Water—Resources Bulletin 8

WATER RESOURCES OF THE JUANA DIAZ AREA, PUERTO RICO

A Preliminary Appraisal, 1966

UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
COMMONWEALTH OF PUERTO RICO

Water-Resources Bulletins

1 WATER PROBLEMS OF PUERTO RICO AND A PROGRAM OF WATER-RESOURCES INVESTIGATIONS, by D. B. Bogart, T. Arnow, and J. W. Crooks, 1960.

2 PUBLIC WATER SUPPLIES IN PUERTO RICO, by Ted Arnow and James W. Crooks, 1960.

3 WATER WELLS IN PUERTO RICO, by P. E. Ward and L. S. Truxes, 1964.

4 WATER RESOURCES OF PUERTO RICO, A Progress Report, by Dean B. Bogart, Ted Arnow, and James W. Crooks, 1964.

5 WATER RESOURCES OF THE GUAYANILLA-YAUCO AREA, PUERTO RICO, by James W. Crooks, I. G. Grossman, and Dean B. Bogart, 1968.

6 WATER RESOURCES OF THE GUANICA AREA, PUERTO RICO, A Preliminary Appraisal 1963, by Neal E. McClymonds, 1967.

7 WATER RESOURCES OF TALLABOA VALLEY, PUERTO RICO, by I. G. Grossman, Dean B. Bogart, James W. Crooks, and José R. Díaz, 1968. [In press]

Other Publications of the Water-Resources Investigation

FLOODS OF SEPTEMBER 6, 1960, IN EASTERN PUERTO RICO, by Harry H. Barnes, Jr., and Dean B. Bogart, 1961, U.S. Geological Survey Circular 451.

HYDROGEOLOGIC MAP OF PUERTO RICO AND ADJACENT ISLANDS, by Reginald P. Briggs and J. P. Akers, 1965, U.S. Geological Survey Hydrologic Investigations Atlas HA-197.

RECONNAISSANCE OF THE WATER RESOURCES OF THE CENTRAL GUANAJIBO VALLEY, by Robert B. Anders, 1968, U.S. Geological Survey open-file report.

WATER RECORDS OF PUERTO RICO, 1958-63, by Frank P. Kipple and others, 1968.

WATER RECORDS OF PUERTO RICO, 1964-67, by James G. Rickher and others, 1970. [In press]

COVER PICTURE.--Northeastward across coastal plain to foothills near Juana Díaz and Cordillera Central from Arús; Río Jacaguas in lower right forground. Photo by Miguel A. Fernández, P.R. Water Resources Authority.

Commonwealth of Puerto Rico

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WATER RESOURCES OF THE JUANA DIAZ AREA, PUERTO RICO

A Preliminary Appraisal, 1966

by
Ennio V. Giusti
U.S. Geological Survey

Prepared by the United States Geological Survey
in cooperation with

Puerto Rico Aqueduct & Sewer Authority
Puerto Rico Water Resources Authority
Puerto Rico Industrial Development Company

1968

RESUME

1. The Juana Díaz area of this report is the drainage area of Ríos Jacaguas, Cañas, and Descalabrado, a total of 100 square miles of land of which 80 is mountains, hills, and river valleys and 20 is flat coastal plain. The water resources of this area were studied during 1966, a moderately dry year, the like of which happens about once every 3 years.

2. The riverflow from the mountains was 19,000 acre-feet. Within the sands and gravels of the coastal plain, 3,000 acre-feet of riverflow infiltrated into the ground and helped to recharge the ground water. Riverflow to the sea was 22,000 acre-feet.

3. Within the coastal plain, wells pumped out 34,000 acre-feet of ground water, resulting in a decline of water levels during the dry season to mid-September when water levels were at their lowest. In the ensuing rainy season, water levels recovered, and by the end of November they were as high as in January.

4. A conservative estimate of the ground-water potential is that another 14,000 acre-feet could have been pumped out in 1966. The most favorable area for further development of ground water is along Río Jacaguas from just south of the cemetery of the town of Juana Díaz to Highway 1. Water for domestic use and up to about 25 gallons per minute can be obtained almost anywhere in the coastal plain.

5. Most of the water is of good quality. Water of poor quality comes from wells drilled in the rocks of a geologic formation named the Juana Díaz. Along Río Jacaguas south of Highway 1, ground-water levels were dangerously low in 1966, and one well pumped salty water. Along Río Descalabrado, though water levels were low, no salty water was pumped.

6. Riverflow that goes into the sea could be stored. The proposed Toa Vaca dam would decrease the loss of water from large floods and eliminate nearly all loss from minor floods. Earth dams of a smaller size also can be placed within the entrenched channels of Ríos Descalabrado and Cañas to provide a modest quantity of water (on the order of 2,000 acre-feet) for the irrigation of the upper terraces now used for pasture.

7. The Juana Díaz area has sufficient water to meet its present (1966) needs most of the time. Serious shortages can occur during droughts, especially if they are consecutive for 2 or 3 years. Records of rainfall show that this has happened, although the severity of the droughts can't be judged because water needs in the past undoubtedly were less than now.

NOTES ON THE REPORT

This report is an areal study of a portion of the south coast of Puerto Rico. It follows similar studies of the Guánica, Guayanilla-Yauco, Tallaboa Valley, and Ponce areas to the west and the Jobos area to the east. It basically is an inventory of the water resources during one year. To this extent it carries no long-term information; however, as rainfall data is available for 50 years or so at some sites within the study area, we can make a qualitative estimate of the water resources under more extreme conditions. The purpose of this report, then, is to evaluate the gross hydrologic features of the area for the future management of the water resources.

Many people helped us in carrying out the investigation. We would like therefore to acknowledge, above all, the assistance of Héctor Colón, who installed and maintained most of the recording stations and collected and computed most of the data; the cooperation of the agencies of the Commonwealth and Federal Governments which provided valuable water data; the helpfulness of the agricultural companies which allowed access to their canefields to gather information from their wells; and the many others who helped.

<u>Cooperation</u>

The study was made possible by the continuing cooperative agreement between the Commonwealth of Puerto Rico and the United States Geological Survey to conduct water-resources investigations, based on essentially equal amounts of funds contributed by the two principal parties. Commonwealth contributions came from these agencies:

Puerto Rico Legislative Assembly
Puerto Rico Water Resources Authority (PRWRA)
Puerto Rico Aqueduct & Sewer Authority (PRASA)
Puerto Rico Industrial Development Company (PRIDCO)

<u>Additional Information Available</u>

Although numerous data were used to arrive at the evaluations made in the report, all the data were not included in the report. Those who need additional information should contact:

Water Resources Division
U.S. Geological Survey
San Juan, Puerto Rico

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A PRELIMINARY APPRAISAL, 1966

DESCRIPTION OF THE AREA

The area studied lies on the south coast of Puerto Rico, and we refer to it as the Juana Díaz area, after the largest town and municipality within the boundaries of the study area. Figure 1 shows its location, and its relation to other areas of the south coast investigated by the U.S. Geological Survey.

Because there are many factors that influence hydrology we will take up each one of them briefly, and as they apply to the area.

The Land

The Juana Díaz area, a total of about 100 square miles, comprises three river basins which drain into the sea. The divides between the river basins are well defined in the mountains and hills. In the coastal plain, the borders of the basins cannot be readily located on the topographic maps or on the ground.

The area can be subdivided according to river drainage, as follows:

Name of area	Drainage area, square miles
Río Cañas at mouth	6.6
Río Descalabrado at mouth	17.7
Río Jacaguas at mouth	59.4
Coastal area between Ríos Jacaguas and Cañas	11.0
Coastal area between Ríos Cañas and Descalabrado	6.4
Total area	101.1

The streams have been tabulated in order of increasing drainage area because commonly the amount of water flowing in a stream correlates with its drainage area.

A second factor that considerably influences the runoff from an area is the land slope, which is closely related to

Figure 1.--Location of Juana Díaz area and of nearby areas studied by the U.S. Geological Survey.

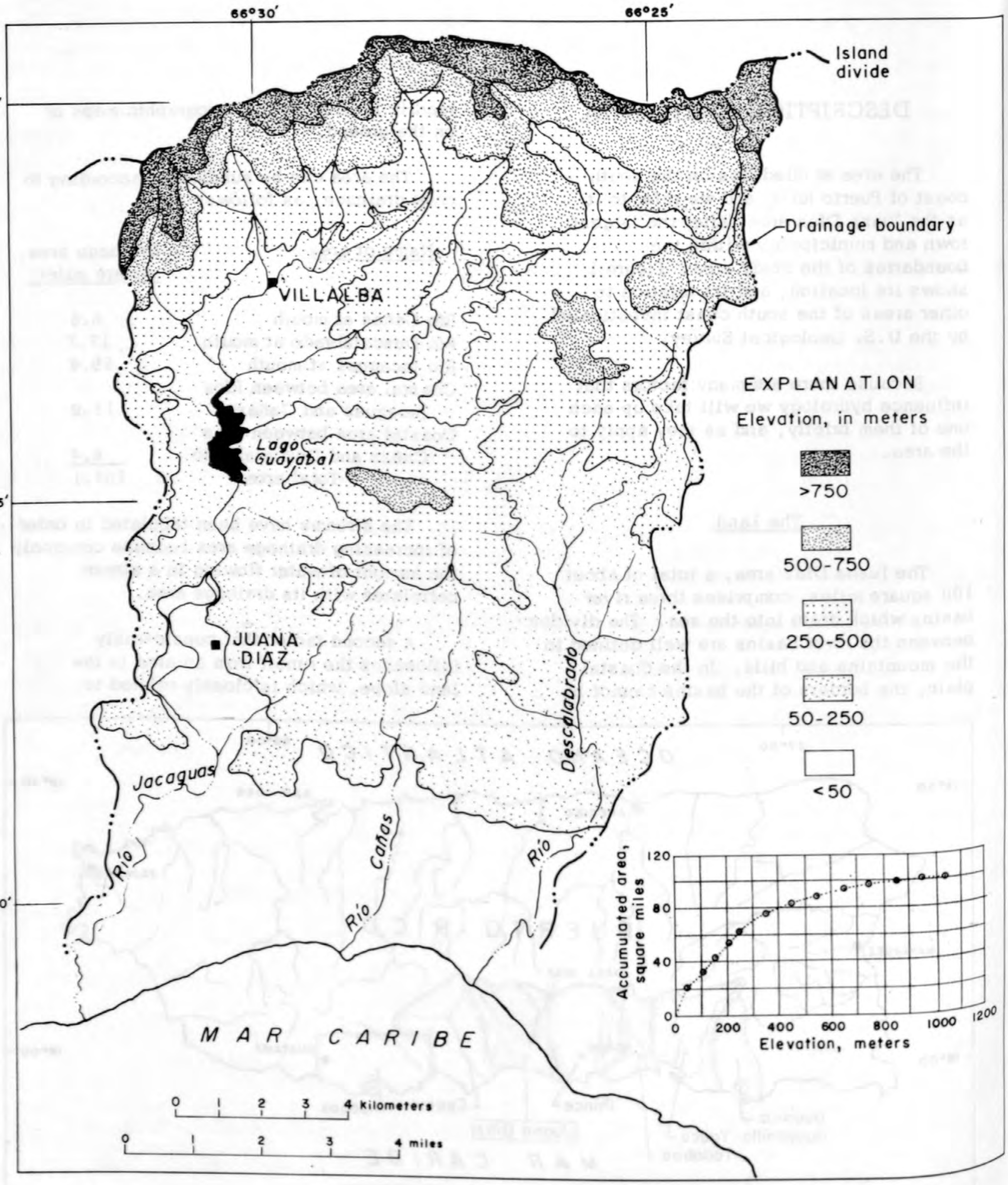

Figure 2.--Distribution of area by elevation.

the relief of the land. The distribution of the relief in the Juana Díaz area is shown in figure 2. Nearly 20 percent of the area, or about 20 square miles, lies at an elevation of less than 50 meters above mean sea level and slopes gently to the sea; it constitutes the coastal plain. The remaining 80 percent, occupied by river valleys, foothills, and mountains, is associated with steeper slopes.

The velocity with which water moves over the land or within a channel is governed in large part by slope. The implication of this, as it affects the runoff of the area, is that rain falling in the mountains soon reaches stream channels because of steep slopes. Once in the channel, water moves downstream with a velocity proportional to the square root of the channel slope.

As shown in the section on climate, rainfall in the Juana Díaz area is predominantly controlled by the mountains. We thus can expect more runoff per unit of area at the higher elevations and, because of steeper slopes, more rapid concentration of flow. The mountainous portions of the rivers then are characterized by flash floods. In the alluvial portion of the streams more-prolonged flooding may take place.

Given suitable soils, underlying geology, enough water to exceed soil-moisture requirements, and time, water also percolates into the ground, contributing to ground-water storage. Hence where the land is horizontal or gently sloping, we can expect to find ground water. This condition occurs in the coastal plain.

Geology

In this report we are mainly concerned with those aspects of geology that contribute to the quantity and the quality of water. Figure 29 (in the pocket at the back of this report), adapted from the hydrogeologic map of Puerto Rico by Briggs and Akers (in Bogart 1964), indicates the general distribution of the rock formations found in the area. Cretaceous volcanic rocks predominate in the upper basins of Ríos Jacaguas and Descalabrado. Tertiary volcanics and limestones predominate in the upper Río Cañas basin and in the middle basins of Ríos Jacaguas and Descalabrado. The lower basins of all three streams are made up of coastal-plain alluvium. Complex faulting occurs within the Cretaceous rocks in the mountains and within the Tertiary belt.

The hydrologic importance of the geology is preeminent during dry periods when water is derived from underground storage and supplies streamflow. Within this context, the volcanic rocks can be considered impervious, except locally where faulting and fracturing can contribute to underground storage. Streams flowing within the volcanic rocks can be expected to show little base flow per unit drainage area. The belt of Tertiary volcanics, because of its extensive faulting and fracturing, and the presence of scattered pockets of limestone, can be considered semi-impervious. But because of steep slopes, it is not recharged to saturation by rainfall and streams make little contribution to ground-water storage during floods.

The Juana Díaz siltstones and the Ponce Limestone are of such limited extent that they have little influence on the overall hydrology of the area. However, the Juana Díaz Formation, being of marine origin and of low permeability, retains some of the original salinity acquired at the time of deposition so that its ground water is invariably salty. Also of limited extent, but locally important for agriculture, are the upper terraces. These are nearly flat pieces of land deeply entrenched by the major rivers (the larger the river, the more extensive are the terraces). They are composed of riverborne alluvium but are generally poor suppliers of ground water. Finally, the coastal-plain sediments are relatively pervious, and the plain is the only part of the area where ground water can be found in abundance. Streams flowing through the coastal plain lose water to the alluvium and contribute effectively to its recharge.

