WATER RESOURCES OF THE HUMACAO-NAGUABO AREA, EASTERN PUERTO RICO

By Robert P. Graves

U.S. GEOLOGICAL SURVEY
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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM UNITS (SI)

For the convenience of readers who may want to use metric (International System) units (SI), the inch-pound units used in this report may be converted by using the following factors:

Multiply inch-pound units	By	To obtain metric units
	Length	
inch (in.)	25.4	millimeters (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09294	square meter (m^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
gallon per day (gal/day)	0.003785	cubic meter per day (m^3/d)
million gallon per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 x (°F-32)	degree Celsius (°C)
	Specific Capacity	
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
	Transmissivity	
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)

U.S. DEPARTMENT OF THE INTERIOR · GEOLOGICAL SURVEY

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ABSTRACT

The Humacao-Naguabo area, located on the east coast of Puerto Rico, has undergone a rapid development of light industries within the last five years. This has placed large demands on local water supplies.

Surface water is the principal water-supply source in the Humacao-Naguabo area, supplying 13.7 million gallons per day. The two major drainage networks are the Río Humacao and Río Blanco. Peak discharge in the streams occurs during the May through December rainy season. Minimum base flow occurs in March or April. Average daily flow for water-year 1983 was 58.8 cubic feet per second for Río Humacao at Highway 3 near Humacao and 67.9 cubic feet per second for Río Blanco near Florida. For 1984 average daily flow was 38.6 cubic feet per second for Río Humacao at Highway 3 near Humacao and 55.8 cubic feet per second for Río Blanco near Florida.

Aquifers are presently of minor importance for water supply in the Humacao-Naguabo area. Daily ground-water use is estimated to be 0.93 million gallons. The principal aquifer in the Humacao-Naguabo area occurs within alluvial sediments, under water-table conditions. The alluvial aquifer is wedge-shaped and ranges in thickness from zero at the bedrock-alluvium contact, to more than 160 feet near the coast. Values of aquifer transmissivity range from about 600 to 2,000 feet squared per day; storage coefficient of the aquifer is approximately 0.02.

The depth to the water table within the alluvial aquifer varies from about 40 feet below land surface near the bedrock-alluvium contact to very near land surface in the coastal areas. The elevation of the water table varies seasonally within an 8-foot range.

Water-quality analyses of ground water revealed that, at several sites, the U.S. Environmental Protection Agency drinking water standards for iron, manganese, and total dissolved solids were exceeded. Manganese concentrations in samples collected from three surface-water sites also exceed the U.S. Environmental Protection Agency drinking water standards. Considerable biological contamination exists in the surface-water resources of the area. Bacteria counts as high as 10,300,000 colonies per 100 milliliter fòr coliform and 1,900,000 colonies per 100 milliliter for streptococci were found in samples from Río Humacao.

A two-dimensional, mathematical ground water flow model of the Río Humacao basin was developed to simulate the ground-water flow system and to determine the effects of additional ground-water withdrawals on the water-table. The model was calibrated with ground-water levels measured in March 1984. Model computed heads were within 3 feet of observed heads. Model results show that, in the lower Humacao basin, if pumpage is increased to more than 0.72 million gallons per day, saltwater intrusion into the aquifer could occur.

INTRODUCTION

The Humacao-Naguabo area, located on the eastern shore of Puerto Rico (fig. 1), has experienced a rapid development of light industries within the last 5 years. These industries are increasing demands on local ground-water and surface-water resources. The increases in water demand have led to concerns regarding the source, availability, and quality of the water resources.

This report summarizes the results of a cooperative investigation started in 1982 between the U.S. Geological Survey (USGS), and the Puerto Rico Industrial Development Company (PRIDCO).

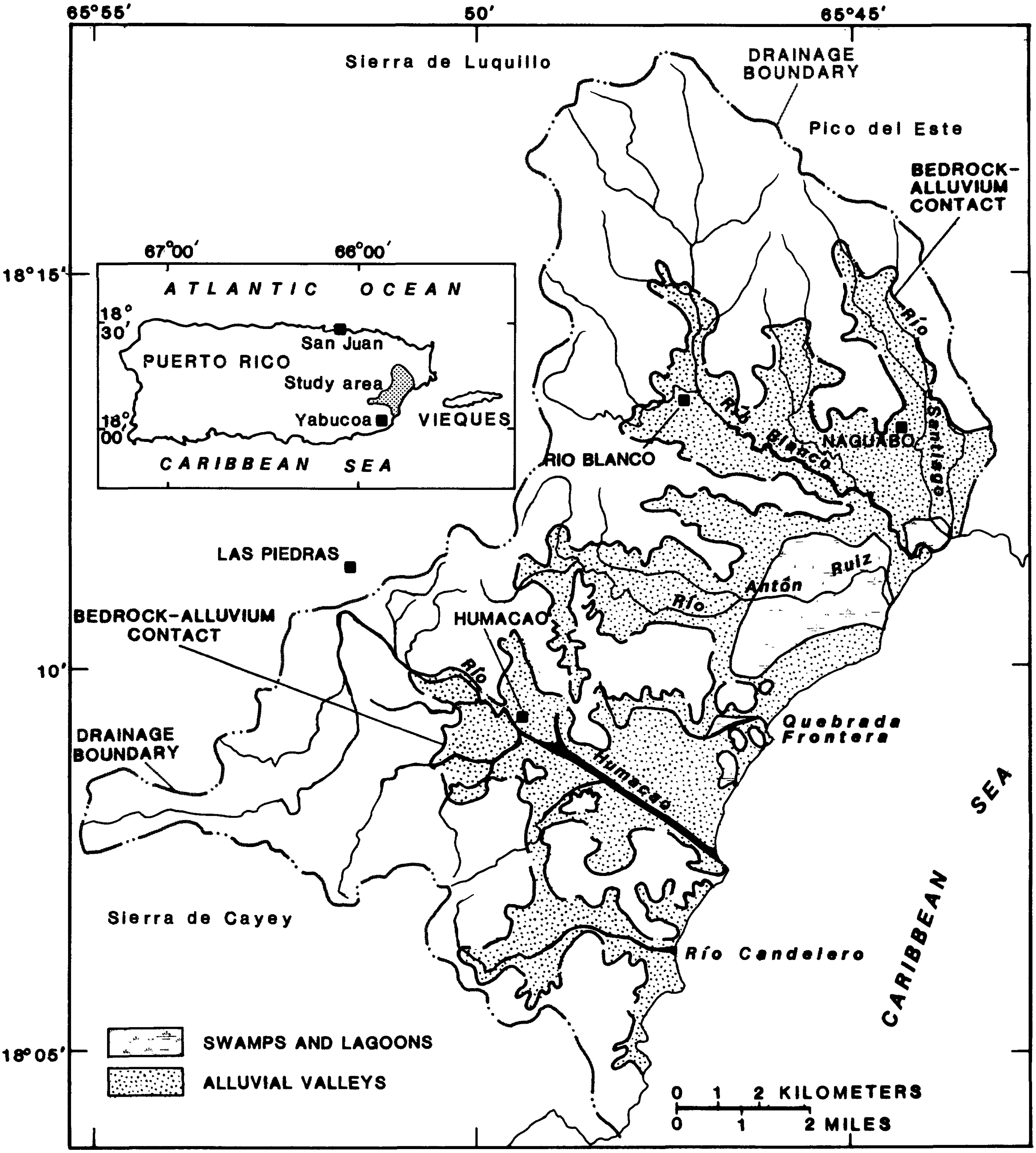


Figure 1.--Location and principal drainage basins of the Humacao-Naguabo area.

Purpose and Scope

The objectives of this study were to define the occurrence, availability, and quality of surface- and ground-water resources of the Humacao-Naguabo area. This comprehensive water-resources appraisal will aid the Puerto Rico Industrial Development Company in providing information concerning water quality and availability to all existing and planned industries located in the area.

The objectives of the investigation were addressed by first evaluating all previous hydrologic studies conducted in the area. Where data gaps existed, a field data-collection program was initiated. This program included a well inventory (1982 through 1984) which describes well characteristics, water levels, yield, drawdown, and water quality. In areas where additional ground-water data were required, test wells were drilled. A total of 24-test wells were drilled in the study area.

Recorders for continuous water-level measurements were installed on four observation wells to monitor water-level fluctuations. Geophysical logs were obtained at selected wells to investigate the physical properties of the aquifer. Eight surface electrical-resistivity and seismic-refraction surveys were conducted. Interpretations of the resistivity and seismic analyses were used to help define depth to bedrock, character of surficial deposits, and areas where the aquifer contained saline water. Aquifer tests were conducted at three sites to determine the transmissivity and storage properties of the aquifer. A two-dimensional, ground-water flow model of the Río Humacao basin was developed to estimate ground-water availability in this area and to determine the effects of additional ground-water withdrawals on aquifer water levels.

Gaging stations equipped with continuous stage recorders were installed at Río Humacao and Río Blanco. Periodic flow measurements were made to establish the relation between stream stage and discharge. A seepage run was conducted on Río Humacao to determine areas of streamflow gains or losses to the aquifer.

In order to determine the suitability of water in a particular area for use as a water supply, data were collected from 25 ground- and surface-water sites and analyzed for major anions and cations as well as for biologic contamination.

The location and descriptions of all wells mentioned throughout this report are presented in figure 2 and table 1. The well numbers apply only to this report, although the site indentification numbers conform with the Survey's Ground-Water Site Inventory classification scheme. A cross reference to wells used in this report, located under the old well-numbering system in the Survey's historical files, is included.

The location and description of all surface-water sites mentioned throughout this report, are presented in figure 2 and table 2. Site numbers conform to the Survey's downstream order classification system.

Acknowledgements

The author gratefully acknowledges the many individuals who provided assistance and cooperation throughout the project. Appreciation is extended to Alcon Laboratories Inc., Antonio Roig Sucesores Inc., General Electric Protective Devices Inc., Puerto Rico Sugar Corporation, and Squibb Manufacturing Inc. for allowing the Survey to conduct aquifer tests on their property. Special acknowledgment is extended to individuals who provided records of their wells, property on which to drill, or access to wells from which data were collected.

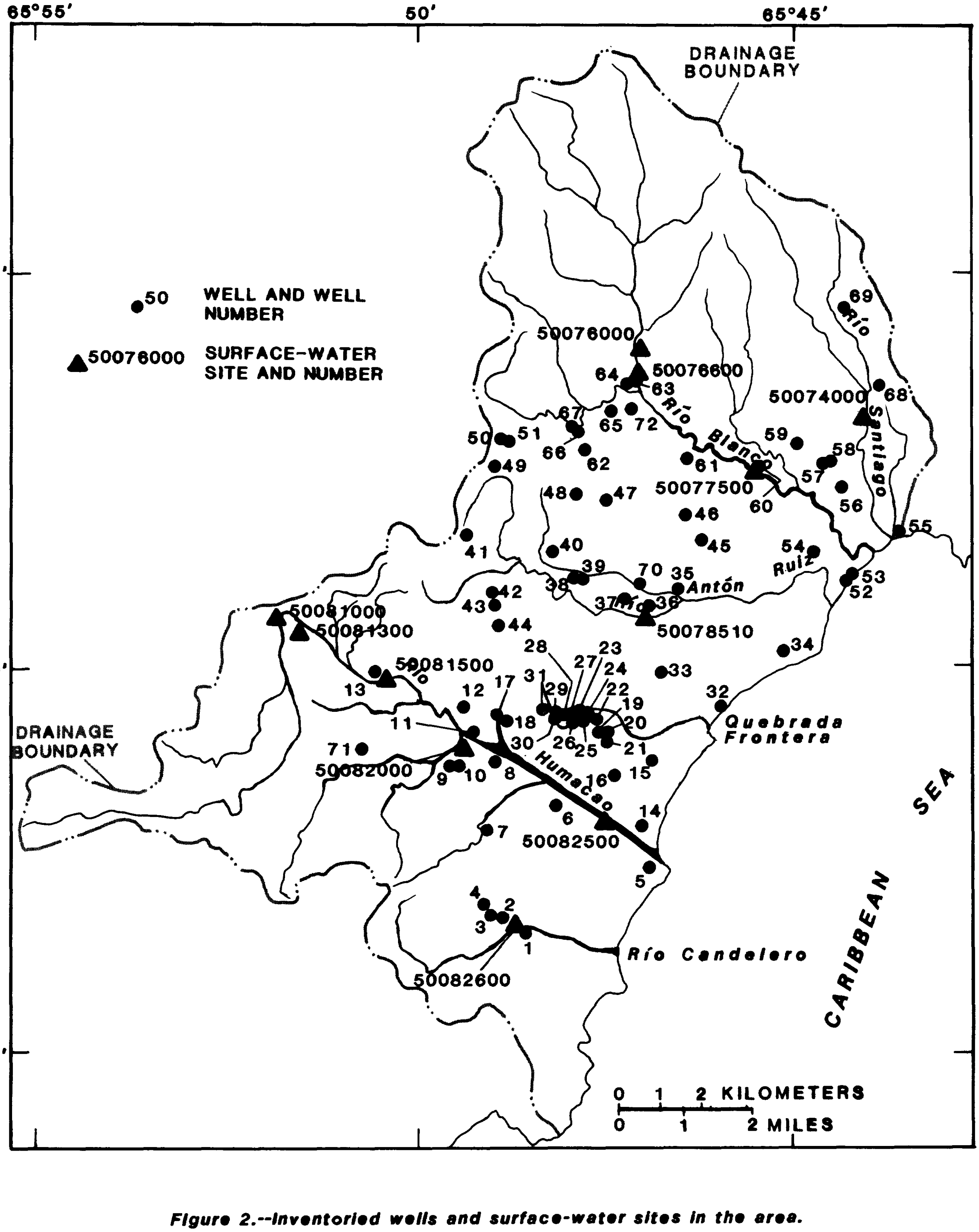


Figure 2.--Inventoried wells and surface-water sites in the area.

