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RECURSOS DE AGUA DEL VALLE ALUVIAL COSTANERO DEL RIO GRANDE DE ARECIBO, PUERTO RICO

EPARTAMENTO DE
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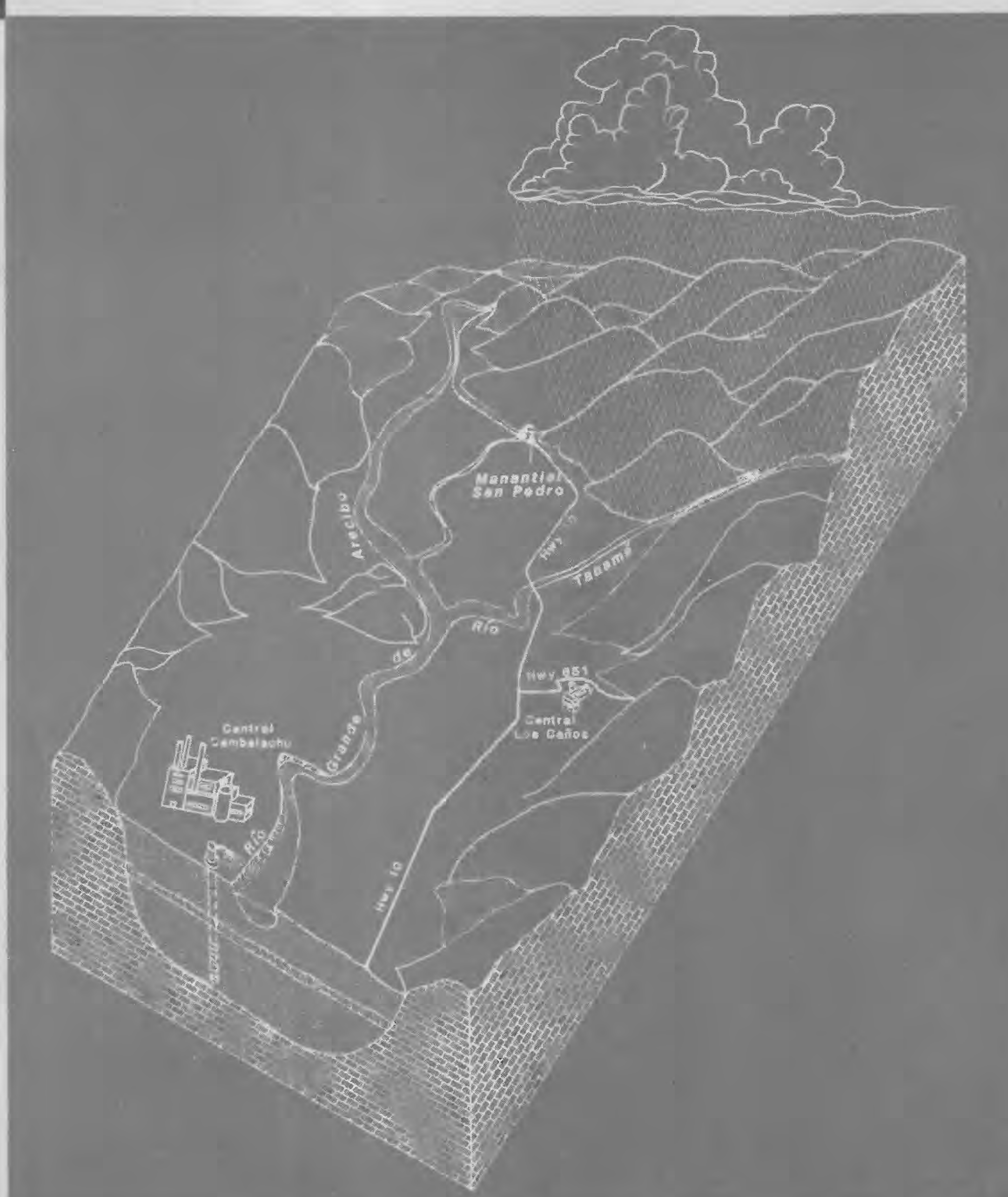
VESTIGACIONES DE
ECURSOS DE AGUA
N 86-1



DEPARTAMENTO
DE RECURSOS
NATURALES

Preparado en cooperación con el
DEPARTAMENTO DEL INTERIOR DE LOS ESTADOS UNIDOS
SERVICIOS GEOLOGICOS, DIVISION DE LOS RECURSOS DE AGUA
Y EL DEPARTAMENTO DE AGRICULTURA DE PUERTO RICO

WATER RESOURCES OF THE LOWER RIO GRANOE OE ARECIBO ALLUVIAL VALLEY, PUERTO RICO

By Vicente Quiñones-Aponte

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS REPORT 85-4160

Prepared in cooperation with the
PUERTO RICO DEPARTMENT OF AGRICULTURE AND THE
PUERTO RICO DEPARTMENT OF NATURAL RESOURCES

San Juan, Puerto Rico
1986

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION TABLE

Factors for converting inch-pound units to
International System of Units (SI)

Multiply Inch-Pound Units	By	To Obtain SI units
inches (in)	25.4	millimeters (mm)
inches per hour (in/h)	25.4	millimeters per hour (mm/h)
	2.54	centimeters per hour (cm/h)
feet (ft)	0.3048	meters (m)
feet per mile (ft/mi)	0.1894	meters per kilometer (m/km)
miles (mi)	1.609	kilometers (k)
square miles (mi^2)	2.590	square kilometers (km^2)
acres	4047.	square meters (m^2)
acre-feet (acre-ft)	1233.	cubic meters (m^3)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
	3785.	cubic meters per day (m^3/d)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
pounds	453.6	grams (g)

TEMPERATURE CONVERSION

°F (degree Fahrenheit)	5/9 (°F-32)	°C (degree Celcius)

SPECIFIC COMBINATIONS

1 Acre-ft/yr = 0.0008921 Mgal/d
= 0.0013804 ft^3/s
1 Acre-ft = 226.2 gal/min, during one day
1 ft^3/s = 448.8 gal/min
1 ft^3/s = 0.65 Mgal/d
1 Mgal/d = 694 gal/min

WATER RESOURCES OF THE LOWER RIO GRANDE DE ARECIBO ALLUVIAL VALLEY, PUERTO RICO

By
Vicente Quiñones-Aponte

ABSTRACT

An assessment of the surface- and ground-water resources of the lower Río Grande de Arecibo alluvial valley was made between 1981 and 1983. Río Grande de Arecibo is the major source of water in the valley with a mean-annual discharge of 527 cubic feet per second (382,000 acre-feet per year). Its lowest mean-daily flow (low flow) during 12 years of record is 50 cubic feet per second. Withdrawals of water from Río Grande de Arecibo exceeding 15 cubic feet per second during periods of extreme low flows could cause reduction of recharge to the aquifer. However, withdrawals of as much as 35 cubic feet per second are possible when base flow ranges from 90 to 200 cubic feet per second without causing a reduction of aquifer recharge.

An unconfined aquifer within the alluvial valley is hydraulically continuous with bordering limestone formations. A clay layer divides the alluvial aquifer into two separate hydraulic system. Ground water from the alluvial aquifer above the clay layer has not been widely developed. However, high-yielding wells presently yield as much as 9.6 million gallons per day (10,800 acre-feet per year) from the aquifers occurring below the clay layer within the alluvium and underlaying limestones.

Transmissivity ranges from 3,000 feet squared per day in the alluvial area to 42,000 feet squared per day in the adjacent limestone areas. Total ground-water flow through aquifers within the study area (excluding water withdrawn by wells) is about 20.6 million gallons per day (23,100 acre-feet per year). Fifty percent of this amount is estimated to flow to the eastern area of Caño Tiburones and discharges as springs and seeps. An estimated 9.4 million gallons per day (10,500 acre-feet per year) of additional ground water can be withdrawn from the aquifers below the clay layer without reversing the northward hydraulic gradient.

Seepage from Río Grande de Arecibo to the ground-water system at the east side of the valley is probably the key to the development of ground-water resources in the Arecibo area. San Pedro spring, with an average discharge of 8.6 million gallons per day (9,600 acre-feet per year), is undeveloped and represents a potential alternate source of water.

INTRODUCTION

The lower Río Grande de Arecibo Valley (fig. 1 and Plate 1) is a water-abundant area of Puerto Rico. Its principal drainage feature, Río Grande de Arecibo, has the highest mean-annual discharge (527 ft^3/s, 13 years of record) of any stream in Puerto Rico. The area also has abundant ground-water resources within alluvial and shallow limestone aquifers.

In recent years the lower valley of the Río Grande de Arecibo has been subjected to intensive ground- and surface-water development for public and agricultural water supplies. At present 9.6 Mgal/d of water are withdrawn from wells throughout the lower valley. Further large scale withdrawal of water from the river is proposed. The Puerto Rico Department of Agriculture (PRDOA) plans to withdraw about 30,000 acre-ft/yr from Río Grande de Arecibo for rice irrigation in Caño Tiburones and in the central and lower parts of the valley (oral comm., Luís Picó, PRDOA, 1983). Conflicting plans exist for diverting 179,360 acre-ft/yr from Dos Bocas reservoir to San Juan to supplement the public-water supply (Santiago Vázquez and others, 1982, p. 29).

In 1981, the U.S. Geological Survey, Water Resources Division, began a 3-year investigation of the water resources of the lower Río Grande de Arecibo Valley. The project was conducted in cooperation with the Puerto Rico Department of Agriculture and the Puerto Rico Department of Natural Resources.

The objectives of the investigation were to:

- o Determine the availability of surface water and of ground water in the alluvium and the Aymamón and Aguada Limestones in the lower Río Grande de Arecibo valley.

- o Determine the general surface- and ground-water quality throughout the study area and estimate the depth and areal location of saline water within the shallow aquifers.

- o Determine the thickness of the alluvial deposits.

- o Locate areas in the valley alluvium that receive the greatest amount of stream seepage and recharge from aquifers within the limestones.

- o Determine the quantity and quality of water discharging from major springs and seeps in the study area.

- o Estimate the hydrologic budget of the lower Río Grande de Arecibo valley.

To meet the project objectives, a data-collection program was implemented throughout the valley (fig. 1 and table 1, in pocket) as follows:

- o Determination of water levels in wells and adjoining surface-water features throughout the valley.

- o Seepage-run studies of Río Grande de Arecibo.

- o Surface-geophysical prospecting (surface-electrical resistivity and seismic-refraction surveys).

- o Operation of streamflow and springflow data collection stations.

- o Pumping tests to estimate the hydraulic characteristics of the alluvial, alluvial-limestone, and limestone aquifers.

- o Collection of water samples

for laboratory determination of major ions, nutrients, and for bacteriological analyses.

This report summarizes the results of the investigation including the flow characteristics of the Río Grande de Arecibo and Río Tanamá, and the occurrence, availability, and chemical nature of ground-water resources in the lower Río Grande de Arecibo alluvial valley. Investigation of the deep artesian systems, occurring below the Aguada Limestone (Giusti and Bennett, 1976, p.17), was beyond the scope of this study.

The assistance of the Puerto Rico Department of Agriculture (PRDOA) and the Puerto Rico Aqueduct and Sewer Authority (PRASA) is gratefully acknowledged. Personnel from both agencies, who provided special assistance and cooperation during the field investigation were: Marcos Mercado (PRDOA), Enid Ramírez (PRASA), José Mercado (PRASA), and Gil Serrano (PRASA). Thanks to Pedro Vivas, Jr., who provided hydrologic data obtained during the drilling of Santana artesian well.

Special acknowledgment is due to personnel of the U.S. Geological Survey (Angel Román-Más and Frank Johnson), who contributed to the success of the investigation.

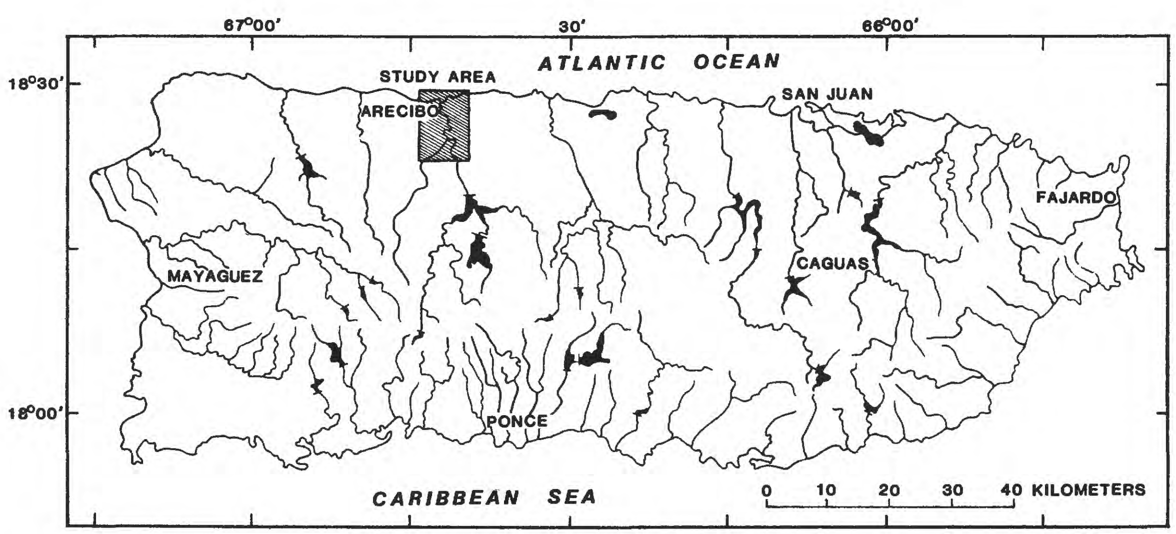


Figure 1.—Location of Lower Río Grande de Arecibo Study Area.

LOCATION AND DESCRIPTION OF STUDY AREA

The lower Río Grande de Arecibo Valley is 45 mi west of San Juan and comprises an area of about 31.5 mi^2 (Plate 1). The study area extends from the Atlantic Ocean on the north to about 7.0 mi inland where the alluvial valley narrows to 0.5 mi in width. The valley is bounded by the town of Arecibo to the west; the Atlantic Ocean, and Caño Tiburones (a former marine slough) to the north and northeast; mogotes (karst topography "haystack" hills) to the east; and cockpit karst topography with steep-walled ridges to the south and west. The western third of the Caño Tiburones and the upper Río Grande de Arecibo basin were included in the investigation when they related hydrologically to studies within the lower valley.

Most of the valley is used for agricultural purposes. During 1982-83 sugar-cane cultivation occupied about 55 percent of the valley, rice plantations about 30 percent, and pastures (for dairy) about 15 percent (fig. 2). However, PRDOA plans to increase rice cultivation to about 65 percent of the total valley area, and reduce the area planted in sugarcane.

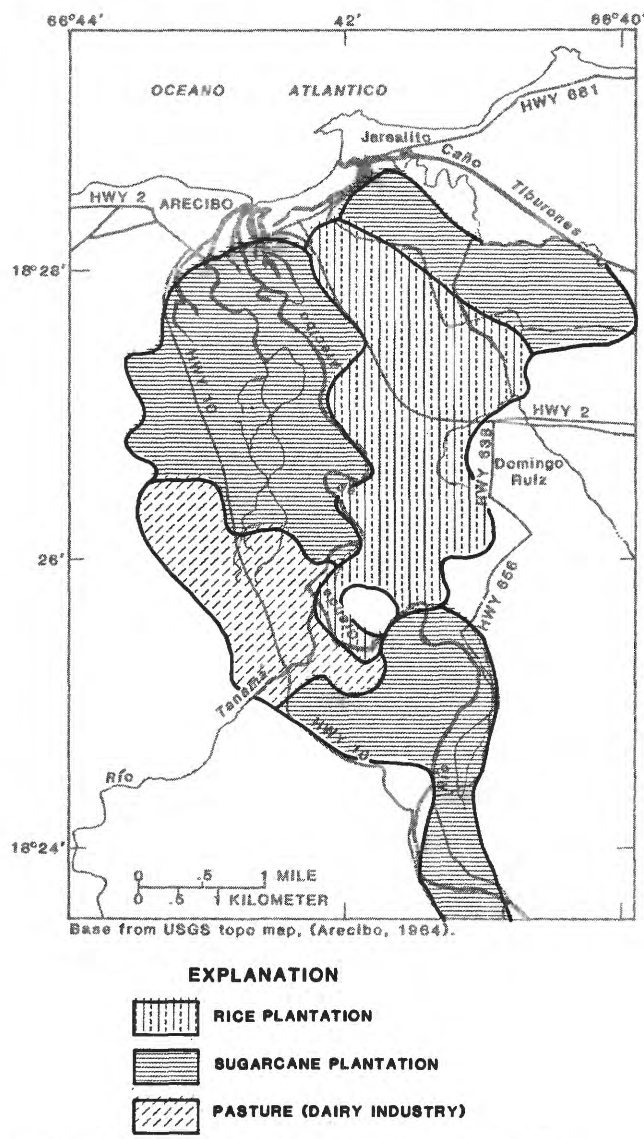


Figure 2.--Generalized land use in the valley, during 1982-83.

Land Forms

The lower Río Grande de Arecibo Valley has very little topographic relief. According to Monroe (1976, p. 17), the formation of this valley commenced with the erosion and dissolution of limestones (early middle Miocene) by abrasion and the effect of slightly acidic rainfall on soluble limestone, forming a wide steep-sided canyon that narrows inland. The rapid erosion which led to the steep-sided canyon was a consequence of the capture of the upper basin by Río Grande de Arecibo from the ancestral Río Culebrinas about 3.8 million years ago (Giusti, 1978, p. 55). Finally, the deposition of sediments transported by that river has formed the alluvial valley (late Quaternary). Abandoned stream channels in the lower part of the valley indicates eastward migration of the river (fig. 3).

Aereal photograph by U.S. Coast and Geodetic Survey (1960).
APPROXIMATED SCALE 1:19,000

Figure 3.--River meandering morphology in the study area.