Flat slopes of the streams in the coastal plain aid this recharge because they slow down the travel time of the flood and increase the time for percolation. Except for the coastal plain, the slope of the land is more decisive than its geology in determining how much recharge occurs during periods of rainfall; and is far more important in determining the flood-flow characteristics of the streams.

Climate

Climate affects the water resources more than any other factor; indeed, one is part of the other.

The Juana Díaz area at various times of the year has the aspect of semiarid land. Gone is the exuberant vegetation, and only meandering strips of green traverse an otherwise drab, yellowish-brown landscape. The effect of mountains--their elevation and orientation--is responsible for this. Moisture-laden air masses are brought to the Island by the northeast trade winds. Because the Puerto Rican mountain chain runs east and west, and because air masses release most rain on the windward side of the mountains, the northern slope and the higher elevations receive most of the rain. The southern slope is screened off and receives only a fraction of it.

The effect of mountains on the rainfall distribution in the Juana Díaz area is shown in figure 3. Rainfall increases with elevation but apparently not in direct proportion; an average of 30 inches falls at sea level, 60 inches at around 450 feet (130 meters), 90 inches at about 1,800 feet (550 meters).

The variability of rainfall with elevation occurs not only on a yearly basis; it persists in the monthly rainfall as well, as is shown in figure 4. The same figure also shows that throughout the area there is a seasonal variation in the rainfall: January, February, and March constitute the dry season; April and May mark the first wet period, followed by a rainfall recession in June and July; August, September, and October are the rainiest season; and November begins the pluvial recession into the dry season.

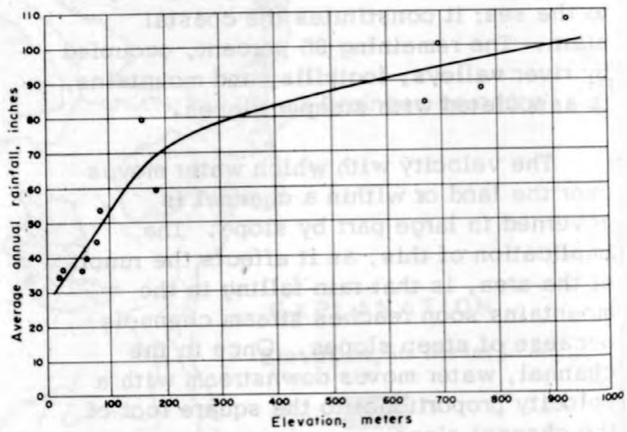

Figure 3.--Effect of elevation on rainfall.

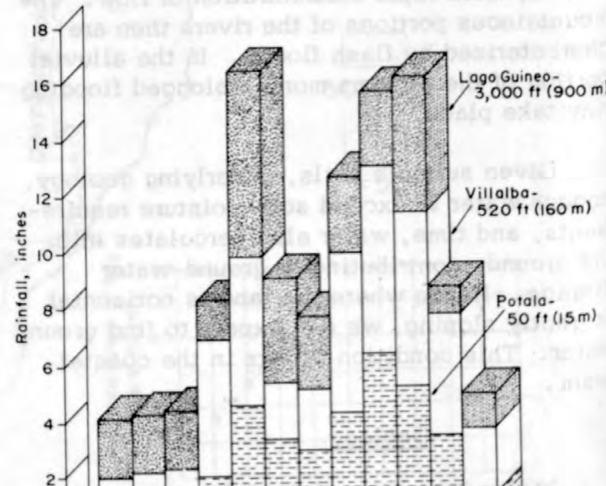

Figure 4.--Rainfall varies during the year and with elevation. (See fig. 7 for location of rainfall stations. Data from U.S. Weather Bureau.)

Temperature of the air shows less variation throughout the year--about 5°F difference between the hottest and coolest months--and a year-long difference of about 12°F between the coastal plain and the highest elevations (see figure 5). Temperature is related to

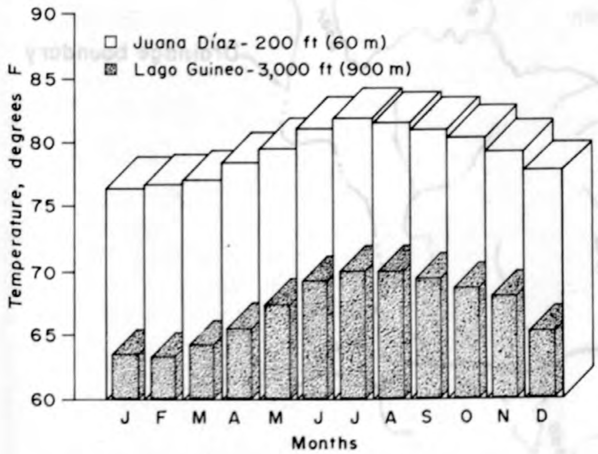

Figure 5.--Variation of mean temperature in the foothills and the mountains. (See fig. 7 for location of stations. Data from U.S. Weather Bureau.)

evaporation. The warmer coastal plain, receiving less rainfall, evaporates water more rapidly than the higher elevations. This combination gives it the appearance of semi-arid land, notwithstanding the 30 or 40 inches of rainfall it receives during the year--the same, for example, as falls in parts of the humid eastern United States.

Land and Water Use

The land use of the area is geared, to some extent, to the soils and the relief, and is almost exclusively agricultural. The higher elevations and the steep slopes are planted with bananas, citrus fruits, coffee, starchy vegetables, and other tropical fruit trees. The original forests were removed long ago. The mountain slopes are not and presumably have never been terraced. In some places, the forests are slowly reclaiming the land and now are sharing it with man's plants. At the lower elevations, between 160 and 800 feet (50 and 250 meters), the land is used mostly for cattle and dairy farms; parts are cultivated for forage without irrigation.

The irrigated coastal plain is planted primarily to sugarcane; a few hundred acres is planted with tomatoes.

There is, as yet, no heavy industry in the area. Mining is limited to limestone at a few places.

There are extensive waterworks in the area, geared to the irrigation of sugarcane in the coastal plain. A complete picture of the water-distribution system and the location of waterworks is shown in figure 6. Lago Guayabal, the largest facility, receives water from the drainage of Ríos Jacaguas and Toa Vaca, and from an intramontane tunnel that brings water from across the northern divide. The water from the reservoir is released for irrigation through an open concrete channel (Canal de Juana Díaz) and a good part of the released water is carried outside the Juana Díaz area. A hydroelectric plant (Toro Negro No. 1), upstream from the reservoir, uses water coming through the intramontane tunnel but does not change its quantity and quality.

The irrigation water transpired by plants is consumed--that is, lost to the area. However, because of furrow irrigation, some water seeps to the water table, its infiltration rate being governed by the permeability of the soil.

More water for the area can come only from increased pumping of ground water and from storage of high flows in reservoirs.

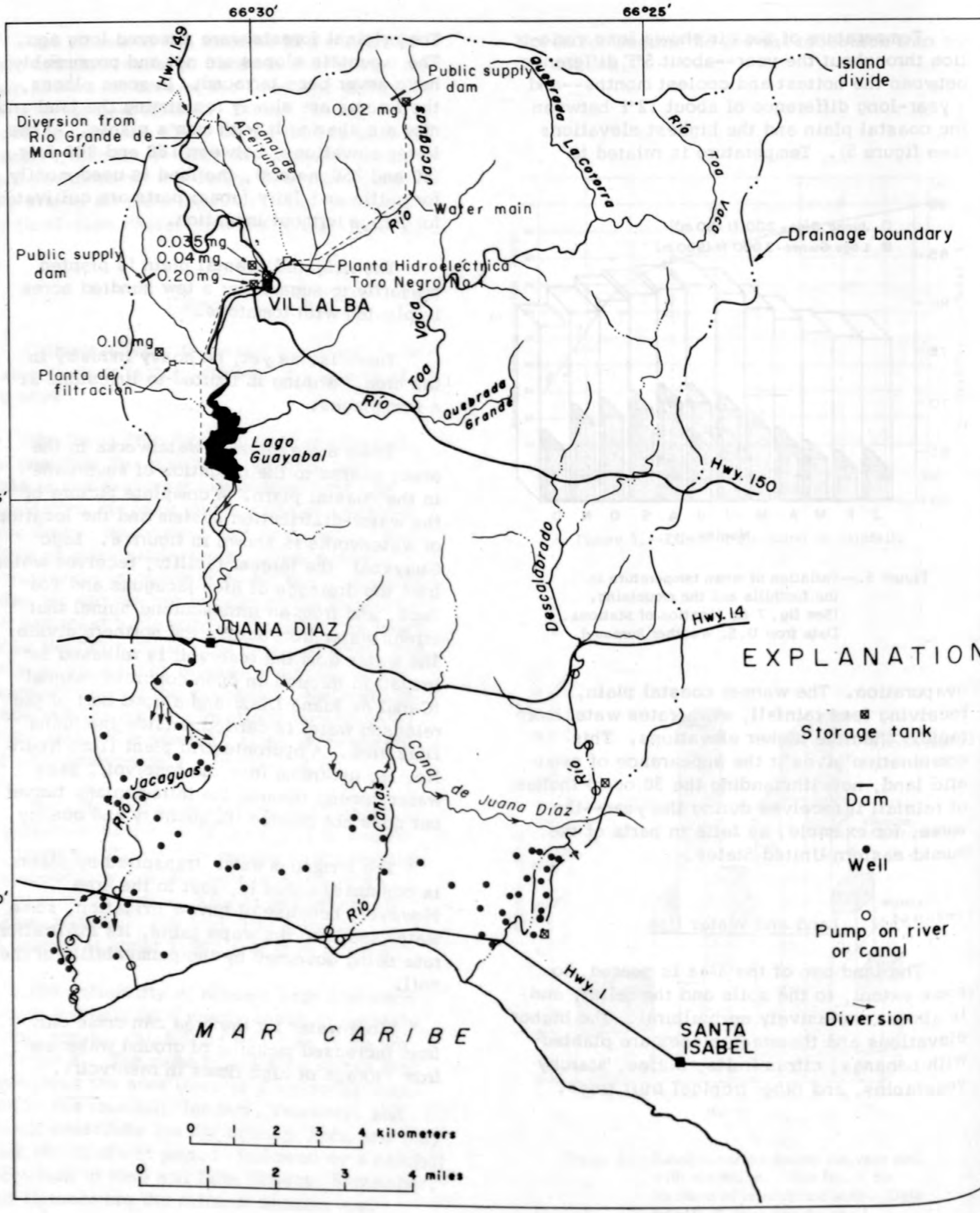

Figure 6.--Waterworks and distribution system in 1966.

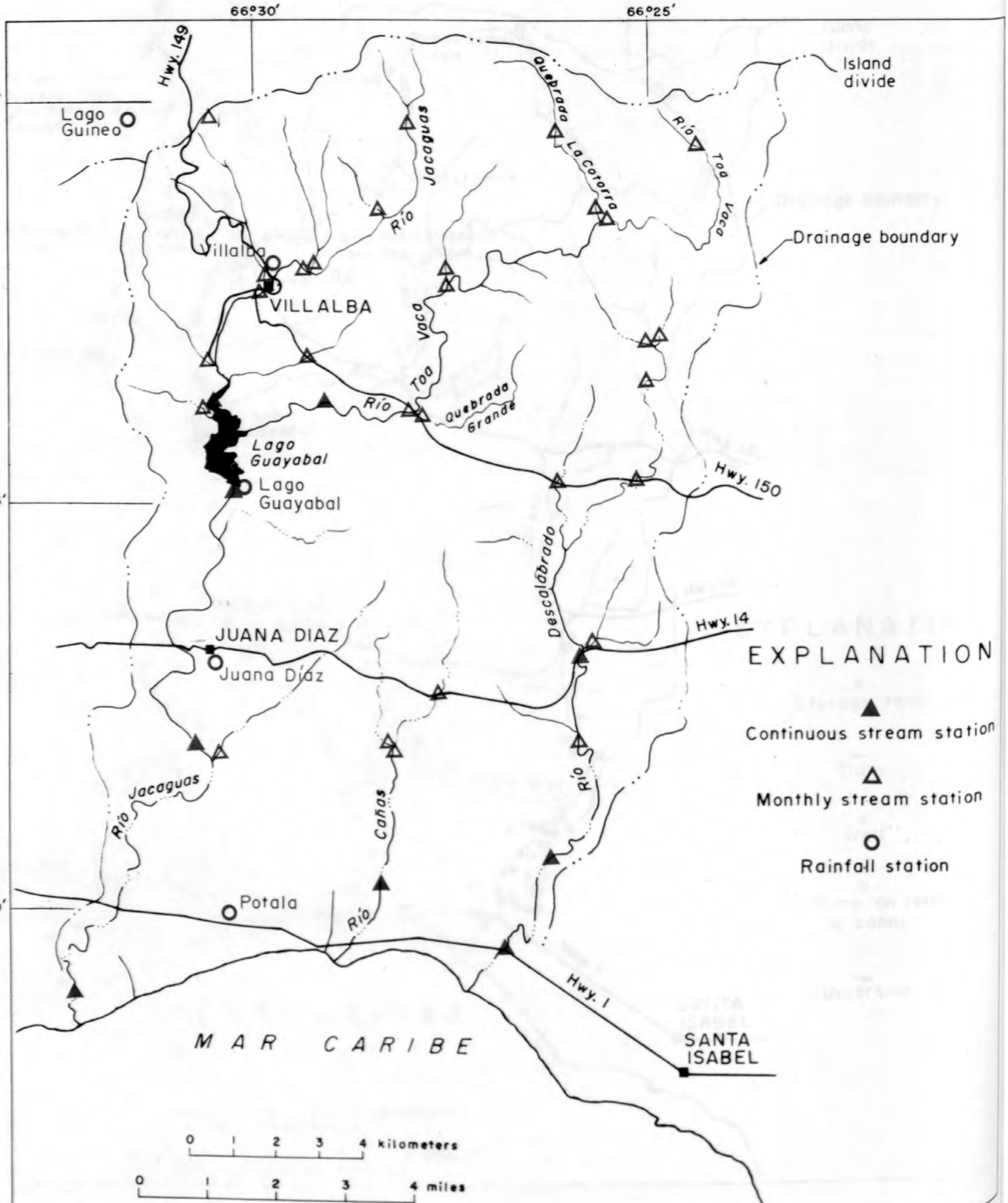

Figure 7.--Streamflow and rainfall measuring stations.

Riverflow

The discharge of rivers was continuously recorded throughout 1966 at the several sites shown in figure 7. During the first six months of the year, riverflow decreased everywhere and the rain that fell during this period contributed little to riverflow. The behavior of Río Descalabrado is shown in figure 8, and this pattern was followed by the other rivers. Although some rain fell in March and May, the riverflow continued to decrease from its' highest in January; it reached its lowest in June, and increased thereafter to its maximum in October. The mildly wet season which usually occurs in April-May, as is shown in the chapter on climate, failed to occur in 1966. The modest 2 inches of rain that fell in March and May was all absorbed by the soil, used by the plants or evaporated. Only a small fraction reached the river channels.

