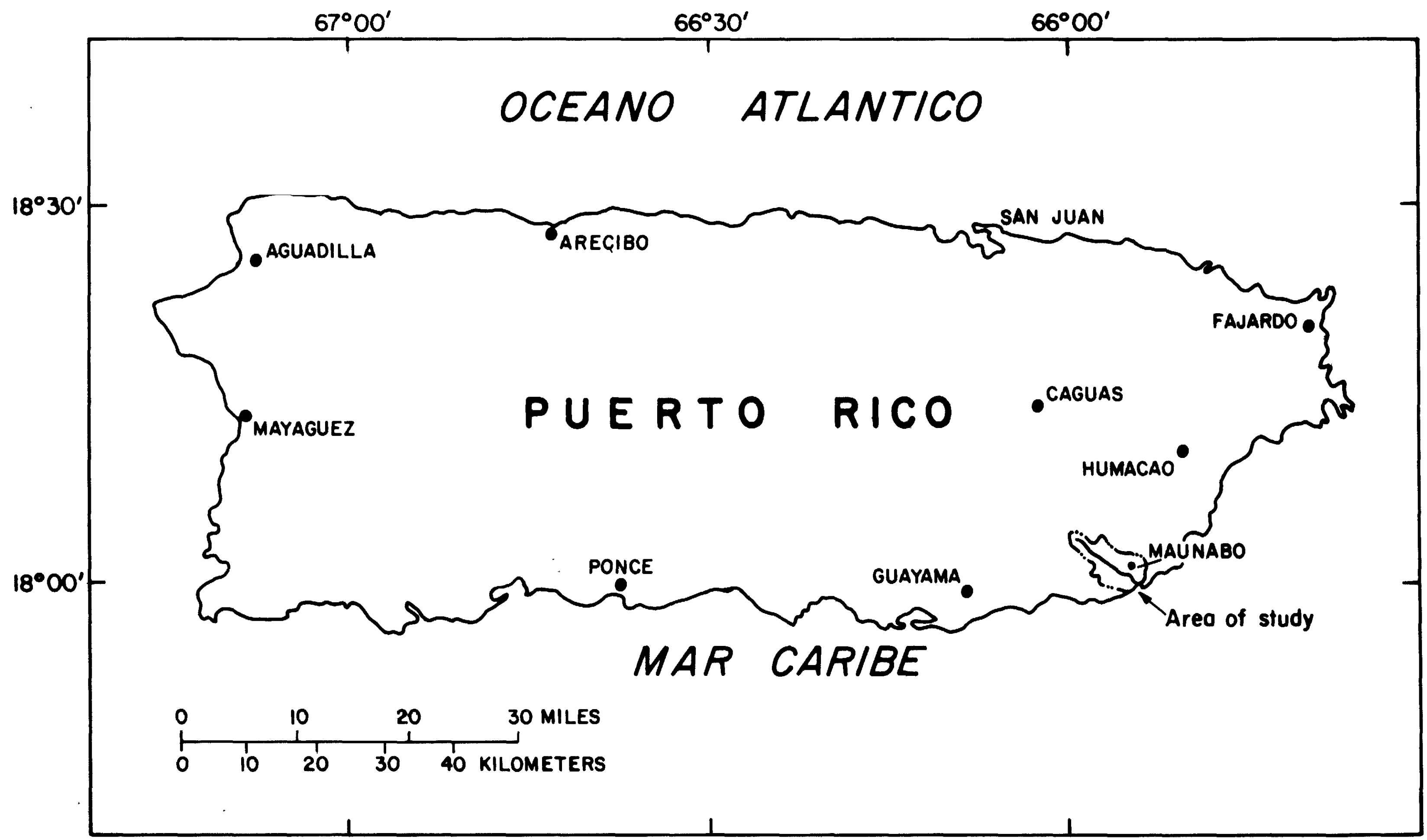

Figure 1.--Location of the Maunabo area.

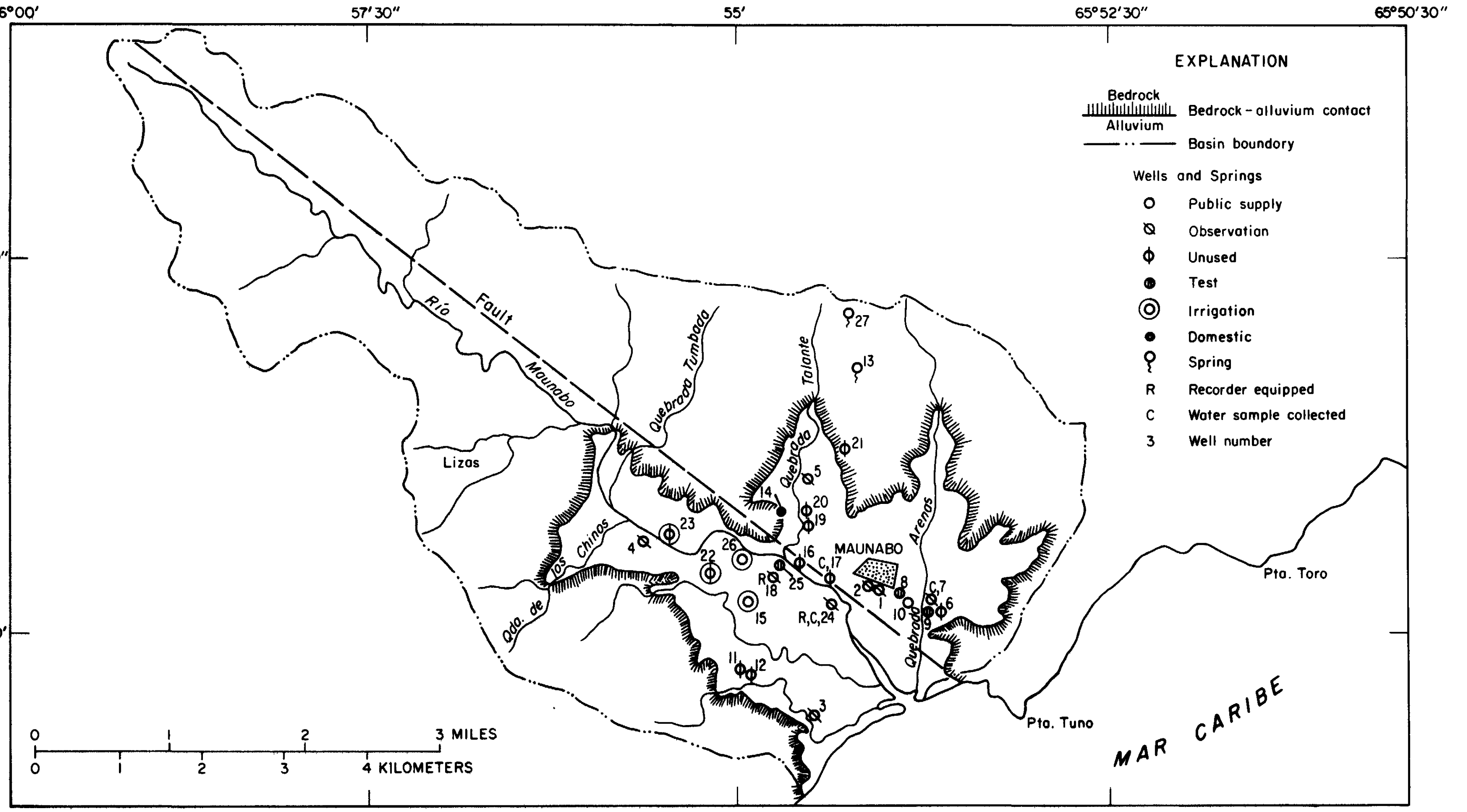

Figure 2.--Alluvial deposits, test holes, wells, springs, and data-collection points.

During lower stands of the sea, the Río Maunabo cut deep gorges in the bedrock. During later higher sea stands, sediment-laden streams deposited material in the lower valley forming a wide flat alluvial plain, with an area of about 3.5 mi^2 (9.1 km^2). Narrow ribbons of alluvium are also present in the gorges of the upper valley.

The configuration of the bedrock surface under the alluvium is irregular because of buried ridges and hills formed by shifts in the position of the ancestral streams. Bedrock often occurs close to the land surface in the middle of the valley, causing the Río Maunabo to make sharp changes of direction. Figure 2a shows the generalized thickness of alluvium underlying the valley.

Large amounts of sand and gravel are being mined from the Río Maunabo streambed above Columbia. The mining operations, consisting of shallow excavations in the active channel and deep excavations along the inactive channel, may eventually affect the stream system.

Bedrock Aquifers

No wells have been drilled in the bedrock aquifer of the valley, because of the availability of the alluvial aquifer. Based upon wells drilled elsewhere in the San Lorenzo batholith, yields of 5 to as much as 50 gal/min (1 to 3 l/s) can be obtained from wells 50 to 150 ft (15 to 46 m) in depth, tapping open joints in the rock. The valleys which generally follow zones of more extensive jointing or faulting are usually the best sites for wells.

Alluvial Aquifer

Ground water in the lower valley is obtained from an unconfined alluvial aquifer that consists of unconsolidated silt, clay, sand, and gravel. Drilling logs show that the lithology varies widely with many lenses and discontinuous bodies of silt, clay, and sand present. The sand deposits are more coarse in some areas of the valley than others. The availability of ground water is related to the configuration of the underlying bedrock surface with the thickest and most permeable alluvium in the buried ancestral bedrock valleys. The greatest depth of alluvium penetrated by drilling is 163 ft (50 m); however, the deposits are estimated to be as much as 200 ft (60 m) thick.

Information on wells, test holes, and springs is given in table 1. The yield of wells in the alluvium ranges from 20 to 1,500 gal/min (1.3 to 38 l/s), whereas, the depth of wells and test holes ranges from 21 to 163 ft (6.4 to 50 m). Where well-sorted sand and gravel deposits are saturated for more than 100 ft (30 m), properly constructed wells can probably sustain yields of more than 600 gal/min (38 l/s). Wells along the Río Maunabo and Quebrada Arenas have high yields because of induced infiltration from the streams.

Pumpage

Seven wells have been drilled in the basin for public water supplies since 1936. Six of the wells have been abandoned because of high concentrations of manganese or chloride. Well 17, drilled for public supply in 1961 and abandoned in March 1974, by the Puerto Rico Aqueduct and Sewer Authority (PRASA), had an average yield of 0.40 Mgal/d (17.5 x 10^{-3} m^3/s). The well, which is 120 ft (37 m) deep, taps the deeper part of the alluvial aquifer. The well was abandoned because the chloride concentration of the water had increased from 30 to 540 mg/l (milligrams per liter).

Table 1.--Information on test holes, wells, and springs in the Maunabo basin.

Owner/Name	Identification number	Year drilled	Use	Depth (ft)
Observation well	1	1973	Observation	26
Observation well	2	1973	do.	60
Observation well	3	1973	do.	31
Observation well	4	1973	do.	28
Observation well	5	1973	do.	25
Bordaleza - PRASA	6	1937	Unused	110
PRASA	7	1958	Observation	100
PRASA	8	1959	Test	163
PRASA	9	--	Test	--
Municipio - PRASA	10	1974	Public supply	125
War Department	11	1942	Unused	158
War Department	12	1942	Unused	130
Municipio de Maunabo	13	--	Public Supply	Spring
Pura Dominques	14	--	Domestic	45
Coop Lafayetta	15	--	Irrigation	--
Miguel Calimano	16	1936	Unused	--
PRASA	17	1961	Public supply	120
Calzada - PRASA	18	1970	Observation	71
Miguel Calimano	19	1970	Unused	80
Miguel Calimano	20	1970	Unused	80
Santiago	21	--	Unused	--
Carlos Calimano	22	--	Irr./Unused	108
Carlos Calimano	23	--	Irr./Unused	140
Valldejuli - PRASA	24	1967	Observation	100
PRWRA	25	1970	Test	80
PRWRA	26	1974	Irrigation	80
Chorro de la Pica	27	--	Public Supply	Spring

NOTE: PRASA = Puerto Rico Aqueduct and Sewer Authority.

PRWRA = Puerto Rico Water Resources Authority.