Climate

Wills (1955, p.72) classified the climate of the lower Río Grande de Arecibo Valley as a "rainy trade wind climate" with abundant precipitation, relatively high temperatures, a large percentage of days with sunshine, and a potential for hurricanes. The general wind direction is from the northeast.

The mean-annual rainfall in the lower valley is about 70 in. (24,300 acre-ft). It varies within the study area from 60 in. at the coast to 80 in. at the most southern extent of the study area (fig. 4). In general, altitude deter-

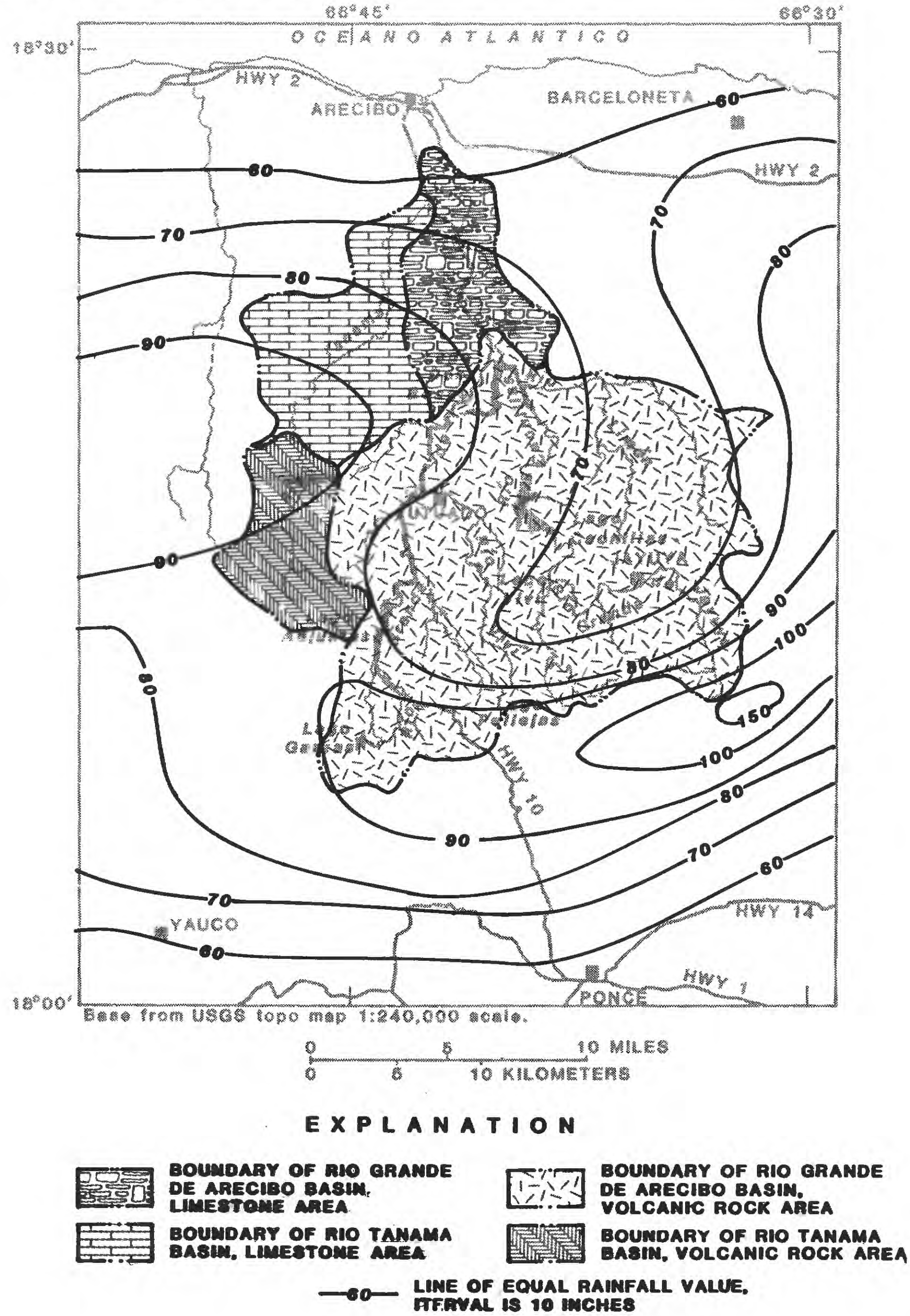


Figure 4.--Isohyetal of mean annual rainfall values over the study area and associated areas (from Calvesbert, R.J., 1970).

mines the rainfall distribution throughout the Río Grande de Arecibo basin (rainfall in the uppermost part of the basin will approach 150 in/yr). Although copious amounts of rainfall can occur at any time during the year, the seasonal variation of rainfall can be categorized as follows: a relatively dry period from December to March, a spring-rainy period in April and May, a relative short dry period in June and July, and a relatively wet season from August to November (fig. 5).

The average-annual air temperature is about 24°C in the Río Grande de Arecibo basin. Daily temperature varies only a few degrees throughout the year within the study area.

Total evapotranspiration (ET), from the lower valley, was estimated as 48 in/yr (16,800 acre-ft/yr) utilizing an empirical relation developed by Giusti (1978, p. 21). According to Giusti, rainfall and ET are controlled by the same climatological factors, although they are not directly related.

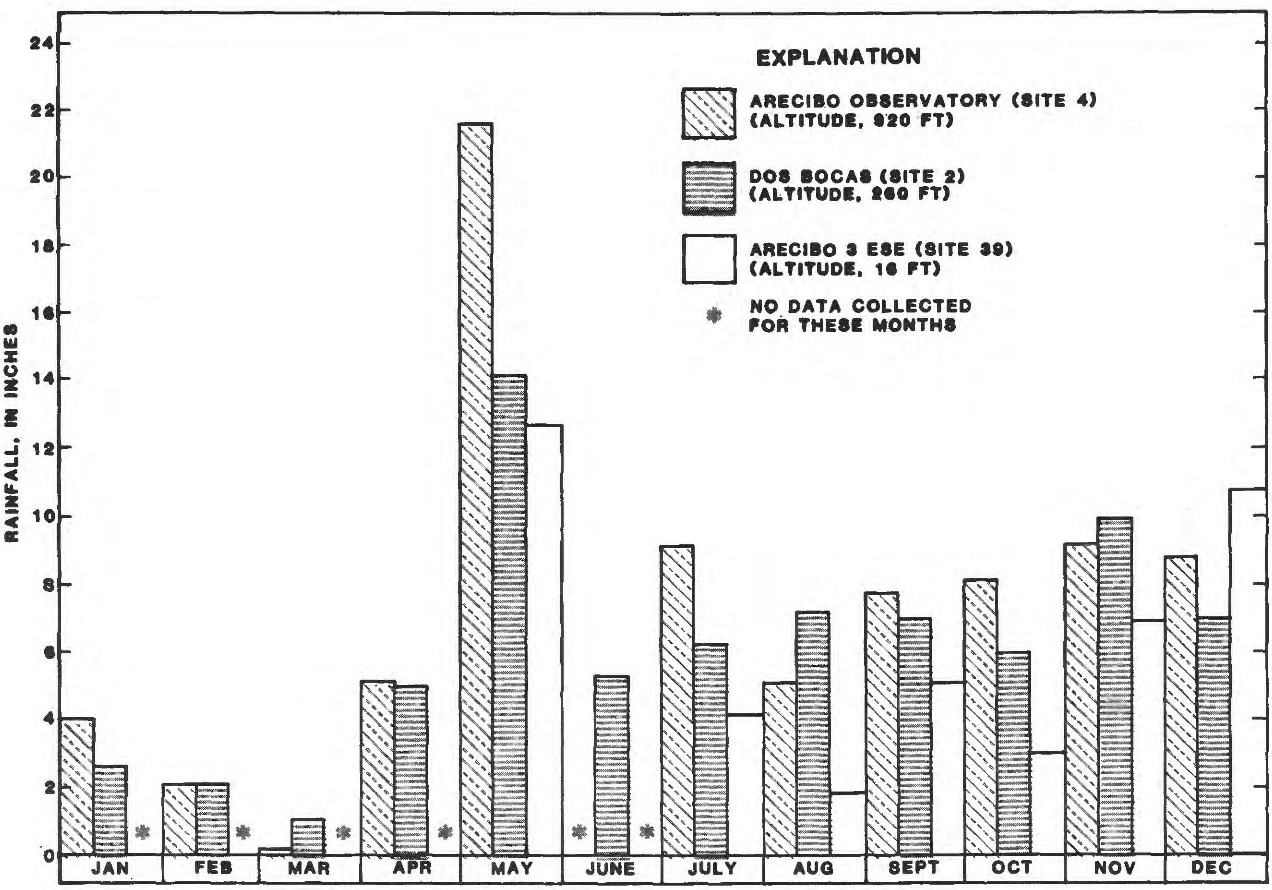


Figure 5.—Mean monthly rainfall at Arecibo observatory, Dos Bocas dam, and Arecibo 3 ESE for 1982. (Data from U.S. National Oceanic and Atmospheric Administration (NOAA), 1982).

The entire Río Grande de Arecibo basin is divided in two sub-basins, based on the geology of the formations underlying the alluvial sediments (fig. 6). This report describes the lower Río Grande de Arecibo Valley which represents less than 15 percent of the total basin drainage area and is incised in limestone deposits of Tertiary age (North Coast Limestone Belt). The upper basin drains volcanic rocks of Cretaceous age (fig. 6). The geology within the lower Río Grande de Arecibo valley is dominated by the following lithologic formations: flood-plain alluvium, swamp deposits, lagoonal deposits, and blanket deposits (fig. 7). The geologic formations through which the lower alluvial valley is cut consists of six Tertiary formations above basement rocks, from oldest, to youngest:

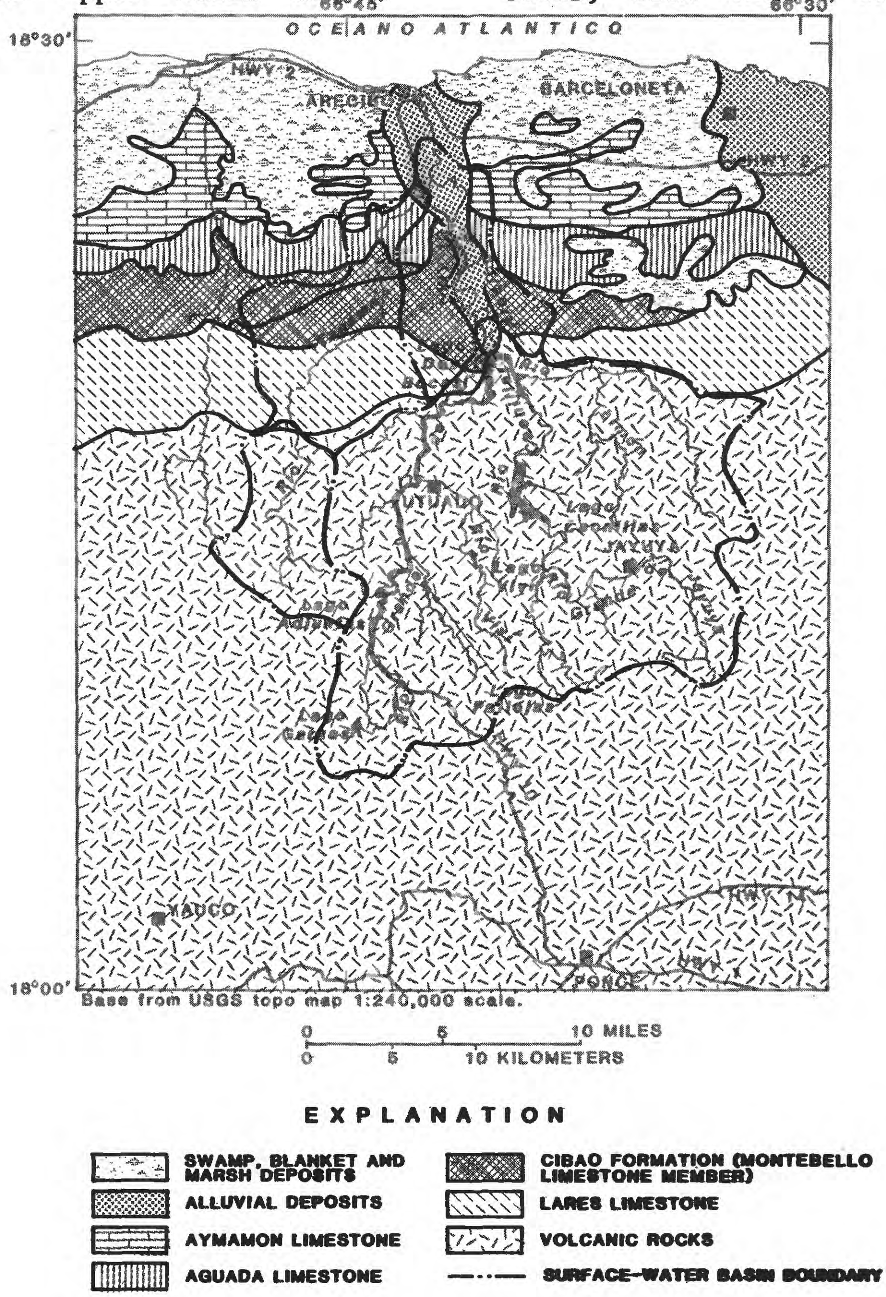


Figure 6.--Generalized surficial geology of Río Grande de Arecibo basin, (modified from Monroe, 1980).

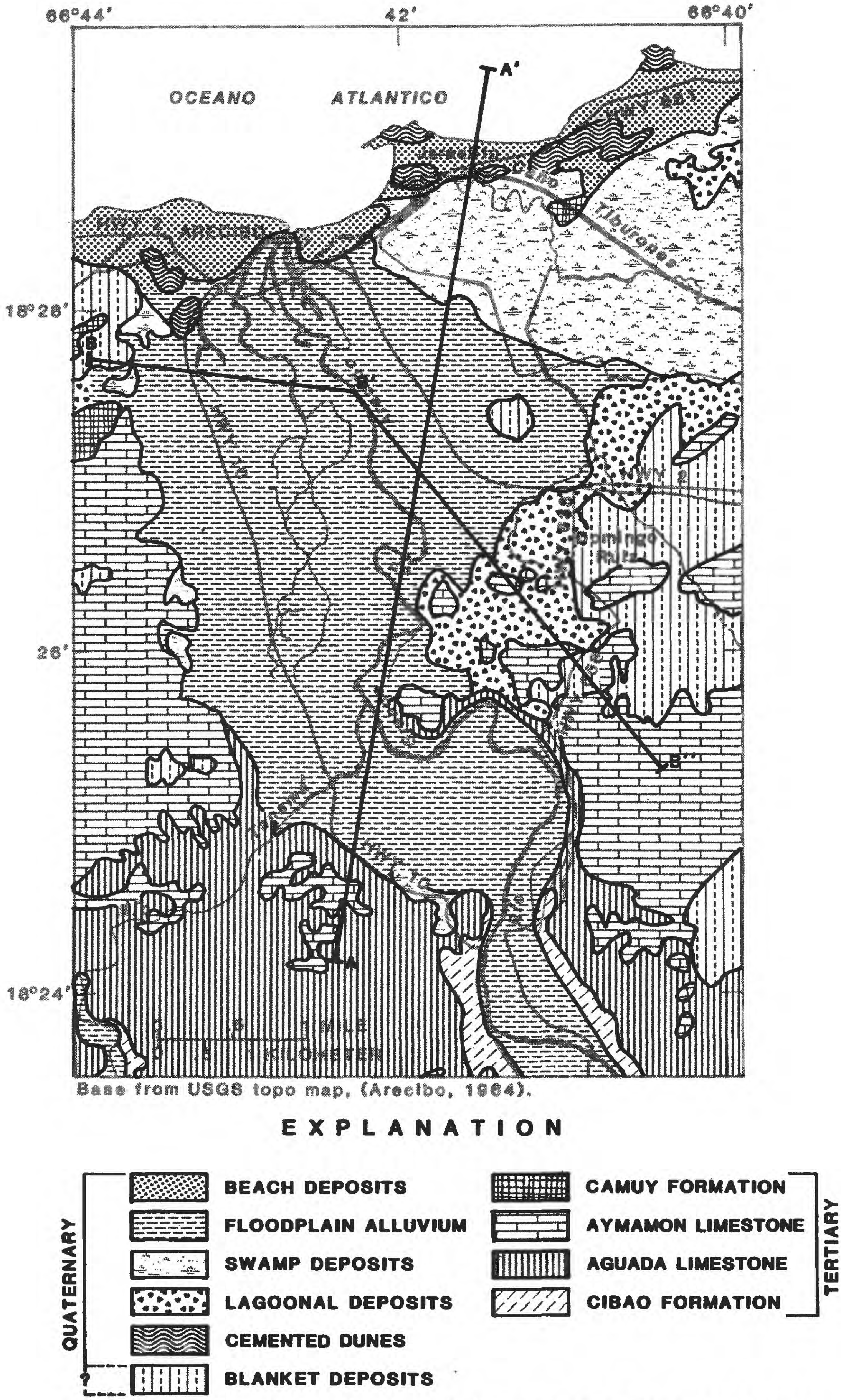


Figure 7.—Generalized surficial geology of the study area. (Modified from Briggs, 1968).

San Sebastián Formation, Lares Limestone, Cibao Formation, Aguada Limestone, Aymamón Limestone, and Camuy Formation (fig. 8 (sections A-A' and B-B'-B")). Briggs (1961) described these formations for the oil test well (4CPR) drilled near the coast at Caño Tiburones. The Camuy Formation has been almost completely eroded in the lower Río Grande de Arecibo Valley.