The monthly flows of the three streams that drain the Juana Díaz area are given in table 1.

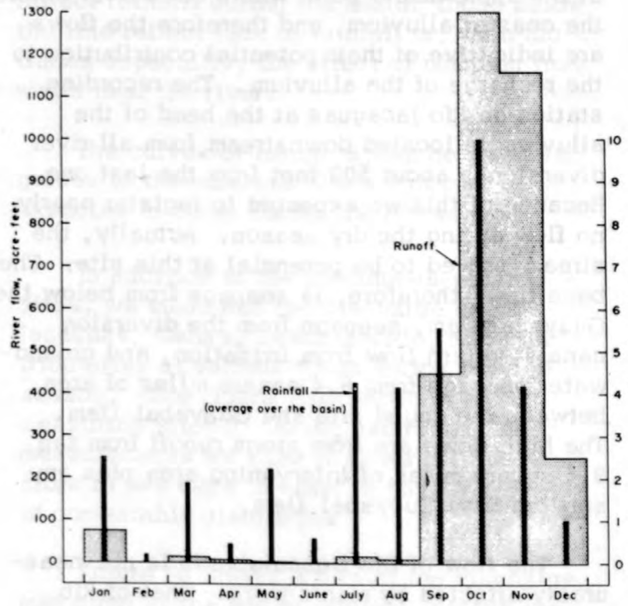

Figure 8.--Rainfall, and runoff of Río Descalabrado in 1966.

Table 1.--Summary of riverflow in the Juana Díaz area, 1966.

	Flow, acre-feet												Yearly total
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	(rounded)
At head of alluvium													
Río Jacaguas	600	90	80	50	90	30	110	20	1,200 b/	9,900 b/	2,800	180	15,200
Río Descalabrado	80	20	20	8	7	2	20	10	410	1,220	1,200	260	3,300
Río Cañas a/	165	50	10	1	20	6	10	20	20	180	150	50	700
										Potential recharge			19,200
At mouth													
Río Jacaguas	600	70	40	20	10	30	10	1	510	14,300	4,300	290	20,200
Río Descalabrado	20	0	0	0	0	0	0	0	60	240	740	100	1,200
Río Cañas	165	50	10	1	20	6	10	20	20	180	150	50	700
										Into sea			22,100
Recharge c/													
Río Jacaguas	140	20	40	30	80	20	100	10	680	930	20	60	2,100
Río Descalabrado	20	0	0	0	0	0	10	2	280	560	170	20	1,100
										Actual recharge			3,200

a/ Only one station, near the mouth. Data are used here to show potential recharge from this stream.

b/ Spillage from Lago Guayabal.

c/ Computed as difference between flow at head of alluvium and flow at the mouth for those days when the flow at the mouth was less than that at the head of the alluvium.

Stream discharges shown in the table are at the approximate point where each river enters the coastal alluvium, and therefore the flows are indicative of their potential contribution to the recharge of the alluvium. The recording station on Río Jacaguas at the head of the alluvium is located downstream from all river diversions, about 500 feet from the last one. Because of this we expected to register nearly no flow during the dry season. Actually, the stream proved to be perennial at this site. The base flow, therefore, is seepage from below the Guayabal Dam, seepage from the diversion canals, return flow from irrigation, and ground-water seepage from 9.4 square miles of area between the gaged site and Guayabal Dam. The high flows are from storm runoff from the 9.4 square miles of intervening area plus any spilling from Guayabal Dam.

The flow of Río Descalabrado is not measurably affected by man's work. That of Río Cañas is affected both by return flow from irrigation during the dry season, and withdrawal by pumping of wells near the river.

The major part of riverflow occurred during the wet season which began in September 1966; for the year, a total of 19,200 acre-feet of water flowed at the head of the alluvium. A yearly total of 22,100 acre-feet flowed out to sea, and at least 3,200 acre-feet percolated into the alluvium and recharged the ground-water reservoir.

Flow From Diversions

A month-by-month summary of diversions is given in table 2. During 1966 nearly 25,000 acre-feet of water was imported to Río Jacaguas via transmontane tunnel. This water was used to generate electricity at a hydro-electric station and then released to the river, unchanged in quantity and quality. About 2,600 acre-feet was taken out of Río Descalabrado where it flows through alluvium, and the water was used nearby for irrigation and processing of sugarcane.

Lago Guayabal released 7,700 acre-feet to Río Jacaguas; but 15,000 acre-feet was diverted from the river below the dam. Because only about half of the irrigation water was furnished by the reservoir, it is apparent that several factors contributed to this increase of water below the dam. Two factors that are important to this study are flow beneath the dam and return flow from excess irrigation. The data available are not sufficient to

Table 2.--Surface-water diversions into and within Juana Díaz area, 1966.

	Jan.	Feb.	Mar.	Apr.	May	Acre-feet June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
Into Juana Díaz area													
Transmontane via Canal de Aceituna	2,160	1,310	2,380	2.120	1,990	1,720	1,150	1,500	2,420	4,550	1,880	1,640	24,820
Within Juana Díaz area													
Lago Guayabal to Río Jacaguas	1,100	764	627	668	590	604	461	415	574	892	485	440	7,620
Lago Guayabal via Canal de Juana Díaz to:													
Río Jacaguas basin	520	513	512	482	484	479	294	213	428	581	444	510	5,460
Río Cañas basin	324	282	167	197	224	112	56	50	175	302	67	294	2,250
Río Descalabrado basin	224	262	324	430	357	220	135	106	253	552	302	300	3,465
Diverted from Río Jacaguas above Hwy 510 and distributed within the Jacaguas basin	1,270	1,230	1,210	1,120	1,170	1,120	907	703	1,160	2,310	1,460	1,150	14,810
Diverted from Río Descalabrado to Central Cortada	54	45	77	80	127	49	57	46	183	590	929	373	2,610

evaluate the magnitude of either factor, and insofar as the water was returned to the river there was no serious loss of water.

Dry-Season Flow

Figure 9, a plot of monthly riverflows versus time, shows in more detail how riverflow decreased during the dry season. An average straight line is drawn through the points and the slope of this line is the rate of decrease of riverflow with time. This rate of decrease is under natural conditions for Río Descalabrado only. Both Río Jacaguas and Río Cañas are affected by pumping and by inflows from diversions from Lago Guayabal.

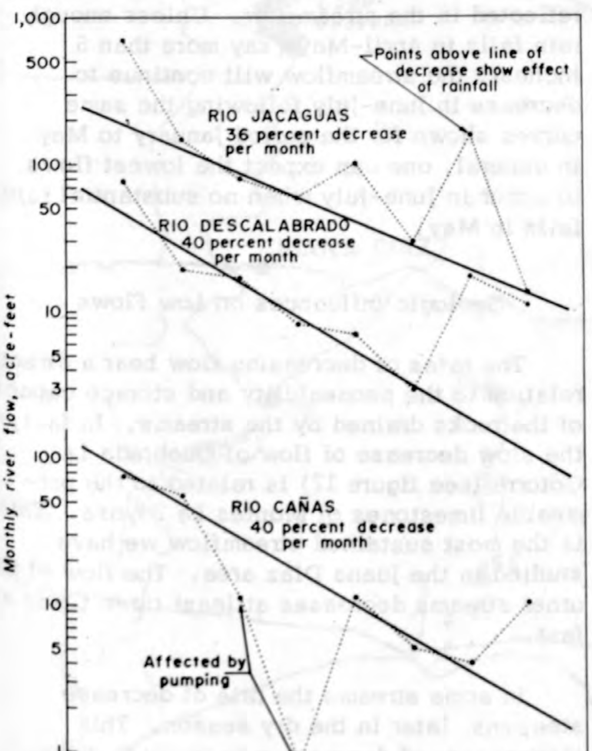

Figure 9.--Rate of decrease of riverflow during the dry season, 1966.

Those points which plot above the line reflect rainfall during the month; those below the line reflect lack of rainfall or, with Río Cañas especially, the effect of pumping from wells near the river.

The curves of figure 9 can be used as guides to the minimum flows that may be expected to occur during the dry season.

In addition to the continuous-record sites, we measured the discharge of Ríos Jacaguas, Cañas, Descalabrado, and their tributaries at various times during the dry season. (See figure 7 for location of measuring sites.) During each round of measurements we tried to cover all the sites in two days in order to have a set of comparable discharges.

Figure 10 shows a plot of the discharge measured at the end of January, versus the drainage area of the streams. The overall

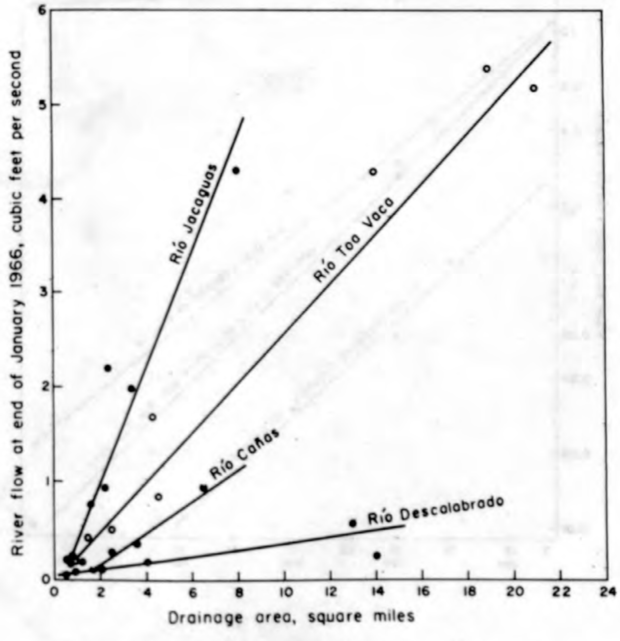

Figure 10.--Relation between riverflow at end of January 1966 and drainage area. (See fig. 7 for location of stream stations.)

scatter of the points is such as to give no reliable criteria for determining the flow at any one site. By separating the individual river basins, however, the data appear to fit four lines, each of which belongs to one river basin. It is apparent that, on the average, the discharge decreases from a maximum for Río Jacaguas to a minimum for Río Descalabrado.

A more complete statement on the low-flow characteristics of rivers is given by the rate at which the riverflows decrease with time during periods of no rain. Figure 11 shows a plot of discharge with time. The slope of the lines represents the rate of decrease of riverflow; and this rate, expressed in percent per month, is plotted in figure 12 next to the measuring sites.

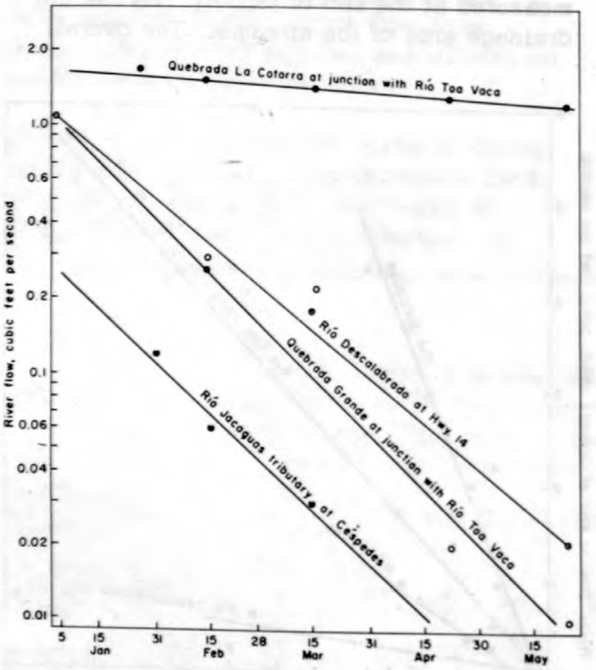

Figure 11.--Base flow of smaller streams in dry season, 1966.

Because only the data we collected are available, we cannot foresee the reliability of figures 11 and 12 for computing riverflow for periods when the preceding rainfall was substantially different from that preceding the study period. Bearing this in mind, figure 13 together with figure 11 may serve as a basis for estimating dry-season flow at any river site within the Juana Díaz area. When a large amount of rainfall occurs during the dry season (say more than 3 inches in any month), the curves will not give reliable results, because then enough water would infiltrate into the ground to increase the base flow of the stream; and the flow would decrease with time from a higher starting level.

The distribution of rainfall by months indicates that April and May constitute a minor wet season. This is not always reflected in the streamflow. Unless enough rain falls in April-May (say more than 5 inches), the streamflow will continue to decrease in June-July following the same curves shown for the period January to May. In general, one can expect the lowest flows to occur in June-July when no substantial rain falls in May.

Geologic Influences on Low Flows

The rates of decreasing flow bear a direct relation to the permeability and storage capacity of the rocks drained by the streams. In fact, the slow decrease of flow of Quebrada La Cotorra (see figure 12) is related to the permeable limestones of Montes La Toyosa. This is the most sustained streamflow we have studied in the Juana Díaz area. The flow of the other streams decreases at least three times as fast.