Table 1. Description of wells in the area

[units - ft, feet; gal/min, gallons per minute; [(gal/min)/ft], gallons per minute per foot of drawdown. Abbreviations - A, Agriculture and stock well; I, Industrial well; M, Municipal well; D, Domestic well (Only wells noted by A, I, M, and D are currently in use)]

Well number	Owner's name	Well type	Site identification[1]	Date drilled	Depth of well (ft)	Depth of casing (ft)	Construction (ft)	Aquifer material	Yield[2] (gal/min)	Specific capacity [(gal/min)/ft]
01	Palmas del Mar Airport Well	A	180618065484201		93	52	open hole 52-93	fractured rock	55	4
02	Palmas del Mar 3		180635065490400 (6-65.49-01-50)		80	43	screen 43-80	alluvium		
03	Palmas del Mar 2		180641065491100		72			alluvium		
04	Palmas del Mar 1		180648065491400							
05	Ochenta Well	A	180708065470100 (7-65.47-01-91)		102					
06	Mayo Well	A	180756065481400 (7-65.48-01-08)		130			alluvium		
07	Soler TW 1		180746065490200	1984	42	2	screen 12-42	alluvium		
08	Soler TW 2		180826065484600	1984	37	18	screen 18-37	alluvium		
09	General Electric Well 2	I	180830065493900	1969	84	37	screen 37-77	alluvium	90	1
10	General Electric Well 1	I	180830065493800		140	103	open hole 103-140	alluvium & fractured rock	135	2
11	Río Humacao G.W. Station		180850065493700	1983	19	16	screen 16-19	alluvium		
12	A.A.A. Llamas Well		180902065493500 (9-65.49-01-84)	1930	140	93	open hole 93-140	fractured rock		
13	Empresas Pérez Gravel Pit Well		180942065505000		165	84	open hole 84-165	fractured rock		
14	Miraflores TW 1		180733065470100	1983	37	10	screen 10-30	alluvium		
15	Roig TW 2		180823065465000	1983	37	10	screen 10-30	alluvium		
16	Roig abandoned Well 2		180820065472601	1930	105			alluvium		
17	Qume 1	I	180905065485801 (9-65.48-03-81)	1950	85				100	
18	Qume 2	I	180905065485301 (9-65.48-02-91)							
19	Roig TW 3		180840065473103	1984	149	50	screen 50-60	alluvium		
20	Roig abandoned Well 4		180840065473101		108	86-108	screen 0-86	alluvium		
21	Roig TW 1		180840065473102	1983	28	24	screen 24-28	alluvium		
22	Squibb Industrial Well 8	I	180906065473300		150			alluvium	75	2
23	Squibb TW 1		180859065473801	1983	42	17	screen 17-27	alluvium		
24	Squibb TW 2		180859065473802	1983	32	17	screen 17-30	alluvium		
25	Squibb Industrial Well 7	I	180859065473803	1969	75		screen 0-75	alluvium	32	

Table 1. Description of wells in the area (Continued)

[units - ft, feet; gal/min, gallons per minute; [(gal/min)/ft], gallons per minute per foot of drawdown. Abbreviations - A, Agriculture and stock well; I, Industrial well; M, Municipal well; D, Domestic well (Only wells noted by A, I, M, and D are currently in use)]

Well number	Owner's name	Well type	Site identification[1]	Date drilled	Depth of well (ft)	Depth of casing (ft)	Construction (ft)	Aquifer material	Yield[2] (gal/min)	Specific capacity [(gal/min)/ft]
26	Squibb Industrial Well 5	I	180857065474400	1969	95		screen 0-95	alluvium		
27	Squibb Industrial Well 10	I	180900065474700	1984	245	205	screen 205-245	alluvium	75	
28	Squibb Obs. Well 3		180908065475000	1969	110	60	screen 60-110	alluvium		
29	Alcón Industrial Well 1	I	180909065475602	1983	150	0-37 140-150	screen 37-140	alluvium & fractured rock	116	7
30	Alcón TW 1		180909065475601	1983	40	27	screen 27-40	alluvium		
31	Antonio Roig La Suiza Well	A	180917065483000 (9-65.48-01-77)	1961	90					
32	Villa Palmira TW 1		180913065455900	1983	39	4	screen 4-19	alluvium		
33	Bajandas TW 1		180936065464600	1983	34	10	screen 10-30	alluvium		
34	Ortiz TW 1		180958065452400	1984	62	17	screen 17-37	alluvium	10	8
35	Antón Ruiz TW 1		181044065462800	1983	37	10	screen 10-30	alluvium		
36	Land Authority TW 1 @ Hwy. 925		181039065465700	1983	25	22	screen 22-25	alluvium		
37	Land Authority Aba. Well @ Hwy.925		181040065470900 (10-65.47-01-39)							
38	Mambiche TW 1		181102065480100	1983	37	10	screen 10-30	alluvium		
39	A.A.A. Pozo Mambiche 1	M	181101065480100	1966	135	25	screen 25-135	alluvium & fractured rock	68	
40	Pozo Antón Ruiz	D	181120065483400	1959	107					
41	Santos Ayala Well	A	181138065493200		240			fractured rock		
42	Reyes Well		181052065491100							
43	Enrique Marti Well		181045065490800 (10-65.49-03-29)	1958	102	76		fractured rock	20	
44	Norbelto Colón Well		181024065490100 (10-65.49-01-60	1959	75	40		fractured rock	13	
45	Las Mulas		181114065460000	1984	52	22	screen 22-52	alluvium		
46	Benitez Well		181137065455900							
47	Humacao Farm & Dairy Well	A	181149065471400		200					
48	Benito Berríos Well		181205065480200		97	50	open hole 50-97	fractured rock		
49	Mambiche Blanco	D	181226065492300		>180					
50	López Garcia Well 1		181234065491600							

Table 1. Description of wells in the area (Continued)

[units - ft, feet; gal/min, gallons per minute;[(gal/min)/ft], gallons per minute per foot of drawdown. Abbreviations - A, Agriculture and stock well; I, Industrial well; M, Municipal well; D, Domestic well (Only wells noted by A, I, M, and D are currently in use)]

Well number	Owner's name	Well type	Site identification[1]	Date drilled	Depth of well (ft)	Depth of casing (ft)	Construction (ft)	Aquifer material	Yield[2] (gal/min)	Specific capacity [(gal/min)/ft]
51	López Garcia Windmill Well		181233065491300							
52	Coco Rico Industrial Well 1		181102065440501 (11-65.44-01-100)	1955	15				33	
53	Coco Rico TW 1		181102065440502	1983	26	11	screen 11-13	alluvium		
54	Coco Rico TW 2		181124065442100	1984	37	10	screen 10-30	alluvium		
55	Cruz Pizarro Dug Well		181132065432000 (11-65.43-01-47)				dug well			
56	Faustel Fuertes TW 4		181206065441400	1983	72	10	screen 10-30	alluvium	7	
57	Faustel Fuertes TW 6		181220065441701	1984	45	27	screen 27-37	alluvium		
58	Faustel Fuertes TW 7		181220065441502	1984	40	25	screen 25-35	alluvium		
59	Shangai TW 1		181230065444900	1983	37	10	screen 10-30	alluvium		
60	Arroyo Well 1		181217065453000	1983	33	10	screen 10-33	alluvium		
61	Nevárez Well	A	181227065463500 (12-65.46-01-57)	1959	75	45	screen 45-75		30	
62	Pinero Well		181241065474600 (12-65.47-02-33)	1959	60	40	screen 40-60			
63	Río Blanco Pump House obs. Well		181318065470600		72		screen 0-72	alluvium		
64	A.A.A. Pozo Planta Tratamiento		181313065471200	1977	268	30	sc.een 30-90 open hole 90-268	alluvium & fractured rock	144	
65	A.A.A. Pozo Río Blanco		181309065473300	1970	42	22	screen 22-42	alluvium & fractured rock	171	
66	A.A.A. Pozo Peña Pobre 2		181250065475800 (12-65.47-03-11)	1963	96	70		alluvium & fractured rock	70	
67	A.A.A. Pozo Peña Pobre 1		181254065480500	1962	100	16	screen 16-100	fractured rock	48	
68	El Duque Well	A	181354065435700							
69	Tablones Dairy Well		181432065442000 (14-65.44-01-47)	1959					13	
70	Aba. farm well @ Hwy 925		181047065465500		83					
71	San Antonio School Well 2	D	180840065505100 (8-65.50-02-32)	1961	16		dug well	alluvium		
72	Pérez Well		181253065471200 (12-65.47-01-18)	1958	72	41	screen 41-61	alluvium		

1 Site identification numbers in parenthesis are historical file numbers.
2 Yield of wells are values given when well was originally drilled, and does not necessarily indicate current well pumpage.

Table 2. Number and name of the surface-water data stations

Site number (See fig. 2)	Site name
50082600	Río Candelero at Highway 906
50081000	Río Humacao at Las Piedras
50081300	Río Humacao at Humacao dam
50081500	Río Humacao near Humacao
50082000	Río Humacao at Highway 3, at Humacao
50082500	Río Humacao at mouth
50078510	Río Antón Ruiz at Pasto Viejo
50076000	Río Blanco near Florida
50076600	Río Blanco at Río Blanco Pump House
50077500	Río Blanco below La Fe
50074000	Río Santiago at Highway 31

GENERAL FEATURES

Land Forms and Drainage

The Humacao-Naguabo area is located 32 miles southeast of San Juan, and includes the two principal cities of Humacao and Naguabo. The area comprises six distinct drainage basins and has a total drainage area of 91 mi^2 (square miles) (fig. 1). The two major drainage networks are Río Blanco and Río Humacao. Río Blanco drains the Sierra de Luquillo mountain range, which reaches an altitude of 3,523 feet above sea level. Río Humacao heads in the eastern foothills of the Sierra de Cayey mountain range where the altitude reaches 1,150 feet. The basins are divided by ridges which are generally sharp and steeply sloped. Altitudes of the ridges range from about 300 to 500 feet.

The broad, flat, alluvium-filled valleys of the basins represent 40 percent of the study area and range in altitude from 0 to about 160 ft. A mangrove swamp has formed along the mouth of the Río Antón Ruiz, and several brackish-water lagoons have developed in depressions along the shoreline.

Climate

The climate of eastern Puerto Rico is humid tropical; the mean annual air temperature recorded by the National Oceanic and Atmospheric Administration (NOAA, 1984) at Humacao is 78 °F. The region is influenced by winds that are predominately from an easterly direction.

Rainfall distribution within the Humacao-Naguabo area is affected by orographic influences of the Sierra de Luquillo mountain range north of Naguabo: high elevations experience greater annual rainfall. For example, annual rainfall at Pico del Este (fig. 1) located at an elevation of 3,448 feet in the upper reaches of Río Blanco, is 158 inches. The city of Río Blanco located at an elevation of 130 feet, in the rain shadow of Sierra de Luquillo, has an annual rainfall of 110 inches. Naguabo at an elevation of 70 feet and Humacao at an elevation of 90 feet, both located in the alluvial valley, have an annual rainfall of 74 and 84 inches respectively. In general, this area experiences a dry season from January thru April, and a wet season from May thru December (fig. 3). Average annual pan evaporation for 1981 and 1982 recorded by NOAA at Yabucoa, five miles south of the project area, was approximately 72 inches (fig. 1).

Geology

An in-depth discussion of the geology of the Humacao-Naguabo area is beyond the scope of this report. The geology is very complex and has been studied extensively by several researchers (M'Gonigle 1978, 1979; Rogers, 1977; and Seiders, 1971). In terms of describing the occurrence, availability, and quality of ground-water resources, the geology can be divided into two basic lithologic types (fig. 4):

1) Surficial alluvial deposits of Pleistocene and Holocene age which are found within the valleys.

2) Plutonic and volcanic rock of Cretaceous and Tertiary age which underlie the surficial deposits and form the ridges and mountains around the alluvial valleys.

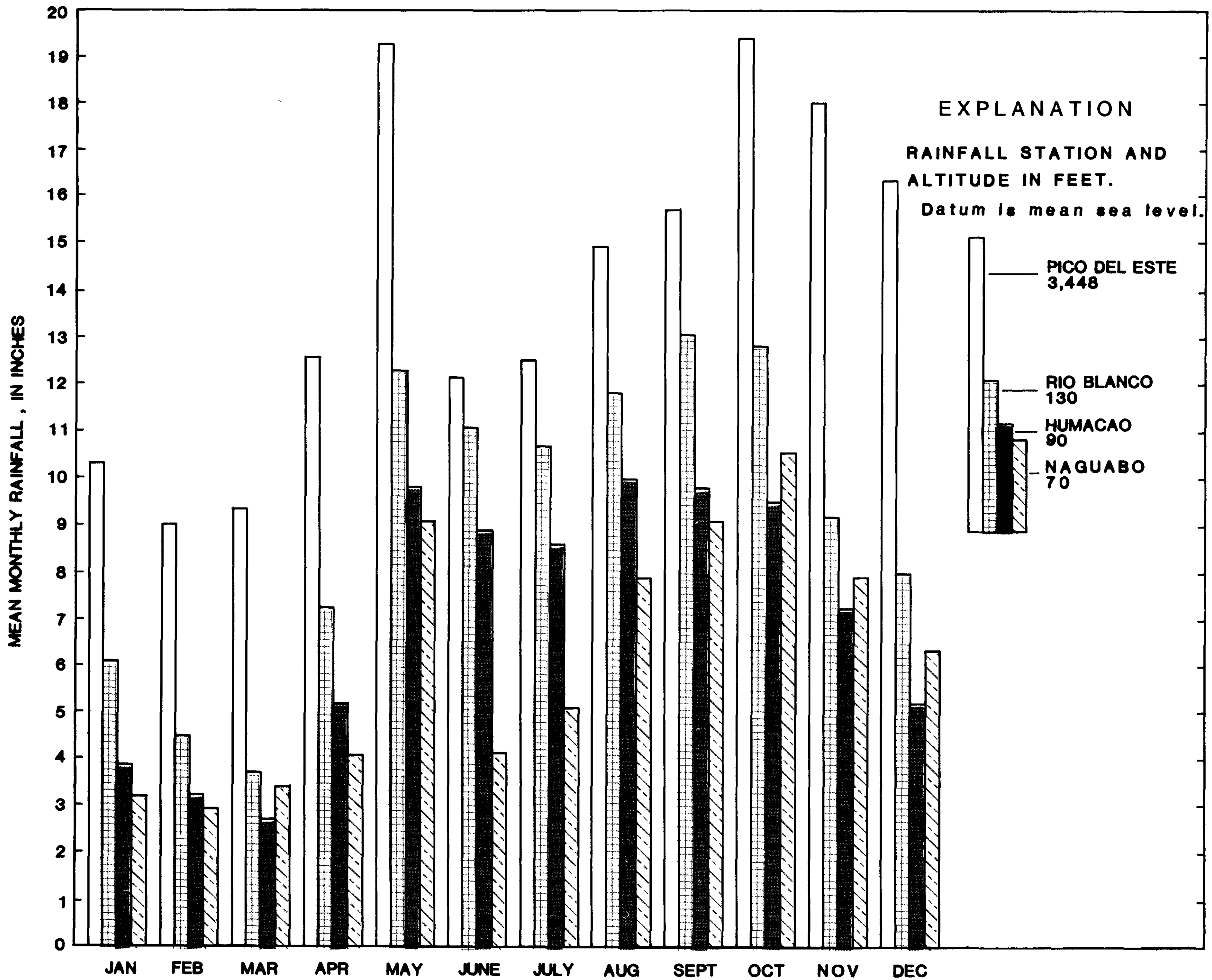


Figure 3.--Comparison of mean-monthly rainfall for a range of altitudes in the Humacao-Naguabo area, 1970-1984. (Data from (NOAA) National Oceanic and Atmospheric Administration.)