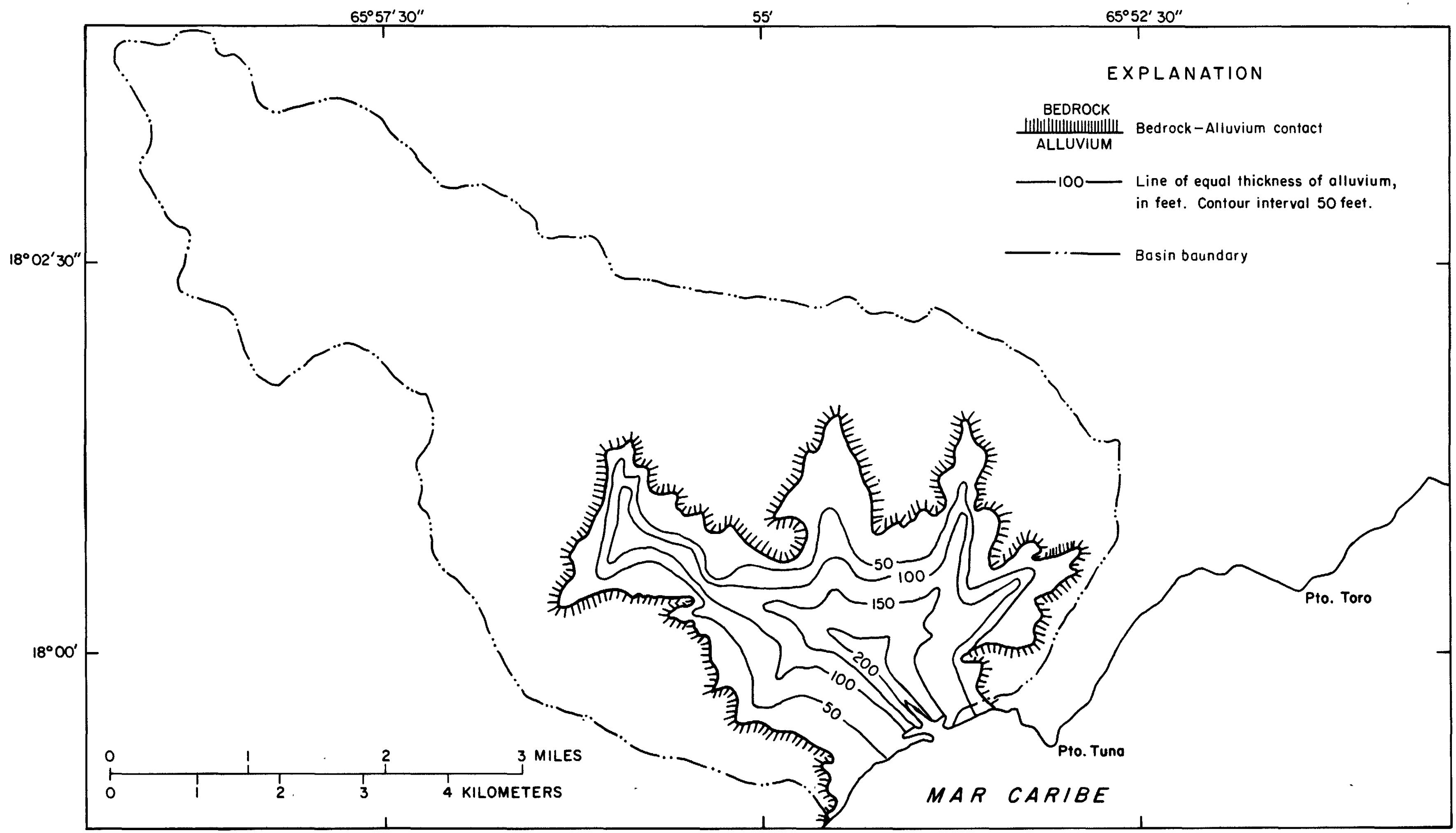

Figure 2a.--Generalized thickness of alluvium.

Well 10, which is 125 ft (38 m) deep, was drilled near the Quebrada Arenas in the spring of 1974 for the new public supply. The well is being pumped continuously at a rate of 325 gal/min (21 l/s). The chloride concentration of the water in a nearby observation well (well 7) was 33 mg/l in September 1973.

Eighty percent of the alluviated valley, about 1,600 acres (650 ha), is being used for growing sugarcane; but at present only about 20 percent, 380 acres (154 ha), of the sugarcane is being irrigated. Prior to 1974 three wells were used to irrigate a total of 860 acres (350 ha).

Two of the wells (22 and 23), located in the upper part of the alluvial valley, irrigated about 480 acres (194 ha) of sugarcane prior to being abandoned. These wells were pumped at rates of 500 and 1,500 gal/min (30 and 95 l/s), respectively. The high yields obtained in this area apparently result from coarser and more permeable alluvium.

Well 15, which had been used to irrigate 380 acres (154 ha) of sugarcane, was converted to a public supply well in 1974. The Puerto Rico Land Authority drilled well 26 as a replacement in 1974. Water from well 26 is pumped to a pond from where it is released to canals to irrigate the fields by gravity flow. In 1974, the well was pumped at a rate of 600 gal/min (38 l/s), generally 8 hours per day from May to December. The average pumping rate for the period was about 0.1 Mgal/d (4.4×10^{-3} m^3/s).

Water Levels

Automatic recorders on two observation wells have been in operation in the valley since 1971. Figure 3 shows the continuous graph of water-level fluctuations for the recorders and graphs for six observation wells whose water levels were measured periodically. The water levels show a seasonal fluctuation closely related to rainfall. Some water levels show the impact of nearby pumping wells, particularly during the dry summer months when water demand for irrigation and public supply is at its peak. Below normal rainfall, during the spring and summer of 1974, caused the water levels in all the wells in the valley to decline to new low water levels. The water-level contours on figure 4 show the altitude of the top of the saturated zone in June 1974. All the wells, except observation well 7, recorded new high water levels in November 1974 after 2 months of above-average rainfall.

The rainfall in the basin varies with altitude. The annual average rainfall at a station in the lower part of the valley is 46.8 in (1,189 mm) and 76.6 in (1,946 mm) at a station in the mountainous part of the valley. The monthly rainfall of the lower station has been plotted for 1971 through 1974 along with the water-level fluctuations on figure 3a.

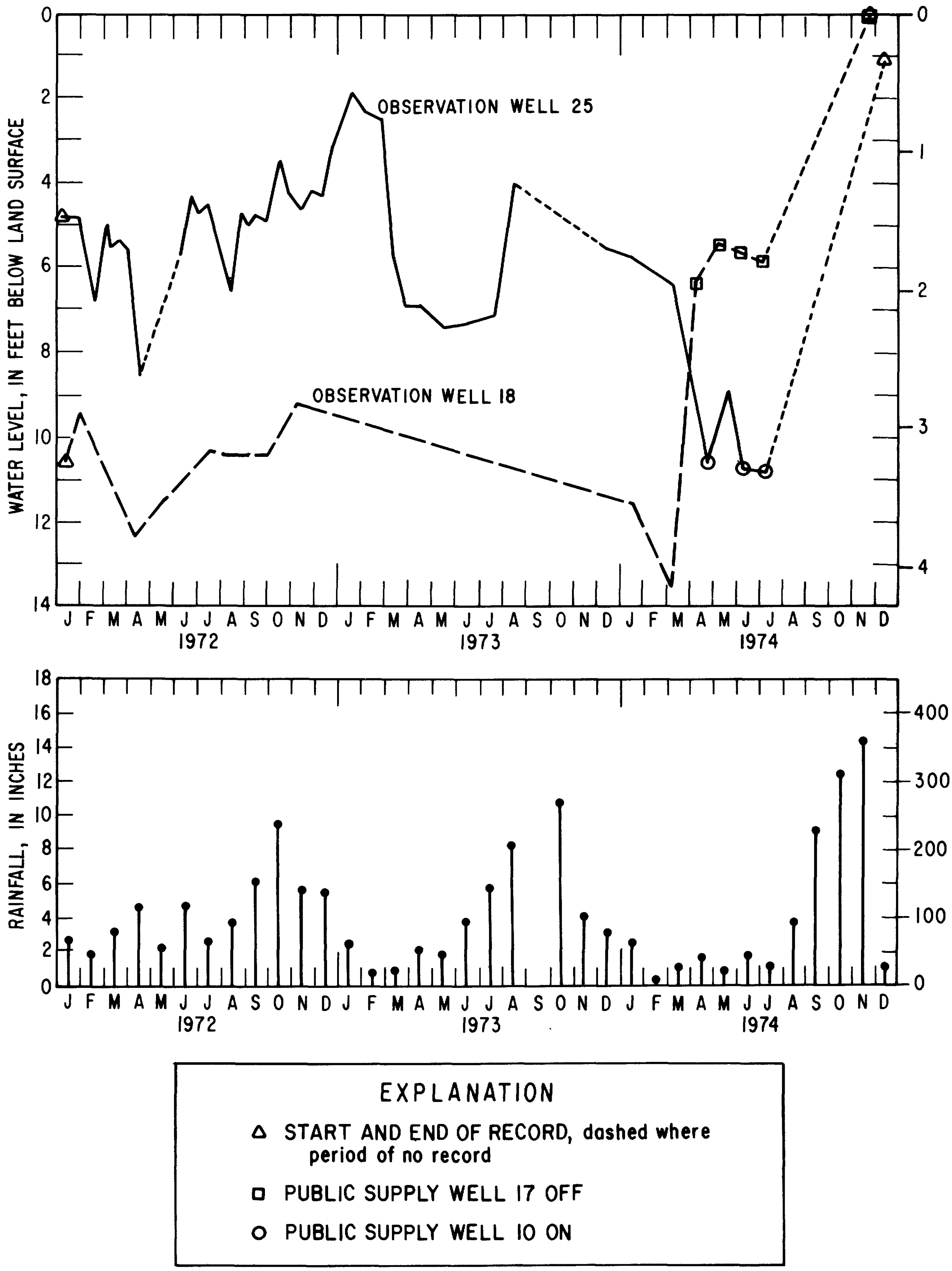

Figure 3a.--Rainfall at Maunabo and water level of observation well 25.

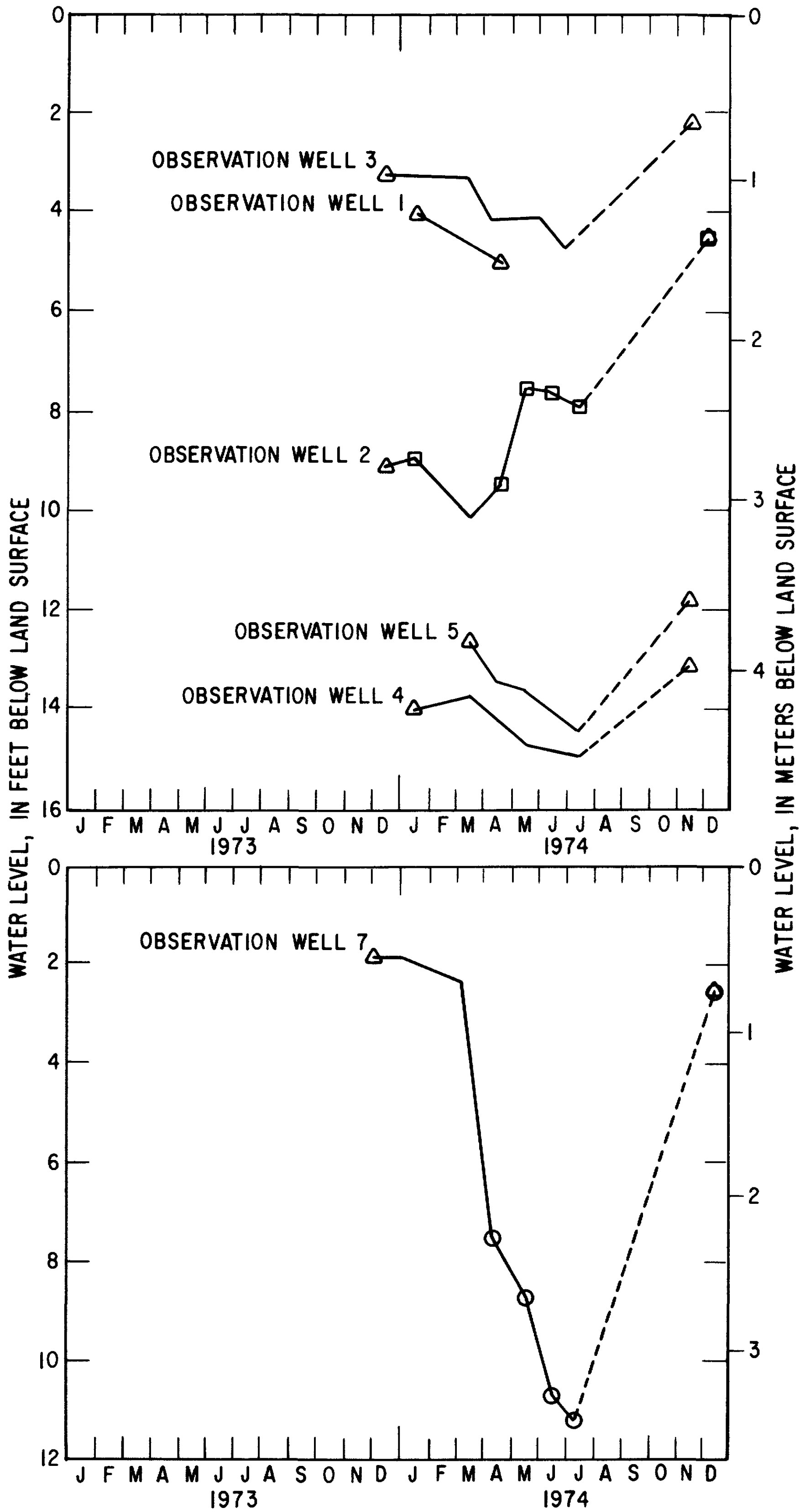

Figure 3b.--Water levels in selected wells in the Maunabo area.