In some streams the rate of decrease steepens later in the dry season. This steeper rate of decrease may imply that the shallow weathered part of the aquifer supporting most of the early flow becomes

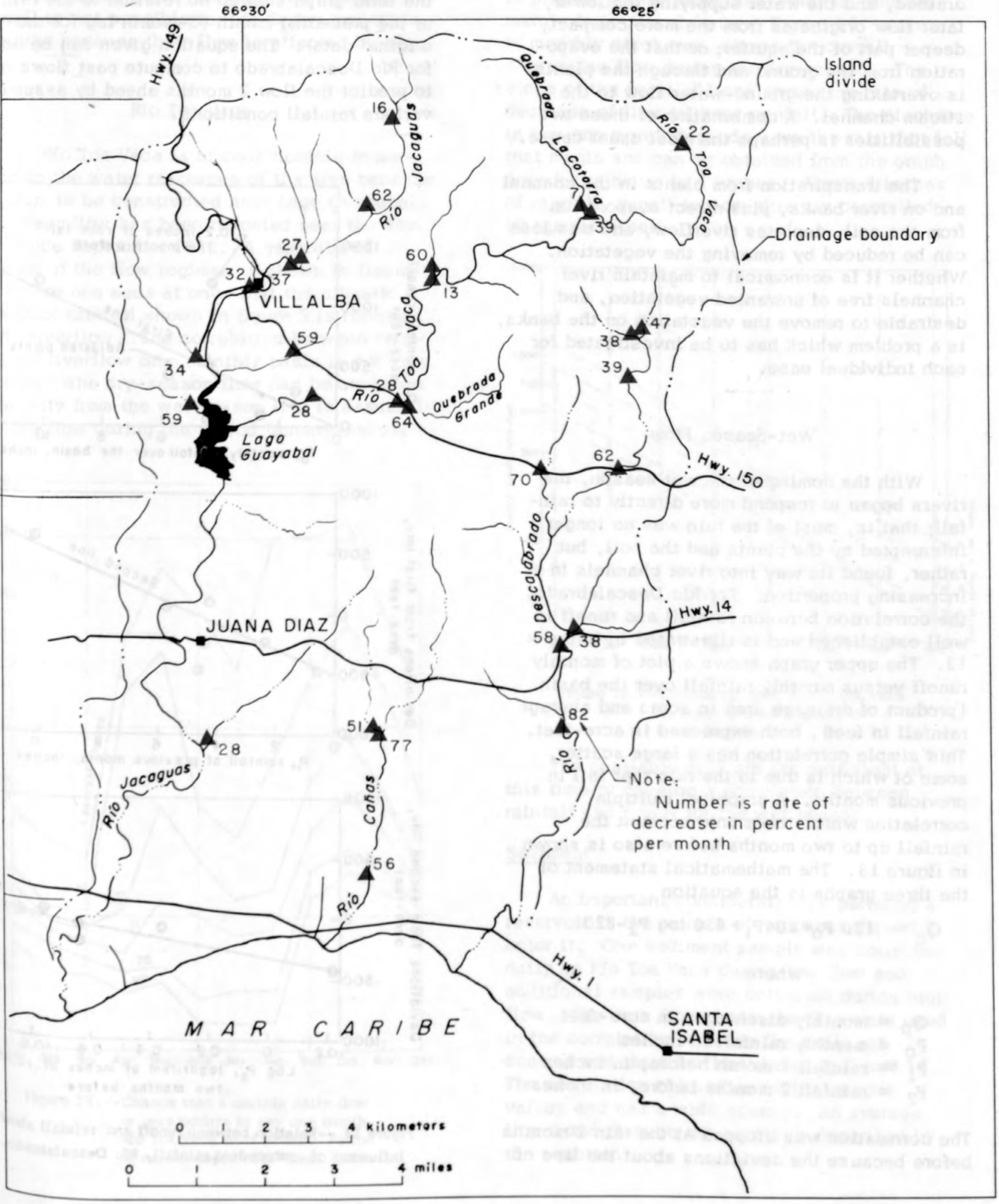

Figure 12.--Streamflow decrease during dry season at miscellaneous sites, 1966.

drained, and the water supplying the lower, later flow originates from the more compact, deeper part of the aquifer; or that the evaporation from the ground and through the plants is overtaxing the ground-water flow to the stream channel. A combination of these two possibilities is perhaps the most usual cause.

The transpiration from plants in the channel and on river banks, plus direct evaporation from the soil, depletes riverflow, and this loss can be reduced by removing the vegetation. Whether it is economical to maintain river channels free of unwanted vegetation, and desirable to remove the vegetation on the banks, is a problem which has to be investigated for each individual case.

Wet-Season Flow

With the coming of the wet season, the rivers began to respond more directly to rainfall; that is, most of the rain was no longer intercepted by the plants and the soil, but rather, found its way into river channels in increasing proportion. For Río Descalabrado the correlation between rainfall and runoff is well established and is illustrated in figure 13. The upper graph shows a plot of monthly runoff versus monthly rainfall over the basin (product of drainage area in acres and average rainfall in feet), both expressed in acre-feet. This simple correlation has a large scatter, some of which is due to the rain that fell in previous months. A graphical multiple correlation which takes into account the rainfall up to two months before also is shown in figure 13. The mathematical statement of the three graphs is the equation

$$Q_o = 120\,P_o + 104P_1 + 450\,\log P_2 - 820$$

where

Q_o = monthly discharge, in acre-feet
P_o = monthly rainfall in inches
P_1 = rainfall 1 month before, in inches
P_2 = rainfall 2 months before, in inches

The correlation was stopped at the rain 2 months before because the deviations about the line of the third graph showed no relation to the rain of the preceding month (3-month lag for the original data). The equation given can be used for Río Descalabrado to compute past flows or to predict the flow 2 months ahead by assuming various rainfall conditions.

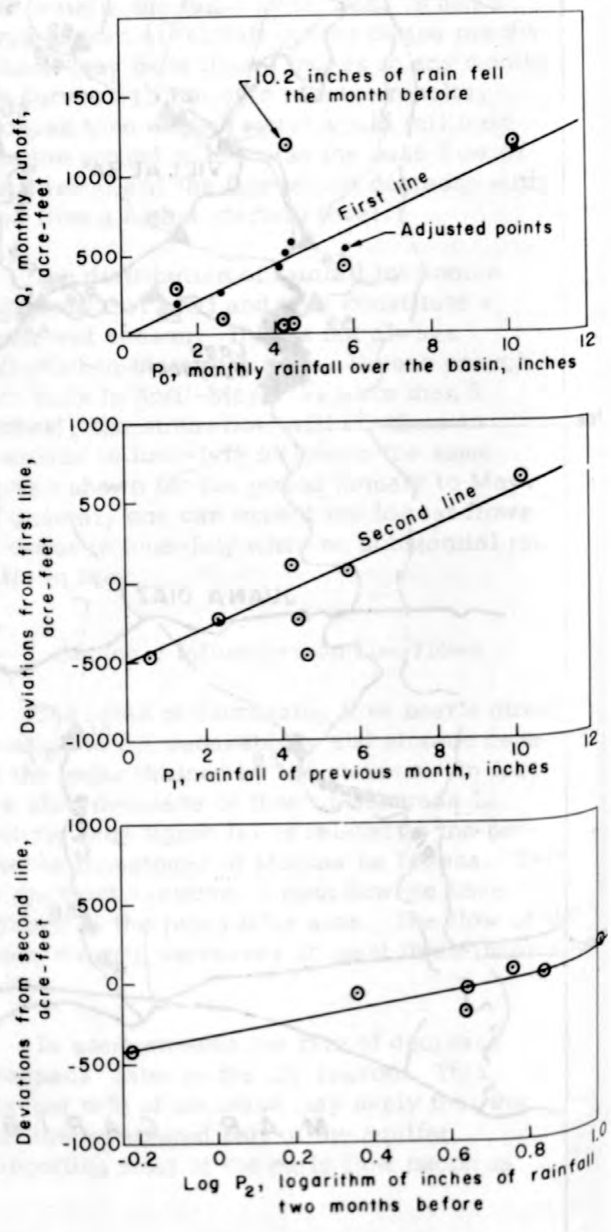

Figure 13.--Relation between runoff and rainfall shows influence of antecedent rainfall, Río Descalabrado.

A similar relation between riverflow and rainfall is not possible for Río Cañas and Río Jacaguas because their flow is affected by man.

Río Toa Vaca

Río Toa Vaca is of considerable importance to the water resources of the area because of a dam to be constructed near Lago Guayabal. The streamflow has been recorded near the dam site since September 1962. A generalized diagram of the flow regimen is shown in figure 14, where one sees at once that the climatic pattern of rainfall shown in figure 5 is repeated in the riverflow. The correlation between rainfall and riverflow on a monthly basis is not very reliable. The dry-season flow can be analyzed separately from the wet season if it is assumed that the flow during the period January-August

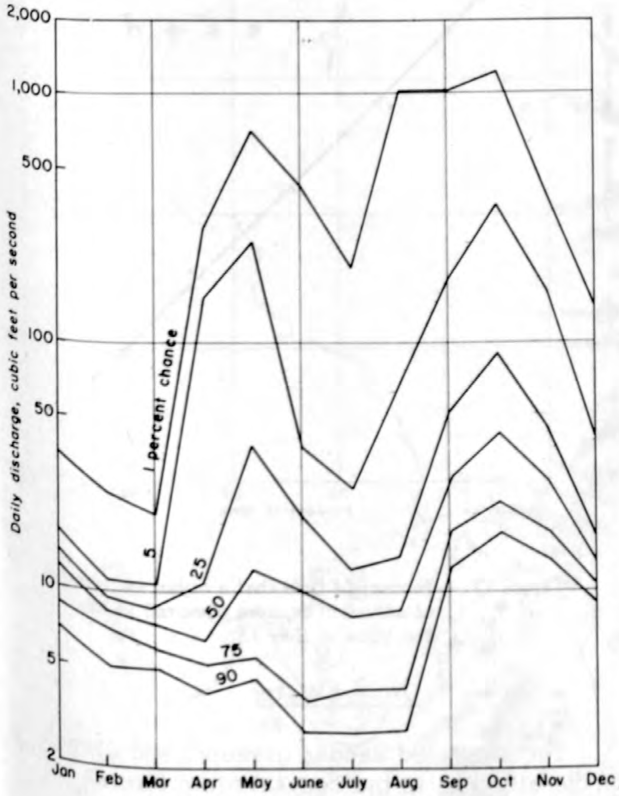

Figure 14.--Chance that a certain daily flow or less occurs in any one month, Río Toa Vaca near mouth. Period of record Sept. 1962-Dec. 1966.

is primarily time controlled--that is, derived mainly from ground water. Figure 15, a plot of monthly discharge, shows the overall decreasing flow during the dry season. The slope of the parallel lines shows the rate of decrease of flow without rainfall. The discharge in any one month depends upon the rain that fell that month and can be obtained from the graph only for rains up to 4 inches. Above 4 inches of rainfall, runoff is more directly controlled by rainfall itself.

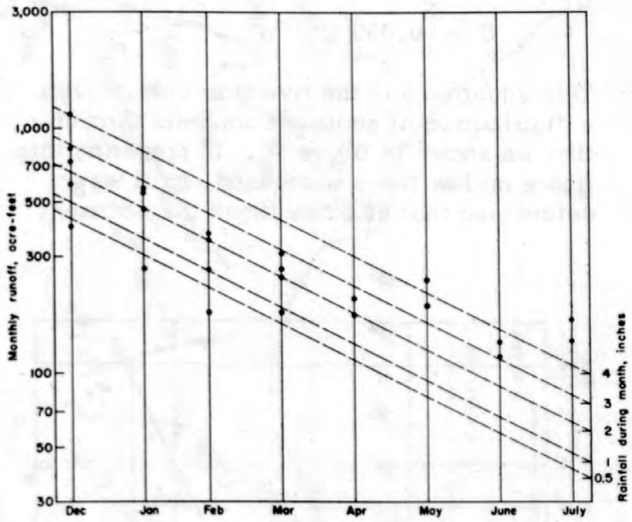

Figure 15.--Dry-season flow of Río Toa Vaca near mouth shows effect of precipitation.

The available data are not sufficient at this time to develop a correlation between rainfall and runoff for the wet season.

Sediment

An important consideration in planning a reservoir is the amount of sediment that will enter it. One sediment sample was collected daily on Río Toa Vaca during low flow and additional samples were collected during high flow. The data from these samples were used in the correlation between the sediment content and the riverflow shown in figure 16. The correlation represents instantaneous values and has a wide scatter. An average line fitted through the points is described by the equation:

$$S = 45 \times 10^{-8} \times Q^2$$

where

S = suspended sediment, in tons per second

Q = riverflow, in cubic feet per second

In tons per day the equation reduces to:

$$S = 0.039\, Q^2$$

This equation and the riverflow data provide a distribution of sediment contents through time as shown in figure 17. In preparing this figure no low flows were used, as it was determined that at those times the sediment content is insignificant. By integrating the values of figure 17, the average yearly sediment discharge was about 108,000 tons for the basin, or about 5,000 tons per square mile. This is the same as that given by Bogart (1964) where the sediment load was derived from the sediment content of Lago Guayabal.

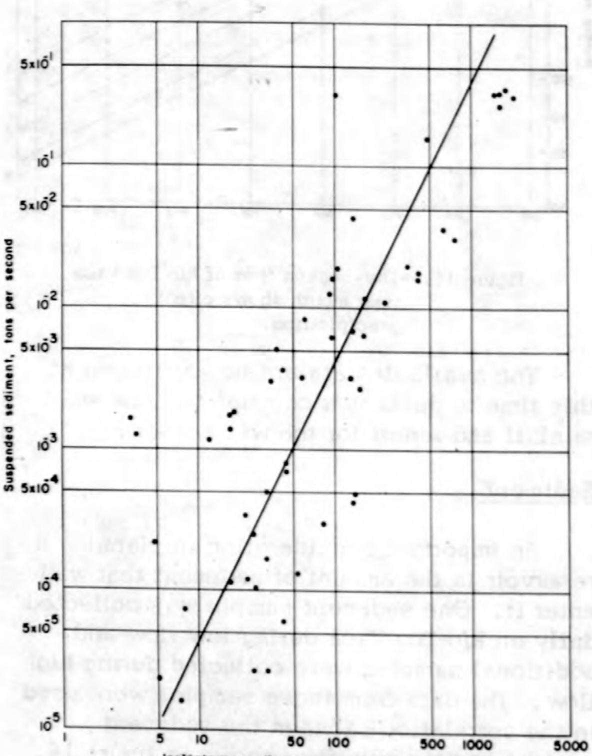

Figure 16.--Relation between suspended sediment and discharge, Río Toa Vaca near mouth.

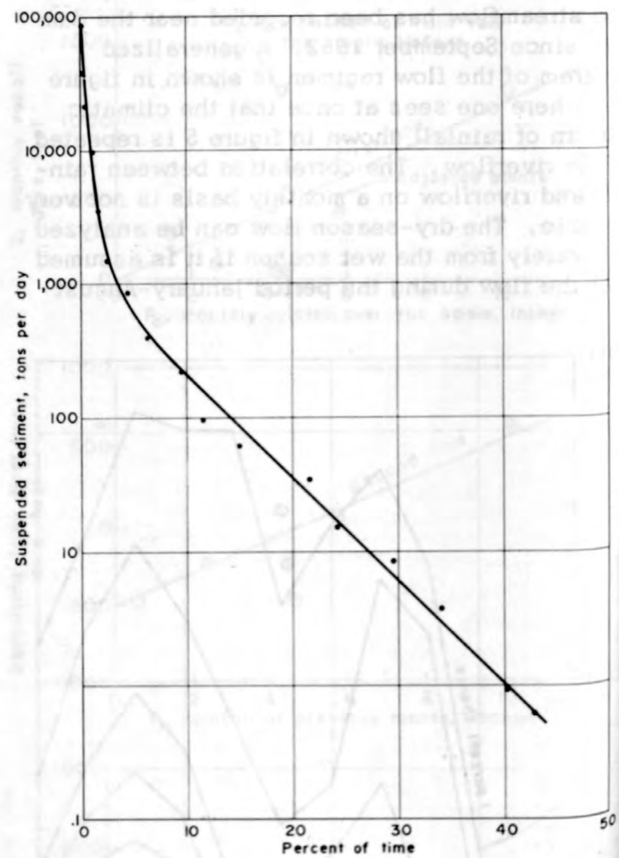

Figure 17.--Percent of time that a given amount of sediment or more occurred in Río Toa Vaca at Hwy 150.