The top of an areally extensive gray clay (about 40 ft thick) occurs throughout the alluvium about 30 to 40 ft below the land surface (fig. 9). The clay con-

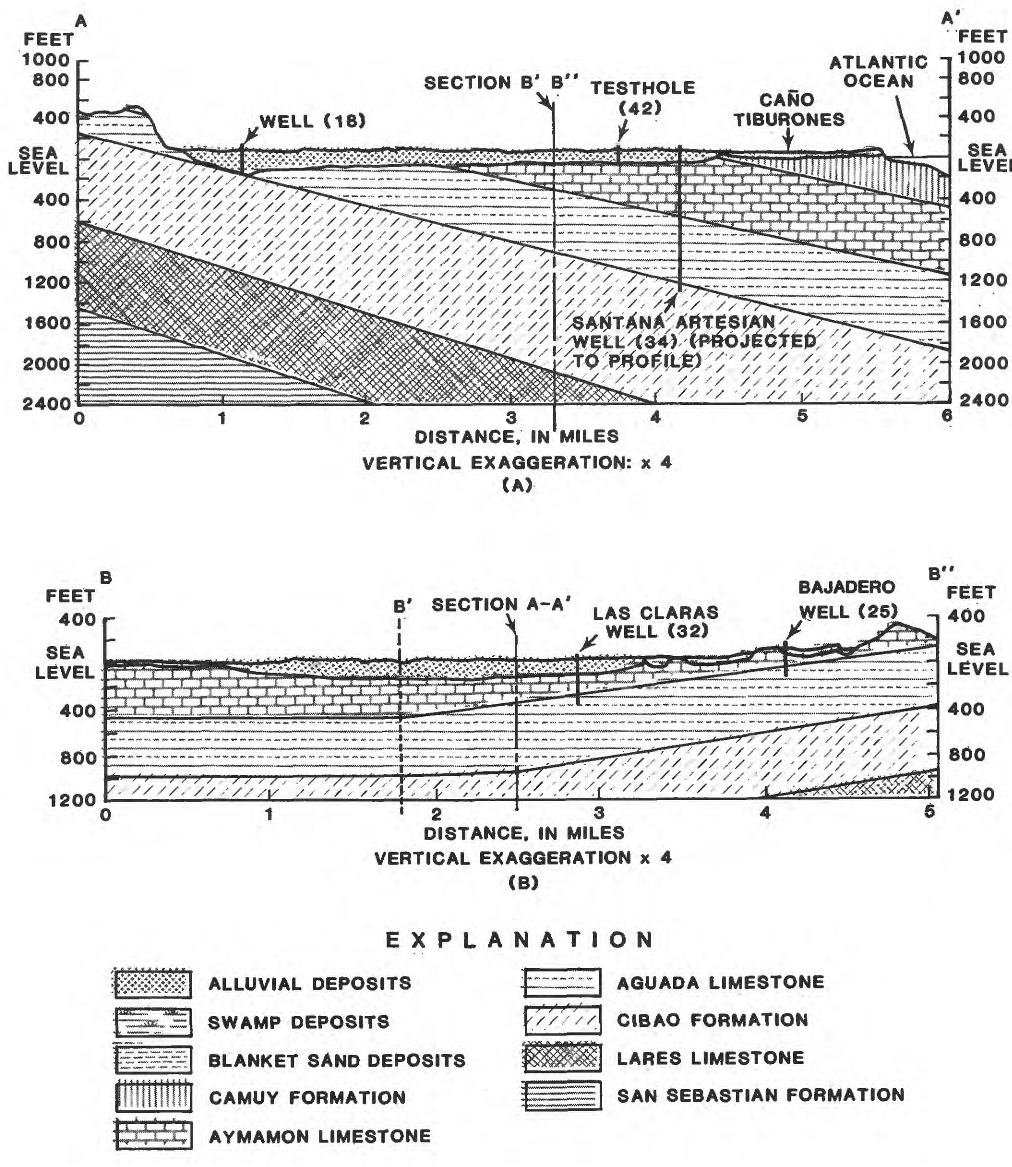


Figure 8.--Generalized subsurface geology for sections A-A', and B-B'-B''. (See fig. 7 for location of sections).

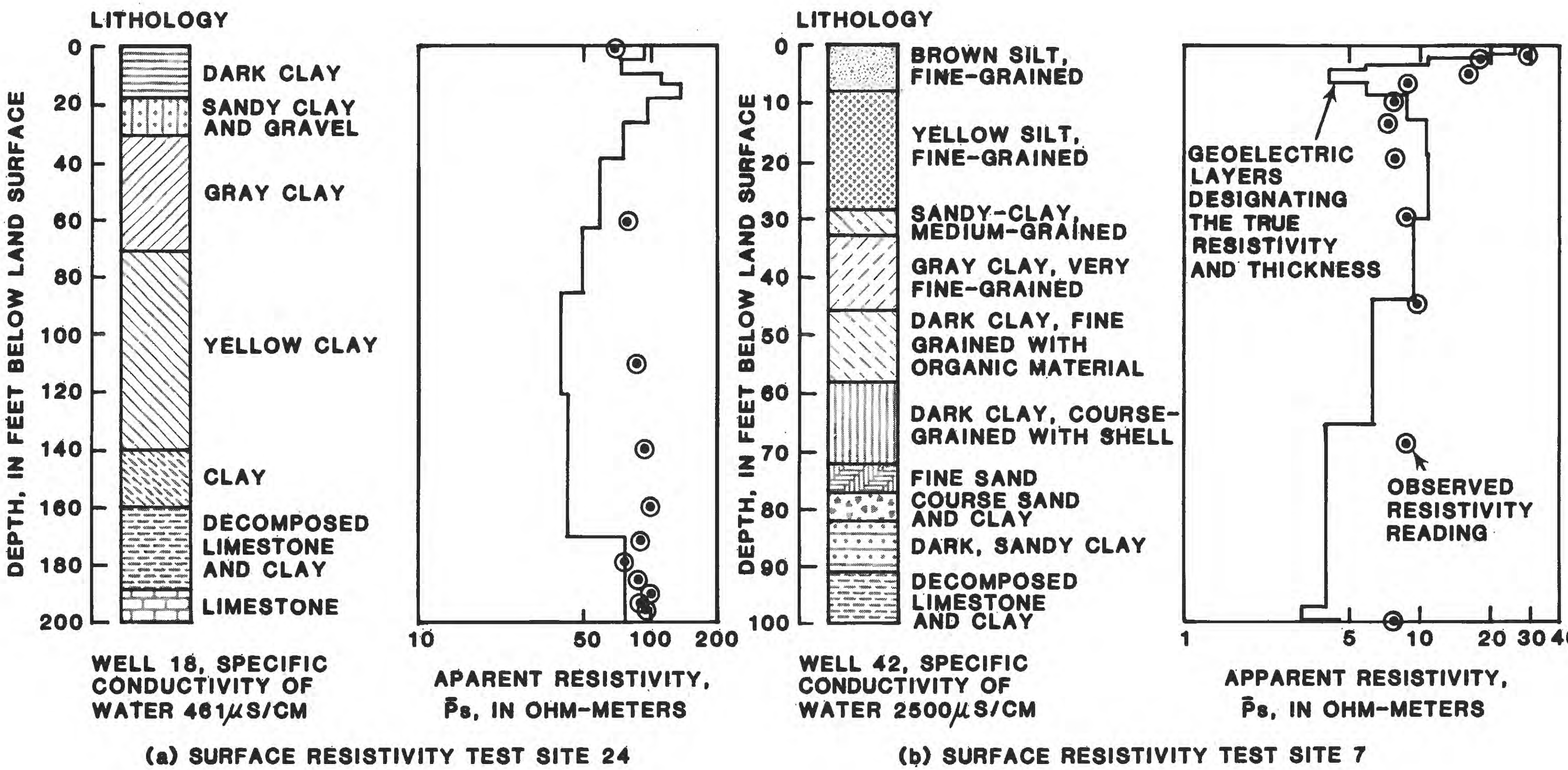


Figure 9.--Effect of specific conductance of aquifer fluids on surface-resistivity profiles for two areas having similar lithology. Observed resistivity data collected by the schlumberger method (Schlumberger well surveying corporation, 1962). Geoelectric layers determined by method described by Zody (Zody, 1973).

tains fine grained sand, residues of organic matter, and shells. The alluvial lithology was determined by interpreting drillers logs of wells 11, 12, 14, 17, 18, 25, 32, and 42, and surface-geophysical testing (fig. 10). Resistivity surveys were utilized to determine the inland extent of saline water in the alluvial aquifer, and seismic surveys were designed to determine the thickness of the alluvium or depth to limestone. Interpretation of results from these tests was made by correlation with drillers logs of nearby wells (fig. 10). Results from surface electrical-resistivity tests are influenced by the specific conductance of aquifer fluids (fig. 9). Therefore, lithologic characterization based on the results of surface-resistivity studies must take into consideration the specific conductance of the water contained in the sediments. Analyses of groundwater-quality data were utilized to identify areas where water quality would affect resistivity values of a particular lithology.

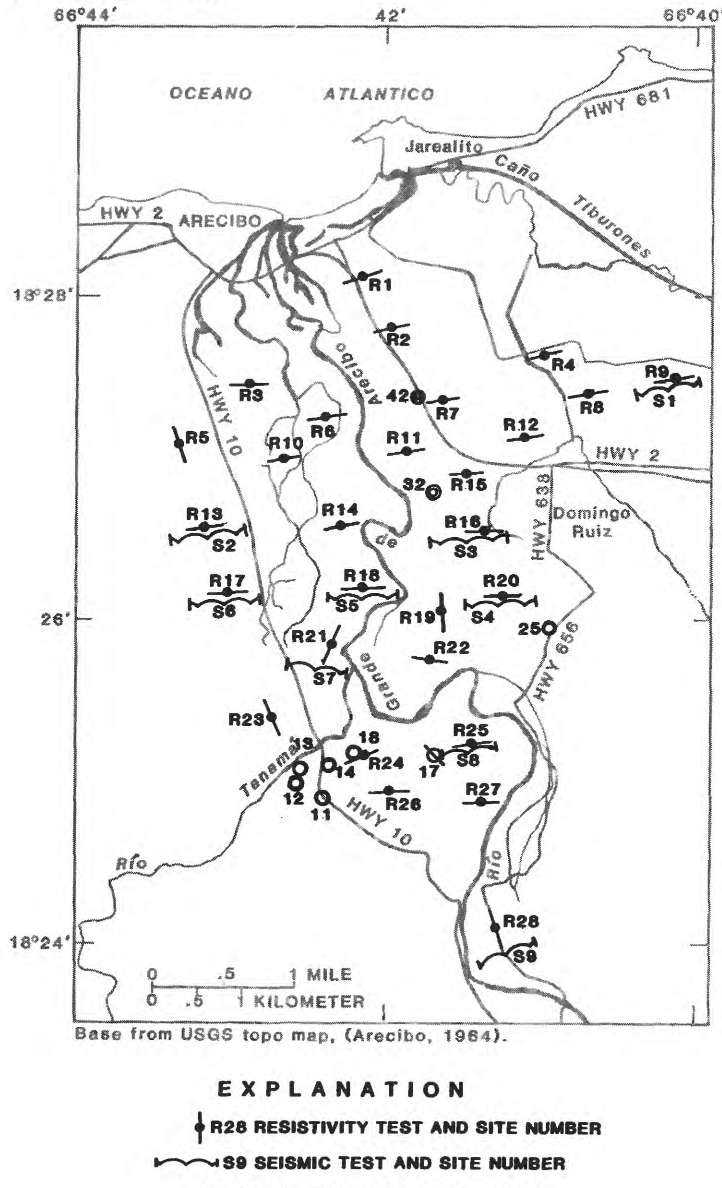


Figure 10.--Location of surface geophysical test and control points, (data collected during 1982-83).

The average thickness of the alluvium above the Aymamón and Aguada Limestones is about 130 ft throughout most of the valley. However, the alluvium is about 300 ft thick in the southeast part of the valley, where a deep canyon was formed several thousand years ago by the river (fig. 11). The depth to which the river cut the valley seems to have been controlled by the sea level minima (the lower altitude of the sea level throughout the glaciation cycle) of the last glaciation (Fairbridge, 1960, p. 8). This thinning of alluvium seaward suggests that at one time Río Grande de Arecibo was a subterranean river flowing underground through soluble limestones, from the southeast of the valley to Caño Tiburones.

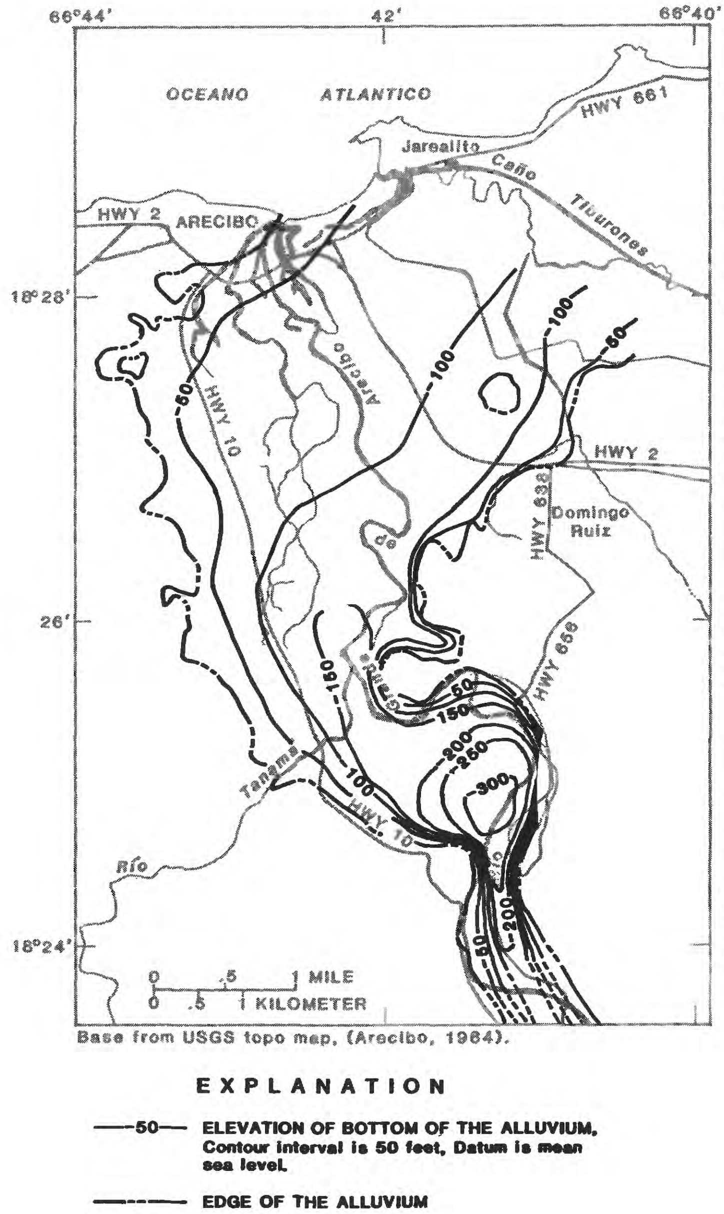


Figure 11.--Lines of equal elevation of the bottom of the alluvium.

HYDROLOGY

Surface Water

The major surface-water features of the lower Río Grande de Arecibo Valley are Río Grande de Arecibo, Río Tanamá, and a small channel which conveys water from San Pedro spring. At the river mouth, drainage areas of Río Grande de Arecibo and Río Tanamá, are about 251 and 51 mi^2, respectively.

Streamflow

Río Grande de Arecibo is the principal stream in the study area and has the largest mean-annual discharge of all streams in Puerto Rico. Its major tributary, Río Tanamá, flows through the alluvial valley into Río Grande de Arecibo 4.6 miles from the mouth of Río Grande de Arecibo. The mean-annual discharge of Río Grande de Arecibo and Río Tanamá are 527 ft^3/s (382,000 acre-ft/yr, 13 years of records, at site 38, Plate 1), and 108 ft^3/s (78,200 acre-ft/yr, estimated at site 10, Plate 1) respectively. Streamflow of Río Grande de Arecibo and Río Tanamá are typical of rivers on the north coast of Puerto Rico: baseflow recession occurs from January to April, a short period of baseflow increases from May to June, another short recession from July to August, and baseflow increases from September to December (fig. 12).