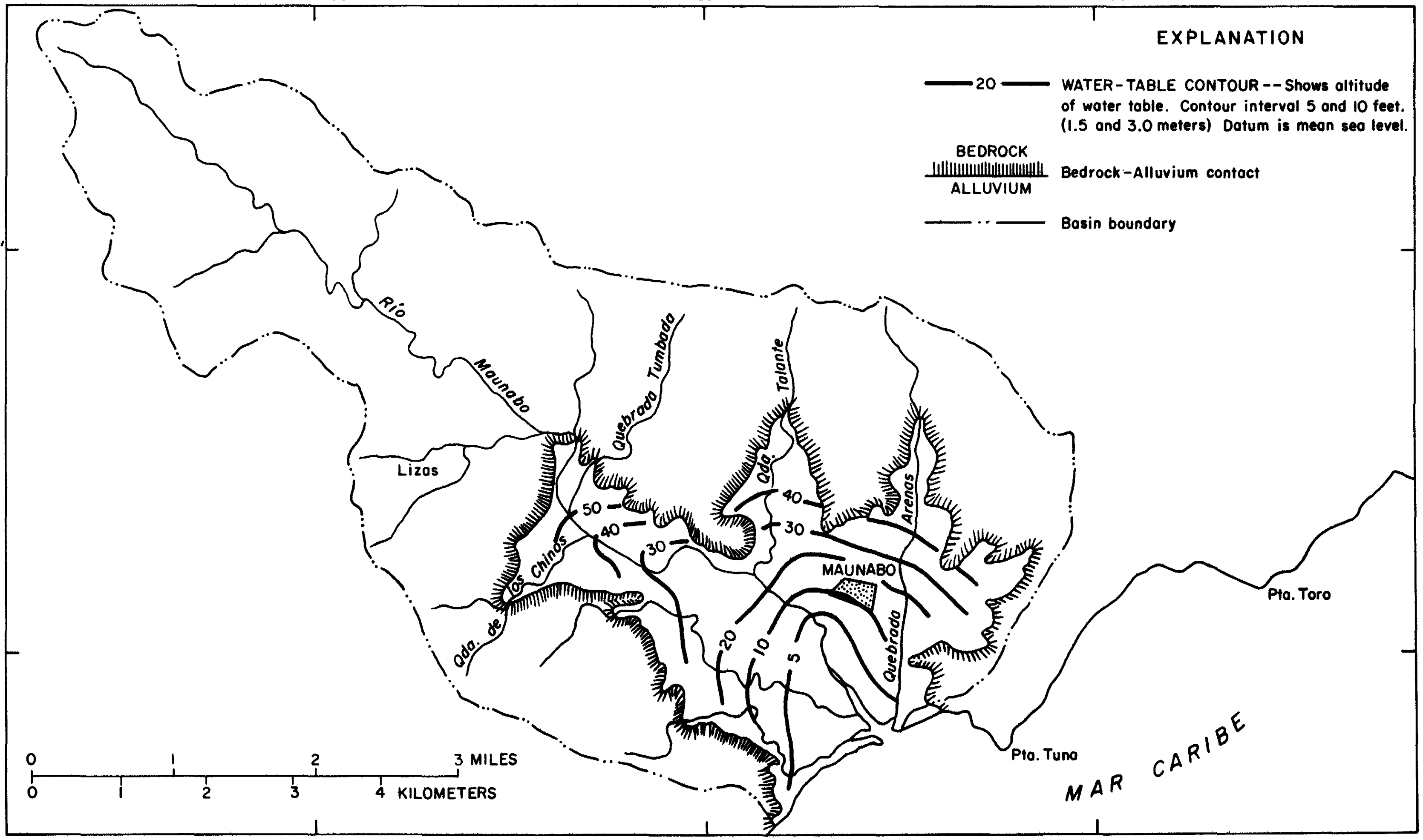

Figure 4.--Water-table contours in alluvial aquifer on June 13, 1974.

Hydrologic Properties

The hydrologic properties of the alluvial deposits were determined from tests made as part of this study and from data of the Puerto Rico Aqueduct and Sewer Authority.

The hydraulic conductivity, which is a measure of the ability of the aquifer material to transmit water, of the metavolcanic and igneous intrusive rocks is believed to be less than 1 ft/d (0.3 m/d). The hydraulic conductivity of the unweathered bedrock is largely dependent upon joints, faults, and shear zones. There is a shallow zone of weathered bedrock which might have a hydraulic conductivity of about 5 ft/d (1.5 m/d) in some areas but is probably too thin to be either a prolific or reliable source of water.

The alluvium that has the greatest hydraulic conductivity, about 100 ft/d (30 m/d), is found along the course of the Río Maunabo. The next most conductive alluvial deposits, about 50 to 75 ft/d (15 to 23 m/d), are found along the main tributaries to the Río Maunabo. The least conductive alluvium, less than 10 ft/d (3 m/d), consists of colluvial deposits adjacent to the bedrock hills. Along the seacoast, there are some coarse beach deposits that are highly conductive.

A pumping test was made by the Puerto Rico Aqueduct and Sewer Authority on public-supply well 17. The results, which were computed from the specific capacity of the well by the Theis, Bowen, and Mayer method (1963), are helpful because they indicate the approximate range of aquifer characteristics in the alluvial valley.

From June 6 to 8, 1961, public-supply well 17 was pumped for 52 hours at rates of 300, 500, and 700 gal/min (19, 32, and 44 l/s). The water level in the well was lowered 34 ft (10.4 m) during this period (fig. 5). When pumping ceased, the water level rose rapidly, and recovered to within 3 ft (1 m) of the static level in 25 minutes. A general performance rate for the well (specific capacity) was determined using an average pumping rate of 435 gal/min (27 l/s).

Well depth, ft	Static water level, ft below land surface	Drawdown after 52 yours, ft below static level	Specific capacity, (gal/min)/ft
120 (37 m)	10 (3 m)	34 (10 m)	12.8 [2.6 (l/s)/m]

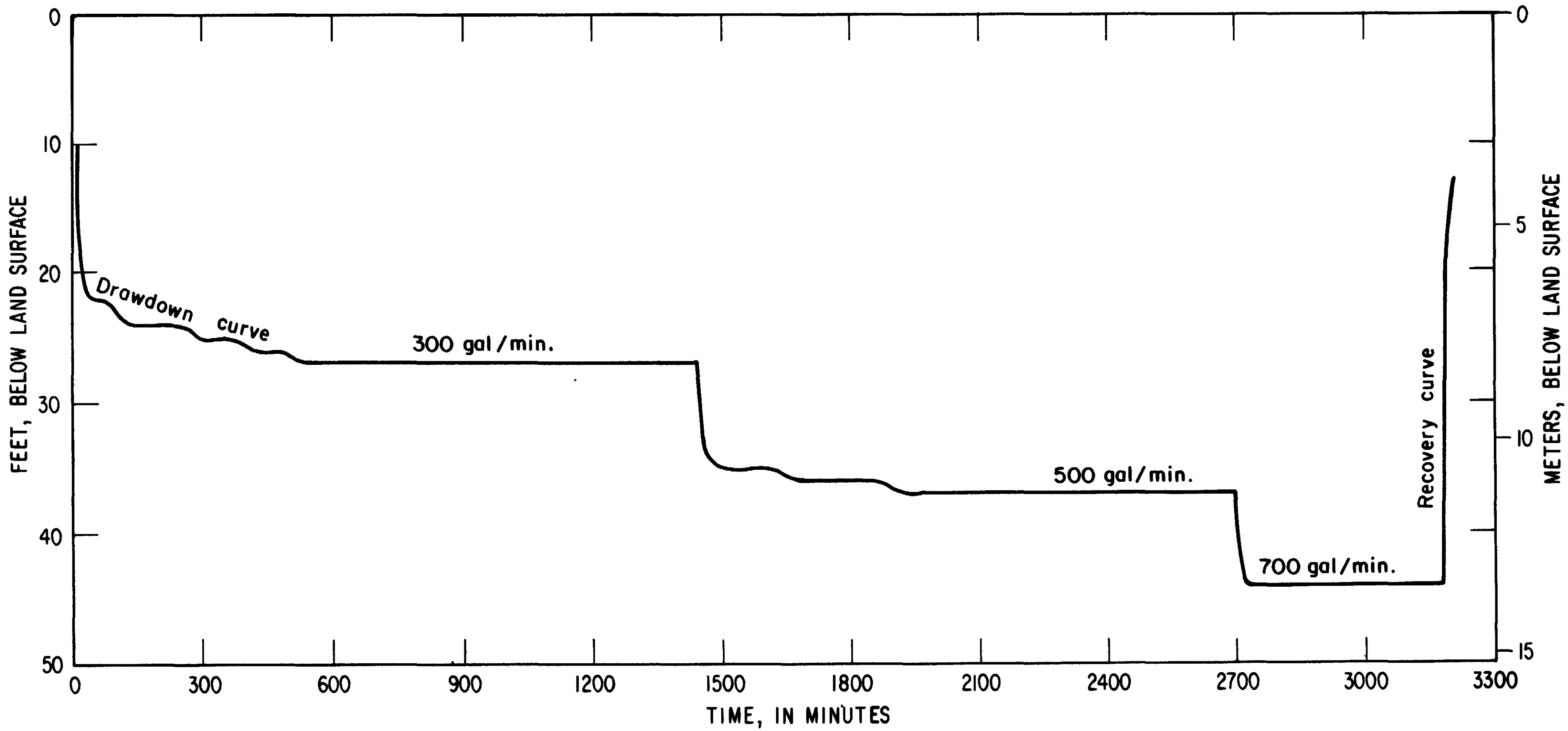

Figure 5.--Drawdown and recovery curves for PRASA well 17.

The test computations are summarized in the following table:

Pumpage increment, gal/min	Drawdown increment, ft	Specific capacity (gal/min)/ft	Transmissivity (T) ft^2/d	Hydraulic conductivity (K) ft/d
300	17	17.6	3500	88
200	10	20.0	4000	100
200	7	28.6	5700	143

The results indicate that the efficiency of the well increased during the production test probably because the silt and fine sand were removed from the aquifer in the vicinity of the well thus permitting freer flow of water. The data suggest that the average transmissivity in the general vicinity of the well is about 4,000 ft^2/d (370 m^2/d). However, test hole data from other wells suggest that the average transmissivity for the alluvium throughout the valley would be considerably lower.

Recharge and Discharge

Most recharge to the aquifers in the alluvium is by direct infiltration of precipitation, ground-water inflow from weathered bedrock, irrigation return flow, and infiltration of surface runoff from surrounding highlands. The amount of recharge that infiltrates the saturated zone depends on topography, vegetation, soil type and moisture conditions, and intensity of precipitation.

Recharge must approximately equal discharge in the Maunabo Valley alluvium because long-term water-level measurements reflect no significant changes in the average amount of ground water stored.

SURFACE-WATER RESOURCES

Streamflow

The channel of the Río Maunabo in the upper reaches is generally well defined, but follows a meandering course through the lower part of the valley. For the 4.3-mi (6.9-km) reach of the river in the igneous area, the average gradient is about 230 ft/mi (44 m/km). However, the average gradient of the alluvial valley through which the river meanders is about 13 ft/mi (2.5 m/km).

The flow of the river is variable, gradually diminishing during the winter and spring months (fig. 6). About 30 percent of the annual streamflow occurs in August, September, and October, whereas about 60 percent of the flow for the year occurs during May to October.

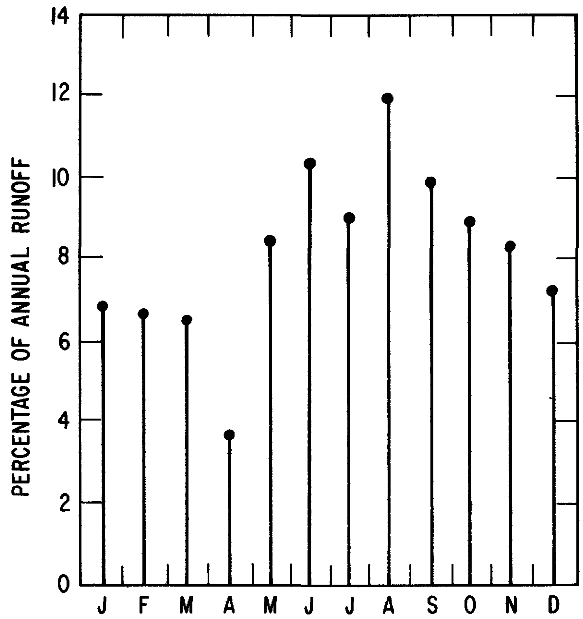

Figure 6.--Monthly distribution of runoff at the Río Maunabo at Lizas gaging station.