Ground Water

The saturated sands, gravels, and clays of the alluvium in the coastal plain furnish ground water to a number of wells scattered throughout the area. This water and the water diverted from Lago Guayabal are used for irrigation of crops.

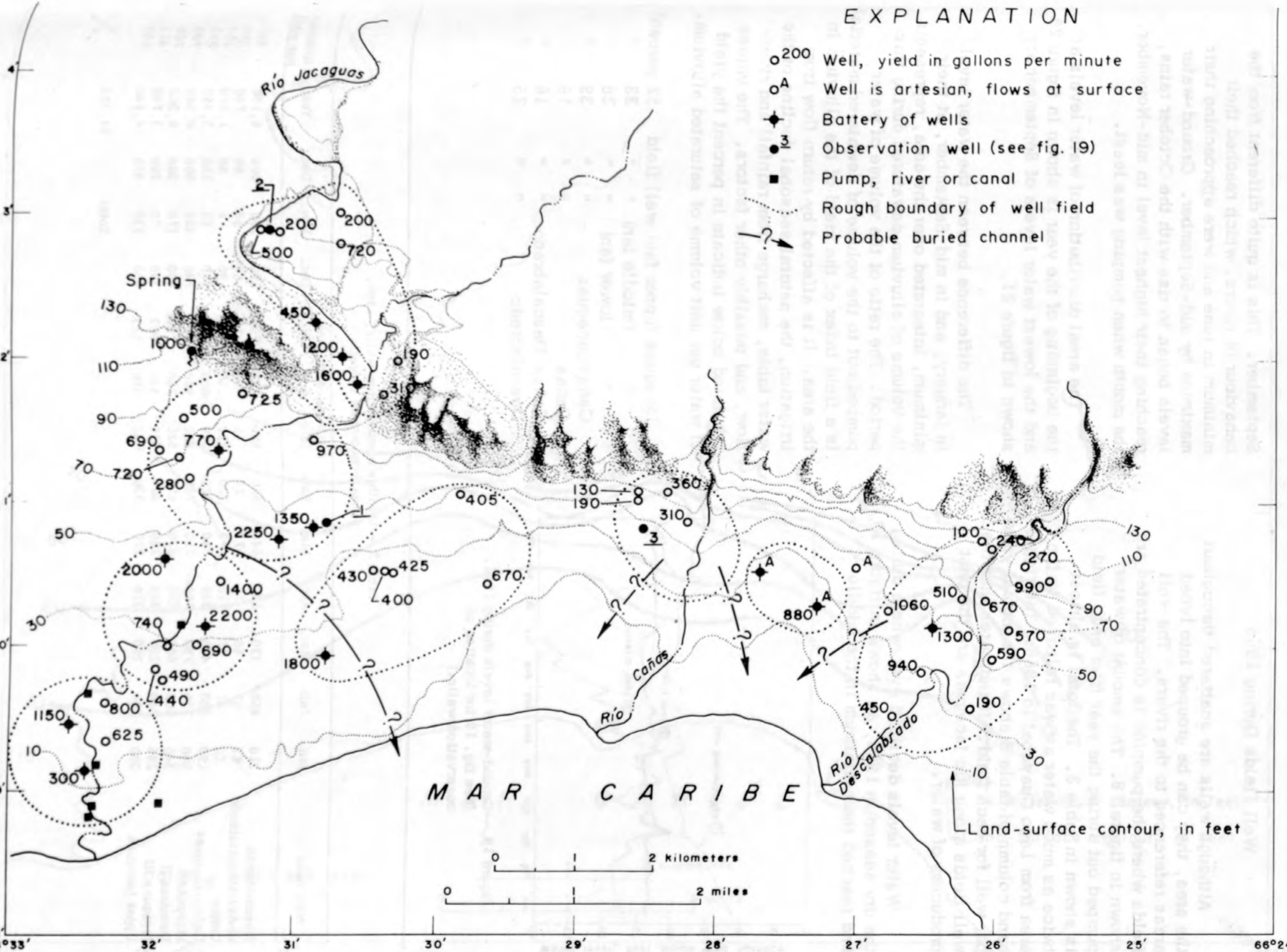

Figure 18.--Well fields of Juana Díaz area.

Well Fields During 1966

Although wells are scattered throughout the area, they can be grouped into broad areas referenced to the rivers. The well fields where the pumping is concentrated are shown in figure 18. The amount of water pumped out during the year from each field is shown in table 3. The total is almost twice as much water as was released to the area from Lago Guayabal in 1966. The right-hand column of table 3 shows the annual yield per well for each field. It indicates that the well fields along Río Jacaguas are the best producers of water.

Water levels declined everywhere during the dry season in 1966, as shown in figure 19, and reached their minimum in the middle of September. This is quite different from the behaviour of rivers, which reached their minimum in June and were approaching their maximum by mid-September. Ground-water levels began to rise with the October rains, reaching their highest level in mid-November, the month when pumping was least.

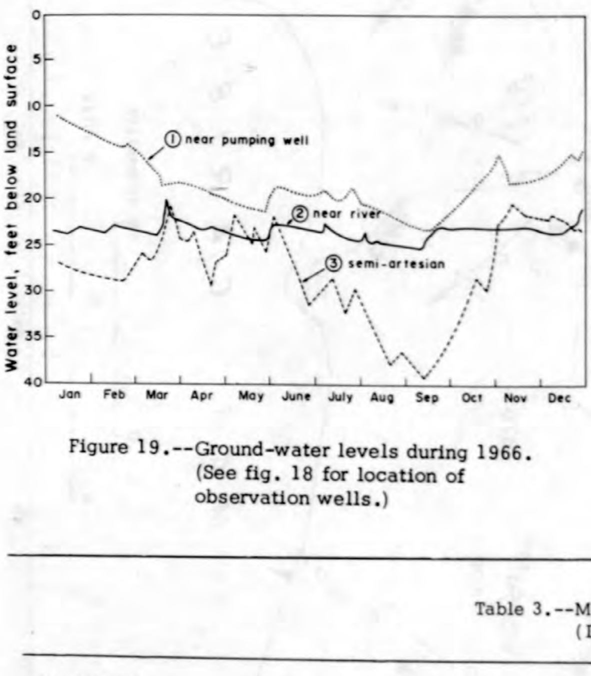

Figure 19.--Ground-water levels during 1966. (See fig. 18 for location of observation wells.)

The areal distribution of water levels at the beginning of the year is shown in figure 20 and the lowest water levels of September are shown in figure 21.

The difference between the water levels in January, and in mid-September, at their minimum, integrated over the area, represents the volume of alluvium dewatered during this period. The ratio of the volume of water pumped out to the volume of dewatered material is a field index of the yield of the alluvium in the area. It is affected by return flow from irrigation, the natural seasonal decline of the water table, recharge from rainfall and river-flow, and possibly other factors. The values tabulated below indicate in percent the yield of water per unit volume of saturated alluvium.

Jacaguas (upper fan)	well	field	52	percent
" (middle fan)	"	"	33	"
" (lower fan)	"	"	28	"
Cañas-Jacaguas	"	"	39	"
Cañas	"	"	16	"
Cañas-Descalabrado	"	"	16	"
Descalabrado	"	"	25	"

Table 3.--Monthly pumpage from wells, 1966.
(Data from owners of wells.)

Well field	Pumpage, acre-feet													
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Averag per we
Descalabrado	310	450	520	530	640	550	600	640	790	570	230	300	6,100	407
Cañas-Descalabrado	63	57	68	70	73	74	65	71	75	55	54	60	790	395
Cañas	50	47	71	110	73	120	210	260	190	90	1	50	1,270	254
Cañas-Jacaguas	190	300	400	330	390	320	270	400	380	260	55	150	3,450	575
Jacaguas I	500	730	790	790	710	780	800	900	930	740	420	500	8,580	780
Jacaguas II	340	500	600	550	630	650	520	760	790	500	170	300	6,300	700
Jacaguas III	245	240	280	320	280	320	420	530	503	340	70	200	3,740	415
Upper Jacaguas	300	280	290	310	270	330	400	480	520	430	230	300	4,140	593
											Total		34,370	

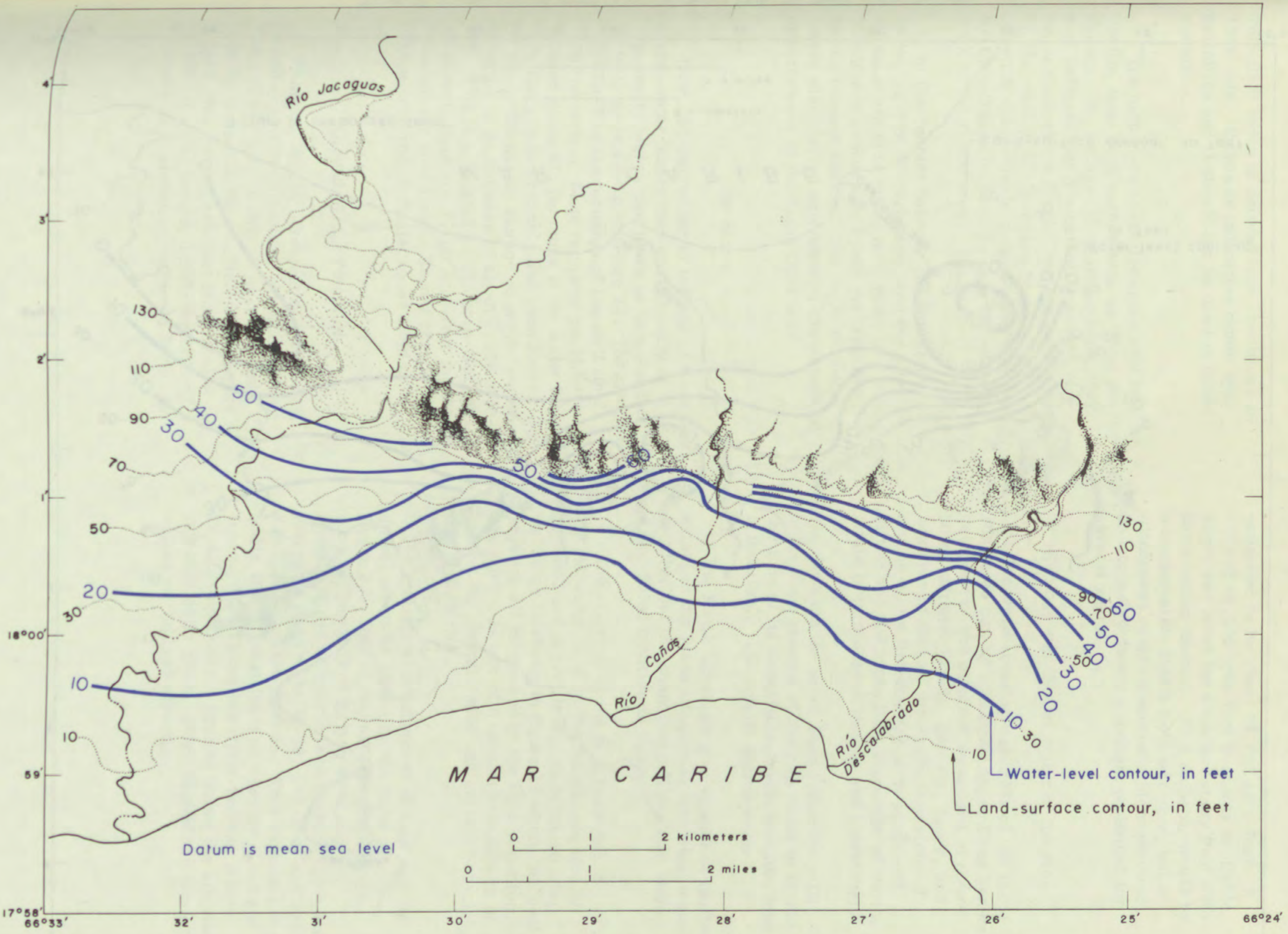

Figure 20.--Ground-water levels in January 1966.

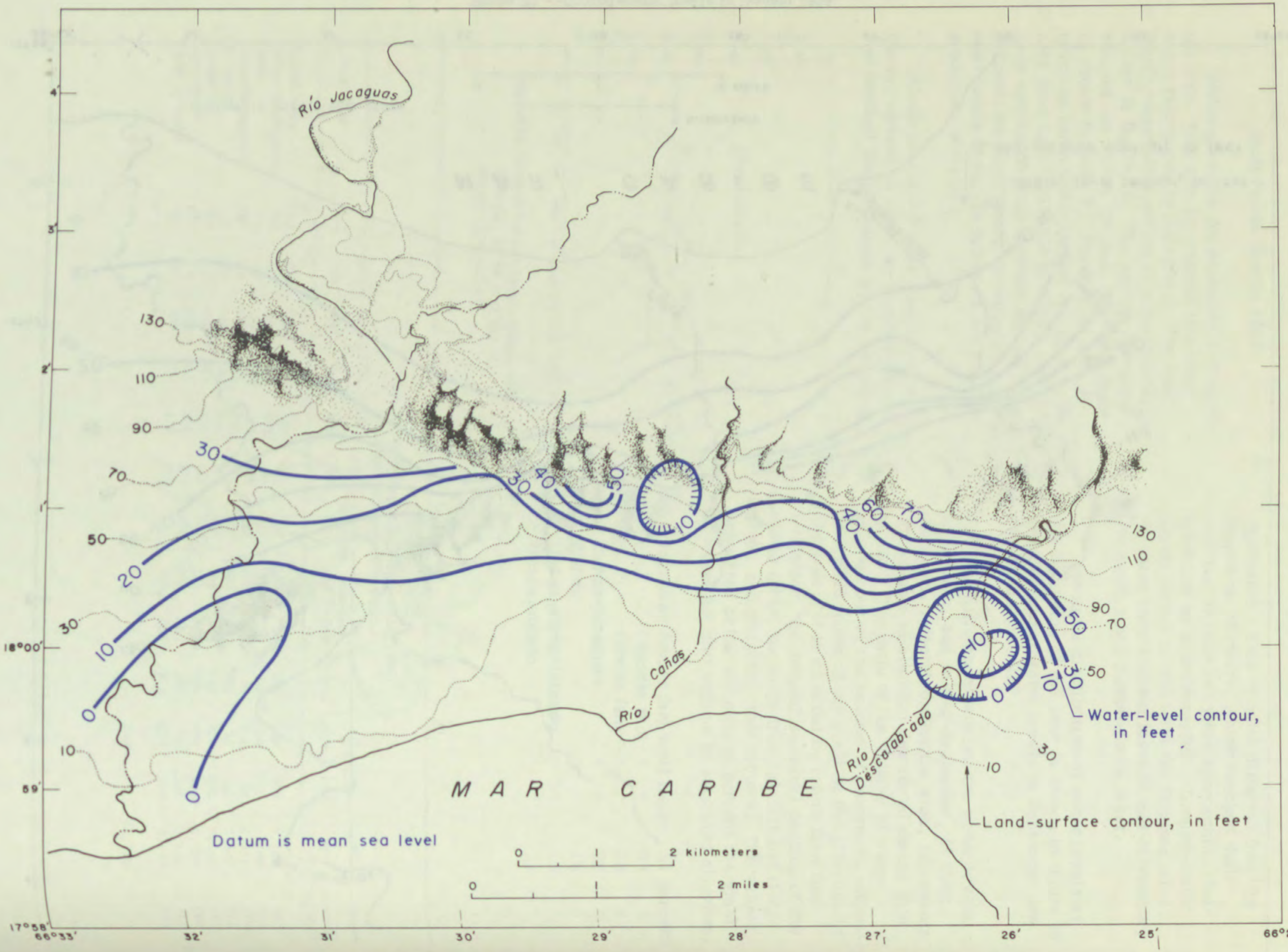

Figure 21.--Ground-water levels in mid-September 1966, the lowest during the year.