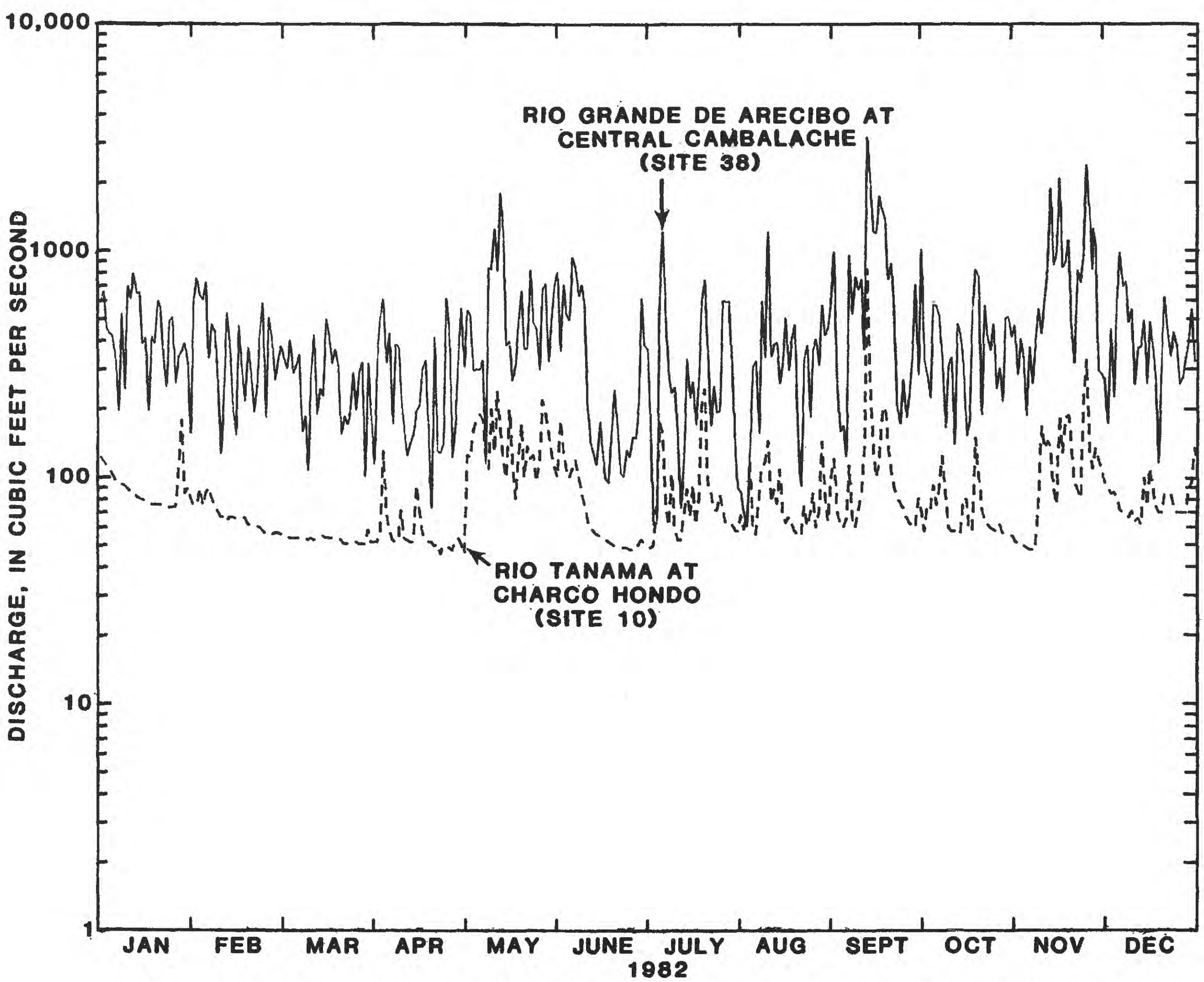


Figure 12.--Mean-daily discharge of Río Grande de Arecibo and Río Tanamá.

Streamflow is regulated at several sites in the Río Grande de Arecibo basin: by a hydroelectric plant at Dos Bocas reservoir (22,000 acre-ft storage), and a public-water supply diversion structure located 1.3 miles upstream from the mouth of Río Tanamá (4.0 ft^3/s, Plate 1).

Although there are other reservoirs (Garzas, Adjuntas, Pellejas, Viví, Jordan, and Caonillas, fig. 6) within the basin, Dos Bocas reservoir and the Río Tanamá diversion are the only regulations which directly affect the streamflow in the study area. A typical daily release of water from Dos Bocas reservoir is about 12,000,000 ft^3 (275 acre-ft, fig. 13).

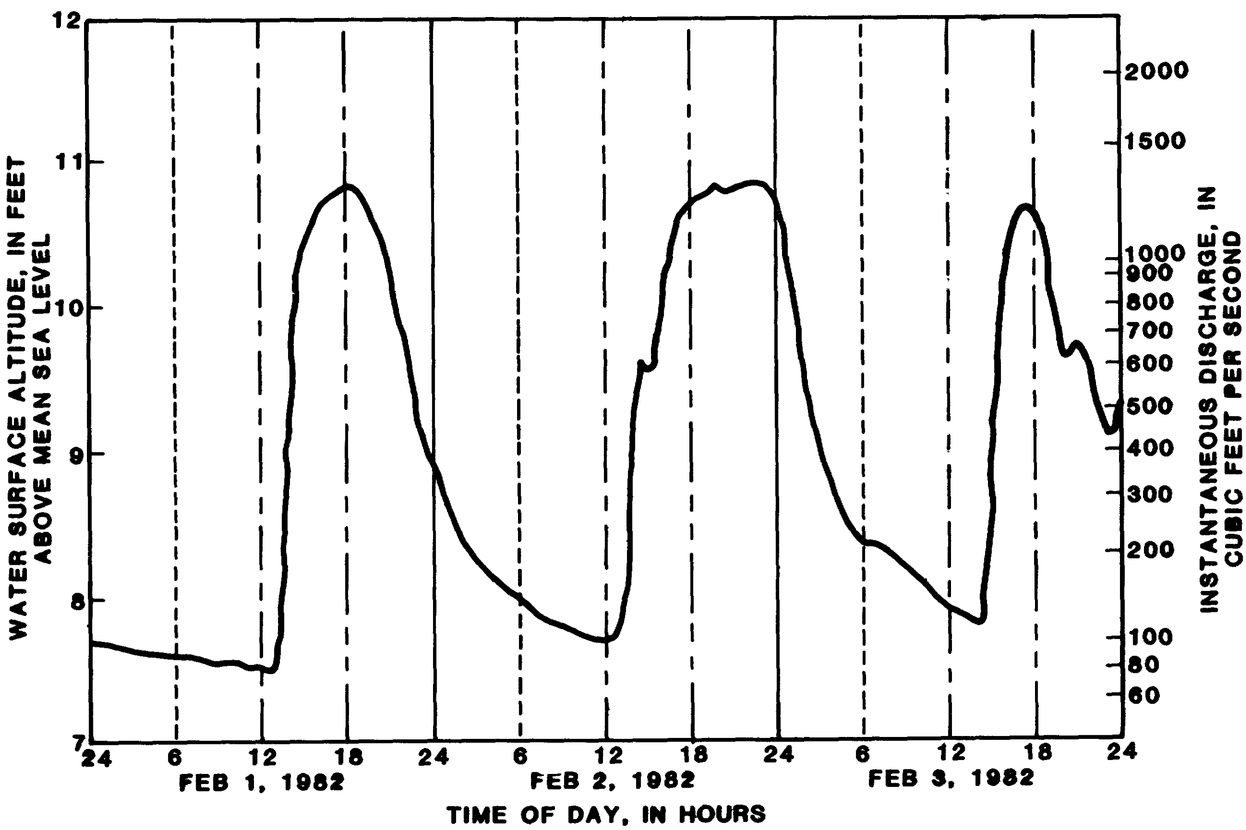


Figure 13.--Stage and discharge variations of Río Grande de Arecibo (site 38) as result of water releases from Dos Bocas reservoir.

Long-term continuous records are required to establish reliable stream-flow statistics. A continuous-record period of at least 10 years has been found to be satisfactory for most purposes. For stream sites which have less than 10 years of records, or for which only instantaneous stream-flow measurements exist, correlations can help to estimate long-term statistical parameters such as the 7-day 10-year minimum flow and mean-annual flow. Correlations between concurrent flows of stream sites within Río Grande de Arecibo basin having short-term and long-term periods of records were used to estimate streamflow statistical parameters at short-record sites within the basin (fig. 14).

Streamflow (Continued)

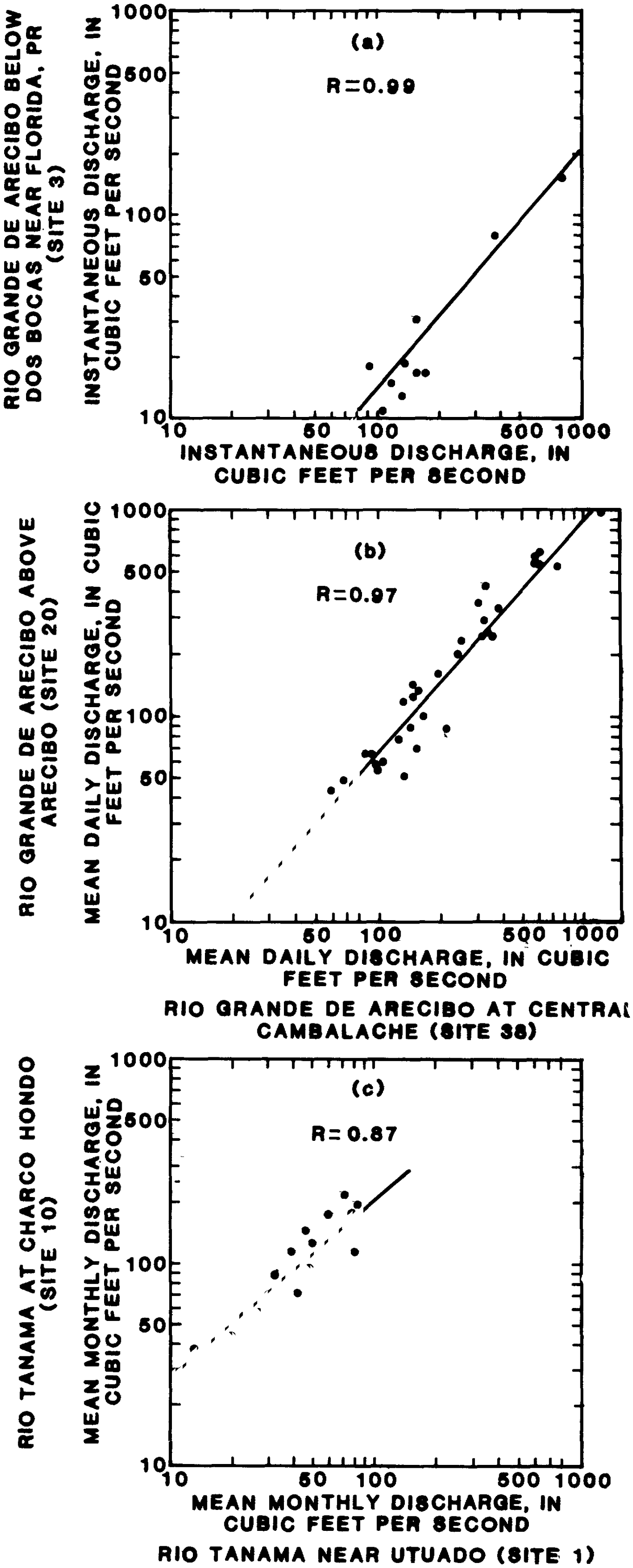


Figure 14.--Correlation between discharges at stream sites: 38 and 3, 38 and 20, and 1 and 10.

Flow Duration

A flow-duration curve is an accumulative frequency curve that shows the percent of time during which a specified discharge is equaled or exceeded in a given period. This statistical tool is useful in stream assessments for hydroelectric power, flooding, water supply, and waste assimilation. Statistical procedures in the development of duration curves are discussed in papers by Foster (1924, 1934), Slade (1936), and others.

Duration curves developed for Río Grande de Arecibo at Central Cambalache and Río Tanamá near Utuado are relatively straight, indicating that flow is controlled either by impoundments or that significant ground-water discharge exists within the basin (fig. 15).

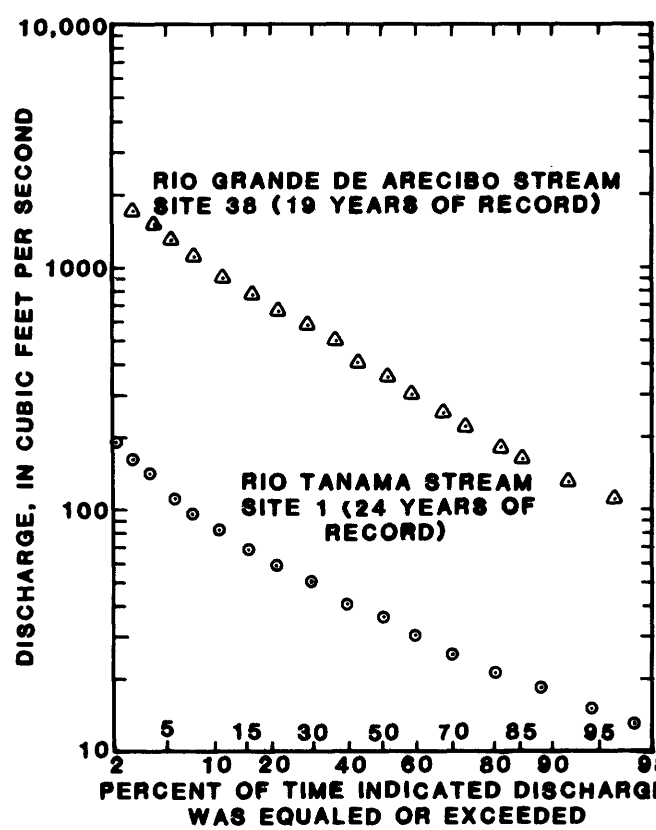


Figure 15.--Flow-duration curves of daily values for Río Grande de Arecibo and Río Tanamá.

Flow Duration(Continued)

Flow-duration curves developed utilizing values for individual months are useful for water-supply studies in which a seasonal evaluation is necessary. A tabulation of values obtained from these curves characterizes the streamflow behavior during the year (table 2).

For Río Grande de Arecibo at site 38, the analysis indicates that for the first 7-consecutive months of the year, the expected discharge would be greater than or equal to 120 ft^3/s during 90 percent of the time, and 275 ft^3/s during 50 percent of the time (table 2).

Table 2.--Summary of monthly flow duration analyses for Río Grande de Arecibo (site 38).

CLASS, IN CUBIC FEET PER SECOND	DURATION FOR PERIOD OF RECORD PERCENT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	100	100	100	100	100	100	100	100	100	100	100	100	100
60	100												
70	100		99					99					
83	99		98			99	99	98	99				
97	98	99	97	98	98	98	97	97	97				
110	96	96	95	95	94	95	93	95	96				97
130	92	89	90	88	88	91	87	90	93	98		98	96
160	86	80	80	79	79	86	81	83	85	94		96	90
180	82	74	75	74	73	84	77	79	80	91	99	94	86
220	73	65	61	63	63	77	70	70	70	86	98	88	75
250	67	58	53	54	57	72	63	62	64	82	97	86	67
300	59	46	42	44	47	65	56	53	55	74	93	80	60
350	51	36	33	34	38	58	51	45	44	67	89	75	54
410	43	28	23	24	31	52	43	36	34	57	80	66	47
480	36	23	14	18	25	43	35	29	27	50	71	59	41
560	29	14	8.5	13	19	35	30	22	21	43	59	49	35
660	22	7.7	2.5	10	14	27	22	15	15	35	49	41	25
780	16	4.0	0.5	6.2	8.5	20	16	8.8	8.8	30	39	33	19
910	12	1.5	0.0	3.2	5.1	14	11	5.1	5.8	24	29	27	12
1100	8.0	0.3		1.0	3.6	9.2	7.4	3.2	3.7	17	22	19	6.7
1300	5.6	0.0		0.5	1.3	6.2	4.3	1.8	2.3	14	17	14	4.7
1500	4.2			0.0	1.0	4.0	4.1	1.4	1.6	10	13	11	4.0
1700	3.0				0.8	3.2	2.9	0.7	0.7	6.9	9.2	7.2	3.5
2000	2.0				0.3	2.0	1.9	0.5	0.2	5.0	5.7	5.1	2.2
2400	1.2				0.3	1.2	1.2	0.2		3.1	2.2	3.3	1.7
2800	0.8				0.0	0.7	0.7	0.2		2.6	2.2	1.8	0.7
3300	0.5					0.3	0.2	0.0		1.7	1.5	1.3	
3800	0.4						0.2			1.4	1.2	1.0	
4500	0.2						0.0			1.0	1.0	0.3	0.3
5300	0.2									0.7	0.7		
6200	0.2									0.7	0.3		
7300	0.2									0.5	0.0		
8600	0.1									0.5		0.0	
10000	0.1									0.0			
12000	0.0												0.0

Minimum Flow

The availability of streamflow to satisfy requirements for waste assimilation, municipal and industrial supplies, supplemental irrigation, and maintenance of suitable conditions for aquatic life is commonly evaluated in terms of minimum-flow characteristics. Values of the 1-, 7-, and 30-day minimum flows are commonly used to evaluate the minimum-flow characteristics of streams. Theory and procedures to determine these values are given by Riggs (1972).

Minimum-flow characteristics can be best visualized by graphics. The 1-, 7-, and 30-day minimum-flow values and probability percent of occurrence decrease as the recurrence interval increases (fig. 16). Therefore, the longer the recurrence interval, the more critical the minimum-flow values become. The 10-year recurrence interval (equivalent to 90 percent probability of occurrence) is the most commonly utilized in Puerto Rico because it is considered sufficiently critical for planning purposes, and streamflow records longer than 20 years of length are often not available. Table 3 summarizes the 1-, 7-, and 30-day minimum-flow values for a 10-year recurrence interval at different locations within the Río Grande de Arecibo basin. In the same manner that Dos Bocas reservoir affects the streamflow of Río Grande de Arecibo, statistical analyses such as minimum-flow statistics are affected.

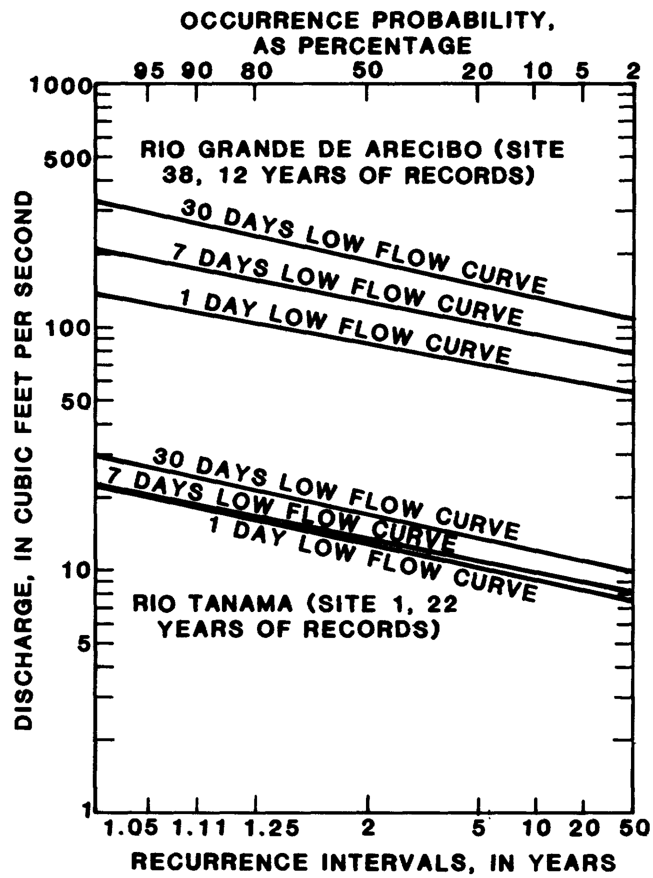


Figure 16.--Minimum flow curves for Río Grande de Arecibo and Río Tanamá.