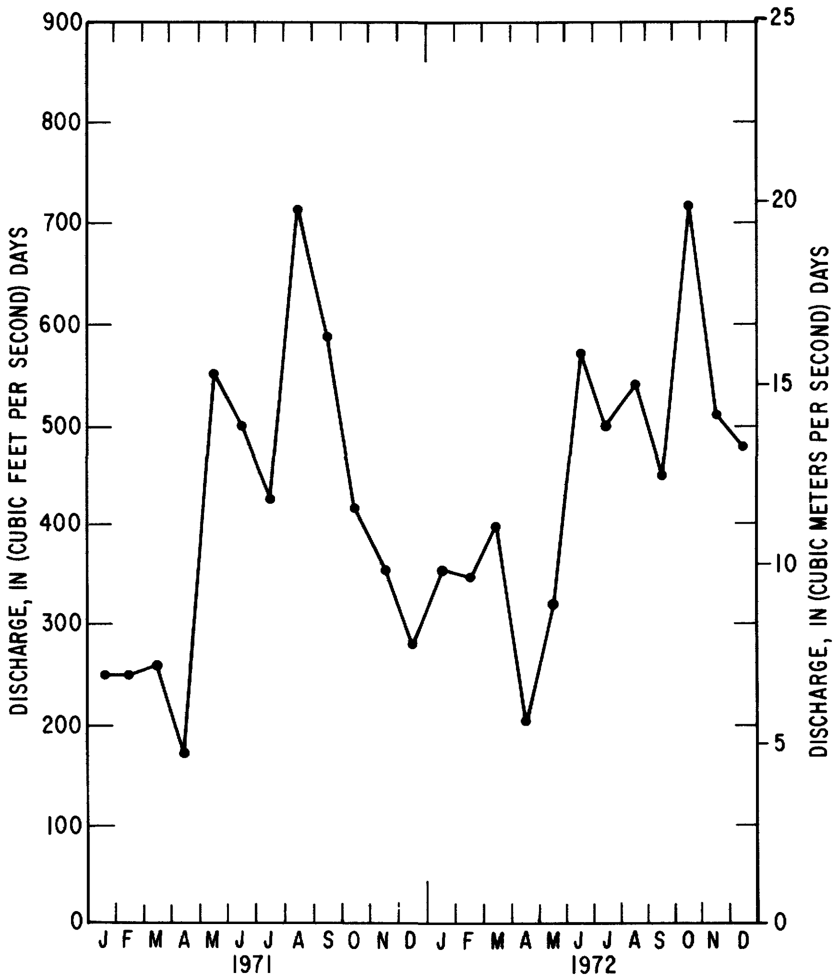

Figure 7.--Monthly discharge at the Río Maunabo at Lizas gaging station.

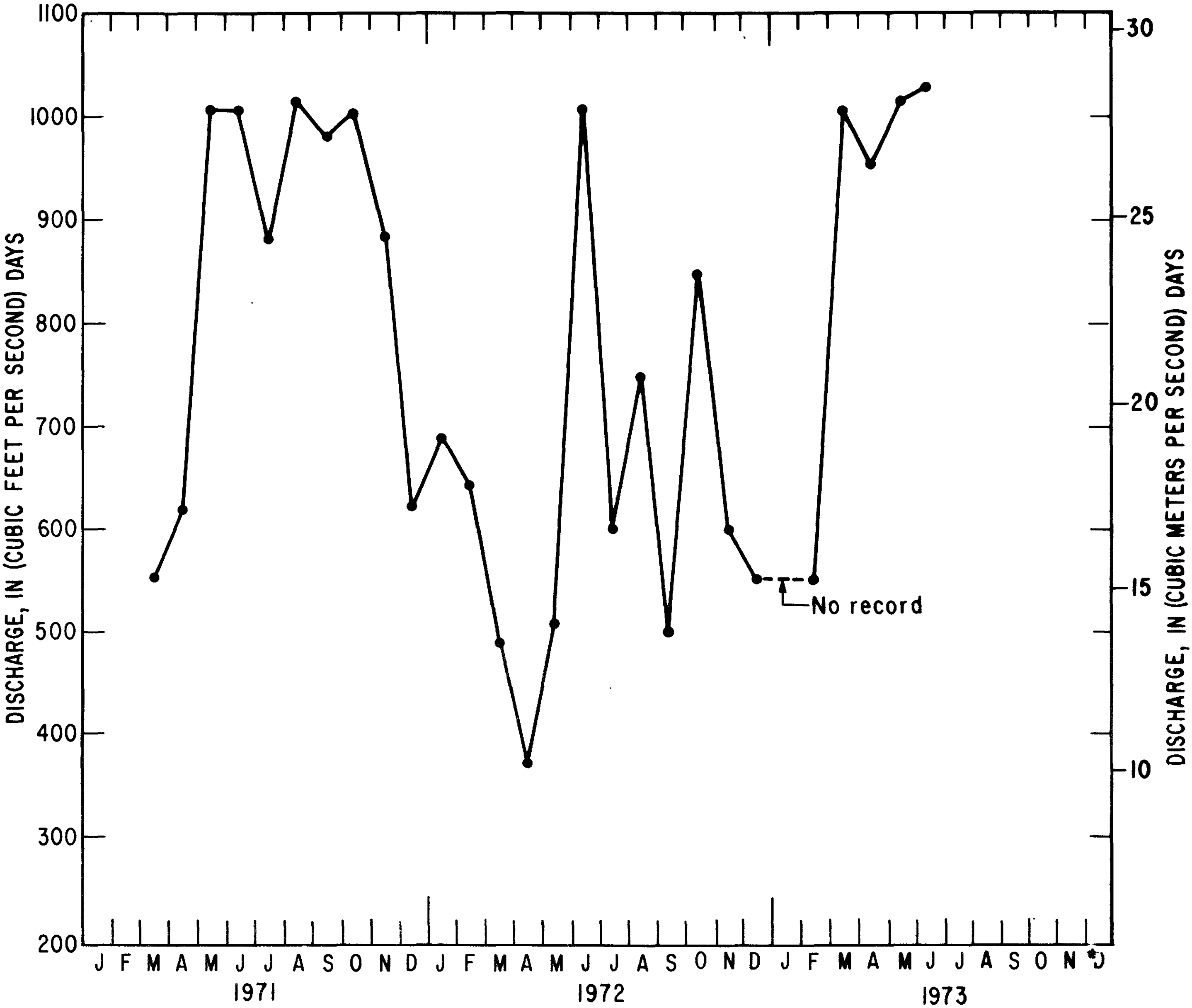

Figure 8.--Monthly discharge at the Río Maunabo near Maunabo gaging station.

The streamflow is continuously monitored at one site and periodically monitored at three sites within the basin. The floodflow, low flow, sediment, and bacteriological and chemical quality are measured.

An average of 10,000 acre-ft (12.3×10^6 m^3) of water per year enters the alluvial valley at the site of the station at Lizas near the upper edge of the alluvium (fig. 7). Downstream at the station near Maunabo average annual discharge is 18,000 acre-ft (22.2×10^6 m^3) per year (fig. 8). The average flow rate of the Río Maunabo and the Quebrada Arenas, which is represented by the width of patterns in figure 9, is the discharge that could be sustained if the runoff were totally regulated. This assumes that there are no additional losses.

The Río Maunabo receives nearly 50 percent of the annual flow from the alluvial aquifer. The ground-water discharge forms the base flow of the river. During much of the year the base flow comprises the total flow, but during periods of high surface runoff it is only a small fraction of the total flow.

The possibility of impounding water for use in the dry season has long been discussed for the Maunabo Valley. Recently the Puerto Rico Association of Soil Conservation Districts (1973) compiled an "Inventory of potential and existing impoundment sites" with technical assistance from the U.S. Soil Conservation Service.

Two impoundment sites were identified in the Río Maunabo drainage basin. (See fig. 9 for the location of these sites and pertinent data regarding their possible utility.) Both sites are above Lizas, which means that for purposes of water supply to the alluvial part of the basin, their capacities can be combined. The combined capacity of the two reservoirs is 8,970 acre-ft.

A storage analysis based on the above reservoir capacity indicates that 1,150 acre-ft (1.42×10^6 m^3) per month could be supplied at Lizas. This assumes that monthly flows correspond to those measured at Lizas from March 1971 to December 1973 and that the reservoir is full at the beginning. No consideration was made for evaporation but approximately 103 acre-ft (127,000 m^3) would be lost per month at normal pool elevation and area. The year 1972 was a very dry year for Puerto Rico and might lower the evaporation estimate.

Low Flow

All the stream tributaries to the Río Maunabo, in the valley area, are intermittent; most of them flow only as a result of surface runoff from precipitation. Tributary streams, which drain areas where there are saturated alluvial deposits such as Quebradas Arenas, Talante, de los Chinos, and Tumbada, generally flow from early summer until early winter because they receive ground-water discharge from the alluvial deposits. The stream tributaries in the mountainous area generally have permanent flow.

Figure 10, a plot of monthly streamflow of the Quebrada Arenas, shows in more detail how streamflow decreased during the dry season. An average straight line is drawn through the plotted discharge measurements. The slope of this line is the rate of decrease of streamflow with time. This illustrates the minimum flows of the Quebrada Arenas at the 300-ft (100-m) altitude that can be expected to occur during the dry season. The stream will begin to respond more directly to rainfall during the wet season.

Floodflow

Large floods have occurred in the Maunabo area. Rainfall from hurricane "San Ciriaco" on August 8, 1899, "San Felipe II" on September 13, 1928, and "Donna" on September 6, 1960, caused some of the worst floods ever recorded along the Río Maunabo. Floodwaters from heavy rainfall on December 30, 1936, August 4, 1945, and August 27, 1961 (Corps of Engineers, 1970, p. 17) also resulted in severe property damage in the valley. Other floods in the valley that have caused severe property damage and loss of life occurred in August 1935, September 1957, and October 1970 (Haire, 1971).

The October 5 to 9, 1970, flood is outstanding becasue of the duration, multiple peaks, and extraordinarily large volume of runoff. During the flood, the peak discharge at the inland edge of the alluvium, drainage area 6.8 mi^2 (17.6 km^2), was 7,400 ft^3/s (210 m^3/s). A peak discharge of 4,900 ft^3/s (139 m^3/s) was determined at a site farther downstream in the alluvial valley, drainage area 12.7 mi^2 (32.9 km^2) indicating the attenuation of floodflow produced by temporary storage in the lower valley. The August 1935 flood area (about 3 ft or 1 m higher than the 1970 flood) in the valley is shown in figure 11. Large floods similar to those described could recur in the Maunabo Valley.

Stream Sediment

The capacity of a stream to carry sediment depends on stream velocity, but the actual sediment discharge depends also upon the availability of sediment. The graph in figure 12 shows the suspended-sediment load, in tons per day, related to discharge based on a few samples from gaging stations 50090500 and 50091200. Variations in sediment discharges result from less sediment being available at one time than at another. However, the peak concentration of sediment usually occurs during storm runoff.

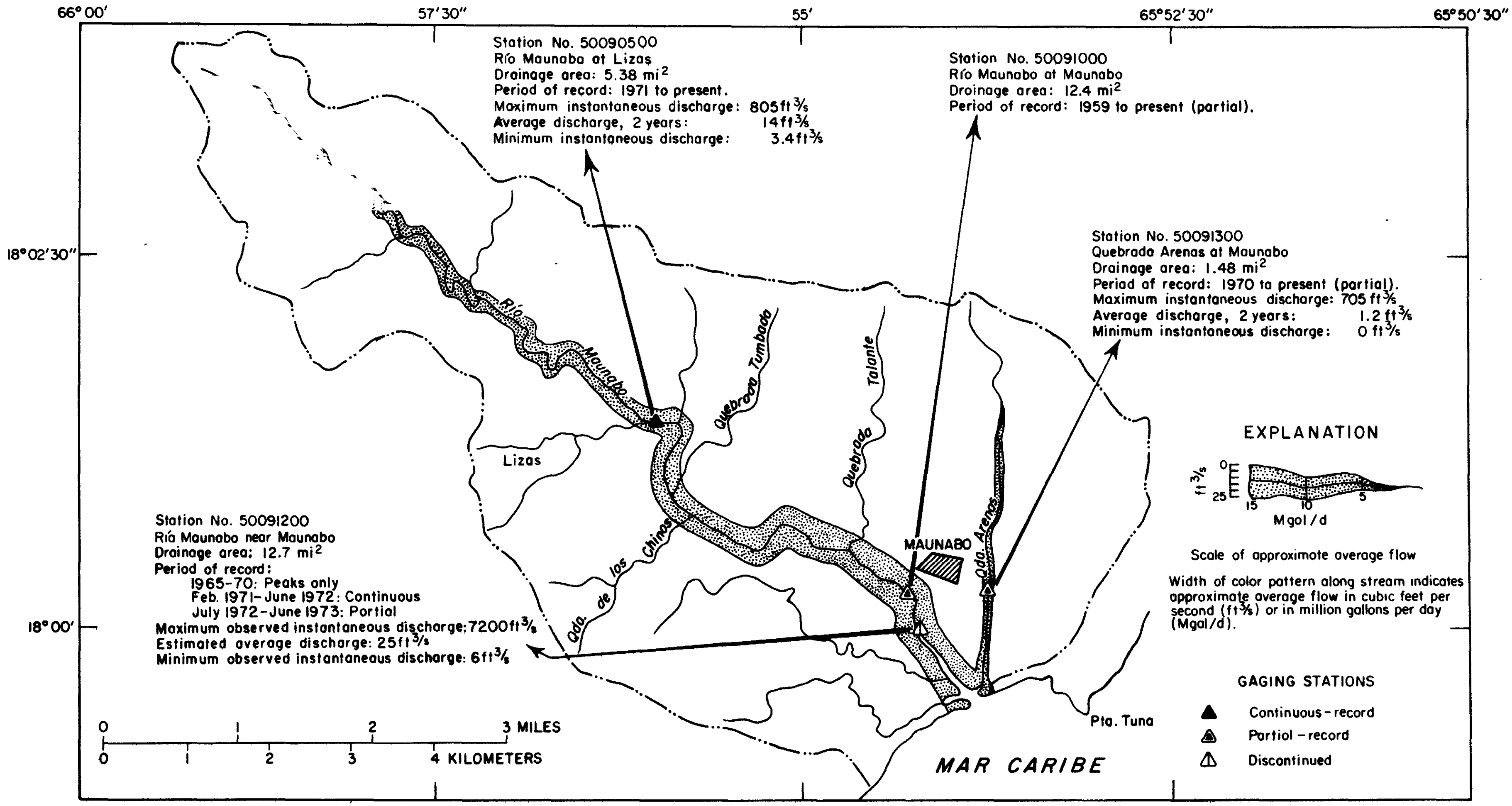

Figure 9.--Streamflow, possible impoundment sites, and gaging station data in the Maunabo basin.