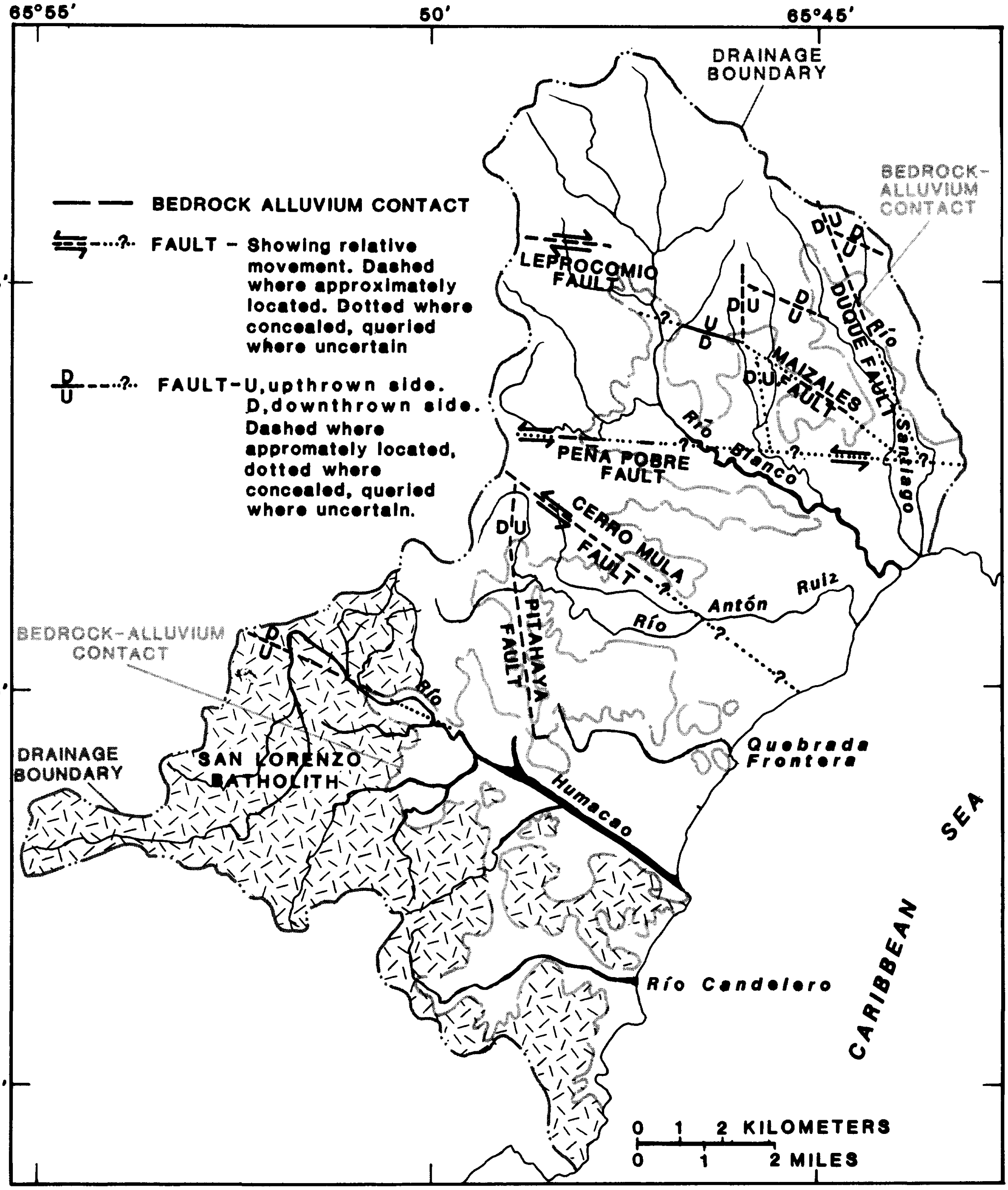


Figure 4.--Generalized geology and structure of the area.

The unconsolidated alluvial sediments are composed of poorly sorted clay, silt, and sand, heterogeneously distributed both areally and with depth. A large percentage of coarse sand from stream-channel deposits occurs along the major streams. The alluvial sediments have an areal extent of 36 mi^2 and are generally, wedge-shaped, ranging in thickness from zero near the bedrock-alluvium contact to more than 160 feet near the coast. The surface bedrock-alluvium contact is generally coincident with the base of the ridges which surround the alluvial valleys.

The plutonic rock is made up mostly of granodiorite and quartz diorite of the San Lorenzo batholith. The volcanic rock is a mixture of medium to thick-bedded volcaniclastic tuff, breccia, sandstone, and conglomerate as well as andesitic lava flows. Volcanic and plutonic rocks are termed bedrock in this report. The bedrock is characterized by a weathered zone approximately 20 feet thick underlying the alluvial deposits, and as much as 40 feet thick in the updip areas of the ridges where it is exposed to the atmosphere.

Localized deposits of magnetite and hematite have been mapped in the study area. Ore removed during open-pit mining operations in the early 1950's in the Las Piedras area was reported to be 60 percent iron (Knoerr, 1952) (fig. 1). Cadilla (1963) reported minor copper mineralization in the area.

The four major faults and fault zones in the area are the Cerro Mula and Peña Pobre fault zones, and the Maizales and Duque faults (fig. 4). The origination of the valleys of most of the streams seems to be controlled by these structures and follow the easterly and southeasterly trending faults (Kaye, 1959; M'Gonigle, 1978) (fig. 4).

SURFACE-WATER RESOURCES

The Humacao-Naguabo study area contains two major and four minor streams that drain an area of 91 mi^2 (fig. 1). The drainage area and length of the streams are as follows:

Stream	Drainage area at mouth			Length of main stream to mouth (miles)
	Upland (Square miles)	Alluvial (Square miles)	Total (Square miles)	
Río Candelero	5	4	9	4.0
Río Humacao	22	7	29	10.5
Quebrada Frontera	2	4	6	4.0
Río Antón Ruiz	1	10	11	5.5
Río Blanco	20	9	29	7.0
Río Santiago	5	2	7	4.0
Total	55	36	91	

The streams generally flow eastward and southeastward, and have a gradient of 50 to 500 feet per mile in the upland areas as compared to about 10 feet per mile in the alluvial valleys. The stream channels in the mountains and foothills are steep and narrow. During heavy rainfall, the streams crest quickly in the upper basins and generally return to base-flow conditions in a short time.

During dry periods, surface outflow to the Caribbean Sea reduces to zero; with water ponding behind sandbars at the mouths of streams. Outflow to the sea resumes with the restoration of streamflow from rainfall runoff which breaches the sandbars.

The area has a history of flooding, a discussion of which is beyond the scope of this paper. However, it should be noted that in the 1960 flood, which is the second largest flood known to have occurred in the area since 1899, the depth of floodwater ranged from 3 to 5 feet in the Río Humacao basin (López, 1967), and 5 to 6 feet in the Río Blanco and Río Antón Ruiz basins (Haire, 1978) (fig. 5). In the upper reaches of the basins the depth of floodwater was as much as 10 feet.

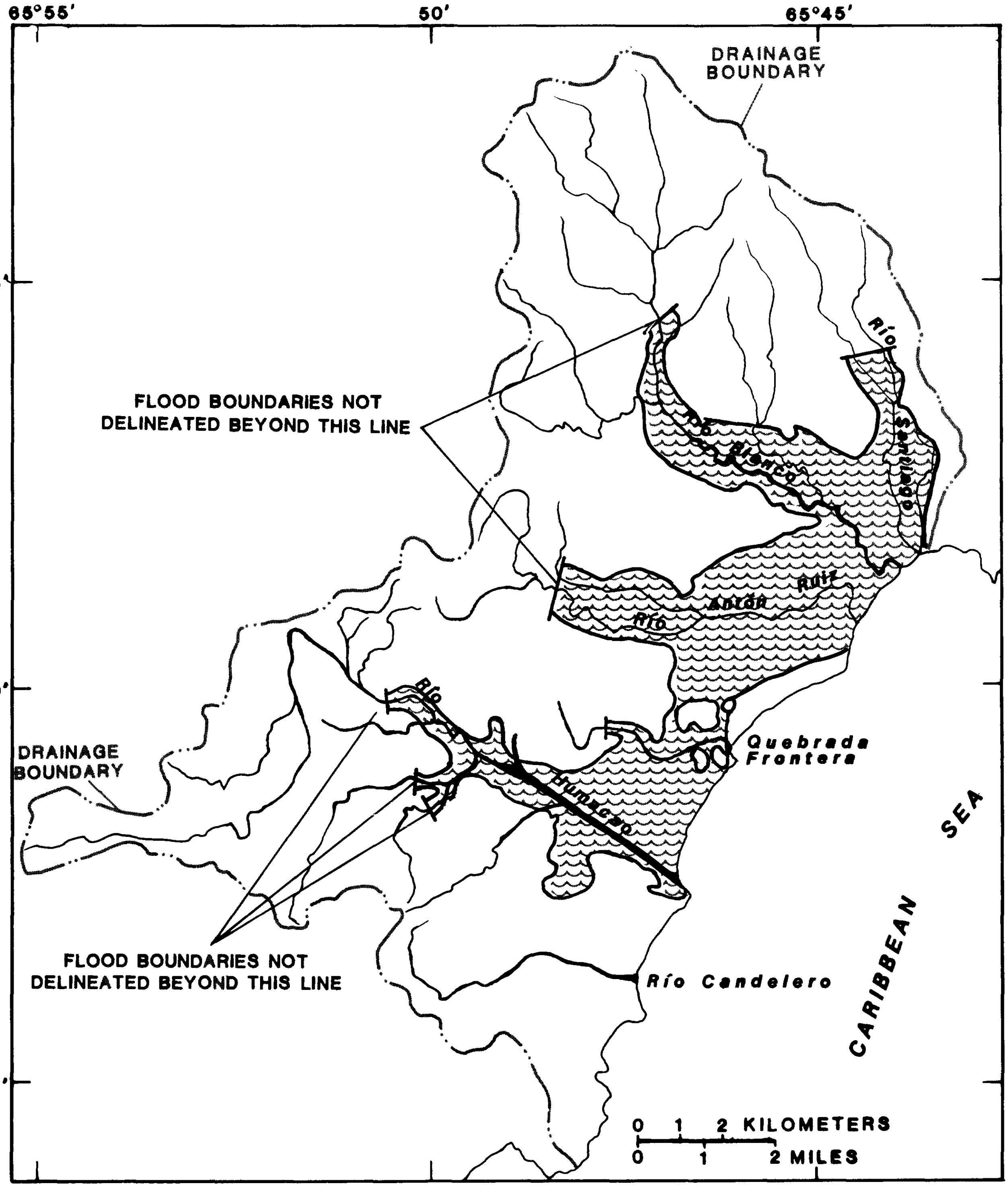


Figure 5.--Area inundated by 1960 flood in the Humacao-Naguabo area. (Adapted from López, 1967 and Haire, 1978.)

Streamflow

Streamflow was monitored continuously during the project at several stations along Río Humacao and Río Blanco, the two principal streams in the study area. Peak discharges in the streams occurred during the May through December rainy season. Minimum base flow occurred in March or April (fig. 6). Discharge data for water years 1983 and 1984 for Río Humacao at Highway 3, at Humacao, and Río Blanco near Florida are as follows:

Station name and number	Water year	Drainage (Square miles)	Average annual flow (cubic feet per second)	Runoff (inches)	Total annual discharge (acre-feet)
Río Humacao at Highway 3, at Humacao (50082000)	1983	17.3	58.80	46.15	42,570
Río Blanco near Florida (50076000)	1983	12.3	67.90	74.97	49,170
Río Humacao at Highway 3, at Humacao (50082000)	1984	17.3	38.60	30.34	27,990
Río Blanco near Florida (50076000)	1984	12.3	55.80	61.80	40,530