Table 3.--Summary of minimum flow values at selected stream sites in Río Grande de Arecibo basin.

STREAM SITE NUMBER	STREAM LOW-FLOW DISCHARGE AT 10 YEARS RECURRENCE INTERVAL (ft^3/s)		
	Q1,10	Q7,10	Q30,10
38	64.0	93.0	130.0
20	35.0*	58.0*	94.0*
1	9.2	9.3	12.0
10	26.4*	26.6*	32.0*

*values estimated through correlation (see figure 14b and 14c).

Floods

The lower Río Grande de Arecibo valley has been inundated several times during the last 83 years (1899-1982). The greatest flood on record occurred on August 8, 1899 with an estimated peak discharge of 242,000 ft^3/s and the second greatest on September 13, 1928 with an estimated peak discharge of 103,500 ft^3/s (Hickenlooper 1968; table 4).

About 32 percent of the peak discharge for larger floods would be attenuated by temporary storage in Garzas, Dos Bocas, and Caonillas reservoirs (Hickenlooper, 1968). These reservoirs were constructed upstream from the study area between 1942-1948. The greatest flood on record after the construction of dams occurred on October 13, 1954. Peak discharge was estimated as 52,000 ft^3/s for this event.

The lower alluvial valley has been completely inundated during major floods with an average of 4 feet of water (fig.17). Overbank flows occur wherever the instantaneous discharge exceeds 17,000 ft^3/s at site 38. Streamflow records indicate that flows of this magnitude or greater can be expected at an average of two times every 7 years.

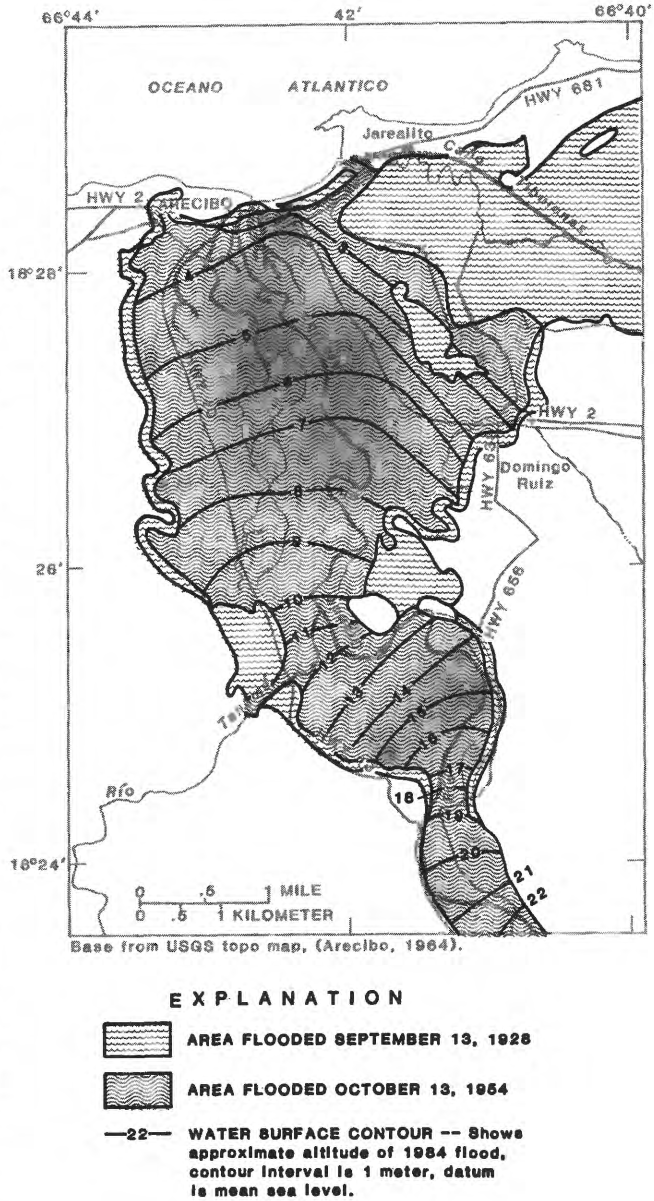


Figure 17.--Approximate area inundated during floods of September 13, 1928 and October 13, 1954 (Hickenlooper, 1968).

Table 4.--Flood discharges of Río Grande de Arecibo at Dos Bocas dam (drainage area is 169 square miles).

DATE	DISCHARGE (ft /s)
08-08-1899	242,000*
09-13-1928	103,500*
05-19-1940	90,000*
10-13-1954	76,000

*Before the construction of Dos Bocas, Caonillas and Garzas dams

Data from Lopez and others, 1979, p.43.

Hydrogeology

Aquifers in the study area, occurring in both limestone and alluvium, are part of the north coast regional limestone aquifer system. This system is composed of unconfined aquifers within the Aymamón and Aguada Limestones, as well as the alluvium. Two deep confined aquifers (fig. 8, section A-A'), one in the Montebello Limestone Member of the Cibao Formation and the other in the Lares Limestone (Giusti and Bennett, 1976, p. 17) are beyond the scope of this report. The alluvium lies in a valley incised into the Aymamón and Aguada Limestones (fig. 8, section B-B'-B"), and is in hydraulic contact with both. Water in the Aymamón and Aguada Limestones occurs under unconfined conditions throughout the area; however, within the valley hydrologic conditions are somewhat different than in the bordering limestone. The areally extensive clay located 30 to 40 ft below the land surface tends to isolate hydraulically the alluvium above the clay from alluvial sediments and limestone below it.

Aquifers

Aquifers in the lower valley occur in three geologic units: the alluvium, Aymamón Limestone, and Aguada Limestone. The water table ranges in depth from 15 ft below land surface in the alluvium to as much as 300 ft below land surface in the limestones upland areas adjacent to the valley. West of the alluvial valley the water table in the limestones is of greater altitude than east of the valley. Natural ground-water flow through the alluvial valley is from southwest to northeast. This flow direction is the same above and below the clay layer within the alluvium; however, a smaller quantity of water flows above the clay layer and is governed by the altitude and gradient of this clayey formation.

Within the alluvial valley, the water table occurs from 20 to 40 feet above the clay layer. The water level in wells screened in the alluvial sediments or limestone below the clay generally is 4 to 9 feet below the water table (fig. 18). The water table varies in elevation from 2 to 5 feet between wet and dry months (fig. 18). These relatively small variations in water levels represent an almost constant recharge from the river to the alluvium. For wells screened in the alluvium/limestone below the clay, the fluctuation of water levels is somewhat greater because larger quantities of water are withdrawn from these aquifers by wells.

Apparently, water from the Río Grande de Arecibo seeps continuously to the alluvial sediments above the clay layer, forming the water-table aquifer. Ground-water withdrawals from aquifers below the clay reduce the head in the lower aquifer which causes water to leak downward through the semi-permeable clay. In addition, it is suspected that some water from the alluvial sediments and limestone leaks to the eastern valley wall. Vertical hydraulic equilibrium in the alluvial valley cannot be achieved; water is continuously added to alluvial sediments above the clay and moves downgradient through the clay. At the same time, ground-water withdrawals and leakage out of the alluvial valley to the eastern valley wall reduces the head in the sediment below the clay.

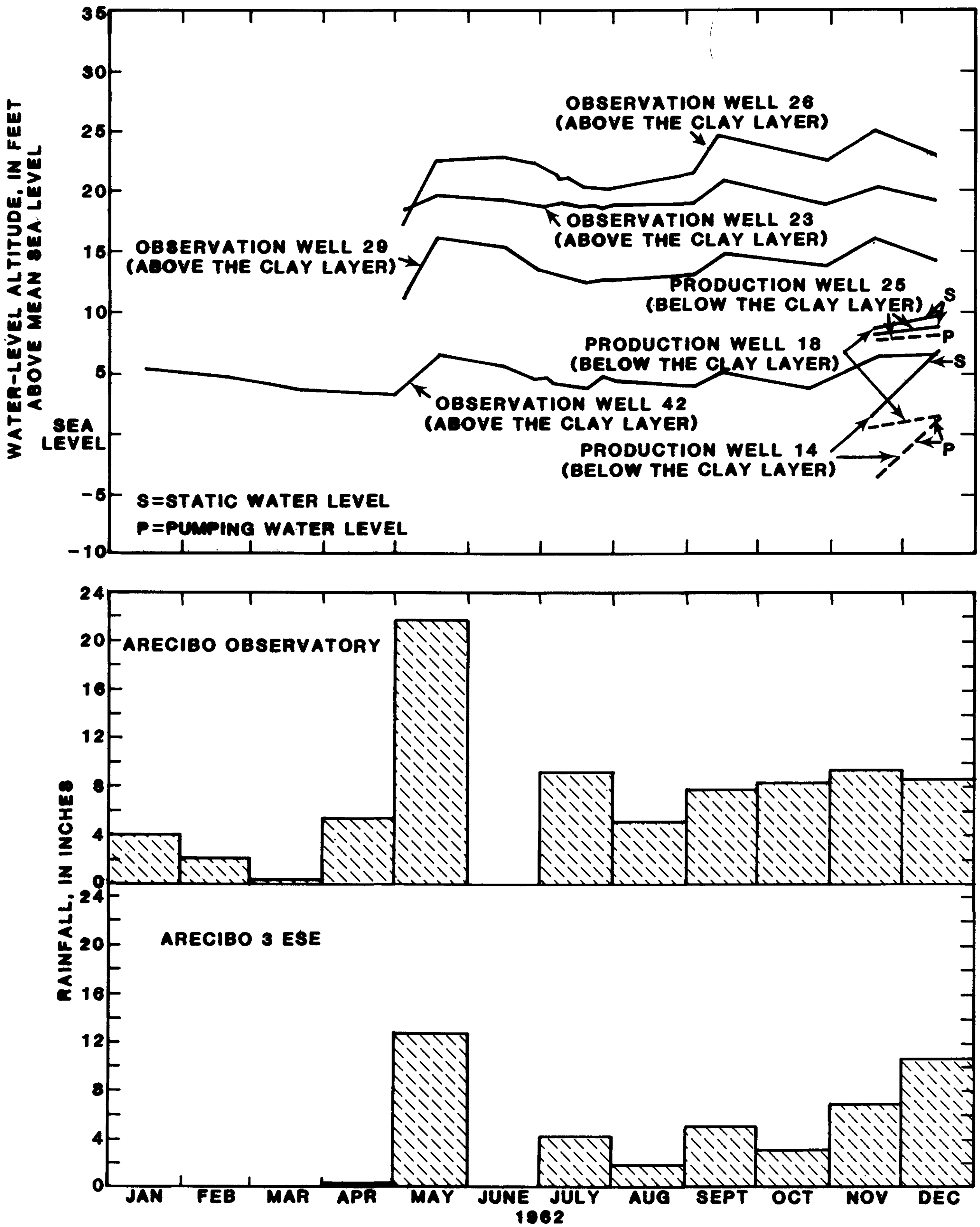


Figure 18.--Water levels in the alluvial aquifer in wells open above or below the clay layer and monthly rainfall in the valley. (See plate 1 and table 1 for locations).

Aquifer Characteristics

The transmissive and storage properties of an aquifer determine its usefulness, in terms of yielding large quantities of water to wells for a long period of time. Pumping tests were conducted at several locations within the valley to estimate the aquifer properties (table 5). The Cooper and Jacob modification of Theis' non-equilibrium equation was used to analyze the tests (Cooper and Jacob, 1946). Estimated values of transmissivity ranging from 3,000 to 5,000 ft^2/d were obtained at wells open to alluvial sediments. An estimated transmissivity value of 42,000 ft^2/d was determined at well 25, which is open to the Aguada and Aymamón Limestones. Pumping tests of wells that penetrate both the alluvium and limestone resulted in estimated values of transmissivity that range between 5,000 and 42,000 ft^2/d.

Estimated values of hydraulic conductivity (K) range from 25 to 40 ft/d for the alluvial aquifer for an average of 33 ft/d.

Giusti and Bennett (1976, p. 21), determined values of average hydraulic conductivity for the Aymamón and Aguada Limestones in the study area as 535 ft/d and 87 ft/d, respectively. Limestone formations are known to be very heterogeneous, particularly where solution cavities occur. Wells are usually open to those parts of the aquifer, generally the upper parts, which are most transmissive. Accordingly, a general value of hydraulic conductivity calculated from transmissivity and saturated thickness will be inaccurate if the entire saturated thickness of the aquifer is assumed to have the same hydraulic conductivity.

Table 5.--Results of selected pumping tests, lower Río Grande de Arecibo valley area.

(1) Well map number	(2) Rate of flow during test (gal/min)	(3) Duration of pumping test (minutes)	(4) Apparent Transmissivity (ft^2/day)
11	510	446	8800
13	740	244	2980
14	690	471	21670
18	400	360	5000
21	2774	408.5	4170
25	455	172	42000

An aquifer test intended to verify the lack of hydraulic connection between aquifers above and below the clay in the alluvium was conducted at well 18 (fig. 19). Two shallow observation wells (25 ft deep) were drilled into the water-table aquifer (above the clay) at distances of 71 and 131 ft from a well 200 ft deep tapping the alluvium and the uppermost part of the limestone (below the clay). The deep well was pumped at 400 gal/min for 26 hours; changes in water levels were not observed in either of the two observation wells. Apparently, the clay layer has a sufficiently low hydraulic conductivity to isolate hydraulically the aquifers within the sediments above and below it (fig. 19) during a short-term aquifer test. This low permeability layer is apparently responsible for the artesian pressures in the upper part of the Aymamón Limestone in Caño Tiburones, reported by Quiñones and others (1970, p. 21), and Zack (1984, p.13). The widespread occurrence of the clay suggests that similar hydraulic isolation occurs throughout most of the valley.

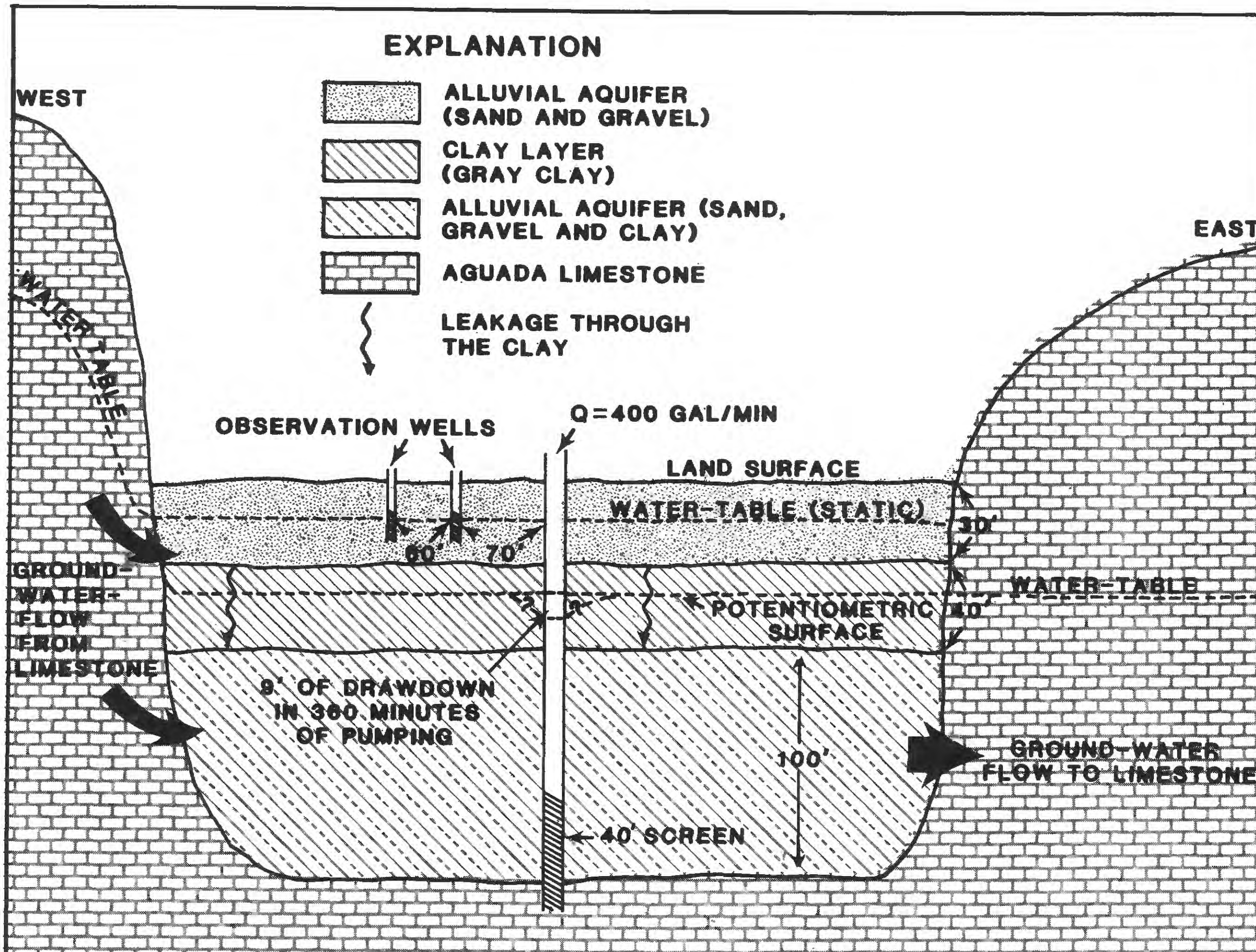


Figure 19.--Schematic representation of some characteristics of the alluvial aquifer and general flow direction at well 18 (not to scale).