This field index is derived from conditions in 1966 only. It thus is indicative rather than definitive and it should not be used in other context.

The high yield of the Jacaguas well fields confirm their good performance as water producers. But because they are so high, they may indicate that a substantial amount of water crosses the divide from Río Inabón basin on the west to Río Jacaguas basin. This possible cross-divide ground-water flow was first mentioned by McClymonds (1970) in his work in the Ponce area.

At the contact between the limestone hill on the west of Río Jacaguas, and the alluvium on the south side of the hill, there is a spring from which as much as 2,000 gpm is pumped during the wet season. The water from this spring also may be derived from the watershed directly west of the Juana Díaz area.

Recharge

From mid-September to the end of November, ground-water levels rose continuously in response to higher riverflows or to prolonged rainfall, as is shown in figure 22. The riverflow contributed to the recharge of the well fields along the rivers. More recharge could have occurred along Río Jacaguas if the water table along the stream channels had been lower. The net yearly change in storage of ground water amounted to an increase of about 1,300 acre-feet. This is allocated as 200 acre-feet for the Cañas well field and 1,100 acre-feet for the Descalabrado well field. No net change in storage occurred in the Jacaguas fields.

Ground-Water Potential

Although 34,000 acre-feet of water was pumped out of the alluvium, more could have been pumped out. Using an assumed and probably conservative coefficient of storage of 0.10, the amount of water stored below the lowest water levels of mid-September, but above zero elevation mean sea level, is estimated to be about 14,000 acre-feet. A total of 48,000 acre-feet thus was available above sea level for a somewhat dry year with little spring rainfall. This probably would be a conservative figure for a wet year, but a withdrawal of this magnitude might prove to be excessive during a drought prolonged for several years.

Geology and Ground Water of the Area

The water-bearing materials of the Juana Díaz area can be classified under three general categories: the alluvium composed of river-borne material (sands, gravels, clays, and mixtures of these); the Ponce Limestone of marine origin (interbedded with sands and silts); and the Juana Díaz Formation of marine origin (interbedded siltstone and limestone).

Because the Juana Díaz Formation still holds some residue of the salt water in it from the time of its deposition, wells pumping from it invariably yield mildly saline water.

The Ponce Limestone, an aquifer of limited extent in the Juana Díaz area, may yield water locally, but the chance of drilling into large water-filled cavities is small.

The alluvium is the best reservoir of ground water, and an overall assessment of the sand and gravel layers as obtained from well logs is shown in figure 23 where the well logs are all referenced to the land elevation. The picture is one of a random assemblage of layers; no general "sand and gravel" horizon can be detected.

A statistical arrangement of sand and (or) gravel layers is shown on the right side of figure 23. This histogram is a graph of the odds (in percent) of finding sand and (or) gravel at 10-foot intervals of depth. The most favorable ranges are 30-50, 140-160, and 220-230 feet below the surface. This indicates that wells should be at least as deep as about 250 feet to tap all possible water-bearing layers. Of course this depth applies where the alluvium is sufficiently thick, which depends to some extent on the land elevation.

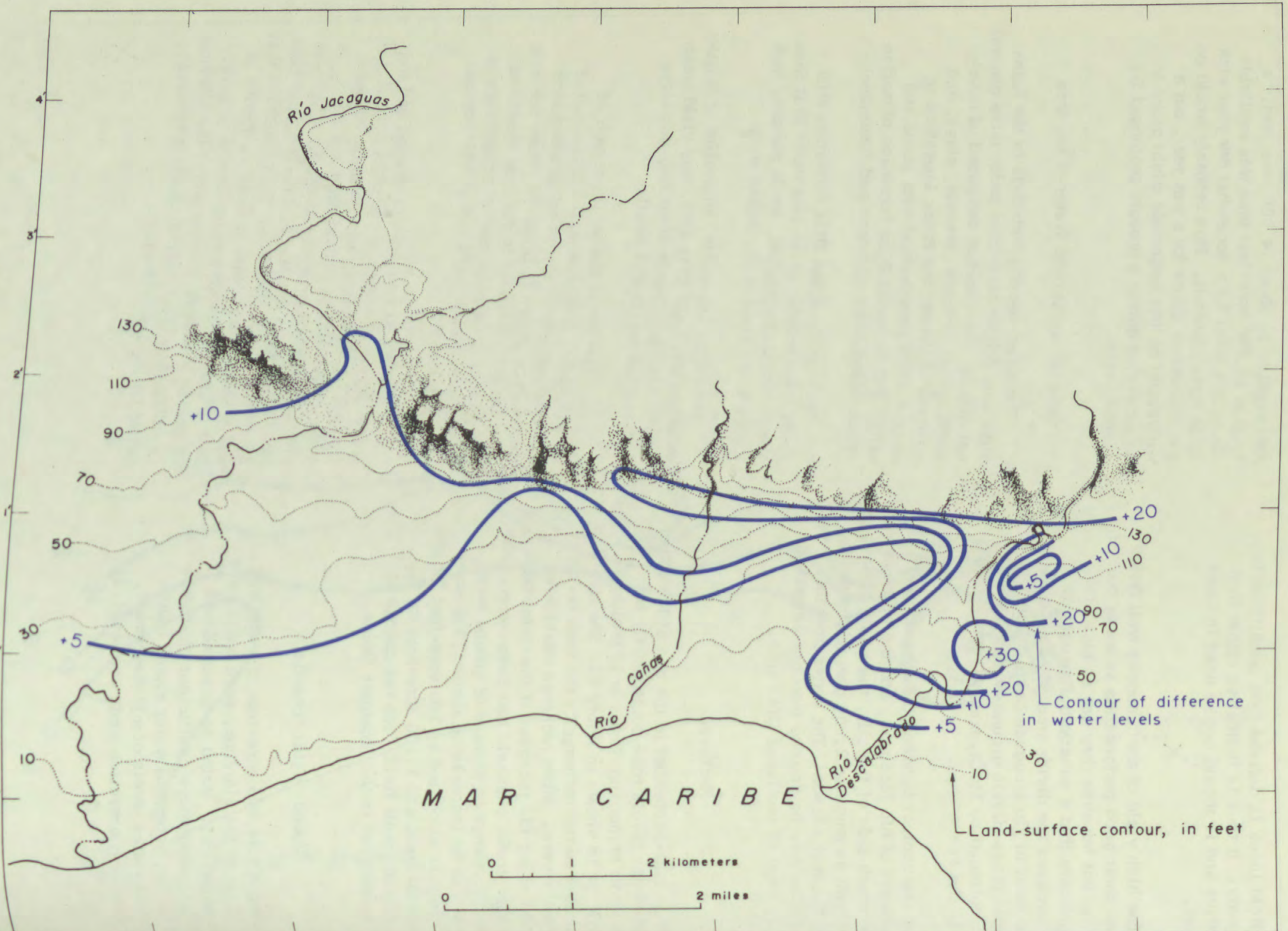

Figure 22.--Recharge of alluvium is shown by increase in ground-water levels between mid-September and the end of November 1966.

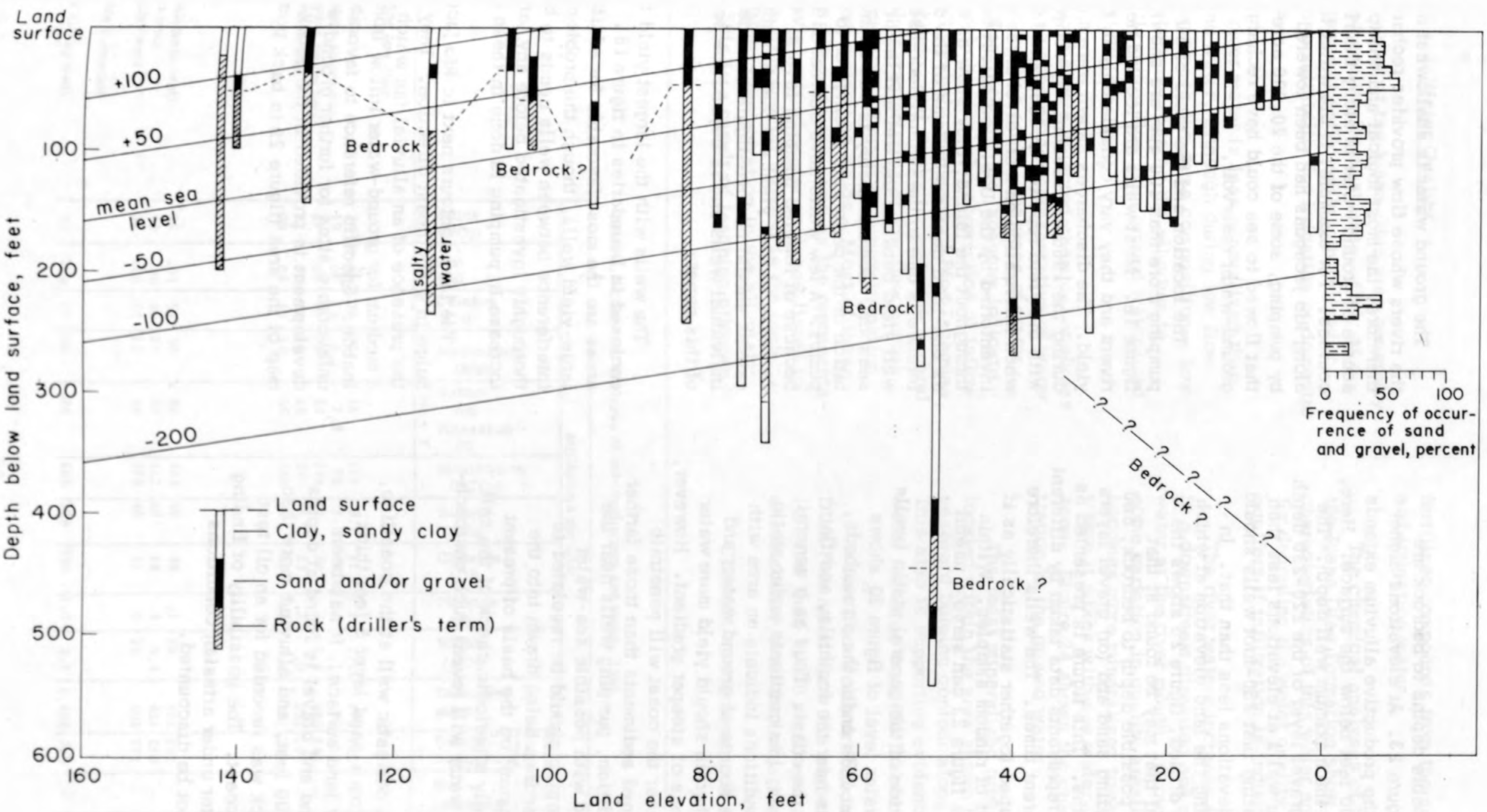

Figure 23.--Composite of well logs, with frequency of occurrence of sand and gravel at various depths.

A few probable depths to bedrock are indicated in figure 23. At elevations higher than 80 feet, the productive alluvium extends to less than 100 feet below the surface. Here, that should be the maximum well depth. The sand and (or) gravel layer of the 220-230 depth is found in four wells at elevations less than 70 feet, indicating that 250-foot wells should be drilled at elevations less than that. In general, knowing the land elevation at which a well is to be drilled, figure 23 shows the type of material that may be found at that elevation, the possible depth to bedrock, and the odds of finding sand and (or) gravel layers at various depths. This figure is presented as a guide and it represents data taken by different people at different times. The wells therefore have been grouped together statistically as if they were a set of random samples. Within this limitations figure 23 can serve a useful purpose.

The elevation of the general static (wells not pumping) water level of figure 20 shows ground-water mounds under the streambeds, steep gradients near the foothills, and flat gradients near the coast. Thus as a general rule for this area, low gradients under static water-level conditions indicate an area with a more reliable source of ground water; and wells drilled therein should yield more water than within areas of steeper gradient. However, wells drilled near the coast will penetrate more fine-grained sediments than those farther inland. In addition, pumping wells near the coast are faced with possible sea-water intrusion. Pumping should be regulated to avoid sea water from being drawn into the cone of depression; on the basis of present information, only a periodic check of the salt content of the water will reveal such encroachment.

One small domestic well at the coastline, pumps water from a sand layer 5 feet thick, 110 feet below land surface. It has been shown that sand and gravel is found at depths of more than 200 feet, and alluvium more than 2,000 feet thick was recorded for an oil test well near the coast. The possibility of finding deep fresh water under artesian conditions therefore cannot be discounted.

The ground water is shallowest next to the rivers whose flow provides recharge; therefore, the most logical and cheapest source of ground water is along the river courses. For example, if the water table along Río Jacaguas had been lowered further by pumping, some of the 20,000 acre-feet that flowed to sea could have recharged the ground-water reservoir.

The location and the yield of all wells pumping more than 100 gpm are shown in figure 18. Most wells are located near the rivers and they vary considerably in their yield. The discharges shown were measured during the 1966 dry season. By comparison with the yield reported in 1958 and 1960, when information on well discharges was inventoried by the U.S. Geological Survey throughout the Island, they show as much as one-third decrease. Some of the difference is due to the natural decrease of well yield between the wet and the dry seasons. Some probably is due to incrustation of the perforated casings or to faulty pumps. A few wells have decreased in yield because of lowered pumping levels. The decrease of well yield not due to natural causes should be investigated for the individual wells and is beyond the scope of this paper.