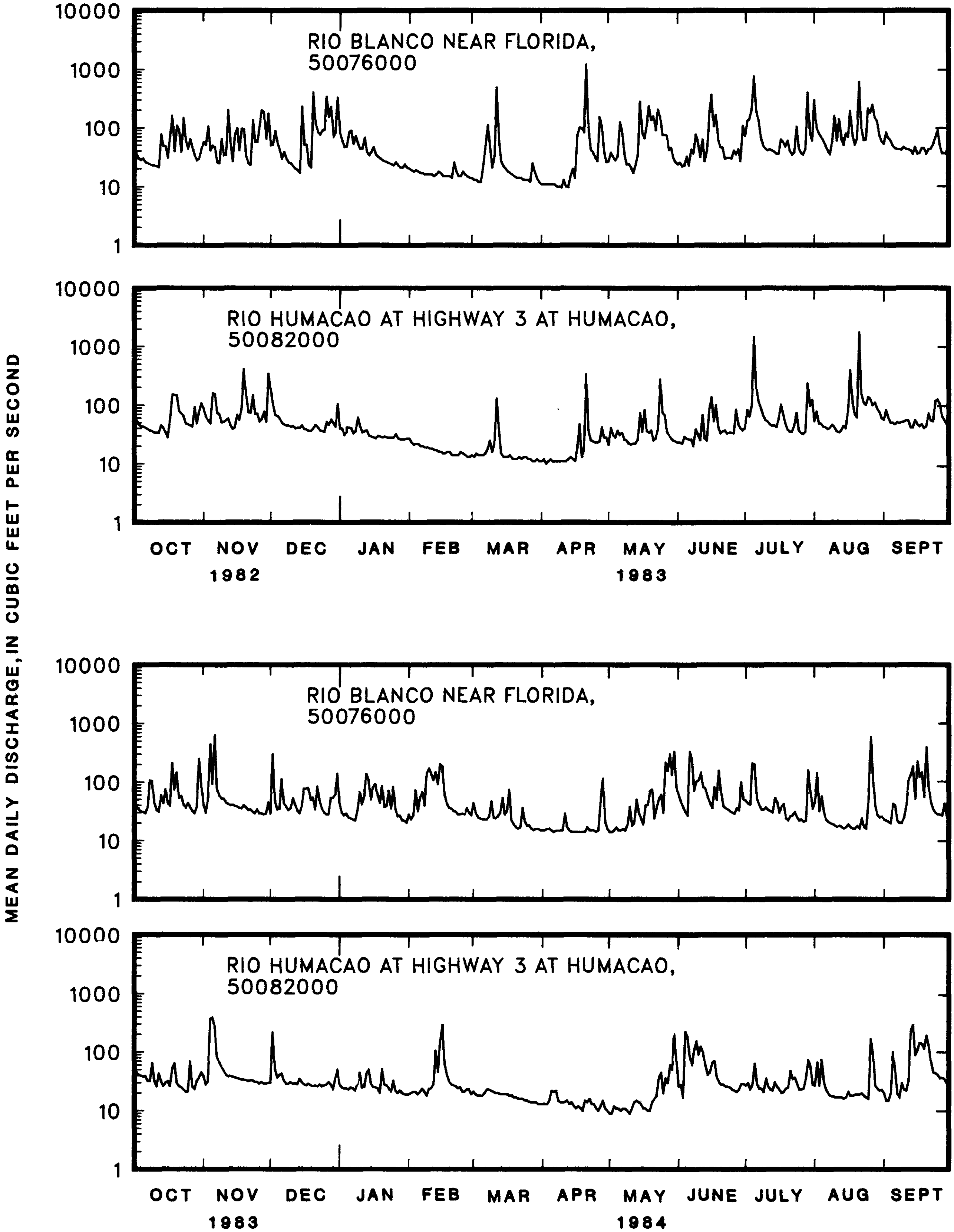


Figure 6.--Daily mean discharge at selected sites on Río Blanco and Río Humacao for water years 1983-84.

Two years of continuous record is insufficient to predict mean annual discharge values. A comparison of stations in adjacent drainage basins where long-term record has been established, indicates that water-year 1983 was a normal year for streamflow, whereas water-year 1984 was an unusually dry year.

Surface-Water Contribution from Ground Water

The base flow of Río Humacao is maintained by water contributed by the adjacent alluvial aquifer. A series of discharge measurements, termed a seepage run, were made and compared along a 5.84 mile reach of Río Humacao and its tributaries on April 3, 1984 to determine the quantity and areas of ground-water gains and losses from the river (fig. 7, table 3). Discharge measurements were made from Barrio Mabu, northwest of the city of Humacao, to within approximately 2,500 feet of the mouth of the Río Humacao. Ponding downstream prevented further measurements. Measurements made where the Río Humacao had ponded indicate there was no flow in the river (Heriberto Torres, USGS, oral communication, 1984). The measurements were made during a period of base flow of the stream. Tributary flow was considered streamflow contribution. In general, Río Humacao was shown to be a gaining stream from site 1 to site 14, with a net gain of 4.77 ft^3/s (cubic feet per second). Near the coast between sites 14 and 17, Río Humacao loses water to the ground-water regime with a net loss of 2.63 ft^3/s. The indicated gains or losses may be somewhat in error, affected by small inaccuracies in discharge measurements, but are considered substantially accurate. The distribution of gains and losses along the stream will change with changes in river stage and elevation of the adjacent water table.

Table 3. Seepage survey data collected at selected sites on Río Humacao, April 3, 1984

[units - ft^3/s, cubic feet per second]

Measurement Sites		Measured discharge (ft^3/s)	Gains (+) or losses (-) (ft^3/s)
Stream site (See fig. 7)	Tributary site		
1		6.90	
			-1.53[1]
2		5.37	
	3A[2]	0.20	
			+0.98
3		6.55	
			-0.21
4		6.34	
	5A	0.23	
			+0.09
5		6.66	
	6	0.22	
			+0.66
7		7.54	
	7A	0.10	
	8	0.04	
	8A	0.10	
			-0.27
9		7.51	
	9A	4.58	
			+1.07
10		13.16	
			+0.60
11		13.76	
	11A	1.07	
			+1.91
12		16.74	
			-0.53
13		16.21	
			+2.00
14		18.21	
	14A	0.33	
			-0.78
15		17.76	
			-0.51
16		17.25	
			-1.34
17		15.91	

[1] Indicated gains or losses may be in error as affected by small inaccuracies in open-channel measurements.

[2] Tributary flow is considered a contribution and not a gain. Tributary sites 6, 8, and 8A are outflows from potable water and sewage-treatment plants.

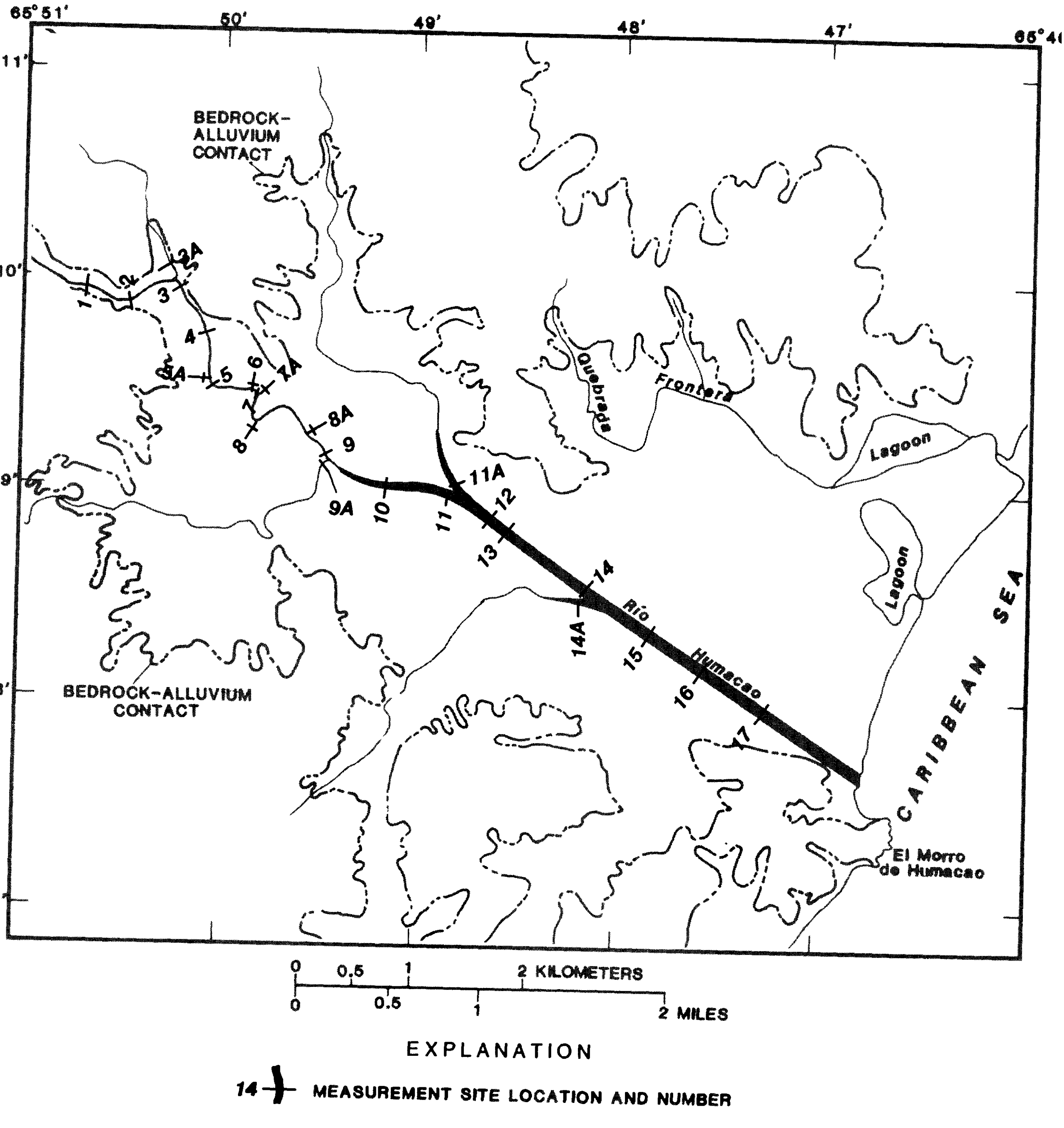


Figure 7.--Locations of measurement sites in the Río Humacao basin for seepage run April 3, 1984.

Surface-Water Use

The rivers within the Humacao-Naguabo area constitute the primary water-supply source in the area. Pumpage at the surface-water filtration plants in the area amounts to 13.7 Mgal/d (million gallons per day) (table 4). Besides providing water to the immediate Humacao-Naguabo area, water also is supplied to Las Piedras and Vieques island (fig. 1).

Most of the surface water developed in the area is intended for domestic use (table 5), but an increasing amount also is used for industrial purposes.

GROUND-WATER RESOURCES

Aquifers are presently of minor importance as sources of water supply for the Humacao-Naguabo area. This is due to the generally low hydraulic conductivity of aquifer materials and a thin layer of freshwater-bearing sediments. However, there is increasing interest in ground-water development in the area, particularly by industries, because of its relatively high quality and accessibility.

Table 4. Surface-water withdrawals at filtration plants in the area, 1983

[units - Mgal/d, million gallons per day;
Source: Gómez-Gómez and others, 1984]

Facility name	Location		Withdrawals (Mgal/d)
	Latitude	Longitude	
Río Blanco at Río Blanco	18°13'18"	65°47'05"	9.8
Naguabo	18°14'43"	65°44'50"	1.3
Humacao-Las Piedras	18°10'22"	65°52'03"	2.6
Total			13.7

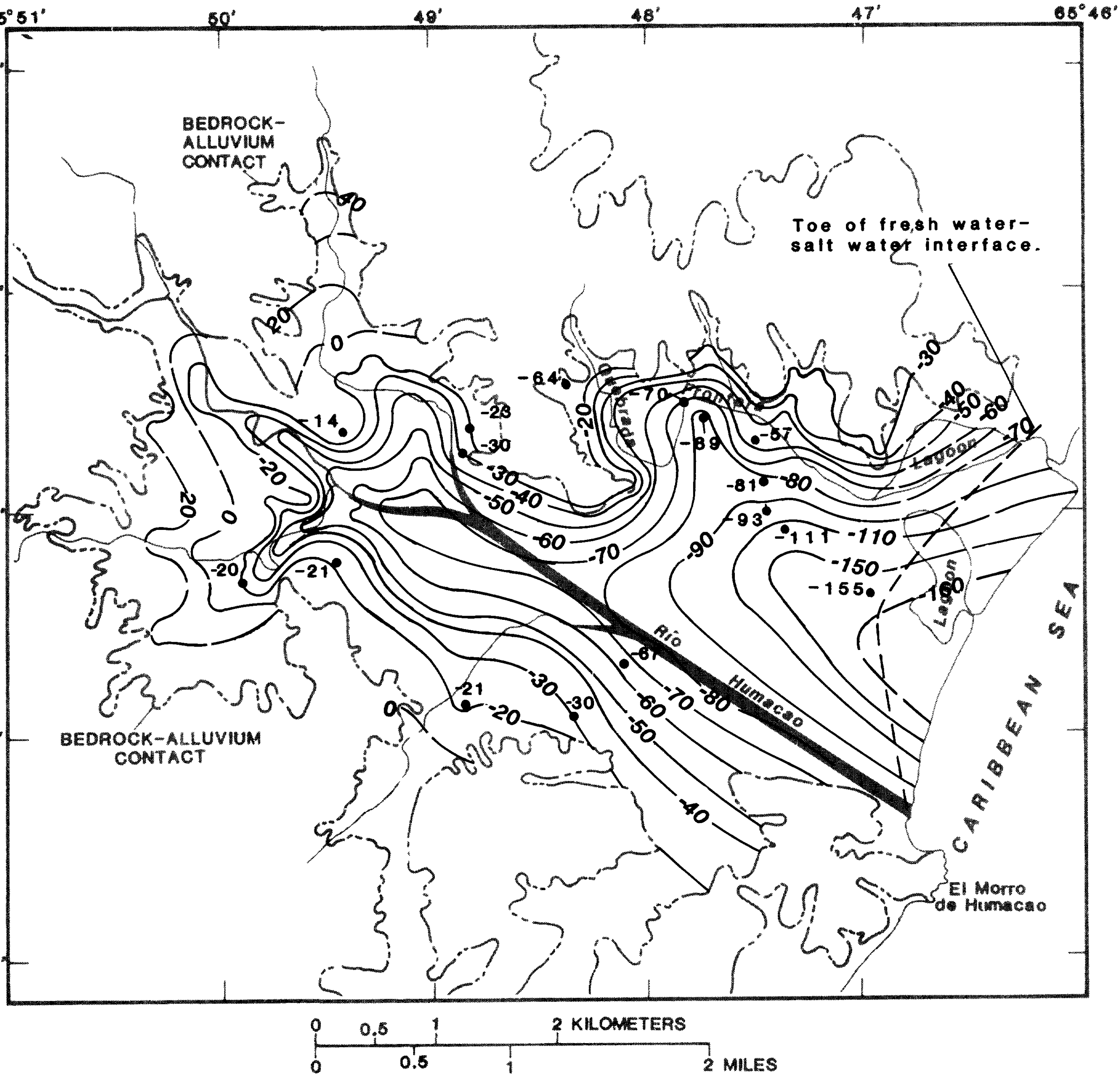
Table 5. Surface-water use in the area, in percent, 1980-83

[Source: Torres, Heriberto, 1985, USGS written communication]

Humacao area:	1980	1981	1982	1983
Domestic use	78	74	72	72
Commercial use	15	17	18	17
Industrial use	7	9	10	11
Daily use, in million gallons per day	3.74	4.28	4.17	4.20
Naguabo area:	**1980**	**1981**	**1982**	**1983**
Domestic use	88	89	89	89
Commercial use	8	8	8	8
Industrial use	4	3	3	3
Daily use, in million gallons per day	1.23	1.19	1.13	1.09

Occurrence

The principal aquifer in the Humacao-Naguabo area occurs within alluvial sediments, under water-table conditions. The alluvial aquifer includes the weathered zone of the underlying bedrock where the bedrock is fractured, permeable, and in hydraulic contact with the alluvium. Below the weathered zone, the plutonic and mixed volcanic bedrock contains little ground water. The depth to the water table within the alluvial aquifer ranges from about 40 feet below land surface near the bedrock outcrops to very near land surface in coastal areas. No important aquifers are believed to occur below the weathered zone of the bedrock. The thickness of the alluvial aquifer ranges from zero at the bedrock-alluvium contact, to more than 160 feet near the coast. In the Río Humacao basin, the base of the aquifer ranges from about 20 feet above sea level in the west, to about 160 feet below sea level near the coast (fig. 8).