Ground-Water Flow

Ground water in the water-table aquifer flows northward and northeasterly to Caño Tiburones (fig. 20). According to Giusti and Bennett (1976, p. 16), ground-water flow below the clay is also northeasterly. Vertical movement of water within the valley aquifer system proceeds from the shallow water-table aquifer to the deeper formations below the clay, from the Aguada Limestone to the alluvium (below the clay) and Aymamón Limestone; from the Aymamón Limestone to the alluvium in the northern part of the valley (fig. 21). Evidence for this ground-water movement (fig. 21) are: 1) the delineation of the salt-water wedge (discussed in a subsequent section), which is a boundary of the aquifer and affects the flow direction, and 2) fresh-water discharge at Caño Tiburones (Díaz, 1973; Zack, 1984, p. 14), which indicates that ground-water flow is discharged to Caño Tiburones rather than being discharged at the shoreline.

The total ground-water flow through aquifers within the study area, excluding water withdrawn by wells, was estimated as 20.6 Mgal/d (23,100 acre-ft/yr). About 50 percent of this amount flows directly to the ocean and the remaining water flows to Caño Tiburones (table 6). Darcy's equation for steady-state flow was used to estimate the ground-water flow.

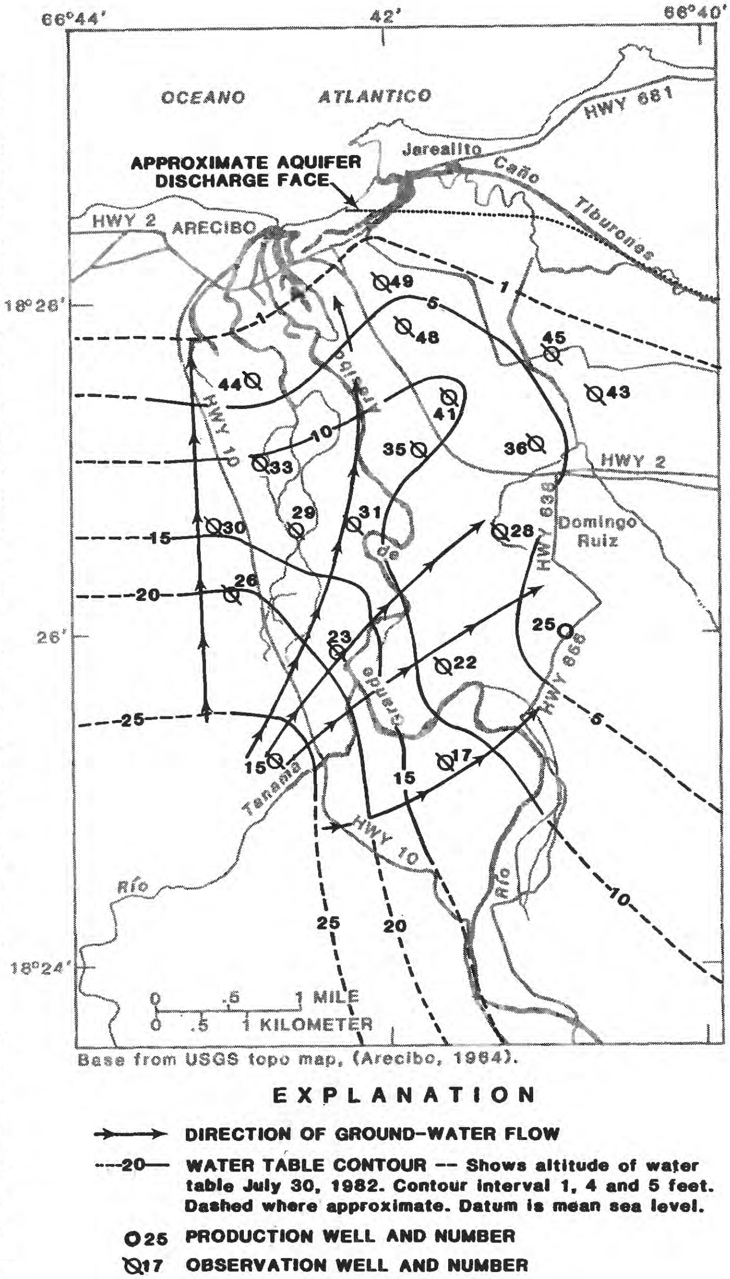


Figure 20.—Generalized altitude of the water table, and estimated flow direction during July 30, 1982.

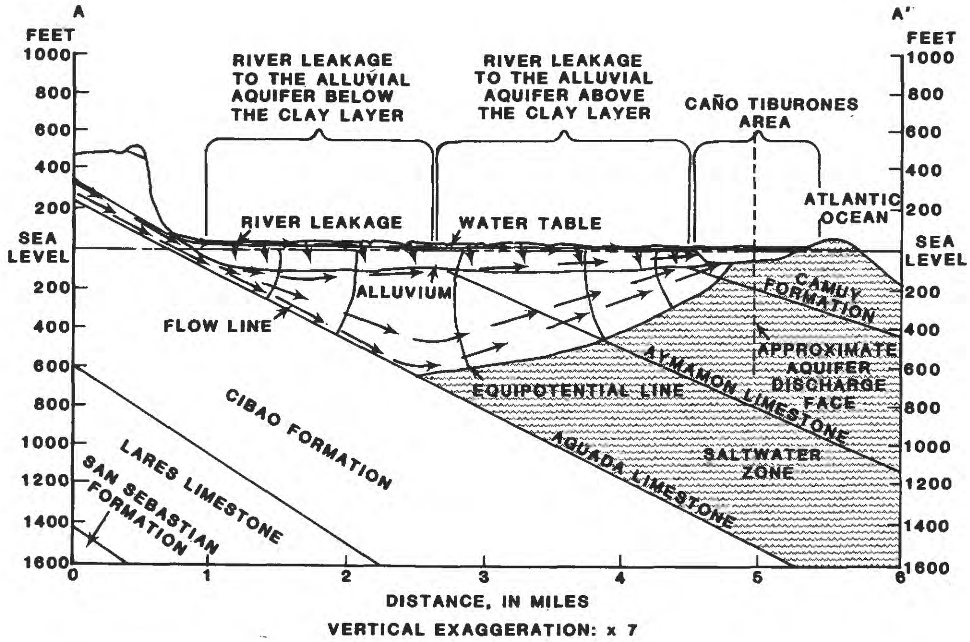


Figure 21.—Generalized flow net across vertical section along line A-A'. (See fig. 7 for location of section).

Table 6.—Ground-water flow through the lower Río Grande de Arecibo valley. (See fig. 8, section B-B'-B'').

Aquifer	Thickness, feet	Gradiant, feet per foot	Hydraulic Conductivity, feet per day	Discharge per mile of width of valley: Cubic feet per day	Discharge per mile of width of valley: Millon gallons per day	Discharge by area: Cubic feet per day	Discharge by area: Million gallons per day
	Flow to Cano Tiburones (section B-B' widths 1.3, 2.1, and 2.9 miles)						
Alluvium (unconfined)	15	0.001685	33	4,400	0.03	5,700	0.04
Alluvium (semi-confined)	85	0.000819	33	12,100	0.09	15,700	0.12
Aymamon	150	0.000819	535	347,000	2.59	728,700	5.45
Aguada	500	0.000819	87	188,100	1.41	545,500	4.08
					total flow	1,295,600	9.69
	Flow to Ocean (section B'-B'' widths 1.35, 1.75, and 1.75 miles)						
Alluvium (unconfined)	15	0.002178	33	5,700	0.04	7,700	0.06
Alluvium (semi-confined)	55	0.000819	33	7,800	0.06	10,500	0.08
Aymamon	325	0.000819	535	751,900	5.60	1,315,800	9.84
Aguada	200	0.000819	87	75,200	0.56	131,600	0.98
					total flow	1,465,600	10.96
					Grand total	2,761,200	20.64

Recharge and Discharge

Recharge to the aquifers in the alluvial valley area (table 7) is derived from: 1) stream seepage, 2) direct infiltration of rain to the water-table aquifer, 3) leakage from the water-table through the clay to underlying alluvial and limestone aquifers, 4) ground-water flow from upland limestones to the alluvial aquifers (fig. 19) and, 5) return flow of irrigation water to the water-table alluvial aquifer.

Table 7.—Quantities of ground-water recharge and discharge for the alluvial aquifer above the clay layer and the alluvial-limestone aquifers below the clay layer, in 1982.

ALLUVIAL WATER-TABLE AQUIFER				AQUIFERS BELOW THE CLAY LAYER			
RECHARGE (acre-ft/yr)		DISCHARGE (acre-ft/yr)		RECHARGE (acre-ft/yr)		DISCHARGE (acre-ft/yr)	
stream seepage	14,500	leakage	10,000	stream seepage to limestone	13,000	ground-water outflow	23,000
rainfall	3,000	ET	8,400	leakage*	10,000	wells	10,800
ground-water inflow	1,100	ground-water outlflow	100	ground-water inflow	6,200		
				stream seepage** to alluvium	3,600		
Totals	18,600		18,500		32,800		33,800

* From the alluvial water-table aquifer through the clay layer.

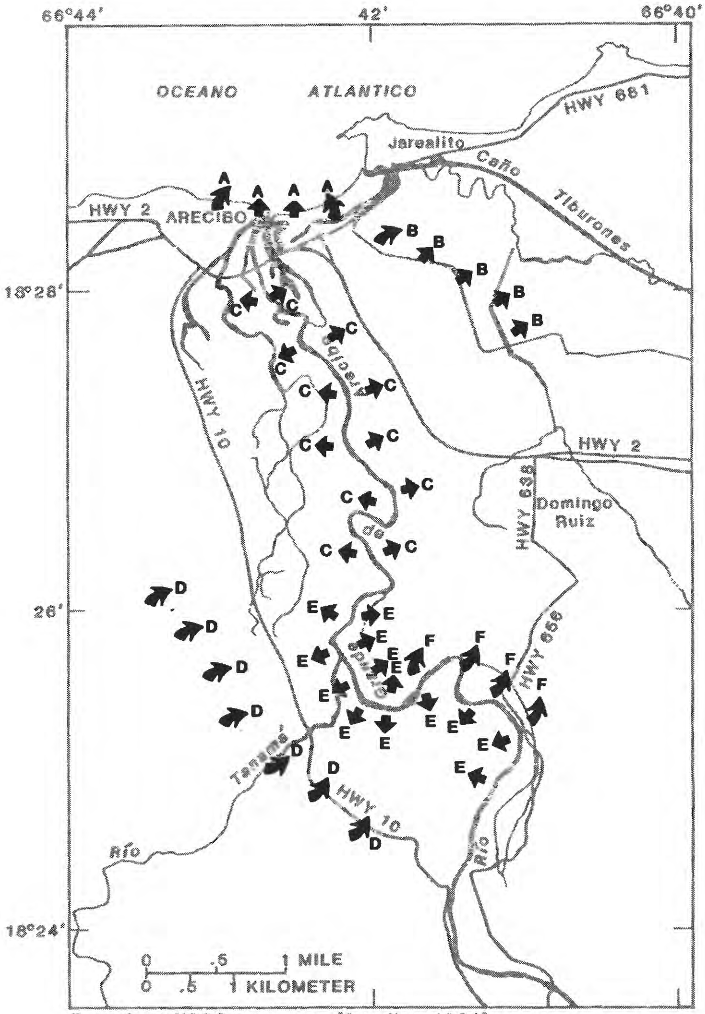
** Where the river have cut the clay layer.

An analyses of stream-flow data indicate that Río Grande de Arecibo and Río Tanamá are losing water during most of the year to the aquifer system (fig. 22). Average seepage losses, along 4.5 miles of river (between stream sites 20 and 38) are about 16.1 Mgal/d (18,100 acre-ft/yr) to the alluvium. In addition, about 11.6 Mgal/d (13,000 acre-ft/yr) is lost from Río Grande de Arecibo to the aquifer within the Aymamón and Aguada Limestones bordering the valley, between river miles 4.8 and 6.3 (fig. 22).

The water-table aquifer is recharged by about 12 percent of the rainfall (8.4 in. or 3,000 acre-ft/yr) on the alluvial sediments. This estimate is based on an analysis of rainfall data and water-level increase at a piezometer isolated from the effect of other sources of recharge. The amount of rainfall recharging the water-table aquifer was defined as the increase in water volume resulted from a water-level rise after a rainfall event.

Leakage through the clay layer from the alluvial aquifer above it to the alluvial aquifer below it was estimated as 8.9 Mgal/d (10,000 acre-ft/yr). Darcy's equation and a hypothetical vertical-hydraulic conductivity of 0.02 ft/d was used for the estimate.

Ground-water flow to the valley is mainly from upland areas of the Aguada Limestone. The estimated ground-water inflow to the water-table and underlying alluvial/limestone aquifer are 0.95 Mgal/d (1,100 acre-ft/yr) and 5.55 Mgal/d (6,200 acre-ft/yr) respectively. These were calculated from



Base from USGS topo map, (Arecibo, 1964).

EXPLANATION

A GROUND-WATER FLOW TO THE OCEAN 10.9 Mgal/d (12,200 acre-ft/yr)

B GROUND-WATER FLOW TO CAÑO TIBURONES 9.6 Mgal/d (10,800 acre-ft/ yr)

C SEEPAGE FROM RIO GRANDE DE ARECIBO TO THE ALLUVIAL AQUIFER ABOVE THE CLAY LAYER 12.93 Mgal/d (14,500 acre-ft/yr)

D GROUND-WATER FLOW RECHARGE FROM UPLAND LIMESTONE AREAS 6.5 Mgal/d (7300 acre-ft/yr)

E SEEPAGE FROM RÍO GRANDE DE ARECIBO TO THE ALLUVIAL AQUIFER BELOW THE CLAY LAYER 3.21 Mgal/d (3600 acre-ft/yr)

F SEEPAGE FROM RIO GRANDE DE ARECIBO TO THE AGUADA AND AYMAMON LIMESTONES 11.6 Mgal/d (13,000 acre-ft/yr)

Figure 22.—Areas of ground-water recharge, discharge, and river seepage in the lower valley area.

Recharge and Discharge (Continued)

Darcy's equation utilizing the gradient of the water-table surface in the upland limestones (Giusti and Bennett, 1976, p. 16).

Recharge from irrigation is minimal because only a small area of the valley is under irrigation. As rice irrigation becomes more widespread, return flow of irrigation water might become an important source of recharge to the water-table aquifer. However, low-soil permeability may keep aquifer recharge from irrigation low.

Ground-water discharge from the entire aquifer system occurs in three different ways: 1) ground-water flow to low-lying areas in Caño Tiburones and to the ocean, 2) withdrawals from the aquifer below the clay through wells for public, agricultural, and industrial supplies, and 3) evapotranspiration from the capillary fringe of the water-table alluvial aquifer. Quantities are summarized in table 7.

Ground-water flow to the ocean and to Caño Tiburones is estimated to be 10.9 and 9.6 Mgal/d (12,200 and 10,800 acre-ft/yr), for a total of 20.6 Mgal/d (23,100 acre-ft/yr) discharged mainly from the aquifers below the clay layer (tables 6 and 7). Discharge through wells from the aquifers below the clay, was about 9.6 Mgal/d (10,800 acre-ft/yr) during 1982. Discharge by evapotranspiration from the water-table alluvial aquifer was estimated at 22.5 inches per year (8,400 acre-ft/yr) which is 50 percent of the total evapotranspiration from the lower Río Grande de Arecibo basin.

There are several springs along the west side of the lower valley at the foot of the bordering limestones. The largest of these, San Pedro Spring (site 8), has an average discharge of 13 ft^3/s (8.6 Mgal/d, 9,400 acre-ft/yr) which represents 94 percent of the total springflow to the valley. The remaining 0.8 ft^3/s is contributed by two other springs located closer to the coast along the west side of the valley (Plate 1, table 8).

Table 8.—Estimated annual springflow to the alluvial valley.

SPRING NUMBER	SPRING NAME	ANNUAL SPRINGFLOW	
		CUBIC FEET	MILLION GALLONS
8	SAN PEDRO SPRING	419,110,000	3140
9	HATO VIEJO SPRING	20,498,000	150
16	EL DIQUE SPRING	6,938,000	50
24	CENTRAL LOS CANOS SPRING	*	*
46	ZANJA FRIA SPRING	277,580,000	2070
	TOTAL SPRINGFLOW	446,546,000	3340**

* FLOW ONLY DURING HIGH INTENSITY RAINFALLS, OVER ITS RECHARGE AREA.

** NOT INCLUDING ZANJA FRIA SPRINGFLOW WHICH FLOW TO CAÑO TIBURONES.

These small springs originate from the Aguada Limestone whereas San Pedro Spring emerges from the Montebello Limestone Member of the Cibao Formation, according to the location of the spring in the geologic map (Briggs, 1968). Near this site, the Río Grande de Arecibo seems to have eroded the limestone sufficiently to relieve the artesian head within the Montebello Limestone Member.

Zanja Fria Spring, located in Caño Tiburones, is the most important spring northeast of the study area. Its average discharge is about 9 ft^3/s (6,500 acre-ft/yr). The following hydrogeologic data indicate that a very high permeable zone conveys water from the lower Río Grande de Arecibo Valley to Zanja Fria Spring:

1. Geophysical tests and drilling logs show that the alluvium is much thicker in the southeast area of the valley. The river may have eroded its deepest cut into the limestone in this area rather than at areas closer to the coast. An abandoned, now buried channel of Río Grande de Arecibo, flowing in a direction toward Caño Tiburones, may be the present conduit connecting the Río Grande de Arecibo to Zanja Fria Spring.