The wells with the largest yield are enclosed in boundaries in figure 18. These areas are the most favorable for additional large-yield wells, though the problem of interference between wells needs to be thoroughly investigated before any large increase in pumping is done in these areas.

The land contours next to Río Jacaguas bulge in a southeast direction. They indicate the presence of an alluvial fan which provides a medium for ground-water inflow from Río Inabón. Specific reference to favorable and unfavorable sites for further ground-water development is provided in the geohydrologic map of the area (figure 29 in back pocket).

Water Quality

The water of the Juana Díaz area generally is of good quality for most uses. Only at a few places is it sufficiently mineralized to approach unsuitability for irrigation or domestic purposes.

The river water is less mineralized than the ground water, although during low flow the two approach the same composition. Low flow in streams crossing the alluvium is principally return flow from ground water used for irrigation.

Table 4 shows selected chemical analyses that can be considered representative of water in the Juana Díaz area. Analyses of water from Río Toa Vaca and Río Jacaguas indicate the general chemical characteristics of inflow to Lago Guayabal. Analyses of Ríos Jacaguas, Descalabrado, and Cañas indicate the general chemical characteristics of low flow across the alluvium as affected by return irrigation water from sugarcane fields. Most of these analyses are much the same as the representative alluvial ground-water analyses listed in the table. Of special interest is the high nitrate (NO_3) concentration in the alluvial water. This is a result of leaching nitrogen fertilizer compounds from the soil by rainfall and irrigation water.

The chemical analyses of the water from the Juana Díaz Formation show the saline characteristics of this water and its potential for degrading the water quality in adjacent aquifers if infiltration is induced.

The river waters increase in mineralization in a downstream direction and merge into sea water at the river mouth. Ground water shows some variation in quality areally and also becomes more mineralized toward the coast, where it mixes with sea water in a transition zone. Figure 24 shows the chloride concentration in the ground water.

The least mineralized ground water is located within the area shown by the southeastward bulging contour along Río Jacaguas. This also is supporting evidence of groundwater recharge from Río Inabón.

Water from wells drilled into the Juana Díaz Formation show the highest salinity (greater than 1,000 mg/l) and approach unsuitability even for irrigation.

Chloride concentration is higher than

Table 4.--Chemical analyses of selected rivers and wells, 1966.

	Milligrams per liter													Specific conductance (micromhos at 25°C)	pH	Temperature °C
												Hardness as $CaCO_3$				
	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) Potassium (K) Na + K	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Calcium, magnesium	Non-carbonate			
RIVERS, during low flow																
Río Toa Vaca	27	0.00	36	11	16	176	8.1	11	0.2	1.1	179	135	-	322	7.7	28
Río Jacaguas above dam	19	.00	14	5.1	7.8	76	2.0	5.8	.4	.1	99	56	-	150	7.2	26
Río Jacaguas below dam	27	.00	60	22	54	334	50	20	.2	5.3	403	240	-	661	8.0	-
Río Descalabrado	22	.00	38	21	28	240	12	23	.2	.0	251	182	-	440	7.5	21
Río Cañas	30	.00	56	24	56	348	36	22	.3	5.8	392	238	-	653	8.1	-
WELLS																
Alluvium																
Descalabrado well	36	.01	56	37	65	364	48	49	.1	20	501	292	-	798	7.8	27
Cañas well	40	.00	46	23	84	412	26	14	.4	9.4	456	210	-	707	7.8	26
Jacaguas well	32	.00	84	15	26	278	46	21	.0	26	401	271	-	607	7.8	27
Juana Díaz Formation																
Upper Cañas well	32	.00	64	38	420	666	108	398	1.0	9.7	1,400	316	-	2,160	7.9	27

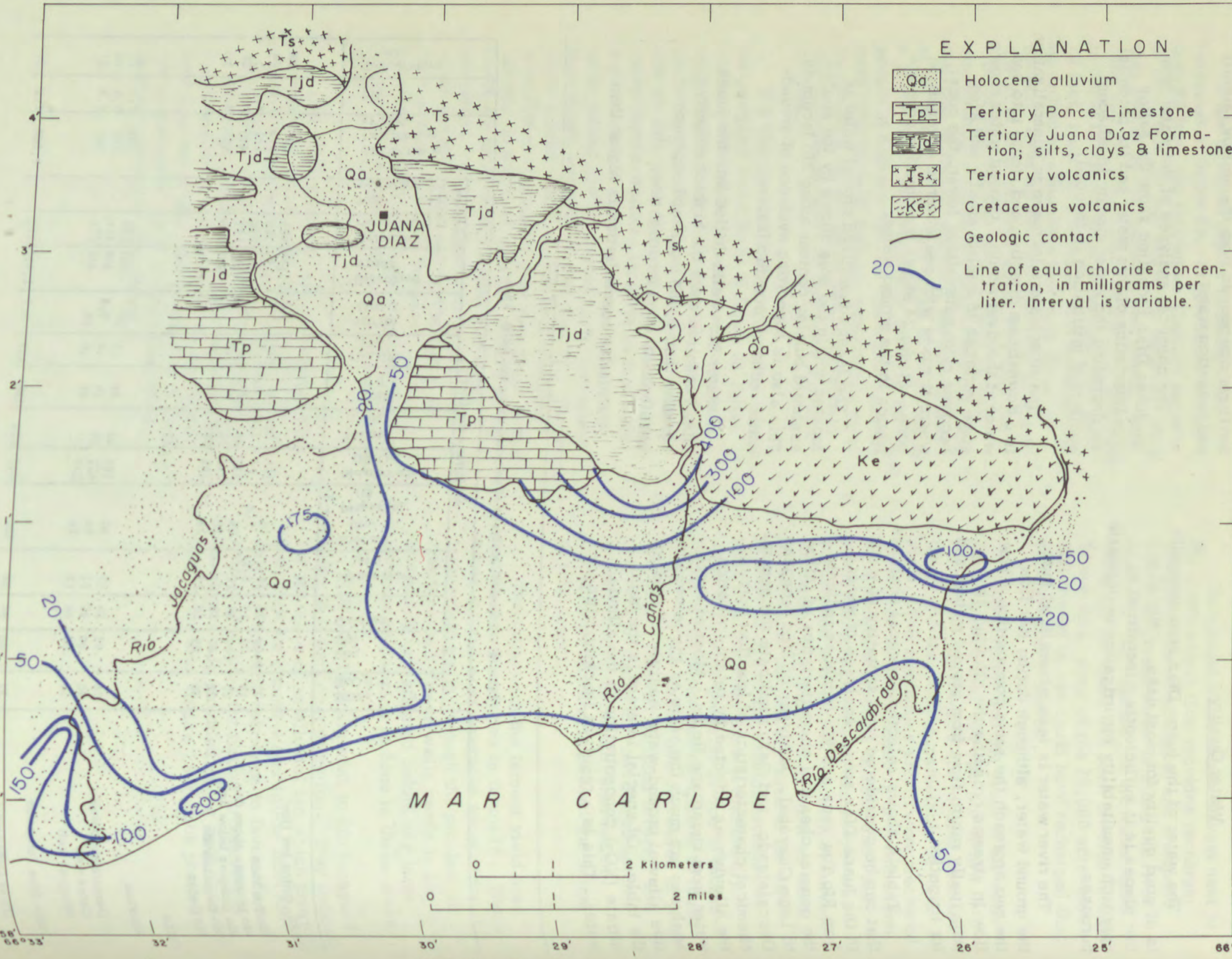

Figure 24.--Concentration of chloride in ground water.

average near the mouths of Ríos Jacaguas and Descalabrado. This indicates possible saline intrusion, and any substantial increase of ground water pumping there should be undertaken with caution.

A series of water-quality monitoring wells should be placed in operation before any large increase in ground-water production takes place. These wells ideally should be placed not only near the river mouths, but also across the entire alluvial area at strategic locations.

Hydrologic Budget

Figure 25 illustrates schematically what happened to the water in the coastal plain in 1966. The numbers underlined are values actually measured. The others are assumed, and however reasonable they may be, they may be either high or low, though their sums

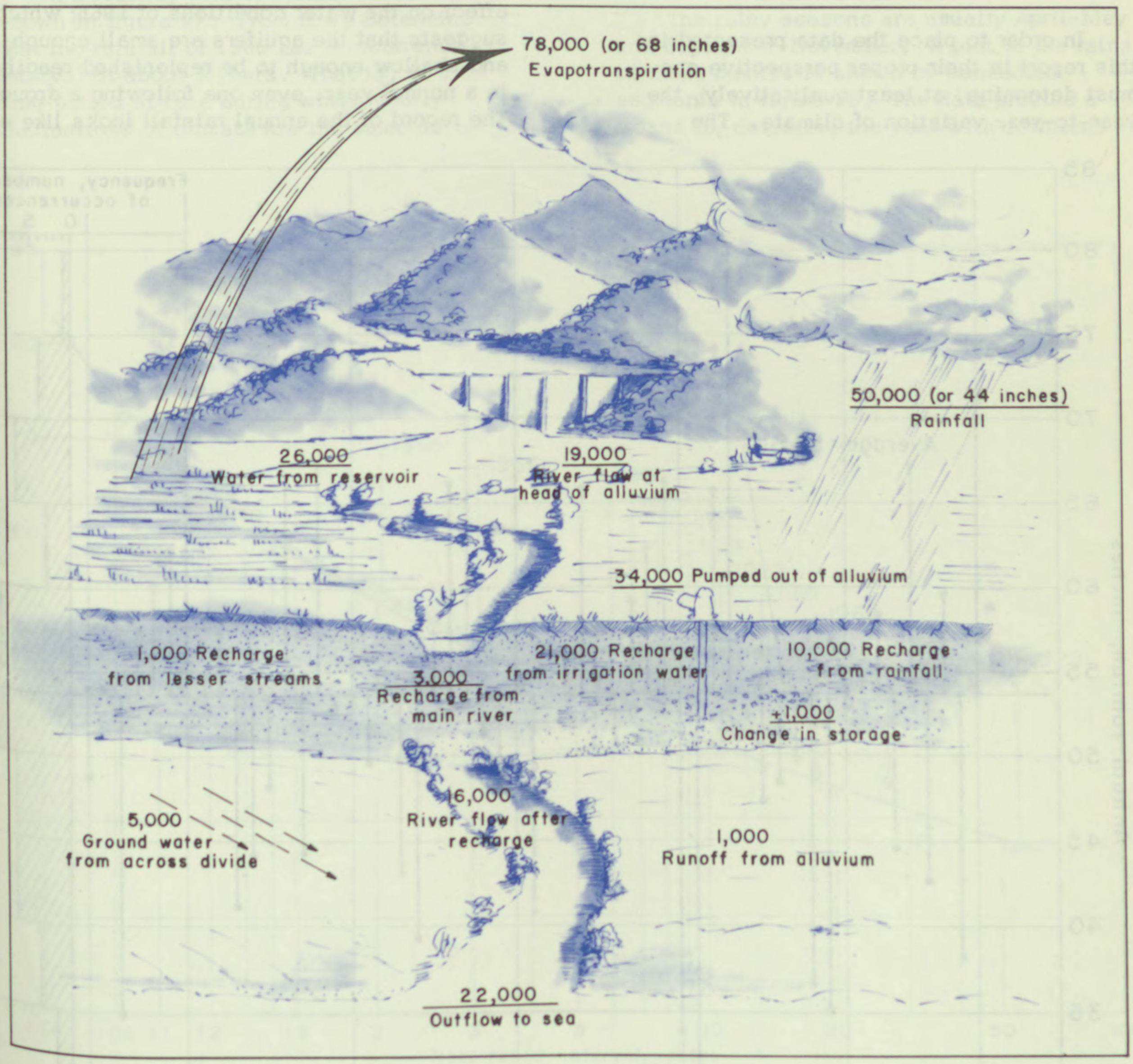

Figure 25.--Hydrologic budget in 1966, Juana Díaz area. Quantities are in acre-feet, underlined if recorded; others are estimates, except evapotranspiration which is a residual.

must balance the measured totals.

Certainly the 22,000 acre-feet that flowed to sea represents a substantial amount of water that could have been stored for later use. The proposed dam on Río Toa Vaca would reduce such losses to sea.

Climatic Variations

In order to place the data presented in this report in their proper perspective one must determine, at least qualitatively, the year-to-year variation of climate. The rainfall data collected at Lago Guayabal since 1912 are used for this purpose.

The yearly rainfall is shown in figure 26, and from it we determine that 1966 was a below-average year. It followed an average year (1965) which in turn followed a severely dry year (1964). Analysis of the data acquired during the study period does not indicate that the drought of 1964 had any effect on the water conditions of 1966; which suggests that the aquifers are small enough and shallow enough to be replenished readily in a normal year, even one following a drought. The record of the annual rainfall looks like a

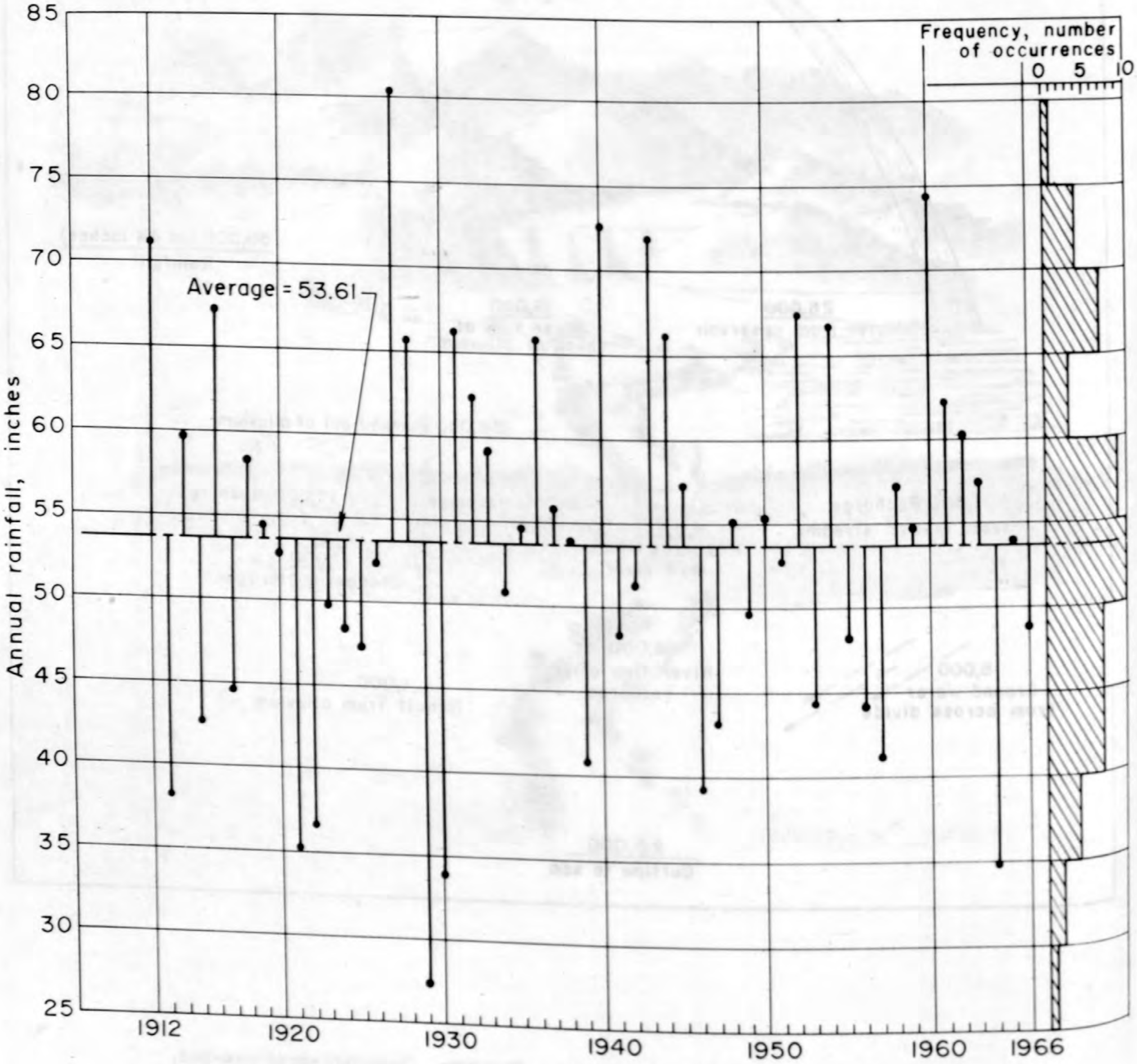

Figure 26.--Yearly rainfall at Lago Guayabal, 1912-66. (Data from Puerto Rico Water Resources Authority.)

random series; that is, the rainfall in any one year bears no relation to what fell the year before or any previous year. A simple statistical test on the "runs"--the consecutive number of values above and below the median--shows that the number of runs of the annual rainfall at Lago Guayabal is about the same as the average found in a sample drawn from a series of random numbers.