EXPLANATION

——-80—— —— STRUCTURE CONTOUR-
Shows altitude of the base of the alluvial aquifer.
Dashed where approximately located.
Contour interval in feet and variable.
Datum is mean sea level.

-155 ● DATA POINT.

Figure 8.--Altitude of the base of the alluvial aquifer and approximate location of the toe of the freshwater-saltwater interface, Río Humacao basin.

Altitude changes in the water table occur seasonally, and generally vary within an eight-foot range. Seasonally, the water table is at its lowest elevation during the dry months of March and April, and generally recovers to its pre-season high by September. Although May is generally a wet month, during 1983 normal heavy rainfall did not occur until the end of May. Three ground-water stations show that during 1984 the lowest water-table elevation occurred in the first part of May (fig. 9). Localized irregularities in rainfall patterns also produced a peak on the Squibb observation well 3 hydrograph in February 1984. The altitude of the water table ranges from a high of 234 feet in the extreme northern part of the area to less than 1 foot in swampy areas near the coast (fig. 10). The direction of flow is generally east, toward the coast, perpendicular to the water-table contours. Ground water flows toward or away from streams, depending on the hydraulic gradient between the stream and adjacent aquifer.

The quantities of water recharging the alluvial aquifer as well as being discharged from it are discussed in later sections. Briefly, the alluvial aquifer is recharged by rainfall and from loss of streamflow in the lower reaches of each basin. Considerable recharge to the aquifer also occurs during floods. In the upper reaches of the stream basins, water stored in the relatively thick weathered zone of the bedrock ridges recharges the updip reaches of the alluvial aquifer, and ground-water discharge into the local streams occurs (fig. 11). Where the water table is within 10 feet of the land surface (near the coast, where wetlands occur) ground water is discharged by evapotranspiration. Ground water is also discharged through pumping wells located throughout the area and naturally to the Caribbean Sea.

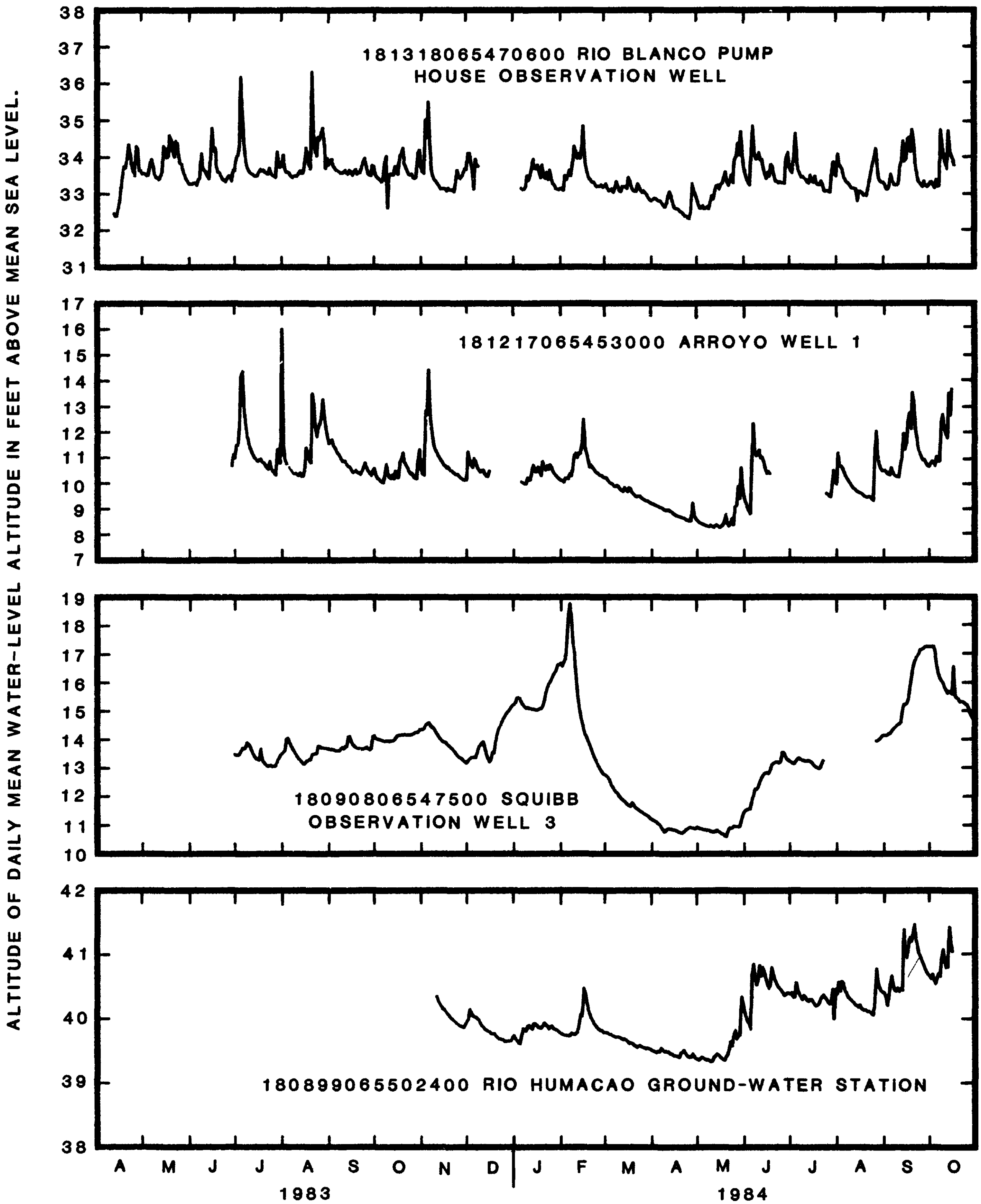


Figure 9.--Daily mean water-level altitude for wells screened in the alluvial aquifer, 1983-84.

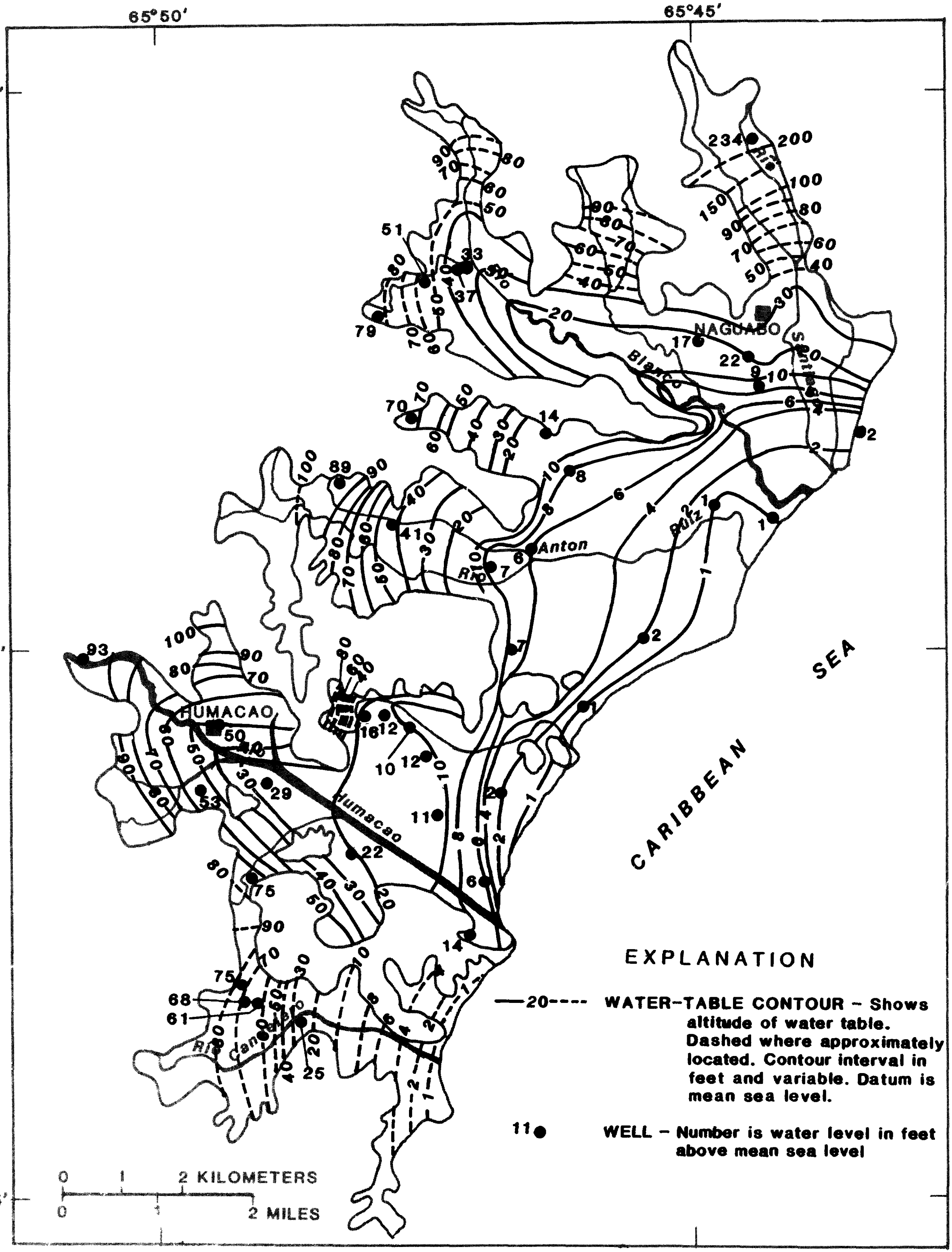


Figure 10.--Configuration of water-table surface, March 1984.

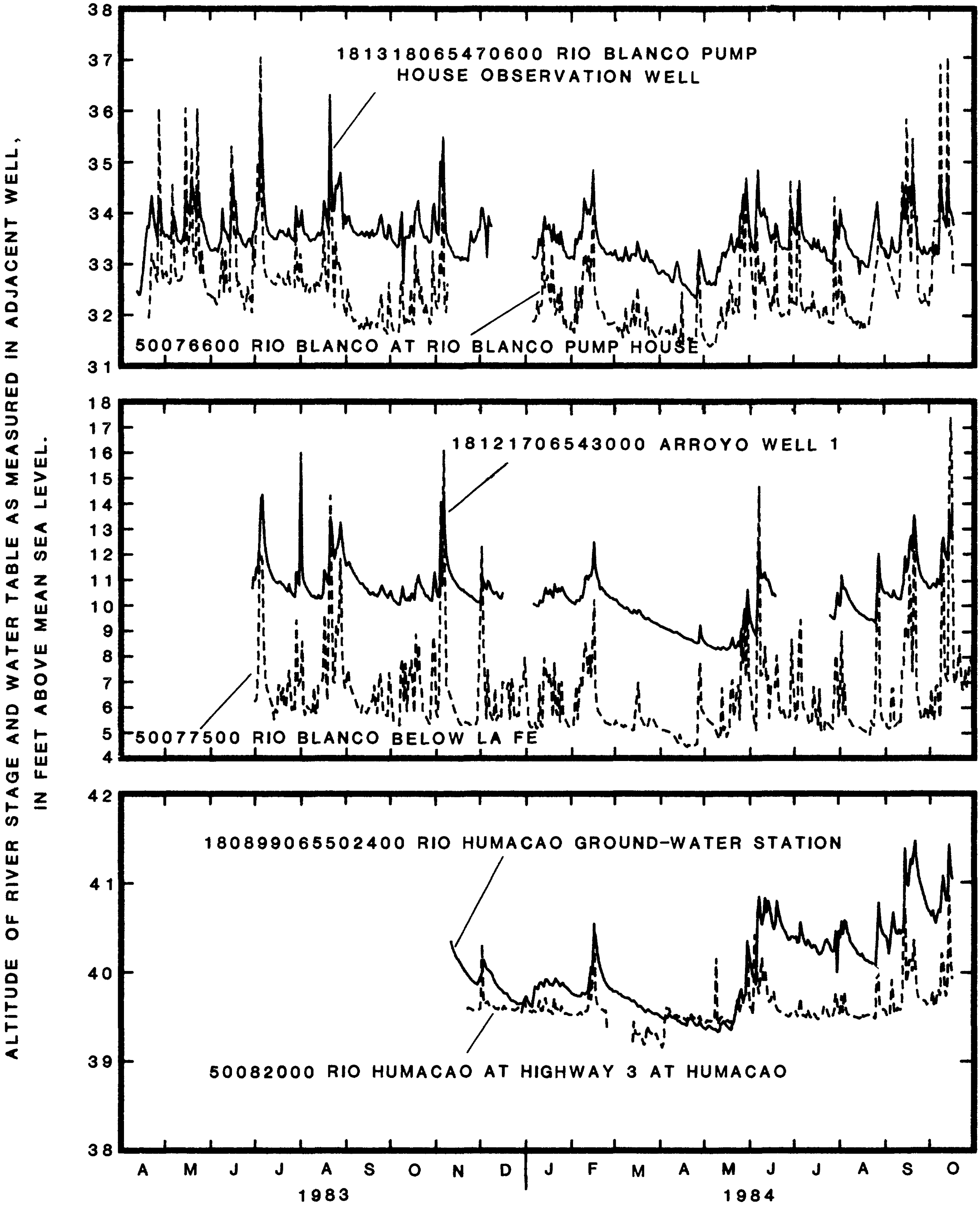


Figure 11.--Relation between altitude of river stage and adjacent aquifer water level for three sites in the area, 1983-84.