2. A seepage loss of about 18 ft^3/s (8,400 acre-ft/yr) between river miles 4.8 and 6.3 was measured during a minimum flow survey conducted in 1982. This is equal to 40 percent of the total groundwater flow through the valley. In terms of water balance, this seepage loss is twice the flow of Zanja Fria Spring (9 ft^3/s or 6,500 acre-ft/yr).

3. Hydrologically, it is unlikely that 5.8 Mgal/d of discharge from Zanja Fria Spring originates from alluvial and limestone aquifers beneath the clay, or from deeper artesian aquifers. Heads in the aquifers beneath the clay are lower in altitude than the head of Zanja Fria Spring, and there is no indication of faults or limestone solution channels connecting the deep artesian aquifers to the surface.

4. The springflow from Zanja Fria has not been affected by the decline in water levels as the result of pumping of the regional limestone aquifers south of the spring (oral commun., Allen Zack, 1983).

Water Quality

Surface Water

The quality of surface water from both Río Grande de Arecibo and Río Tanamá is suitable for most domestic and industrial purposes. Chemical analyses show sum of principal constituents to be less than 260 mg/L (table 9). Analysis using a multiple-trilinear diagram (Piper, 1944) show that water in the valley is mostly of calcium bicarbonate type (fig. 23). High concentrations of fecal coliform and fecal streptococcal bacteria constitute a major surface water quality problem (fig. 24). The U.S. Environmental Protection Agency (1973, p. 351) recommends the utilization of water for irrigation containing fecal coliform densities less than 1,000 colonies per 100 milliliters. Bacteriological analyses of water samples from Río Grande de Arecibo show fecal bacteria densities greater than 1,000 colonies per 100 milliliters for some months during 1981-82 (fig. 24). Variations in fecal bacteria concentrations throughout years 1981-82 indicate that runoff and streamflow seasonally affect the amount of bacterial contamination reaching the river (fig. 24) with a major increase occurring in conjunction with the May rains.

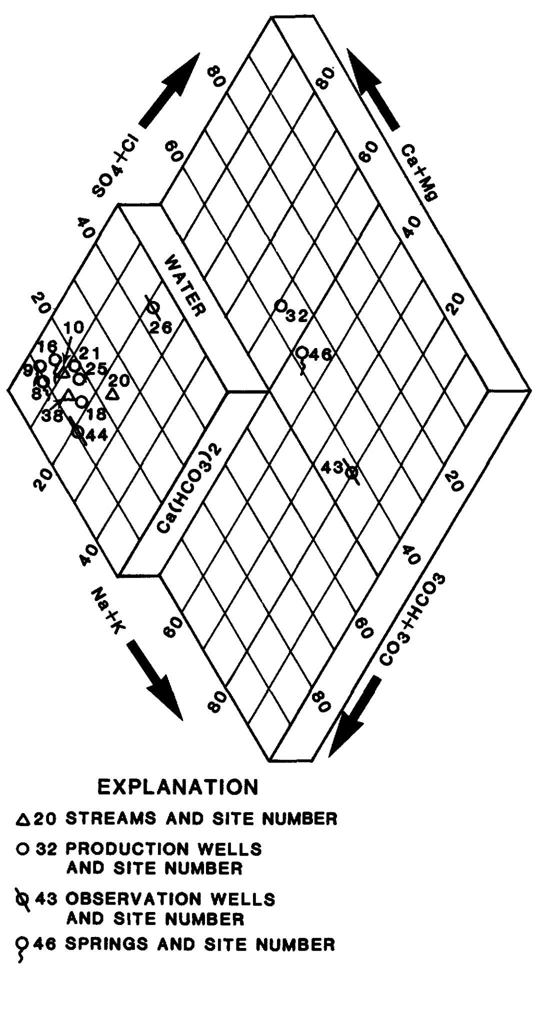


Figure 23.--Chemical classification of water in percent of total milliequivalents per liter.

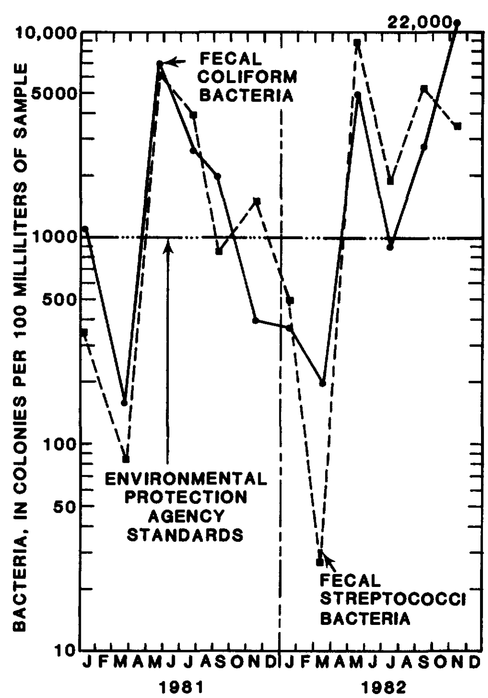


Figure 24.--Seasonal fluctuations of fecal-coliform and fecal-streptococci bacterias at Río Grande de Arecibo at Central Cambalache (site 38, plate 1).

Table 9.--Physical properties and chemical characteristics of water at lower Río Grande de Arecibo valley.

SAMPLING SITE	DATE OF SAMPLING	INSTANTANEOUS DISCHARGE (FT3/S)	SPECIFIC CONDUCTANCE (UMHOS)	pH (UNITS)	TEMPERATURE (DEG C)	HARDNESS (MG/L AS CACO3)	HARDNESS NONCARBONATE (MG/L CACO3)	CALCIUM DISSOLVED (MG/L AS CA)	MAGNESIUM, DISSOLVED (MG/L AS MG)	SODIUM DISSOLVED (MG/L AS NA)	POTASSIUM, DISSOLVED (MG/L AS K)	ALKALINITY FIELD (MG/L AS CACO3)
STREAMS												
10	06-22-83	39.2	287	7.8		140	33	51	3.7	6.6	1.0	110
20	06-16-83	.7	215	7.3	25	91	0	26	6.4	11	1.7	97
38	06-16-83	324	253	8.2	27	110	0	36	5.5	9.2	1.6	120
WELLS												
18	04-12-83	.91	461	7.6	26	210	0	79	4	17	.8	218
21	04-28-83	6.2	350	7.0	25	170	7	55	7.8	11	1.7	156
25	04-12-83	1.02	480	7.4	26	230	19	77	7.8	16	1.4	210
26	04-13-83	---	512	6.5	28.5	210	53	54	17	23	.2	152
32	04-12-83	3.41	1070	7.2	25.5	330	150	100	18	86	2.2	185
43	04-13-83	---	1860	7.0	28.5	190	0	25	30	340	1.6	405
44	04-14-83	---	637	6.6	26	240	0	65	19	29	2.6	310
SPRINGS												
8	06-02-83	19.1	353	7.0	26	190	23	72	3.1	3.8	1.6	170
9	06-15-83	.86	500	7.3	24	230	0	67	16	8	1.0	250
16	06-22-83	.29	388	7.1	24	180	33	68	3.3	7.5	.9	150
46	12-08-82	10	1390	7.2	25	320	77	95	19	160	4.9	240

Table 9.--Physical properties and chemical characteristics of water at lower Río Grande de Arecibo valley (Continued).

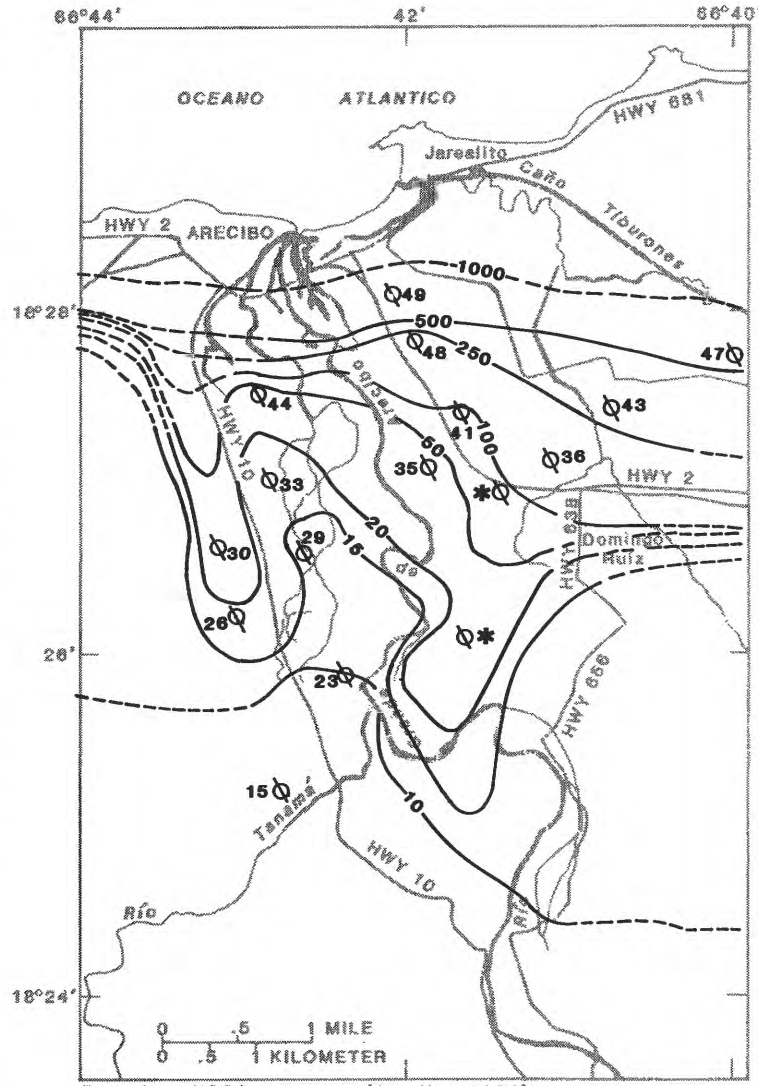
SAMPLING SITES #	SULFATE DISSOLVED (MG/L AS SO4)	CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	SILICA, DISSOLVED (MG/L AS SIO2)	PHOSPHORUS, ORTHO TOTAL (MG/L AS P)	IRON, DISSOLVED (UG/L AS FE)	MANGANESE, DISSOLVED (UG/L AS MN)	NITROGENE, DISSOLVED NO2+NO3 (MG/L AS N)	CARBON, ORGANIC DISSOLVED (MG/L AS C)	CARBON, ORGANIC SUSPENDED (MG/L AS C)	SUM OF CONSTITUENTS (MG/L)
STREAMS											
10	7.8	8.8	.2	10	.01	5	5	.63	---	---	223
20	12	11	.2	21	.03	3	12	.42	---	---	252
38	10	9.8	.1	17	.02	3	6	.53	---	---	236
WELLS											
18	18	15	.1	12	.03	17	7	.17	---	---	512
21	18	11	.1	23	.05	3	1	.55	---	---	318
25	14	19	.1	21	.04	8	1	2.3	---	---	412
26	84	23	.1	32	.01	1100	340	.1	---	---	419
32	31	210	.1	23	.03	8	1	.45	---	---	696
43	85	330	.8	4.4	.03	670	410	.85	---	---	1324
44	5.5	26	.1	36	.04	13000	1	.10	---	---	561
SPRINGS											
8	10	8.1	.2	5.5	.07	14	3	.75	4.2	---	311
9	12	11	.5	10	---	3	3	---	2.3	4.0	430
16	5.7	11	.1	8.9	.01	3	1	2	2.1	---	288
46	41	280	.1	6.8	---	8	1	---	---	---	900

See Plate 1 and table 1 for locations.
MG/L = Milligrams per liter.
UG/L = Micrograms per liter.
Umhos = Micromhos per centimeter at 25 degrees celsius.

Ground Water

The quality of water from aquifers and springs varies with location, source of recharge, and in some areas with depth. Ground water is, in general, a calcium bicarbonate type, but becomes more of a sodium chloride type near the coast (fig. 23). Chemical analyses of all samples collected indicate that calcium, bicarbonate (as alkalinity), sodium, sulfate, and chloride comprise the greatest percentage of dissolved solids (table 9). In general, ground water is very hard, ranging in hardness (as $CaCO_3$) from 170 to 330 mg/L; concentrations of calcium range from 25 to 100 mg/L (the higher concentrations are obtained from deeper sediments); bicarbonate ranges from 118 to 494 mg/L; sodium ranges from 3.8 to 340 mg/L; sulfate from 5.5 to 85 mg/L; and chloride from 8.1 to 330 mg/L. These constituents primarily are derived from the dissolution of minerals, with the exception of chloride and sodium, which owe their derivation to seawater and sulfate which can be atmospheric.

The areal distribution of chloride in the alluvial water-table aquifer was determined from samples collected at shallow observation wells (fig. 25). The chloride distribution indicates that a large amount of water is leaking from the river to the water-table aquifer in the middle of the valley.



Base from USGS topo map, (Arecibo, 1964).

EXPLANATION

—10— LINE OF EQUAL CHLORIDE CONCENTRATION, IN MILLIGRAMS PER LITER, SEPTEMBER 16-17, 1982 Interval variable. Dashed where approximate

15 OBSERVATION WELL AND NUMBER

* WELLS USED ONLY FOR THIS SAMPLING

Figure 25.--Lines of equal chloride concentration in the alluvial aquifer above clay layer (35 feet below land surface). (Sampling during September 16-17, 1982).

An estimate of depth to the salt-water interface (17,000 mg/L chloride) was determined based on sampling at wells 18, 32, 42, and 34 (fig. 26). This depth was determined at other locations by applying the modified Dupuit-Ghyben-Herzberg mathematical model (Fetter, 1980, p. 143), which permits approximations based on the location of the aquifer discharge face near the coastline. The aquifer discharge face utilized in this approximation was adjusted to account for the actual seaward limit of the freshwater aquifer obtained from previous studies in the Caño Tiburones (Díaz, 1973).

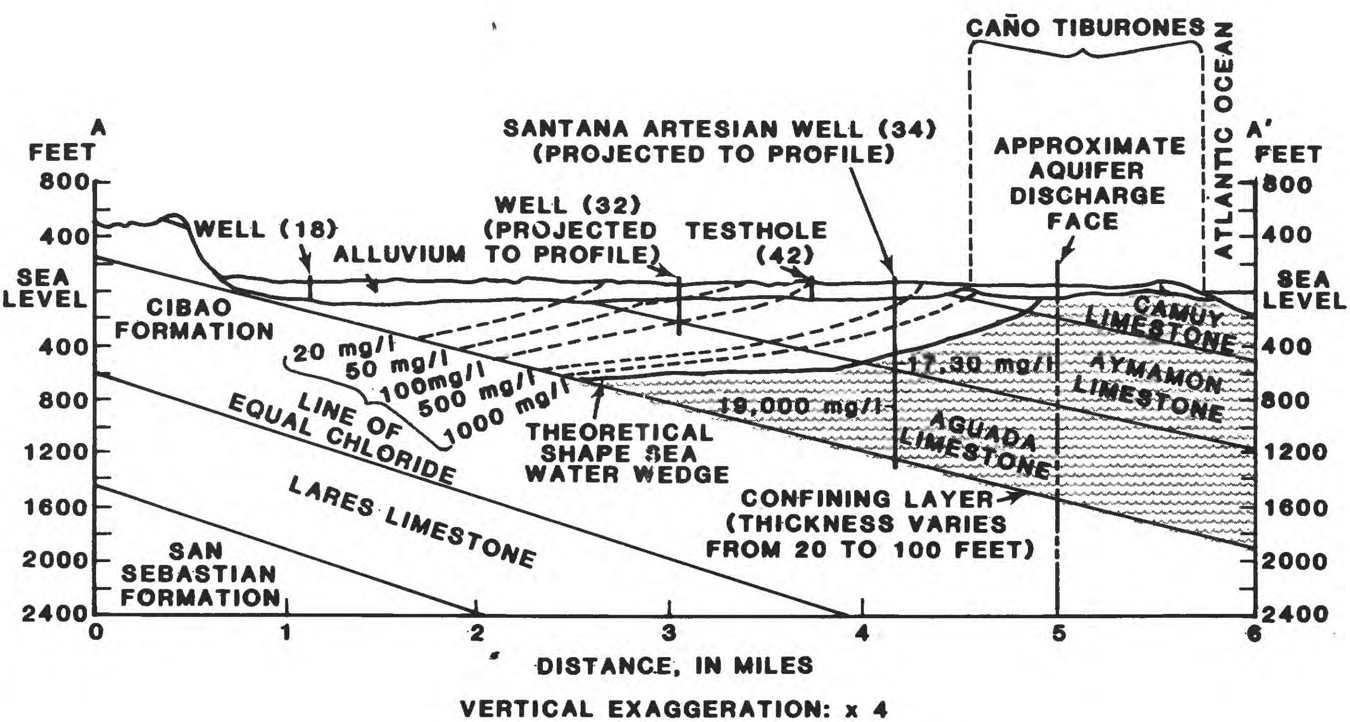


Figure 26.--Location of saline water through aquifers in the Aguada and Aymamon Limestones and the Alluvium, along section A-A'. (See fig. 7 for location of section).

Hydrologic Budget

The hydrologic budget of the alluvial valley area is a balance between water gains, drainage-basin storage, and water loss over a given period of time. The hydrologic budget for the lower alluvial valley area in 1982 (fig. 27) was estimated using:

- o rainfall -- mean-annual precipitation.
- o springflow -- instantaneous measurements during the year (1982).