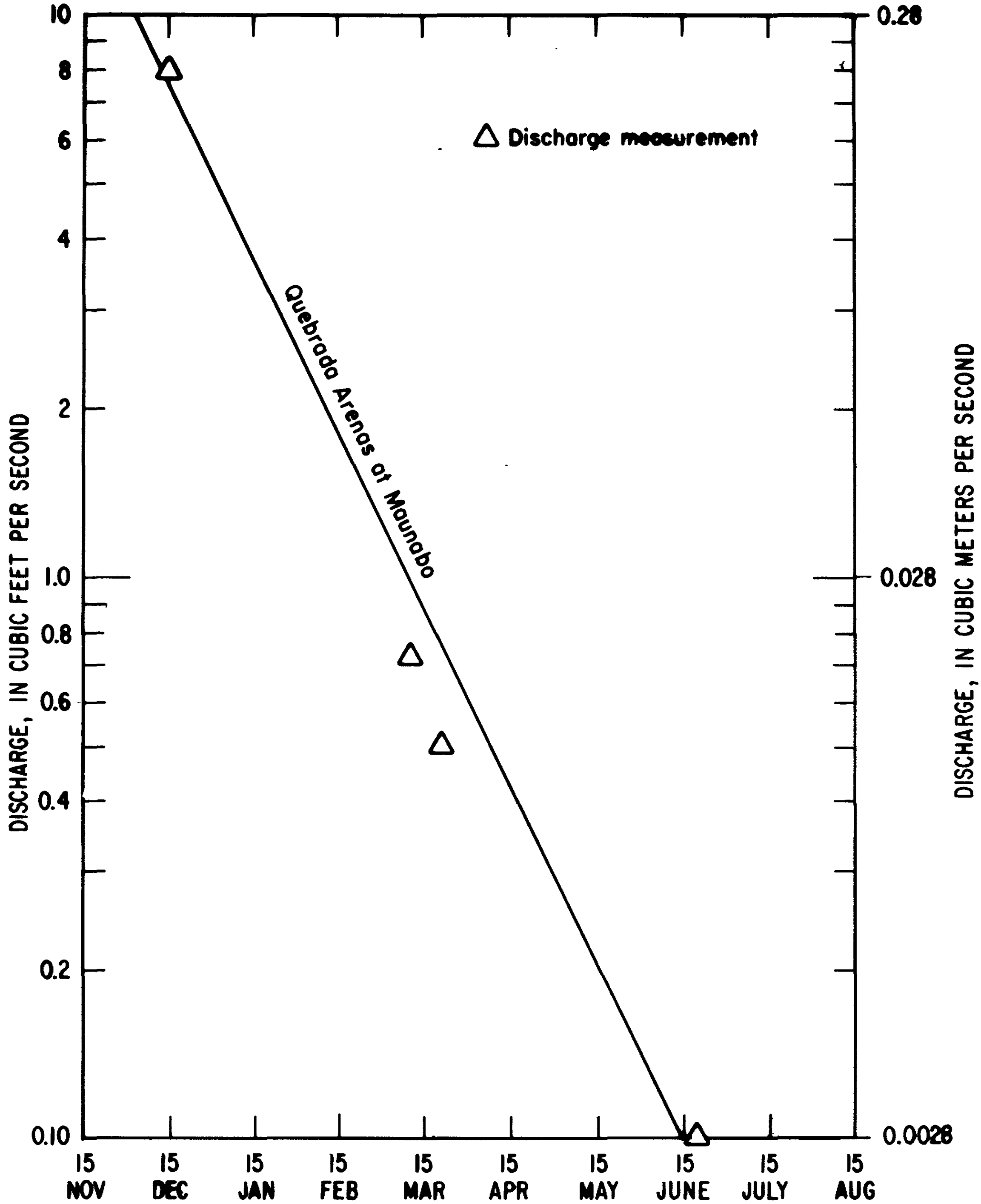

Figure 10.--Base flow of the Quebrada Arenas at the 300-foot (100-meter) altitude in the dry season, 1973.

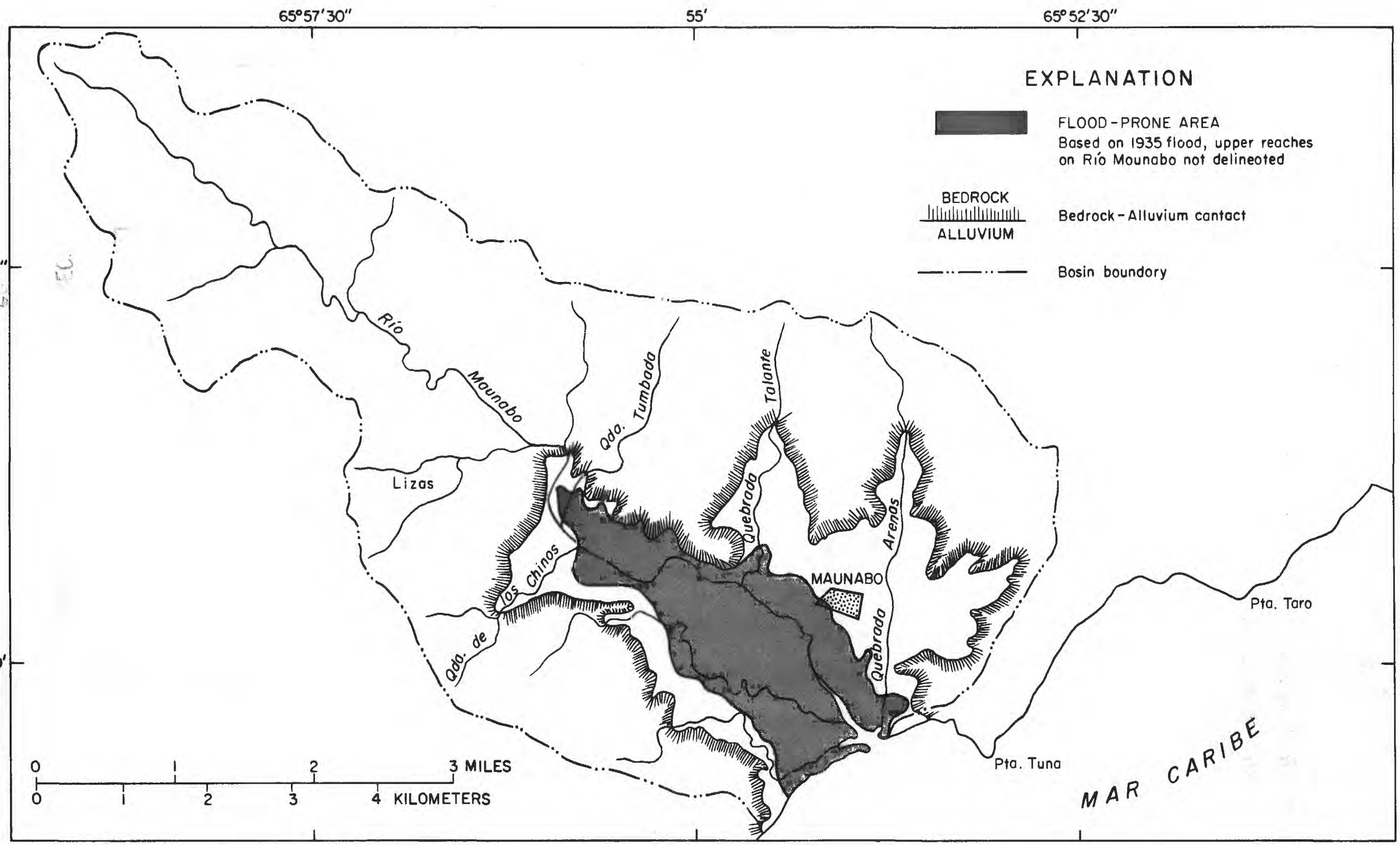

Figure 11.--Flood-prone area along the Río Maunabo.

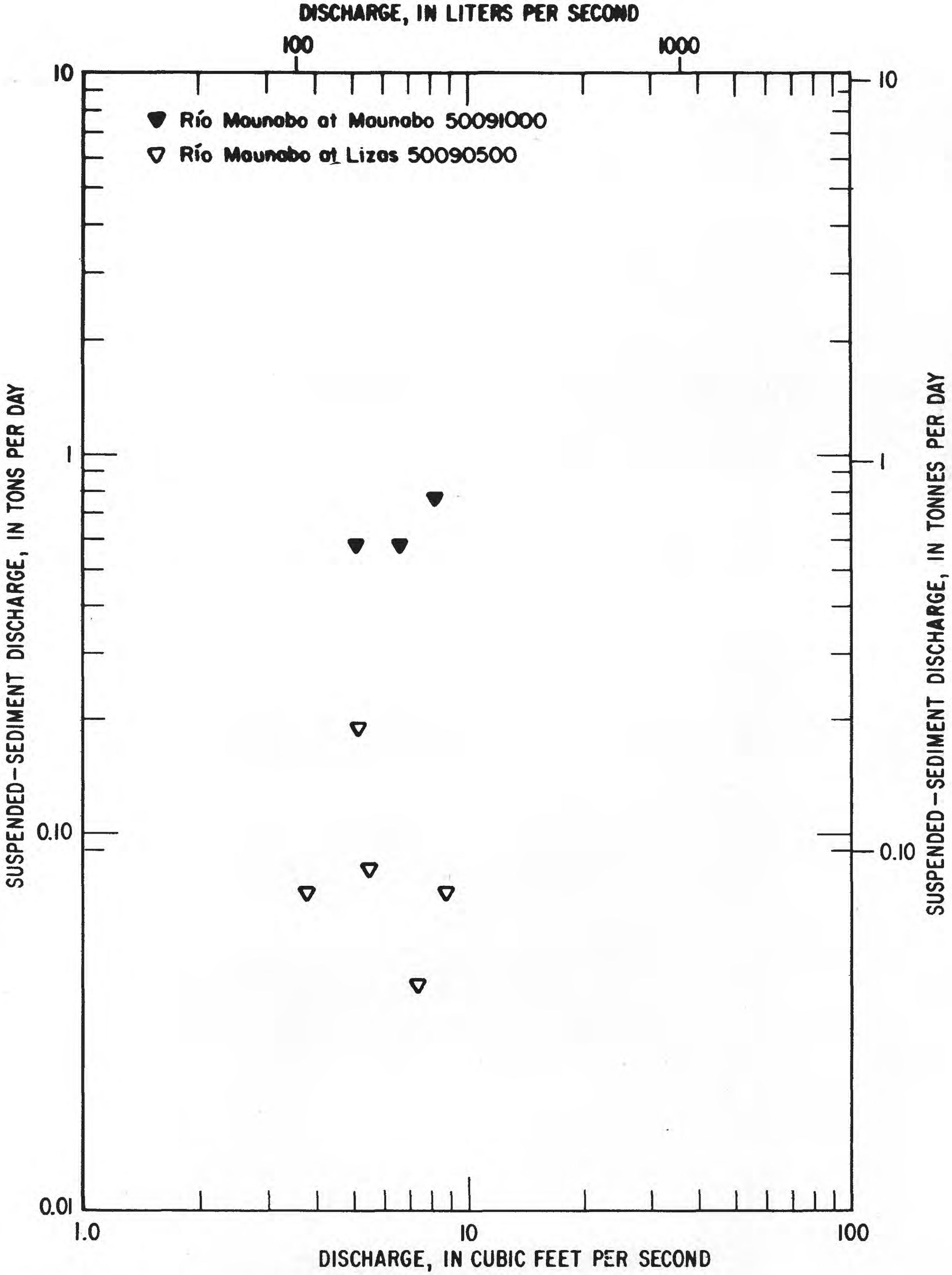

Figure 12.--Suspended stream-sediment load related to stream discharge.

HYDROLOGIC BUDGET

The hydrologic budget of a drainage basin is the balance between water gain, drainage-basin storage, and water loss over a given period of time. The budget, (table 2) which is based on average figures and estimates, presents a representative outline of water gain, storage, and loss for the basin.

The average annual precipitation for the basin is about 65 in (1,650 mm), based on U.S. Weather Service records for the period 1908-73. Precipitation is greatest in the northern part of the basin, more than 76 in (1,930 mm), and least in the southern part with less than 47 in (1,200 mm).

Figure 13 is a representation of the annual water budget. Average annual runoff leaving the basin is 21,800 acre-ft (26.9×10^6 m^3) of which about 9,950 acre-ft (12.3×10^6 m^3) is from ground-water inflow from the alluvial aquifer. This figure was computed from gaging-station records on the Río Maunabo. Ground-water outflow to the sea is that water leaving the basin through the ground-water reservoir. Model analyses suggest that about 610 acre-ft (0.75×10^6 m^3) per year leaves the basin to the sea through the alluvium. Ground-water pumpage from the ground-water reservoir is about 500 acre-ft (0.62×10^6 m^3) per year.

Table 2.--Approximate annual-water budget for the Maunabo basin.