Ground-Water Availability

Ground-water availability depends upon the capability of an aquifer to transmit, store, and release water to wells. Transmissivity is a measure of the aquifer's ability to transmit water and is a product of the hydraulic conductivity of aquifer material and the aquifer thickness. The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. The mathematical definitions of these hydraulic characteristics are beyond the scope of this investigation but are presented in Lohman (1979).

Hydraulic characteristics of the aquifer were determined from aquifer tests and specific capacity determinations. Aquifer tests conducted within the Río Humacao basin reveal that transmissivity ranges from about 600 to 2,000 ft^2/d (feet squared per day) (table 6). Transmissivity values calculated from five specific-capacity tests on wells located throughout the Humacao-Naguabo area (table 7), range from 200 to 1,500 ft^2/d. The storage coefficient determined from the aquifer tests in the Humacao basin is approximately 0.02 (table 6). This value is somewhat lower than values normally considered for water-table aquifers and could be influenced by the delayed yield of clays draining within the anisotropic aquifer.

Table 6. Aquifer characteristics from aquifer tests

[units - ft^2/d, feet squared per day; min., minutes; NA, indicates data not available]

Well number (See table 1)	Trans-missivity (ft^2/d)	Storage co-efficient	Type of material screened	Length of test (min.)
21	800	NA	Alluvium	300
24	600	0.02	Alluvium	1440
30	2000	0.01	Alluvium & fractured rock	1440

Table 7. Estimated transmissivity from specific well capacity

[units - (gal/min)/ft, gallons per minute per foot of drawdown; ft^2/d, feet squared per day].

Well number (See table 1)	Specific capacity [(gal/min)/ft]	Trans-missivity (ft^2/d)	Type of material screened
01	4	900	Fractured rock
09	1	200	Fractured rock
35	8	1500	Alluvium
56	3	700	Alluvium
63	5	1200	Alluvium

Estimates based on method described by Meyer (1963).

The quantity of water actually contained within the alluvial aquifer is estimated to be 2.3 x 10^5 million gallons. However, only part of this quantity can be considered available for ground-water development. The low transmissivity of the aquifer limits the amount of ground water available to wells, most of which are capable of pumping only 30 to 100 gallons per minute.

Ground-Water Use

Ground-water use is limited in the Humacao-Naguabo area; only 21 of the 72 wells inventoried in the study area were in use in 1984 (table 1 and 8). The Puerto Rico Aqueduct and Sewer Authority (PRASA) reports only one municipal well in operation. Nine other PRASA wells have been abandoned because of low yields or elevated iron and manganese concentrations in the water. In the Humacao-Naguabo area PRASA obtains its water from surface-water sources including Río Blanco, Río Humacao, and Río Santiago. Although the industries in the area have developed ground-water supplies for some operational purposes, the wells have often been found to provide inadequate quantities of water. The industries continue to depend on PRASA to provide the additional water.

Table 8. Estimated ground-water use in the area, 1985

Ground-water use	Agricultural	Industrial	Municipal	Domestic	Total
Daily pumpage, in million gallons per day	0.07	0.63	0.10	0.13	0.93
Number of wells in use	8	9	1	3	21

WATER QUALITY

The suitability of ground water and surface water for domestic, agricultural, or industrial use is dependent on the chemical constituents in the water and their concentrations. Much of the ionic composition of ground water is derived from the soil and rocks through which the water passes. Ground water can also be affected by the quantity of saline water that occurs in the aquifer. Surface water usually contains less chemical constituents than ground water but can contain considerable quantities of bacteria and organic contaminants.

Ground Water

Samples were collected from 18 wells in the Humacao-Naguabo area and analyzed for major cations and anions, as well as for trace metals of iron and manganese (fig. 12, table 9). Water samples from nine wells contained TDS (Total Dissolved Solids) concentrations which exceeded U.S. Environmental Protection Agency (EPA, 1973) drinking water standards. Water samples from four of the wells had concentrations of dissolved iron or manganese that exceeded EPA drinking water standards (table 10). Samples from wells cased with PVC were analyzed for total recoverable iron and manganese. Concentrations of iron and manganese were as high as 25,000 ug/L (micrograms per liter) and 7,600 ug/L, respectively.

Elevated iron and manganese concentrations found in the ground water in the study area could be derived from two sources. Ionic iron and manganese are likely to have been concentrated by organic activity within the ancient coastal swamps of the area, producing iron and manganese ores within the alluvial deposits. The weathering of these ores as well as the weathering of magnetite, hematite, and manganese-bearing minerals found in the fractured bedrock ridges could produce the elevated iron and manganese concentrations.

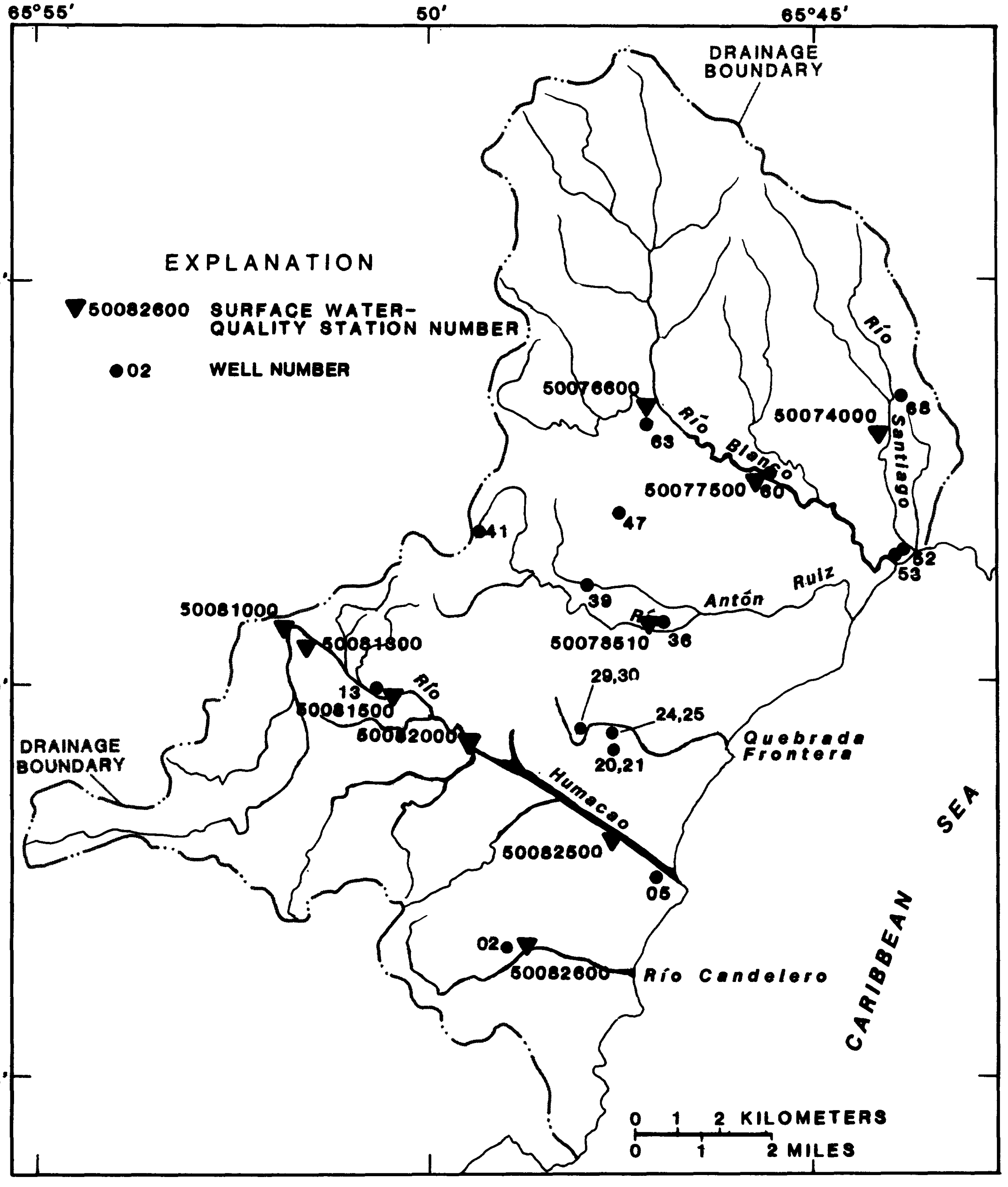


Figure 12.--Location of water-quality sites.

Table 9. Chemical analyses of ground-water samples

[units - ft, feet; mg/L, milligrams per liter; uS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; deg C, degrees Celsius; ug/L, micrograms per liter; NA, not applicable].

Well number (See Table 1)	Date of sampling	Depth of well (ft)	Type of casing (ft)	Silica dis- solved (mg/L as Si)	Cal- cium dis- solved (mg/L as Ca)	Magne- sium dis- solved (mg/L as Mg)	Sodium dis- solved (mg/L as Na)	Potas- sium dis- solved (mg/L as K)	Alka- linity field (mg/L as $(CaCO_3)$	Sul- fate dis- solved (mg/L as SO_4)	Chlo- ride dis- solved (mg/L as Cl)	Fluo- ride dis- solved (mg/L as F)	Nit- rate dis- solved (mg/L as NO_3)	Nit- rite dis- solved (mg/L as NO_2)
02	01-27-84	80	STEEL	27	17	09.0	42	1.8	103	15.0	40	0.2	0.06	0.04
05	01-17-84	102	STEEL	42	16	15.0	130	1.0	213	45.0	100	0.7	0.54	<0.01
13	01-27-84	165	STEEL	22	55	8.2	28	1.7	215	12.0	21	0.5	0.14	0.04
20	09-19-83	108	STEEL	35	42	19.0	67	0.8	240	24.0	52	0.3	0.38	0.02
21	09-20-83	28	PVC	40	30	18.0	59	0.9	190	18.0	49	0.4	0.08	0.02
24	09-14-83	30	PVC	48	51	29.0	89	0.9	260	35.0	110	0.1	<0.09	<0.01
25	09-14-83	75	STEEL	37	34	15.0	95	0.4	250	23.0	62	0.4	<0.09	<0.01
29	09-14-83	150	PVC	32	53	17.0	74	0.6	270	15.0	72	0.3	1.79	<0.01
30	09-14-83	40	PVC	34	36	20.0	110	0.2	260	18.0	90	0.3	2.09	<0.01
36	09-20-83	25	PVC	36	150	79.0	91	0.9	230	130.0	430	0.3	<0.09	<0.01
36	01-26-84	25	PVC	35	140	83.0	97	0.8	226	130.0	450	0.2	0.07	0.03
39	01-24-84	NA	STEEL	43	29	13.0	30	0.5	149	5.0	24	0.2	1.99	<0.01
41	01-17-84	240	STEEL	65	13	12.0	57	0.8	169	3.6	18	0.3	0.78	<0.01
47	01-24-84	200	STEEL	35	38	16.0	39	1.0	184	17.0	25	0.4	0.99	<0.01
52	09-22-83	15	STEEL	15	78	19.0	120	14.0	300	10.0	190	0.3	0.09	<0.01
53	09-22-83	26	PVC	13	130	180.0	1600	60.0	390	200.0	1700	0.6	<0.09	0.01
60	09-15-83	33	PVC	51	85	53.0	65	0.4	240	32.0	210	0.3	0.09	<0.01
63	09-21-83	72	STEEL	35	30	12.0	17	2.3	130	10.0	22	0.1	0.09	<0.01
68	01-24-84	NA	STEEL	59	24	15.0	37	3.1	157	11.0	23	0.3	0.09	<0.01

Table 9. Chemical analyses of ground-water samples (Continued)

[units - ft, feet; mg/L, milligrams per liter; uS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; deg C, degrees Celsius; ug/L, micrograms per liter; NA, not applicable].

Well number (See table 1)	Total dis- solved solids (mg/L)	Hard- ness (mg/L as $CaCO_3$)	Hard- ness noncar bonate (mg/L $CaCO_3$)	Spe- cific con- duct- ance (uS/cm at 25°C)	pH (units)	Temp- ature (deg C)	Iron dis- solved (ug/L as Fe)	Man- ganese dis- solved (ug/L as Mn)	Iron total (ug/L as Fe)	Man- ganese total (ug/L as Mn)
02	259	80	0	308	6.1	31.0	1300	2500	NA	NA
05	563	100	0	800	6.8	26.0	14	11	NA	NA
13	366	170	0	387	7.0	31.0	280	2100	NA	NA
20	480	180	0	679	7.1	26.5	NA	NA	440	150
21	405	150	0	589	6.7	27.5	NA	NA	2500	700
24	623	250	0	938	6.2	29.0	NA	NA	13000	1000
25	517	150	0	713	7.0	27.5	NA	NA	360	160
29	536	200	0	766	7.3	26.5	NA	NA	100	<10
30	571	170	0	836	6.8	27.5	NA	NA	17000	370
36	1147	700	480	1860	6.5	28.5	NA	NA	25000	7600
36	1170	690	470	1880	6.7	28.0	2400	6200	NA	NA
39	296	130	0	333	7.7	26.0	<3	32	NA	NA
41	339	82	0	350	7.5	26.0	<3	3	NA	NA
47	356	160	0	420	7.3	25.0	4	11	NA	NA
52	746	270	25	1080	7.3	28.0	NA	NA	4400	260
53	4274	1100	700	6530	7.3	27.0	NA	NA	1200	210
60	737	430	190	1050	6.5	27.5	NA	NA	16000	2100
63	259	120	0	385	6.7	28.0	NA	NA	9700	2500
68	330	120	0	373	6.7	26.5	140	120	NA	NA

Table 10. Well sites and sample concentrations where U.S. Environmental Protection Agency drinking water standards of 1986 for iron, manganese, and total dissolved solids were exceeded

[units - ug/L, micrograms per liter; mg/L, milligrams per liter; <, sample concentration did not exceed standards; NA, data not available; Source: U.S. Environmental Protection Agency, 1986, Quality criteria for water year 1986: EPA 440/5-86-001, Office of Water Regulations and Standards, Washington, D.C.]