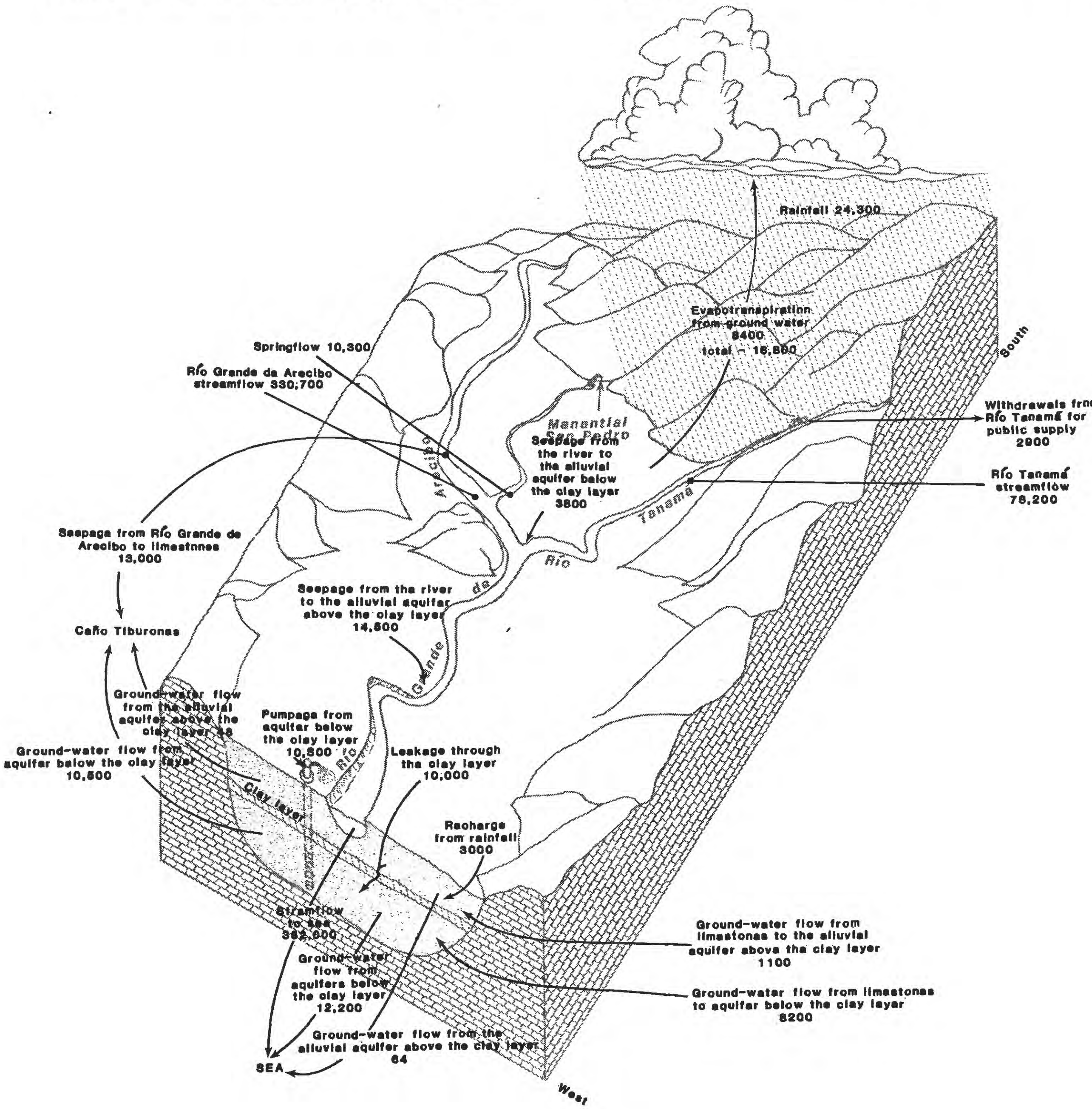


Figure 27.--Hydrologic budget for the lower valley area. Values are estimated for 1982, in acre-feet per year.

o streamflow -- mean-annual discharges.

o ground-water flow recharge -- Darcy's equation.

o ground-water discharge to lowlands or ocean -- Darcy's equation.

o recharge from rainfall -- rainfall against water-level changes analysis.

o withdrawals -- water-use data.

o evapotranspiration -- as 50 percent of the total evapotranspiration obtained from Giusti's (1978, p. 21), empirical relation.

o seepage from river to the alluvial aquifer -- differences between stream inflow and outflow during base-flow period.

o seepage from river to limestone aquifer bordering the alluvial valley -- seepage study.

o downward leakage from the water-table aquifer through the clay to underlying alluvial and limestone deposits -- using Darcy's equation and utilizing a vertical hydraulic conductivity of 0.02 ft/d.

Totals for the budget are:

	Inflow = 450,800 acre-ft/yr
-	Outflow = 432,600 acre-ft/yr
+	storage = 18,200 acre-ft/yr

Positive storage indicates that 18,200 acre-ft/yr was accumulated in the aquifer during the year.

Requirements of Water

Water withdrawals from surface- and ground-water sources during 1982 amounted to 12.2 Mgal/d. Aquifers supplied about 9.6 Mgal/d, and 2.6 Mgal/d was withdrawn from Río Tanamá (fig. 28a). During 1982, no water was withdrawn from Río Grande de Arecibo within the alluvial valley area. Public supply was the main use of water during 1982 (10.7 Mgal/d) and industrial and agricultural uses were minimal (fig. 28b). Projections for 1990 (PRASA, 1969) estimate that water demand for public supply will be close to 12 Mgal/d (fig. 29). This projection has changed to 34 Mgal/d based on analysis of recent water-use data (PRASA, 1971-1980), and PRASA future plans (fig. 29). Plans for water development encompass two phases: a short-term phase consisting of incremental ground-water withdrawals to a maximum of 20 Mgal/d, and a long-term phase which will include the exportation of 45 Mgal/d from Dos Bocas reservoir and Río Grande de Arecibo to the San Juan metropolitan area (Santiago Vázquez and others, 1982, p. 29).

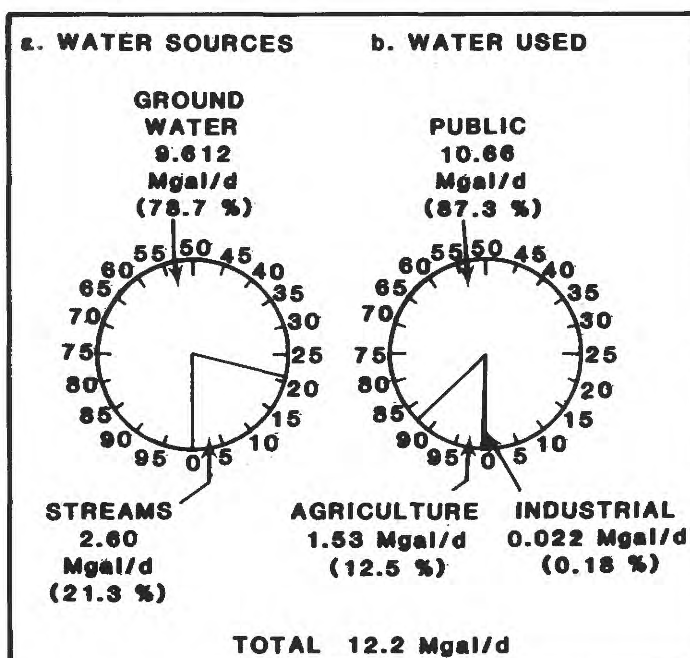


Figure 28.--Percentage of water withdrawn from aquifers and streams and uses for different activities during 1982.

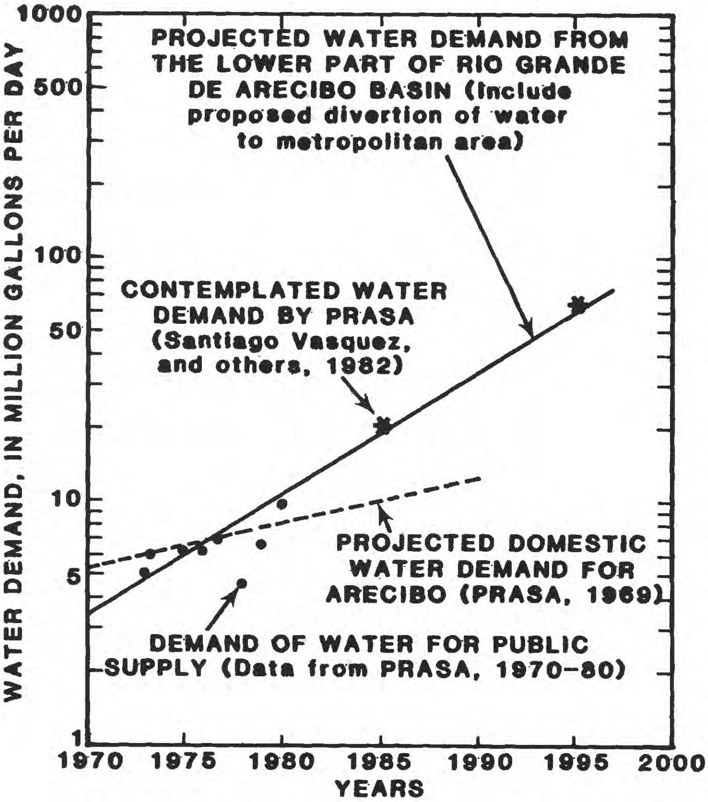


Figure 29.--Projections of water demand in the lower Río Grande de Arecibo basin for 1995.

Alternatives for Water-Resources Development

The extent of water-resources development depends on present and future demands of water for public, industrial, and agricultural uses. Public supply constituted the greatest single use of water during 1981-83. Water use for irrigation began increasing in 1982, associated with an increase in rice cultivation in the Arecibo area. Full development of water resources from Río Grande de Arecibo, and alternate withdrawals of ground water when river flows are low, can be coordinated to optimize water use for the valley.

Surface Water

Río Grande de Arecibo has the greatest potential of all streams in the basin for large-scale development. It provides the greatest amount of water that recharges the aquifers in the valley and adjacent areas. Excessive water withdrawals from this river will reduce recharge to the aquifers, thereby adversely affecting the ground-water systems.

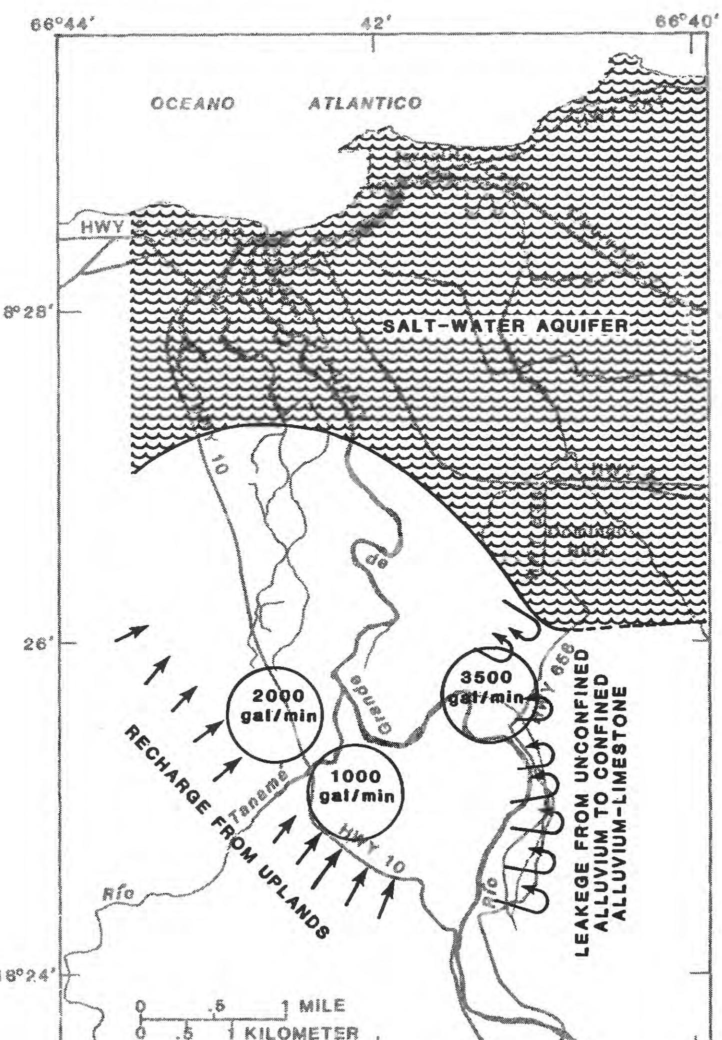
On the basis of flow duration and minimum-flow statistics (figs. 15 and 16; tables 2 and 3), water withdrawals exceeding 15 ft^3/s during minimum-flow period (about 50 ft^3/s) of Río Grande de Arecibo may reduce significantly the recharge from the river to the aquifers; consequently, pumping wells would induce intrusion of saline water from the mixing zone. During base flow of 90 to 200 ft^3/s, however, water withdrawals can be increased up to 35 ft^3/s without a reduction in the recharge to the aquifers. About 500 ft^3/s of released water from Dos Bocas reservoir (fig. 13) is available as it flows through the valley.

Ground Water

Ground-water resources are only partly developed in the valley. The southwest part of the valley, near Río Tanamá, has been developed mostly for public supply, with average ground-water withdrawals of 4.2 Mgal/d (4,700 acre-ft/yr) for the town of Arecibo.

Additional withdrawals of about 9.4 Mgal/d (10,500 acre-ft/yr), can be made from the aquifers occurring below the clay. Areas with the greatest potential for ground-water development are located on or near recharge areas (fig. 30). Locating wells in these areas might induce more fresh-water recharge from uplands or the river by increasing the hydraulic gradient.

The maximum depth from which ground-water withdrawals can be made is determined by the occurrence of saltwater in the aquifer. Wells are completed at shallower depths near the coast to avoid inadvertent salt-water migration into the well bore. Ground-water resources in these areas need to be developed cautiously to prevent salt-water intrusion as a result of lowering the water levels and thereby reversing the hydraulic gradient.



Base from USGS topo map, (Arecibo, 1984).

Figure 30.--Areas of potential development of ground-water resources and proposed rates of withdrawals.

A simple mathematical model was used to approximate the quantity of water that can be withdrawn from the aquifer beneath the clay without reversing the hydraulic gradient. Theis' mathematical model of water-level response to ground-water withdrawals and the principle of superposition to account for boundary effects on water levels were utilized to test the response of this aquifer to various assumed stresses under certain critical conditions. It was assumed that ground-water flow from uplands would be the only source of recharge to the aquifer, and the overlying clay layer (fig. 19) would not allow seepage from the river or from the water-table aquifer. A storage coefficient of 0.10 was used for the computations. Results of the mathematical model show that the aquifer would approach steady-state condition in about 90 days after ground-water withdrawals begin. Drawdowns at steady state are shown to be less than 20 ft. The mathematical model and the location of recharge areas were used to select areas within the alluvial valley appearing to have the greatest ground-water development potential (fig. 30). The area east of the valley, where limestone crops out and is in contact with the alluvium, is likely to be where Río Grande de Arecibo loses water to the limestone (fig. 30). To optimize this estimate, a digital model would be required because of the complexity of this hydrogeologic system.

Artificial recharge to aquifers may be the best alternative in utilizing water surplus from Río Grande de Arecibo, which otherwise flow to the ocean. Some of the water released from Dos Bocas reservoir (fig. 13), could potentially be stored underground.

SUMMARY

The major source of water within the study area is Río Grande de Arecibo with a mean-annual discharge of 527 ft^3/s (382,000 acre-ft/yr). Flow-duration curves for Río Grande de Arecibo indicate that river discharge is more than 120 ft^3/s (79,700 acre-ft/yr) during 90 percent of the time. Minimum-flow statistics indicate that the 7-day, 10-year minimum flow of Río Grande de Arecibo ranges from 50 ft^3/s upstream to 93 ft^3/s downstream within the alluvial valley. Flood flows of the river can produce over-bank flow at the central and lower parts of the valley when discharge exceeds 17,000 ft^3/s.

Ground water occurs under unconfined conditions throughout the valley. The water-table alluvial aquifer contains a relatively impermeable clay 40 ft thick, which hydraulically isolates an underlying alluvial and limestone aquifer. The alluvial aquifer beneath the clay is between 40 and 100 ft thick and underlain by limestone aquifers that can be several hundreds of feet thick. Estimated transmissivity values range from 3,000 to 5,000 ft^2/d in the alluvium to 42,000 ft^2/d in the limestone. The average hydraulic conductivity of the alluvial sediments was estimated as 33 ft/d. Average hydraulic conductivity of limestones as estimated by Giusti and Bennett (1976) are 535 ft/d for the Aymamón Limestone and 87 ft/d for the Aguada Limestone. Natural ground-water flow was estimated at about 20.6 Mgal/d (23,100 acre-ft/yr).

Seepage from Río Grande de Arecibo to limestone aquifers at the east of the alluvial valley is about 11.6 Mgal/d (13,300 acre-ft/yr).

Total-annual springflow through the alluvial valley is about 3,340 Mgal (10,250 acre-ft). San Pedro and Zanja Fria are the major springs within the area. Water from San Pedro Spring can be utilized as an alternate source for water supply. Zanja Fria Spring in the Caño Tiburones, appears to originate from an abandoned, now buried channnel of Río Grande de Arecibo.

Fecal-bacteria contamination is the principal water-quality problem of Río Grande de Arecibo. Relatively high concentrations of dissolved solids are common in ground water near the coast indicating the presence of saline water in the aquifers.

Water withdrawal from Río Grande de Arecibo exceeding 15 ft^3/s (10,860 acre-ft/yr) during minimum flows of the river may reduce significantly the recharge from the river to the aquifer; consequently pumping wells would induce saline water from the mixing zone. Withdrawals during base flow of 90 to 200 ft^3/s can be increased to 35 ft^3/s (25,360 acre-ft/yr). As much as 500 ft^3/s is available while water released from Dos Bocas reservoir passes through the valley.

Ground-water resources are only partly developed in the study area. The area of greatest ground-water development in the valley is south of Río Tanamá, from which 4.2 Mgal/d (4,700 acre-ft/yr) are withdrawn for public water supply. Ground-water withdrawals can be increased by an additional 9.4 Mgal/d (10,500 acre-ft/yr). Steady state would be approached in about 90 days after ground-water withdrawals begin. Capture of seepage from Río Grande de Arecibo to the ground-water systems at the east side of the valley, is probably the key to the development of the ground-water resources in the valley.

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