	Volume of water, acre-ft per year	Million gallons per day	Loss, in percent
Water gain:			
Precipitation, 65 inches	63,800	56.9	--
Total gain	63,800	56.9	--
Water loss:			
Surface runoff	21,800	19.5	34.2
Ground-water outflow to sea	610	.5	1.0
Ground-water pumpage	500	.4	.8
Evapotranspiration	40,890	36.5	64.0
Total loss	63,800	56.9	100.0

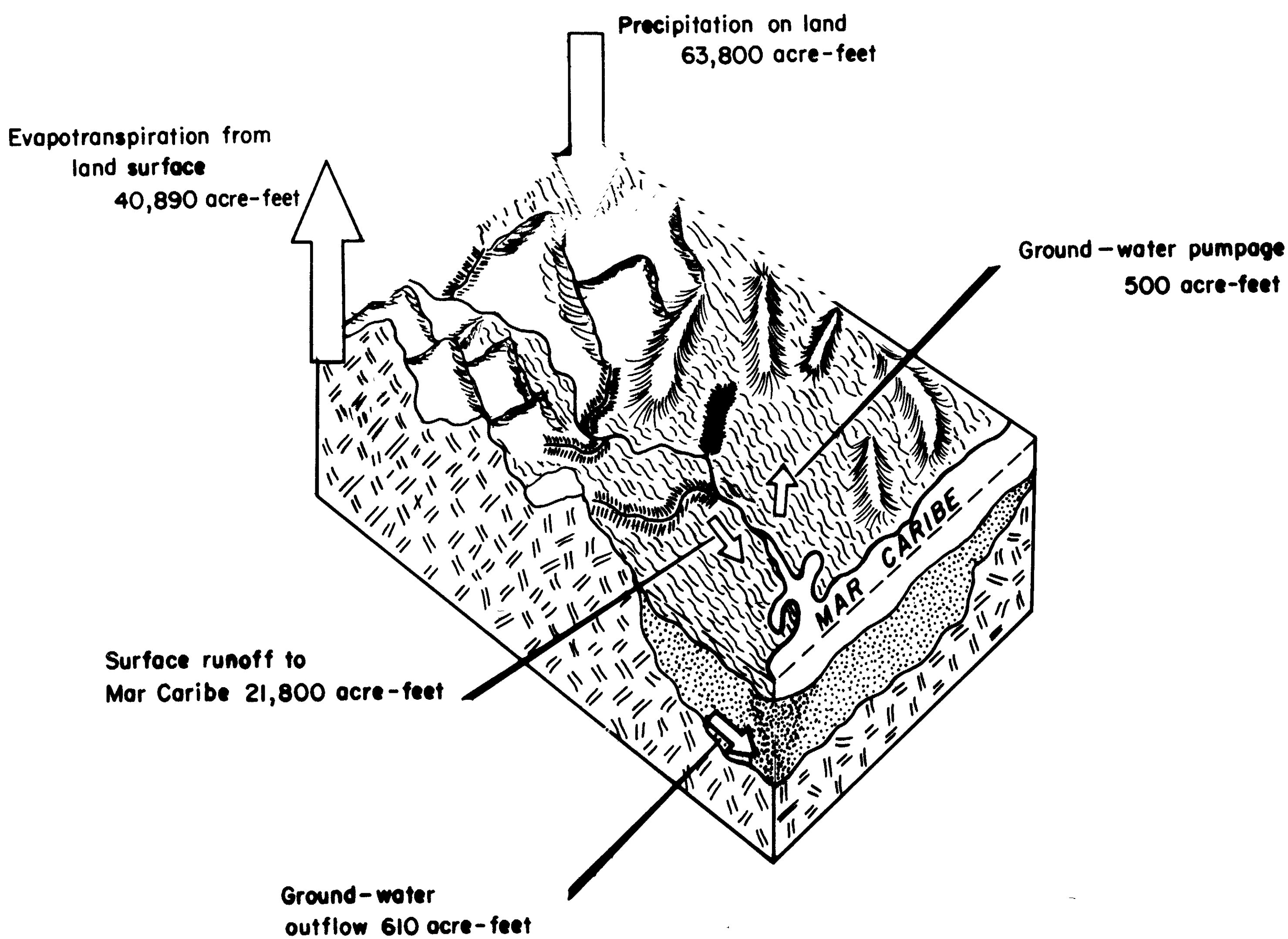

Figure 13.--Approximate annual hydrologic budget, Río Maunabo Valley.

Evapotranspiration is the return of water to the atmosphere by a combination of evaporation from open water, foliage surfaces, and the land surface; and transpiration from plants. Average annual evapotranspiration is estimated to be 40,890 acre-ft (50.4×10^6 m^3), which is the difference between precipitation and the sum of runoff, pumpage, and outflow.

The quantities of these budget items fluctuate from year to year. Outflow remains fairly constant, pumpage and evapotranspiration fluctuate somewhat, but proportionately, precipitation and runoff show the greatest changes.

In the winter of 1974, the alluvial aquifer held an estimated 10,000 acre-ft (12.3×10^6 m^3) of water in recoverable storage. This is based on the assumption that the alluvial aquifer has an average saturated thickness of 80 ft (24 m), has a specific yield of 0.10, is about 2 mi^2 (5 km^2), and occupies a total volume of 100,000 acre-ft (123×10^6 m^3).

QUALITY OF WATER

The suitability of water from a given supply is determined by its chemical and physical properties. These properties, most of which can be measured in the laboratory, are influenced both by natural factors such as climate, geology, and topography and by man's activities such as irrigation, drainage, and waste disposal. The influence of these factors differs with location and may vary with time.

The greater mineralization of the water in the different reaches of the streams is, in part, due to the longer distance that the water has traveled. Water dissolves part of the soluble mineral constituents of rock or other soil particles as it moves through an aquifer or over the land surface. The amount of minerals dissolved depends principally on the concentration and type of soluble materials and the length of time the water is in contact with them.

The greatest future demands for water in the Maunabo area are for public and domestic supply and industrial uses. Therefore, the discussion of water quality in this report is concerned mostly with water for those uses.

When water is evaluated for a particular use, several chemical characteristics must be considered. The quality of water for public supply and domestic use commonly is evaluated in relation to standards of the U.S. Public Health Service (1962) for drinking water, as follows:

Constituent	Recommended concentration, milligrams per liter
Iron (Fe)	0.3
Manganese (Mn)	.05
Sulfate (SO_4)	250
Chloride (Cl)	250
Fluoride (F)	1.5
Nitrate (NO_3)	45
Dissolved solids	500

Most of the water from the alluvium in the upper part of the valley and all of the water from the Río Maunabo and its tributaries does not exceed indicated standards and therefore is satisfactory for drinking purposes.

Hardness in water is caused primarily by ions of calcium and magnesium. No specific standards for hardness have been established, but the following categories have been used in several reports of the U.S. Geological Survey:

Hardness, milligrams per liter	Rating	Suitability
0-60	Soft	Suitable for many uses without softening
61-120	Moderately hard	Usable except in some industrial applications
121-180	Hard	Softening required by laundries and some other industries
181 +	Very hard	Requires softening for many uses

The uses of water by industry are many, and the quality-of-water requirements are highly diverse. Generally, the water from ground and surface supplies in most parts of the basin would be suitable for most industrial uses. A summary of water analyses, grouped by source, is given in table 3.

Ground-Water Quality

The quality of water from aquifers in the basin varies with location, quality, and source of recharge, and in some cases, depth. Water in the southern half of the basin has a relatively high dissolved solid concentration and is moderately hard; whereas, water from the northern half has a relatively low dissolved solid concentration and is soft. The average silica concentrations and the values for pH are similar in the northern and southern halves of the basins.

High concentrations of manganese and iron are present in the water in some wells in the alluvium. Chemical analyses of water from test wells, drilled by the Puerto Rico Aqueduct and Sewer Authority in 1970, showed that the maximum manganese concentration was 0.55 mg/l (milligrams per liter) and iron concentration was 4.2 mg/l. High manganese and iron concentrations are objectionable because they can stain plumbing fixtures and clothes during laundering and clog pipes. Waters with high iron concentrations also have a characteristic taste which some people find unpleasant. The source of the manganese and iron is probably the underlying weathered igneous rock or swamp deposits in the alluvium.

Table 3.--Chemical analyses of selected rivers, wells and springs in the Maunabo basin, 1973 (Results in milligrams per liter, except iron which is in micrograms per liter)

Description	Milligrams per liter														Specific conductance micromhos per centimeter at 25° C)	pH	Temperature °C
	Silica (SiO_2)	Iron +2 and +3	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Non-carbonate			
Rivers, during low flow:																	
Río Maunabo at Lizas	45	--	13	5.7	16	0.9	88	2.4	13	0.2	0.0	139	56	0	183	6.8	31.0
Río Maunabo near Maunabo.	39	--	22	9.9	25	1.7	112	15	32	.3	.5	201	96	4.0	314	7.3	32.5
Quebrada Arenas........	37	0	15	8.1	19	1.4	86	4.9	21	.0	.03	149	71	0	207	--	--
Quebrada Talante	38	10	15	8.0	18	1.5	78	7.4	19	.0	.40	145	70	6.0	205	--	--
Quebrada Tumbada	38	0	20	10	21	1.8	99	10	21	.0	.20	171	91	10	248	--	--
Quebrada Chinos	39	0	18	7.5	16	1.6	90	5.2	15	.0	.61	147	76	2.0	205	--	--
Wells, alluvium:																	
Bordaleza well No. 4.....	5.8	--	20	18	40	6.7	200	10	33	.2	.0	233	124	.0	438	7.5	--
PRASA well No. 5	0.5	--	180	19	140	5.2	40	12	560[a]	.0	.7	908[a]	477	444	1,820	6.9	--
Batey Columbia	38	--	190	16	120	2.4	232	92	360[a]	.5	5.2	918[a]	516	325	1,640	6.9	--
Spring																	
Chorro de la Pica[1]......	44	0.0	12	4.4	18	1.0	77	2.4	15	.2	1.5	136	48	0	196	7.3	22.0

[1] From Bogart, D. B., Arnow, Ted, and Crooks, J. W., 1964; sample collected 02-19-60.

[a] Exceeds U.S. Public Health Service (1962) drinking water standards.

Specific conductance of the water is related to the amounts and kinds of minerals dissolved in the water. The limit recommended by the U.S. Public Health Serive (1962) for dissolved solids in drinking water is 500 mg/l. This corresponds to a specific conductance somewhere between 700 and 900 micromhos per centimeter, depending on the type of ions present.

Analyses of ground water from wells in the alluvium had a specific conductance between 300 and 2,000 micromhos per centimeter at 25°C. The conductance of the water increased from the upper part of the valley to the central-lower part (fig. 14). The higher conductance is probably due to seawater encroachment in the alluvium.

The seawater encroachment in the central-lower part of the valley is due to heavy pumping of public-supply well 17. Before heavy pumping began in 1936, the chloride concentration of the water in this part of the valley ranged from 30 to 40 mg/l. As a result of continuous pumping, the drawdown in the vicinity of the well, and the resulting steep hydraulic gradient toward the well, the chloride concentration of water from the well increased from 340 mg/l in September 1970 to 420 mg/l in August 1972. In September 1974, the chloride concentration was 540 mg/l. As the pumping continued, the seawater encroachment moved farther and farther inland in response to the withdrawal of fresh ground water and the concurrent lowering of ground-water levels.

The chloride concentration of the water withdrawn from wells in the lower part of the valley will increase progressively over the years, under present (1974) pumping conditions. The likelihood of this long-term increase occurring will be greater if additional ground water is withdrawn from well 17 or from nearby wells.

Areas near the sea do not yield water suitable for drinking; however, ground water in most of the upper valley generally is of such quality that it could be used for industrial, public supply, and domestic uses. However, manganese and iron, when present in excessive quantities, may need to be removed.

Surface-Water Quality

Analyses show that the chemical quality of surface water is generally good. Water from the lower reaches of the Río Maunabo is higher in dissolved solids than water from the upper reaches. Dissolved solids of water samples collected from the Río Maunabo ranged from 100 to 30 mg/l at the lower station, and from 30 to 140 mg/l at the upper station. The tributaries contain water similar in quality to the Río Maunabo (figs. 15 and 16). The diagrams in the figures show the analytical patterns in milliequivalents per liter, which are computed by dividing the reported concentration of the individual constituents in milligrams per liter by the equivalent weights. Patterns show general chemical character of water for calcium (Ca), sodium (Na), magnesium (Mg), bicarbonate (HCO_3), chloride (Cl), and sulfate (SO_4). Anions are plotted to the right of the center line and cations to the left. The area of the pattern is an indication of dissolved-solids concentration. Changes in configuration reflect changes in chemical character.