	Iron (ug/L)	Manganese (ug/L)	Total dissolved solids (mg/L)
U.S. Environmental Protection Agency drinking water standards, 1986	300	50	500
Well number (See table 1)			
02	1300	2500	<
05	<	<	563
13	<	2100	<
24	NA	NA	623
25	NA	NA	517
29	NA	NA	536
30	NA	NA	571
36	2400	6200	1170
52	NA	NA	746
53	NA	NA	4274
60	NA	NA	737
68	<	120	<

Dilute saltwater as indicated by chloride concentration was observed in several of the 25 water samples withdrawn from wells near the coast (fig. 13, table 11). Near the Antón Ruiz mangrove swamp, in wells 32, 34, 53, and 54, the aquifer contains salty water in areas downdip from the swamp and near the shore where wave surges from coastal storms cause inflows of seawater. Elevated chloride concentrations were also found updip from the swamp, in wells 36 and 60, in the Río Antón Ruiz and Río Blanco basins. These elevated chloride levels are probably remnants of seawater intrusion into coastal swamps during the recent geologic past. Evidence of ground-water recharge from the weathered zone of the bedrock ridges is found where the chloride concentration abruptly changes from 59 to 450 mg/L (milligrams per liter) in wells 35 and 36 respectively in the Río Antón Ruiz basin. The freshwater that recharges the aquifer from the bedrock ridges has flushed the connate ground water that is found in the downdip areas of the aquifer.

Table 11. Specific conductance and chloride concentrations of selected ground-water sampling sites, March 1984

[units - uS/cm at 25 °C, microsiemens at 25° Celsius; mg/L, milligrams per liter]

Well number (See table 1)	Specific conductance (uS/cm at 25°C)	Chloride (mg/L)
01	2080	555
02	303	40
05	800	100
06	880	86
08	393	36
09	700	71
13	387	21
14	306	46
15	611	107
20	679	52
24	938	110
30	836	90
32	3170	780
33	776	57
34	4340	1280
35	388	59
36	1880	450
38	391	29
47	420	25
53	6530	1700
54	2550	710
56	640	44
59	795	150
60	1050	210
63	385	22
68	373	23

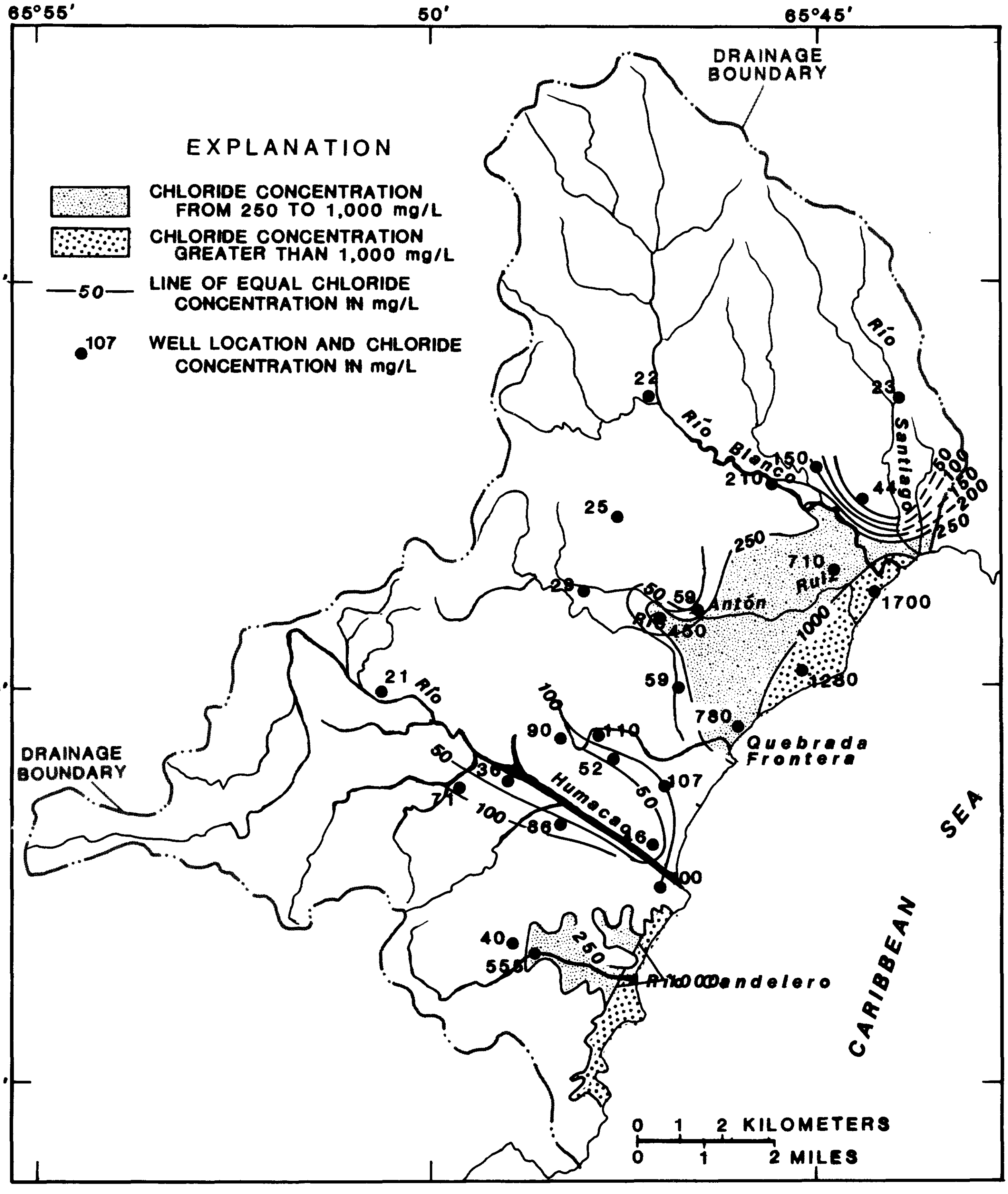


Figure 13.--Chloride concentration of water in the alluvial aquifer.

The concentration of industrial pumpage in the Río Humacao basin has not caused the saltwater-freshwater interface to migrate shoreward. Apparently seepage from Río Humacao to the aquifer creates a freshwater mound that prevents the interface from moving inland.

Surface Water

Samples were collected from seven surface-water sites in the study area and analyzed for the principal cations and anions, as well as for trace metals of iron and manganese (fig. 12, table 12). Water samples from three of the sampling sites (stations 50082600, 50082000, and 50078510) had concentrations of dissolved manganese that ranged from 63 to 200 ug/L and exceeded the EPA drinking water standards of 50 ug/L. Biological contamination was also found in the surface-water analyses. Raw surface-water samples were collected for determination of fecal coliform and streptococci bacteria. Results showed counts as high as 10,300,000 cols./100ml (colonies per 100 milliliter) for coliform and 1,900,000 cols./100ml for streptococci (table 13). Sources of this contamination are probably runoff from pasture lands and discharge from wastewater-treatment plants into the streams.

Table 12. Chemical analyses of surface-water samples

[units - ft^3/s cubic feet per second; mg/L, milligrams per liter; uS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; deg C, degrees Celsius; ug/L, micrograms per liter; NA, data not available]

Station number	Station name	Date of sampling	Instantaneous discharge (ft3/s)	Silica dissolved (mg/L as Si)	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 ($CaCO_3$)	Sulfate dissolved (mg/L as SO_4)	Chloride dissolved (mg/L as Cl)	Fluoride dissolved (mg/L as F)
50082600	Río Candelero at Highway 906	01-27-84	5.46	24	16.0	5.0	32.0	2.6	67	12.0	36	0.20
50081300	Río Humacao at Humacao dam	01-19-84	10.24	37	13.0	4.1	19.0	2.0	57	10.0	17	.10
50082000	Río Humacao at Highway 3, at Humacao	01-19-84	NA	36	21.0	6.2	23.0	2.1	77	16.0	26	.20
50078510	Río Antón Ruiz at Pasto Viejo	01-25-84	4.10	23	23.0	13.0	38.0	2.0	143	9.9	27	.20
50076600	Río Blanco at Río Blanco pump house	09-23-83	NA	24	10.0	3.0	9.9	1.0	43	4.4	16	.10
50077500	Río Blanco at La Fe	09-15-83	NA	24	12.0	3.8	10.0	1.2	49	5.4	12	< .01
50074000	Río Santiago at Highway 31	01-18-84	4.70	25	9.5	4.9	15.0	1.7	51	7.0	15	.10

Table 12. Chemical analyses of surface-water samples (Continued)

Station number	Nitrate dissolved (mg/L as NO_3)	Nitrite dissolved mg/L as NO_2)	Total dissolved solids (mg/L)	Hardness (mg/L as $CaCO_3$)	Hardness noncarbonate (mg/L $CaCO_3$)	Specific conductance (uS/cm at 25°C)	pH (units)	Temperature (deg C)	Iron dissolved (ug/L as Fe)	Manganese dissolved (ug/L as Mn)	Iron total (ug/L as Fe)	Manganese total (ug/L as Mn)
50082600	0.23	<0.01	195	61	0	245	7.5	26	12	200	NA	NA
50081300	0.63	0.07	160	49	0	198	7.9	23	68	23	NA	NA
50082000	0.71	0.01	208	78	0	240	7.4	25	8	96	NA	NA
50078510	0.10	<0.01	279	110	0	331	8.1	27	39	63	NA	NA
50076600	0.09	0.01	112	41	0	139	7.8	27	NA	NA	380	60
50077500	0.09	0.01	117	46	0	146	7.0	30	NA	NA	3500	350
50074000	0.10	<0.01	130	44	0	160	8.3	30	250	21	NA	NA

Table 13. Bacteria concentrations at selected surface-water stations

[units - cols./100 ml, colonies per 100 milliliters]

Site name	Site number (figure 2)	Coliform, Fecal (Cols./100 ml)	Streptococci, Fecal (Cols./100 ml)
Río Candelero at Highway 906	50082600	410,000	270,000
Río Humacao at Las Piedras	50081000	75,000	200,000
Río Humacao at Humacao Dam	50081300	765,000	500,000
Río Humacao near Humacao	50081500	180,000	122,000
Río Humacao at Highway 3 at Humacao	50082000	10,300,000	1,900,000
Río Humacao at Mouth	50082500	900,000	134,500
Río Antón Ruiz at Pasto Viejo	50078510	95,000	32,000
Río Blanco at Río Blanco pump house	50076600	220,000	66,000
Río Blanco below La Fe	50077500	450,000	400,000
Río Santiago at Highway 31	50074000	260	180

GROUND-WATER FLOW SIMULATION

Two-Dimensional Finite-Difference Model

The alluvial aquifer in the Río Humacao basin was modeled assuming steady-state conditions using the finite difference ground-water flow model of McDonald and Harbaugh (1984) (fig. 14). Steady-state conditions imply that the quantity of water flowing into the system equals that which flows out of the system. There is no water derived from or added to aquifer storage under steady-state conditions. The steady-state model can simulate maximum head gains or losses, but cannot predict when these changes will take place.

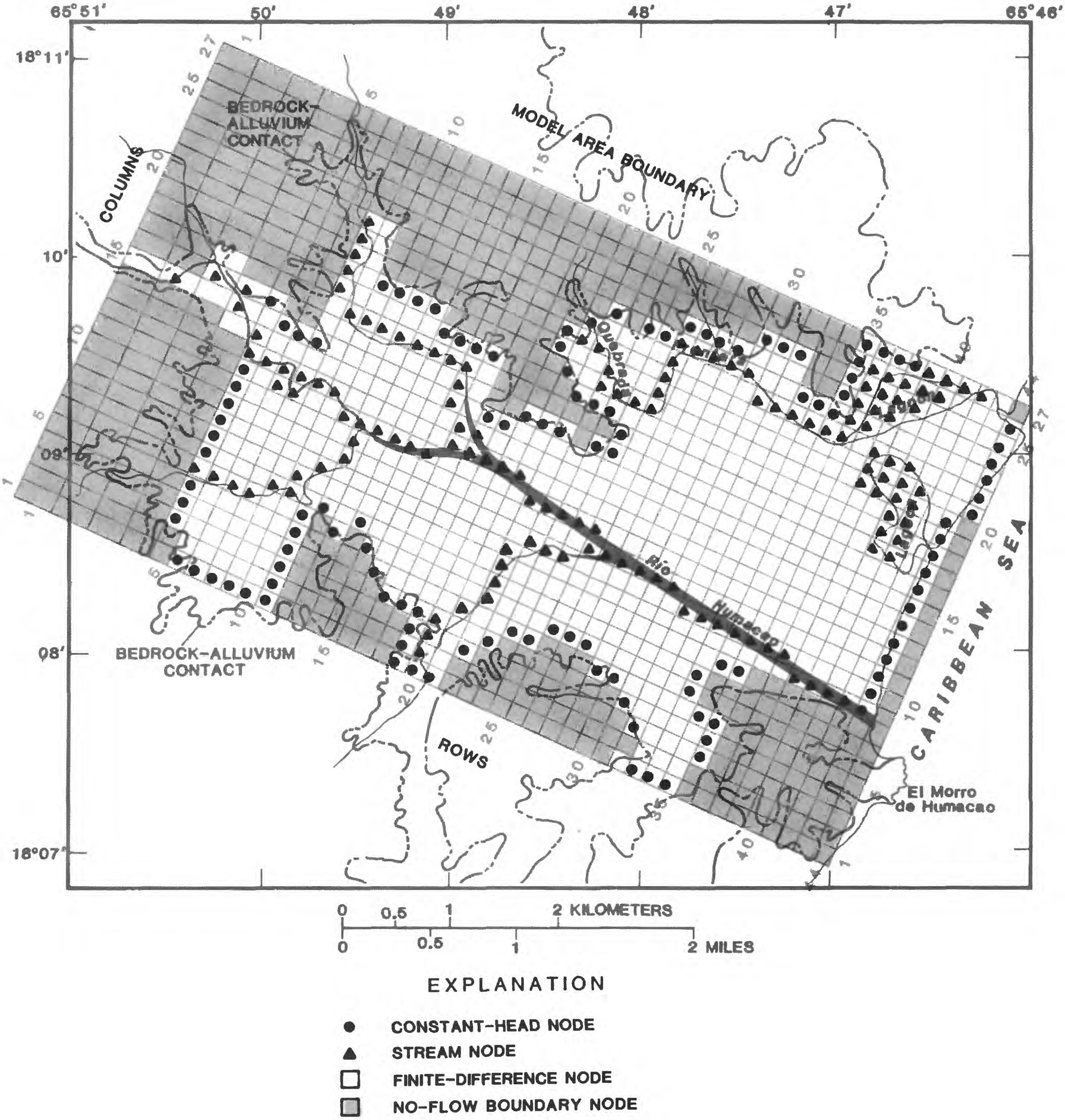


Figure 14.--Finite-difference grid and boundary conditions used for modeling the Río Humacao basin.