A frequency plot of annual rainfall is shown in figure 27. From it we determine that the rainfall of 1966 has a recurrence interval of about 3 years. That is, in a long period of time during which yearly fluctuations of climate are the same as those found here, in 1 out of 3 years we can expect the rainfall to be about the same as that of 1966. The return period of the rainfall of 1964 is about 15 years, and that is how often we can expect a drought as serious as the one of 1964. The rainfall of 1929 and 1930 are the lowest recorded and have return periods of 55 and 27 years, respectively. Another severe drought occurred in 1921 and 1922.

The rainy seasons are usually April-May and September-November. A plot of the rains of those months is shown by connected segments in figure 28. The data provide a means for detecting the year with deficient

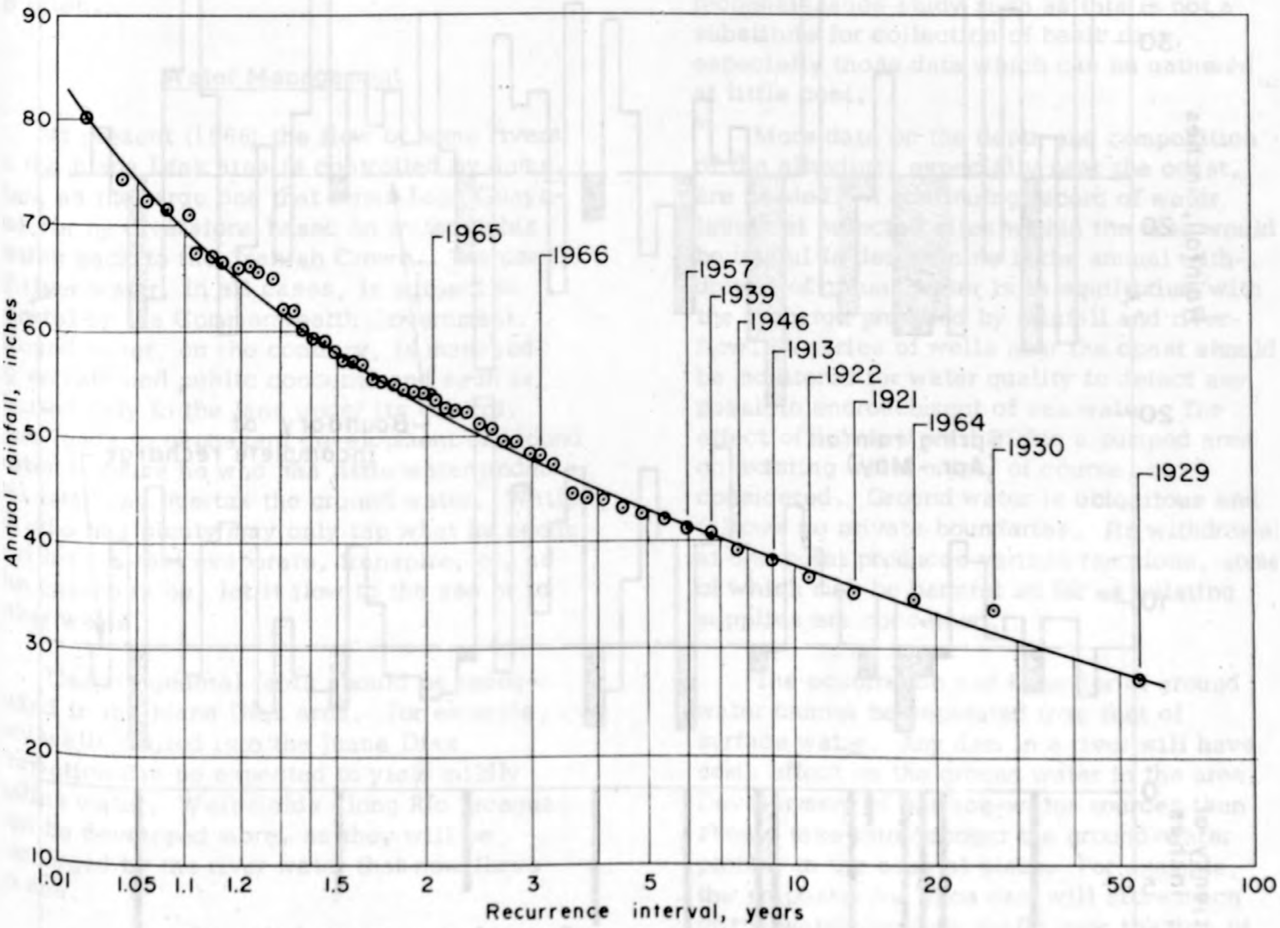

Figure 27.--Frequency of occurrence of annual rainfall, Lago Guayabal, 1912-66.

rainfall for ground-water recharge. As little recharge from spring rainfall took place in 1966, we can estimate a "boundary of no recharge" at about 7 inches of spring rainfall. From the recovery of water levels in the fall of 1966, we can also estimate a "boundary of incomplete recharge" at about 23 inches of autumn rainfall. The years when rainfall was less than 7 inches in the spring and less than 23 inches in the fall form a series of years of deficient recharge. If we add the deviations below the boundaries we obtain an estimate of the severity, as shown at the top of figure 28. Though 1964 stands out as

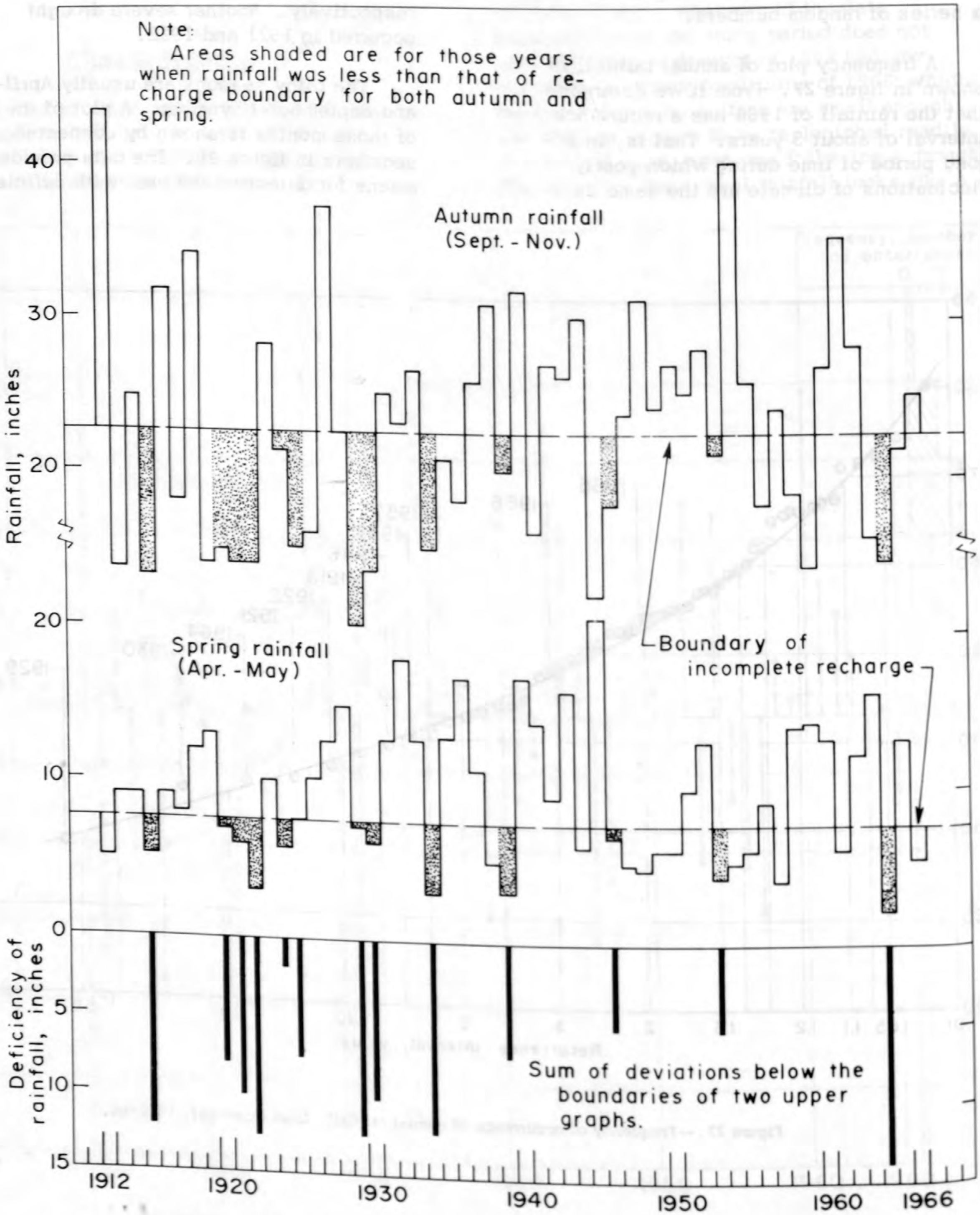

Figure 28.--Relation of rainfall and ground-water recharge.

the driest of all, we have no doubt that in the years 1920-22 and 1929-30 the drought was more intense because of one very dry year following another. (The criteria of drought used here are based on the pumpage during 1966. If pumpage were increased, higher rainfall would be needed to maintain the recharge necessary to continue.)

During work in the field and in talking to farmers we never heard a comment on the shortage of water during the 1920's. Everyone seemed to recall 1964 only; a few mentioned a period in the 1950's. Yet the record speaks clearly--the refrain that history repeats itself is an axiom in hydrology. Water managers who do not take it into consideration and plan accordingly, may find little to manage every so often.

Water Management

At present (1966) the flow of some rivers in the Juana Díaz area is controlled by dams, such as the large one that forms Lago Guayabal, or by diversions based on water rights dating back to the Spanish Crown. The use of river water, in all cases, is subject to control by the Commonwealth Government. Ground water, on the contrary, is managed by private and public concerns and each is limited only to the land under its control. This leads to haphazard development of ground water because he who has little water under his land may overtax the ground water. While he who has plenty may only tap what he needs and let the rest evaporate, transpire, or, as the case may be, let it flow to the sea or to other wells.

Certain general facts should be recognized in the Juana Díaz area. For example, any wells drilled into the Juana Díaz Formation can be expected to yield mildly saline water. Well fields along Río Jacaguas can be developed more, as they will be recharged by the river water that now flows to sea.

We cannot, of course, elaborate in detail on specific sites for well drilling; however, areas worthy of further development are shown in the geohydrologic map of the area (figure 29 in back pocket).

At best, only limited records of water levels, pumpage and pumping rates, and well data are available. Of these, pumpage figures perhaps are the sparsest but most needed data for use in water management. The use of totalizing meters on all wells in the area that pump more than about 10 gpm would afford very useful information for such management.

Unless more and better data are routinely collected and stored at a central location, water managers may have continued difficulty in gathering information on ground water. A reconnaissance study such as this is not a substitute for collection of basic data, especially those data which can be gathered at little cost.

More data on the depth and composition of the alluvium, especially near the coast, are needed. A continuing record of water levels at selected sites within the area would be useful in determining if the annual withdrawal of ground water is in equilibrium with the recharge provided by rainfall and riverflow. A series of wells near the coast should be monitored for water quality to detect any possible encroachment of sea water. The effect of any new well within a pumped area on existing wells must, of course, be considered. Ground water is ubiquitous and follows no private boundaries. Its withdrawal at one point produces various reactions, some of which may be harmful so far as existing supplies are concerned.

The occurrence and behavior of ground water cannot be separated from that of surface water. Any dam in a river will have some effect on the ground water in the area. Development of surface-water sources then should take into account the ground-water picture in the coastal plain. For example, the proposed Toa Vaca dam will store much of the water that now spills over the dam of Lago Guayabal. However, some of this water could be used to recharge the well fields along Río Jacaguas if the water table is lowered through increased pumping. Without such recharge, the pumping from the well field along Río Jacaguas can be increased only moderately.

Areas of critical water shortage are the upper terraces, found along the rivers before they enter the coastal plain. The rivers flow in entrenched channels several tens of feet below the terraces--notably Río Descalabrado where it cuts through two hills before entering the coastal plain. Here, reservoirs storing two or three thousand acre-feet of water could be built without large acquisition of land. Sedimentation, always a problem, would determine the life of the reservoirs, possibly in the neighborhood of 15 years. The water would be available for stock and for irrigation of some of the upper terraces where, during 1964, the shortage of water was serious enough to require emergency action by the Commonwealth Government.

Again one must balance this possible program with the effect it will have on the recharge of the wells in the alluvium where the flow of Río Descalabrado provided most of the recharge in 1966.

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