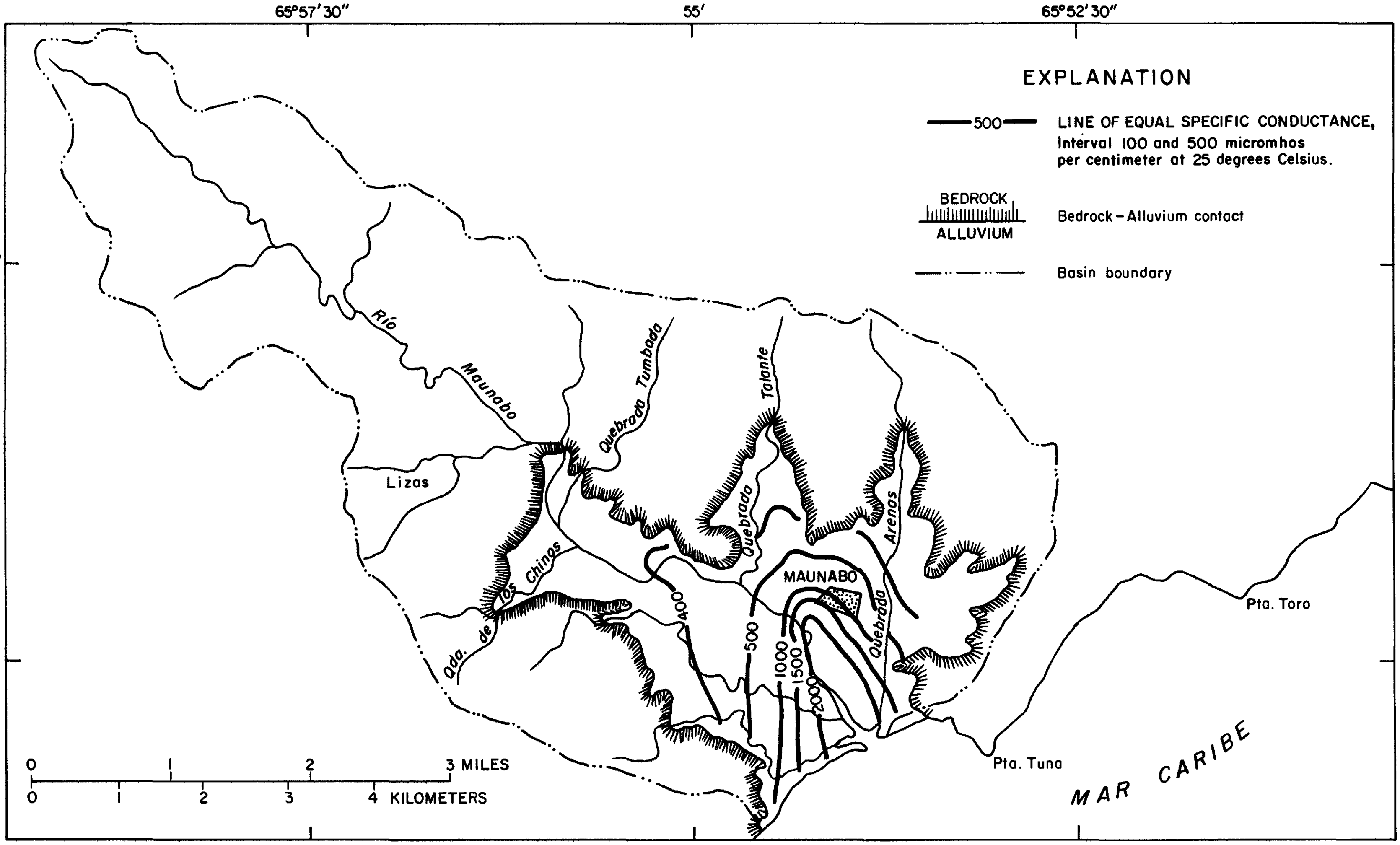

Figure 14.--Specific conductance of water in alluvial aquifer on June 13, 1974.

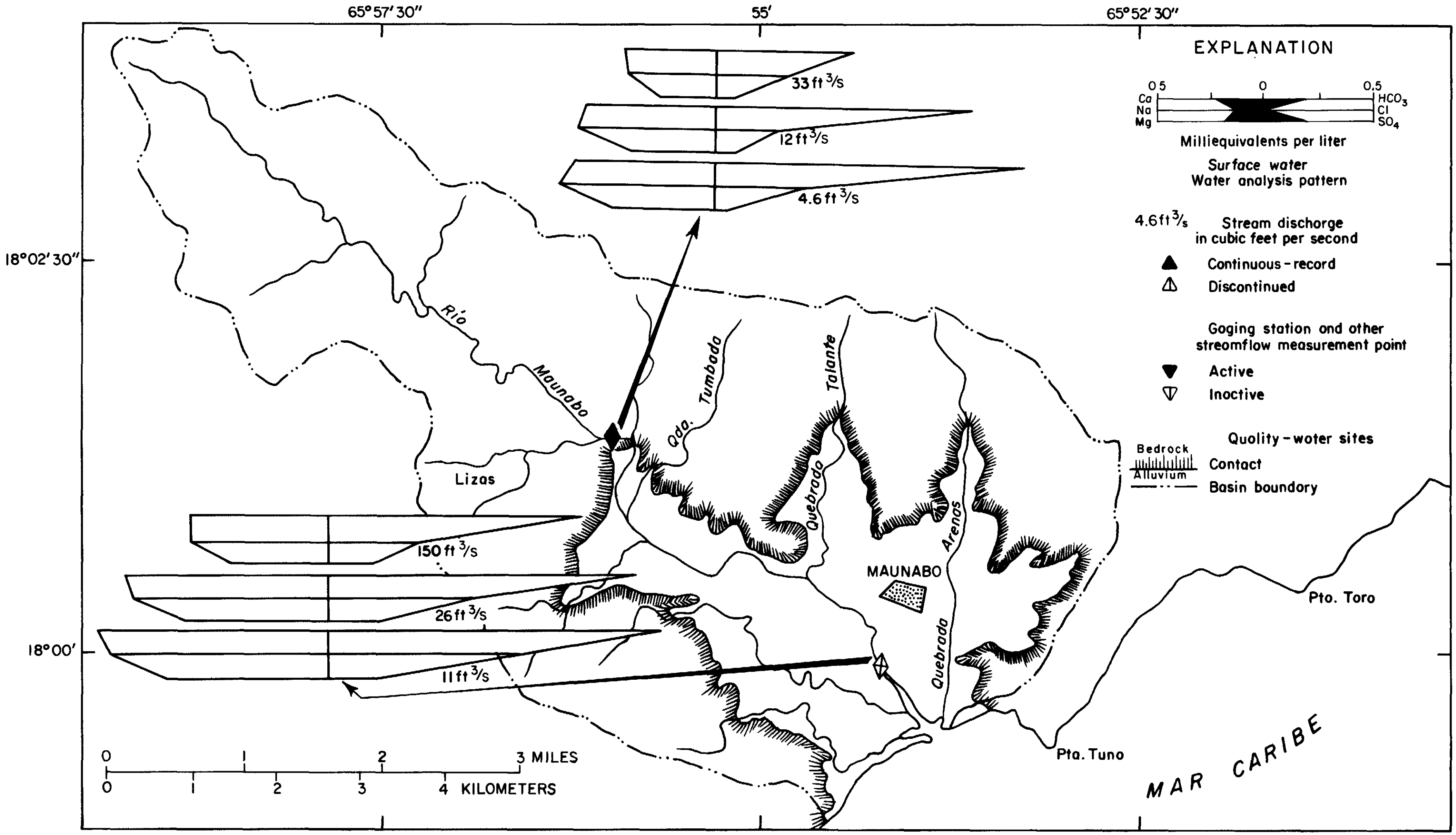

Figure 15.--Water quality in the Río Maunabo.

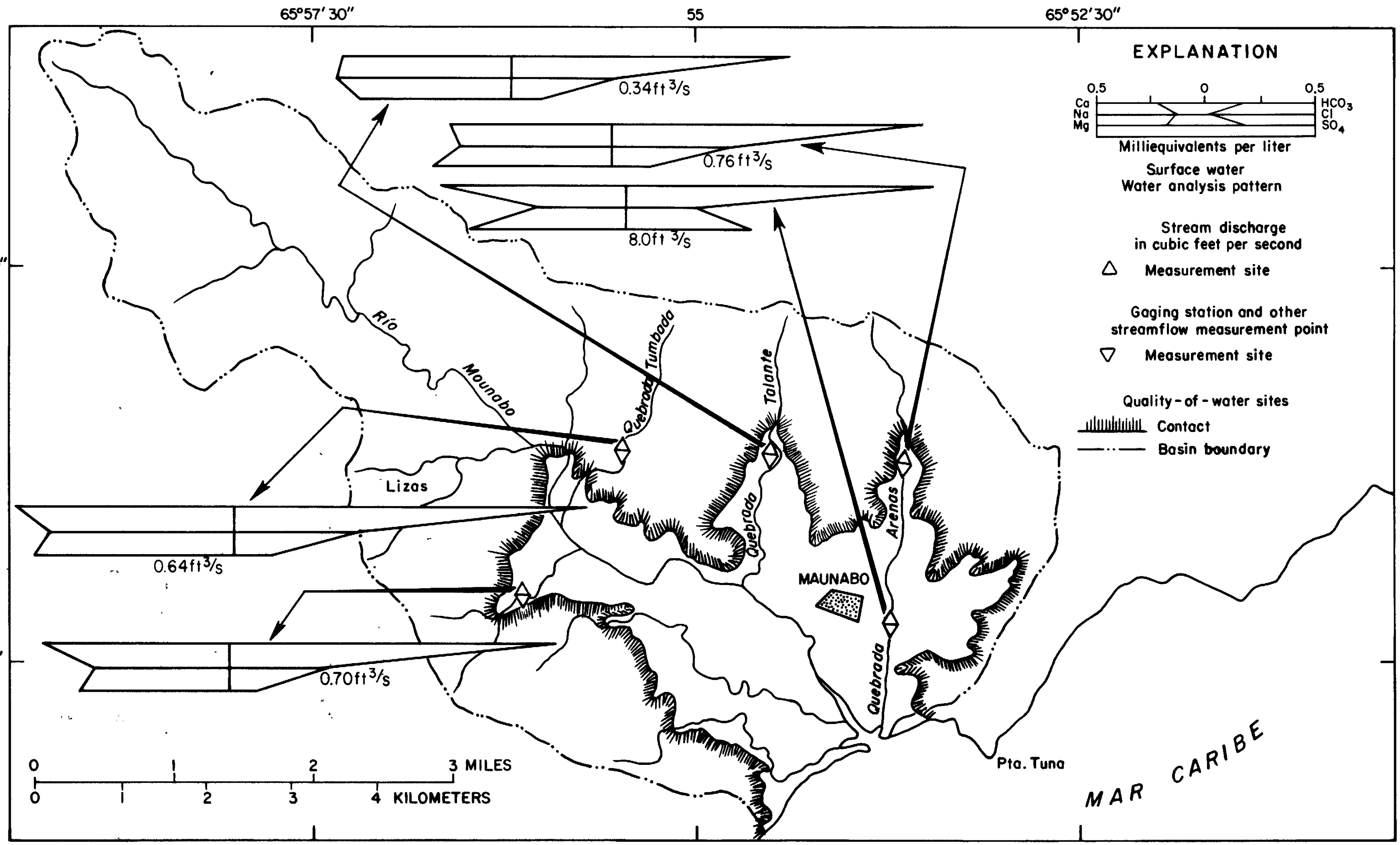

Figure 16.--Water quality in tributaries to the Río Maunabo.

Water quality of streams in the Maunabo basin has been degraded by contamination from partially treated sewage. Fluctuation in the number of fecal coliform and fecal streptococci groups of bacteria from the Río Maunabo and Quebrada Arenas is shown in figure 17.

The ratio between the fecal coliform and streptococci coliform bacteria in samples collected from the site at station 50091000, Río Maunabo near Maunabo, suggests that the contamination is predominantly from sewage effluents (Geldreich, 1969). The station is located below a heavily populated area.

Data from station 50091300, Quebrada Arenas at Maunabo, which is in a sparsely populated rural area, has lower bacterial counts than the lower Río Maunabo station. The bacterial groups are probably due to nonhuman sources. The fecal coliform-to fecal streptococci ratio suggests that the high number of bacteria in December 1972 from the Quebrada Arenas could be from a combination of livestock, poultry wastes, and storm-water runoff.

A DIGITAL MODEL FOR AQUIFER EVALUATION

A digital model of the Maunabo alluvial aquifer was constructed in order to evaluate some alternative schemes for development of future ground-water resources. The digital model solves the nonsteady partial differential equation of ground-water flow (equation 1) for a bounded two-dimensional, one-layer aquifer by finite-difference techniques.

$$\frac{\partial}{\partial x_i}\left[K_{ij}\, b \frac{\partial h}{\partial x_j}\right] = Sy \frac{\partial h}{\partial t} + W(x,y,t) \qquad (1)$$

where i = the index in the x dimension

K_{ij} = the hydraulic conductivity tensor

j = the index in the y dimension

Sy = the specific yield of the aquifer

h = the head in the water-table aquifer

b = the saturated thickness of the aquifer

$W(x,y,t)$ = the source or sink function

t = time.

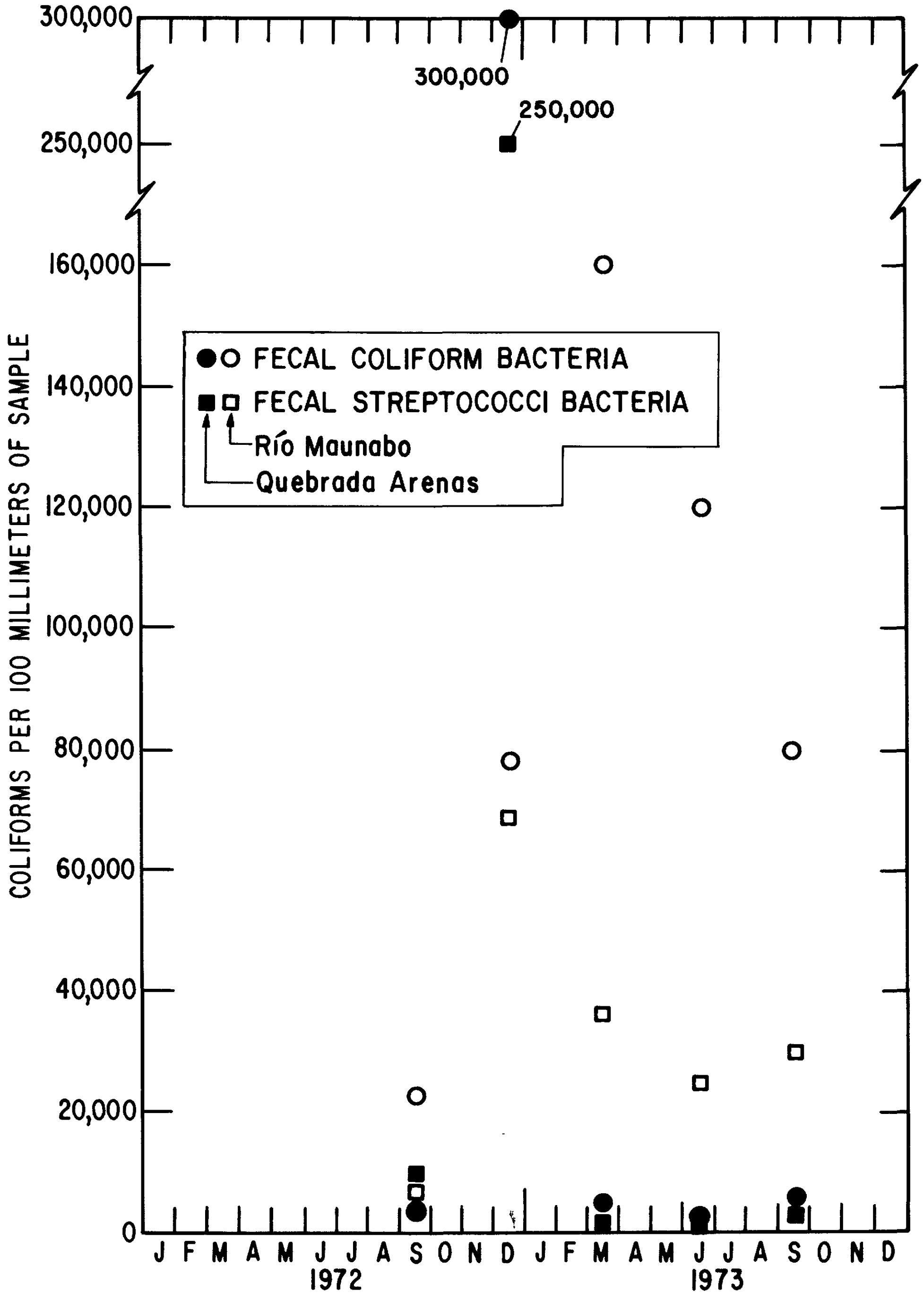

Figure 17.--Fecal coliform bacteria and fecal streptococci bacteria fluctuations from the Río Maunabo and Quebrada Arenas.

The model uses the iterative, alternation-direction implicit (ADI) scheme described by Pinder and Bredehoeft (1968) and revised by Trescott (1973). The grid system (fig. 18) for the model is 37 x 24 nodes and covers an area of 3.5 mi^2 (9.1 km^2) or roughly 20 percent of the basin area. A decision was made to use a uniform grid, because of two primary considerations. First, as described by Trescott (1973), the use of a uniform grid would minimize convergence problems in the ADI method. Second, the locations of well fields, which will be used for future water development, were spread over much of the aquifer with no specific area of the model necessitating superior definition. Approximately two-thirds of the 888 model nodes have hydraulic conductivities greater than zero.

Input to the model consists of hydrologic parameters in the form of matrices and constants. Each node is assigned an initial head, hydraulic conductivity, depth to bedrock, land-surface elevation, and recharge value. The recharge values on the perimeter nodes simulate inflow from the weathered bedrock outside the limits of the model aquifer. The outermost nodes are assigned zero conductivity and act as a no-flow boundary. The nodes representing the sea boundary are assigned constant heads and are treated as having infinite storage. In order to simulate discharge to (or infiltration from) the streams overlying the alluvial aquifer it was necessary to assign a vertical hydraulic conductance to the bed beneath the streams. The vertical hydraulic conductivity of the bed was provided by an additional parameter matrix. It was necessary to adjust this rate to simulate the true streambed area represented by one node.

Evapotranspiration loss from the water table or capillary fringe is primarily a function of depth to water from the land surface. This is an important factor as part of the evapotranspiration loss to water depth functions are exponential. The digital model requires a linear function, specified by a maximum loss depth and a minimum loss depth. Maximum loss would occur with the water table at the land surface and is comparable to pan evaporation. A pan evaporation of 0.156 in (3.96 mm) per day was estimated from a similar study by Giusti and Bennett (1976). Examination of the data of Gardner and Fireman (1958) indicated there is little change in the evapotranspiration rate when the water declines to 6 ft (2 m) below land surface. By using 6 ft (2 m) as the zero evapotranspiration-loss depth, a water recovery of 0.026 (in/d)/ft [(2.2 mm/d)m] of drawdown is indicated. The maximum recovery for the alluvial aquifer was computed to be 6.2 Mgal/d (23,000 m^3/d). Verification of the digital model was based on steady-state and transient performance of the model. A water-level profile map for June 1974 (fig. 4) was used in the stready-state simulation. Minor adjustments were made to the hydraulic conductivity and recharge matrices until the simulated water levels showed no significant deviations from the 1974 map. The error criteria or the closure value for the steady-state simulation was 0.01 ft (0.003 m).

In late 1974, a 3-month period of heavy rainfall affected the ground-water levels throughout the aquifer. When an equivalent amount of recharge was induced on the model, similar changes in head were recorded for the same time period. This provided a satisfactory transient verification of the model.

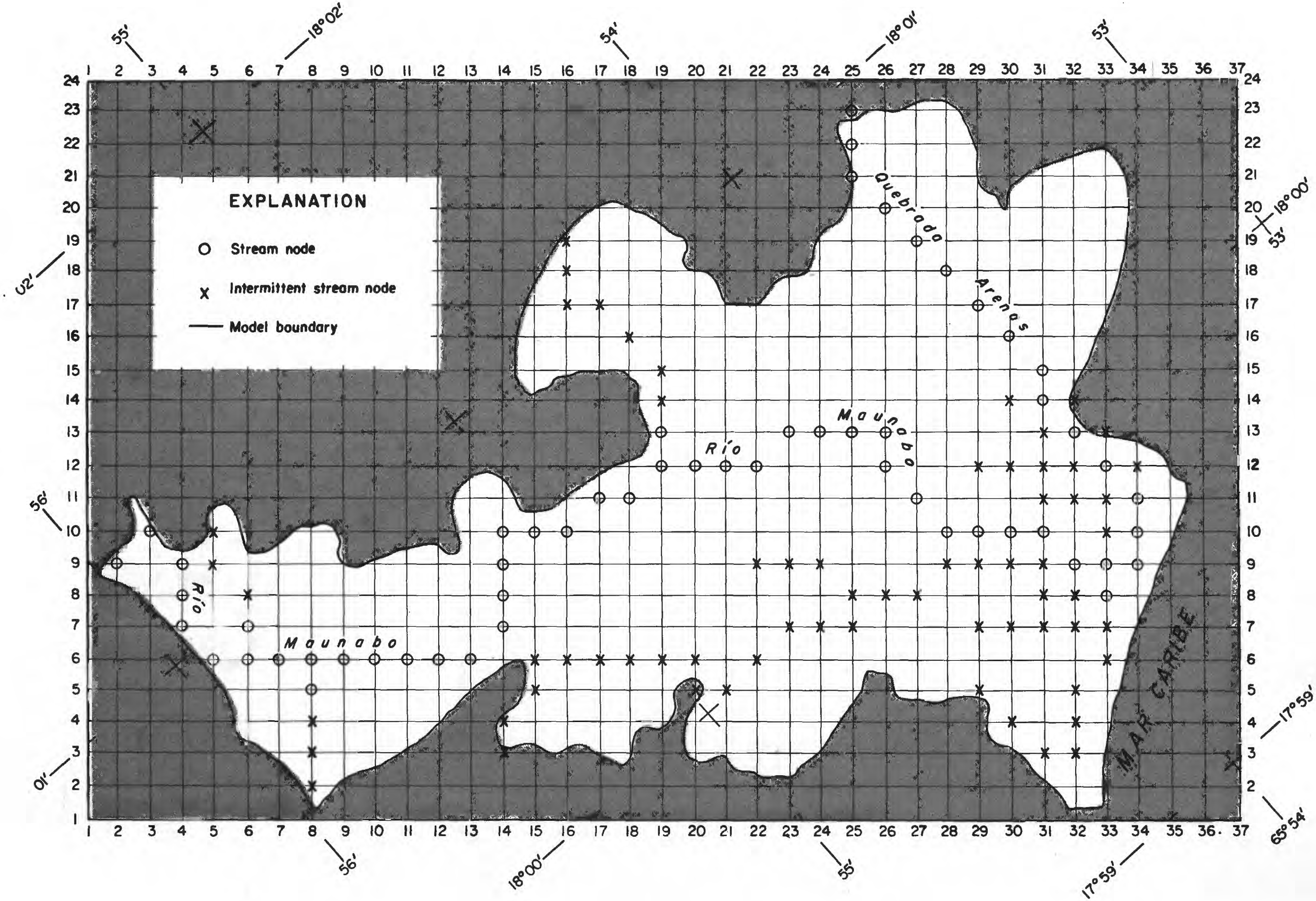

Figure 18.--Stream nodes on grid system of alluvial aquifer.

A new stress, simulated pumping, was then applied to the model in order to evaluate the yield of the aquifer. Intuition suggested a site in the upper part of the alluvial valley where the possibility of induced infiltration from the Río Maunabo existed, where inflow from the weathered bedrock was great, and where the saturated thickness was greatest. After varying both the locations and yields of three test wells, it was estimated that 2.0 Mgal/d or 8,000 m^3/d would be an optimum sustained yield from this section of the aquifer under present conditions.

The model is now available as a predictive tool to evaluate future plans for developing the alluvial aquifer. Whenever additional hydrologic data are made available, the model can easily be refined and additional simulations run. Caution must be exercised in evaluating long-term projections as the longer the simulation the more it is subject to error.

SUMMARY AND CONCLUSIONS

The Río Maunabo drainage basin consists of an area of 18.5 mi^2 (47.9 km^2) in southeastern Puerto Rico. The basin includes a 3.5-mi^2 (9.1-km^2) alluvial plain surraounded by hills of metavolcanic and igneous intrusive rocks. Nearly all of the basin is underlain by dioritic and granodioritic rock of the San Lorenzo batholith. Annual rainfall averages about 65 inches over the basin and annual evapotranspiration is estimated to average 41 inches. Surface runoff, ground-water outflow to the sea, and ground-water pumpage account for the other 24 inches of the annual rainfall.

Although no test wells have been drilled in the bedrock aquifer of the valley during the study, yields of 5 to as much as 50 gal/min (1 to 3 l/s) are obtained in the basin from wells 50 to 150 ft (15 to 46 m) in depth. The yield of wells in the alluvium ranges from 20 to 1,500 gal/min (1.3 to 38 l/s). Drilling logs show that the greatest depth of alluvium penetrated is 163 ft (50 m); however, the deposits are estimated to be as much as 200 ft (60 m) thick.

The average annual flow of the Río Maunabo is 10,000 acre-ft (12.3×10^6 m^3) near the upper edge of the alluvial valley and is 21,800 acre-ft (26.9×10^6 m^3) near the confluence with the Caribbean Sea. The Río Maunabo receives nearly 50 percent of the river flow from the alluvial aquifer.

Ground water, free from high-chloride concentration, will continue to meet the municipal and agricultural needs of the immediate future if the present wells are not overpumped. However, if the valley is to undergo considerable development the water needs would have to be supplemented by the construction of surface-water control structures in the upper reaches of the Río Maunabo and by additional wells in the upper part of the alluvial valley.

Two proposed impoundment sites above Lizas have a combined capacity of 8,970 acre-ft. A storage analysis based on the above reservoir capacity indicates that 1,150 acre-ft (1.43×10^6 m^3) per month could be supplied at Lizas.

In order to develop the ground-water resources to their maximum potential in the upper part of the alluvial valley, additional wells could be located along the west side of the river. The amount of water that could be pumped continuously from these wells would depend upon the hydrologic properties of the aquifer. A series of test holes drilled in the area would indicate where the aquifer has the greatest thickness, permeability, and areal extent. Data from test holes and existing wells indicate that the sustained yield from the aquifer would be about 200 to 500 gal/min (13 to 32 l/s) per well.

Based on an analysis of data from a digital model, which was constructed in order to evaluate some alternative developmental schemes of the alluvial aquifer, it is estimated that 2.0 Mgal/d (8,000 m^3/d) would be an optimum sustained yield from the aquifer in the upper part of the valley under present conditions. The model is available now as a predictive tool to evaluate future developmental plans for the alluvial aquifer.

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