The model was constructed and calibrated to the March 1984 water level contour map, and ground water-surface water seepage data of April 1984. Aquifer water levels in the Río Humacao basin were still declining during March 1984 (fig. 9); therefore, true steady-state conditions did not exist. However, when comparing March 1984 water levels (Fig 9., Squibb Observation Well 3 and Río Humacao Ground-Water Station) to the average annual water levels, there is only a maximum difference of approximately 1.5 feet. Accordingly, steady-state assumptions are considered to be appropriate for a preliminary model analysis in the Río Humacao basin.

For modeling purposes, flow in the water-table aquifer was assumed to be two-dimensional i.e., all ground-water flow is considered to be in the horizontal plane with no vertical movement. The stratigraphy of alluvial sediments within the Río Humacao basin is similar to the alluvial basins on the south coast of Puerto Rico. Here, the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity was observed to range from 1000:1 to 100:1 (Bennett, 1976). Thus, modeling ground-water flow in a horizontal plane with no vertical flow components is considered to be a reasonable simplification of the real flow system.

Model Construction

The finite-difference technique requires that the ground-water system be divided into nodes or blocks. Values of aquifer parameters (hydraulic conductivity, rainfall recharge, water-table elevations, and evapotranspiration) were assigned to every block in the finite-difference grid by extrapolating and interpolating from nodes where measured values exist. The Humacao model covers an area of approximately 12 mi^2, and is subdivided into a grid of 44 rows and 27 columns (fig. 14). All columns have a spacing of 500 feet. Rows one through four have a spacing of 1000 feet, rows five through 44 have a spacing of 500 feet.

The base of the aquifer was defined as the top of the plutonic and volcanic bedrock underlying the alluvium (fig. 8). However, in areas where the bedrock is weathered and/or fractured, these horizons are considered as part of the aquifer, consequently where the top of bedrock was determined from the seismic-refraction surveys, geophysical logs, and drillers logs, the thickness of the alluvial aquifer was extended by 20 feet to include the weathered or fractured bedrock.

Estimates of the location of the freshwater-saltwater interface were determined from the Ghyben-Herzberg principle (Fetter, 1980) (fig. 8 and 15). Where the interface was determined to be above the bedrock, the interface was used as the base of the aquifer.

The Ghyben-Herzberg method does not account for vertical ground-water flow within the coastal discharge zone. Interpretation of the April 1984 seepage-run data and chloride-contour map (fig. 13) indicates that there is a vertical ground-water flow component to the Caribbean Sea. The accurate location of the coastal discharge zone is beyond the scope of this report. For this reason, and the fact that the two-dimensional model considers all ground-water flow in the horizonal direction, the Ghyben-Herzberg method is assumed to be an accurate simplification of the location of the freshwater-saltwater interface.

Two types of boundary conditions were incorporated into the model (fig. 14). No-flow boundaries were assigned to the volcanic and plutonic ridges around the basin. Constant-head boundaries were designated where the alluvial valley extends beyond the modeled area, and along the coastline. Lateral ground-water movement into and out of the modeled aquifer occurs across these boundaries (fig. 16). Flow lines indicate that there can be a component of recharge into the aquifer across the bedrock-alluvium contact from the fractures in the plutonic and volcanic ridges. To account for this ground-water movement into the basin, constant head nodes were assigned to all nodes adjacent to the bedrock-alluvium contact.

The initial values of hydraulic conductivity assigned to the model ranged from 2 to 21 ft/d (feet per day). Estimates of hydraulic conductivity were calculated from specific-capacity tests and as the quotients of the transmissivity computed from aquifer tests and aquifer thickness at that site. Values of hydraulic conductivity as determined from these tests did not exceed 15 ft/d. Therefore, in the lower reach (row 26 through 44, fig. 14) of the Río Humacao basin, where all aquifer tests were conducted, the maximum value of hydraulic conductivity used in the model was 15 ft/d. In the upper to mid reaches (row 1 through 25, fig. 14) values of hydraulic conductivity used in the model were slightly higher, ranging up 21 ft/d.

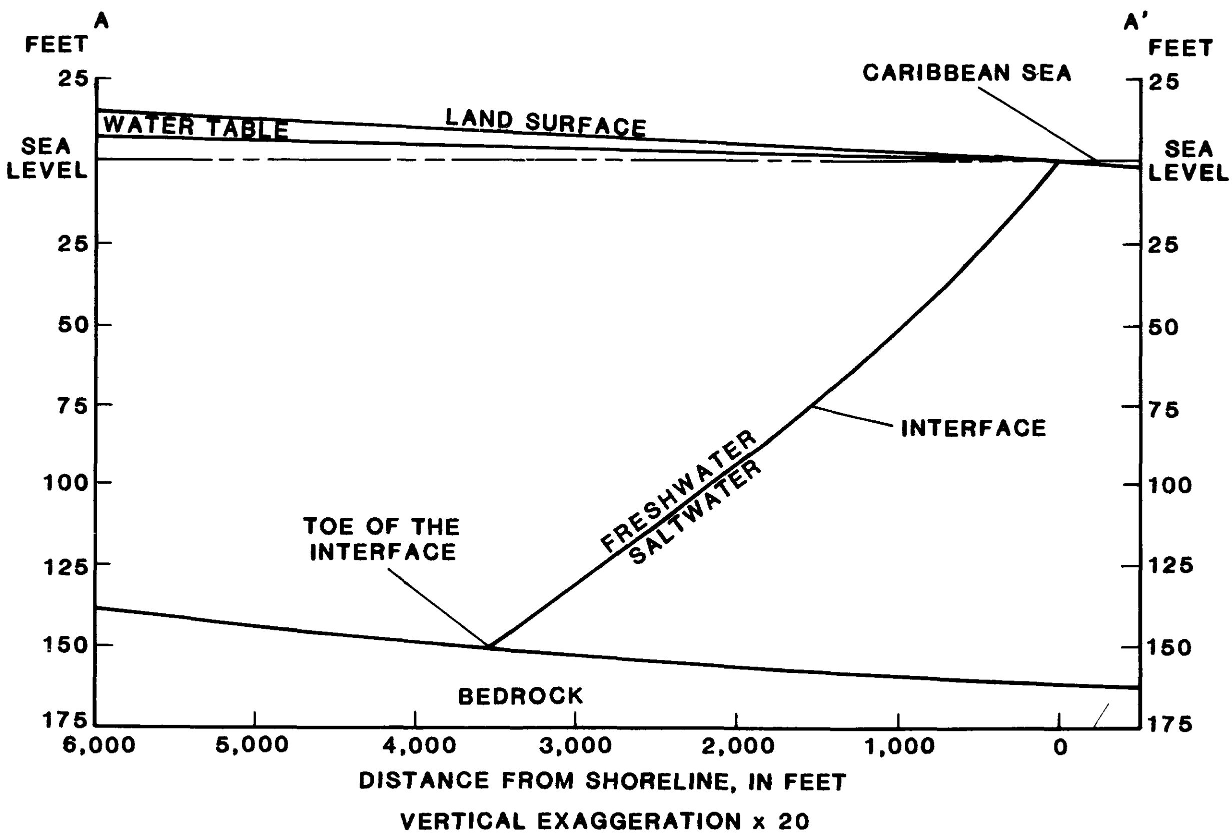
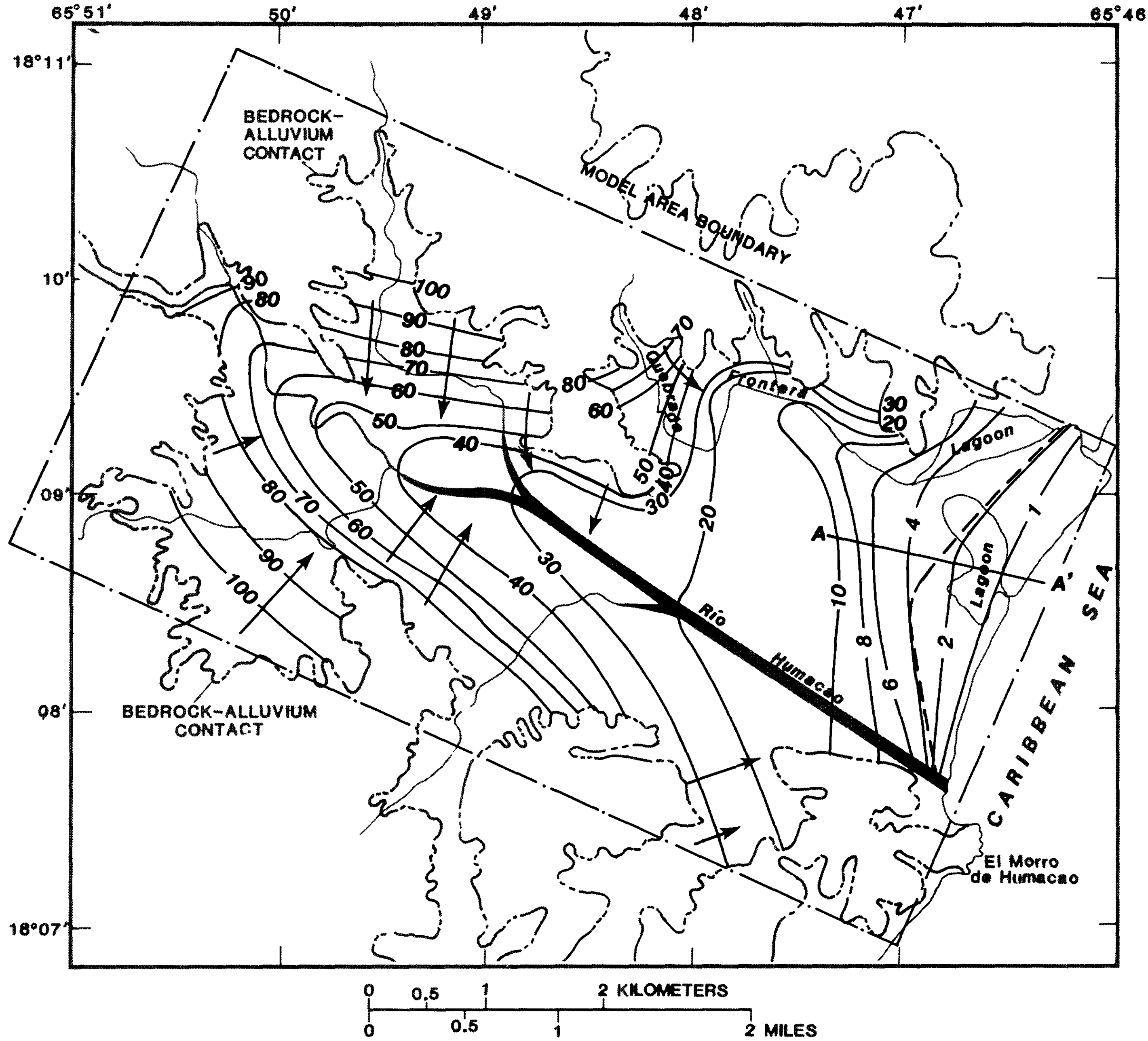


Figure 15.--Freshwater-saltwater interface along cross-section A-A' as interpreted from the Ghyben-Herzberg method, Río Humacao basin, March 1984.



EXPLANATION

——40——	WATER-TABLE CONTOUR IN FEET. Shows altitude of water-table. Contour interval in feet and variable. Datum is mean sea level.
←——	DIRECTION OF GROUND-WATER FLOW.
— — — —	LOCATION OF TOE OF FRESH WATER-SALT WATER INTERFACE.
A——A'	LOCATION OF CROSS-SECTION A-A'.

Figure 16.--Configuration of water-table surface, direction of ground-water flow, the toe of freshwater-saltwater interface, and cross-section A-A' in the Río Humacao basin, March 1984.

The increase in hydraulic conductivity in the mid to upper reach of the Río Humacao basin is due to the physical nature of the alluvial deposits. In the lower reach of the Río Humacao basin low energy fluvial deposits of clay, silt, and fine sand are the predominate aquifer materials. In the upper and mid reach of the Río Humacao basin coarser grained aquifer materials are found. Coarser grain aquifer materials in this area are expected due to the high energy, fluvial depositional environment which dominated the drainage of the steeply sloped ridges during the recent geologic past. These coarse-grain alluvial deposits subsequently allow larger values of hydraulic conductivity to be used in the model.

Recharge to the alluvial aquifer originates as rainfall, seepage from the fractured bedrock (mentioned earlier), and river seepage to the lower alluvial valley. Because the criteria for model calibration was to match the field-observed aquifer water levels of March 1984 and ground water-surface water seepage data of April 1984, initial estimates for rainfall recharge were calculated for the same period. March and April of 1984 was an unseasonally dry period with an average of 1 inch of rainfall per month recorded in the study area (NOAA, 1984). Therefore, aquifer recharge from rainfall was limited, and initial esimates for rainfall recharge to the modeled aquifer were 25 percent of the 1 inch of monthly rainfall for March and April or 3 inches per year.

The river package of the modular model was used to simulate river seepage. The river package allows for the simulation of aquifer recharge by a losing stream as well as aquifer discharge by a gaining stream. The gains or losses are dependent on the head gradient and riverbed conductance between the river and the aquifer at each node. Data collected from the seepage run on April 3, 1984 revealed that Río Humacao is a gaining stream in the upper basin (row 1 through 25, fig. 14) and a losing stream in the lower basin (row 26 through 40, fig. 14). The gains and losses to streamflow in the model were simulated to match the pattern determined from the April 3, 1984 field observations. Although seepage data were collected only for Río Humacao, all significant tributaries in the upper basin were modeled as gaining streams. Riverbed conductance initially was estimated to be 1 percent of the prevailing average hydraulic conductivity determined from aquifer tests, or 0.15 ft/d.

A comparison between the altitude of the water surface of the lagoons and the aquifer indicated that the lagoons are ground-water discharge sites. The lagoons were therefore simulated as gaining streams.

Discharge from the aquifer also occurs through pumpage and ET (evapotranspiration), effective to an extinction depth of 10 feet. Maximum ET in the area is estimated to be about 35 inches a year (Giusti and Bennett, 1976). The model assumes maximum ET when the water table is at land surface, and declines proportionately to zero as the aquifer head declines to the assigned extinction depth. Daily ground-water pumpage from 10 wells was estimated to be 0.65 Mgal/d (fig. 17).

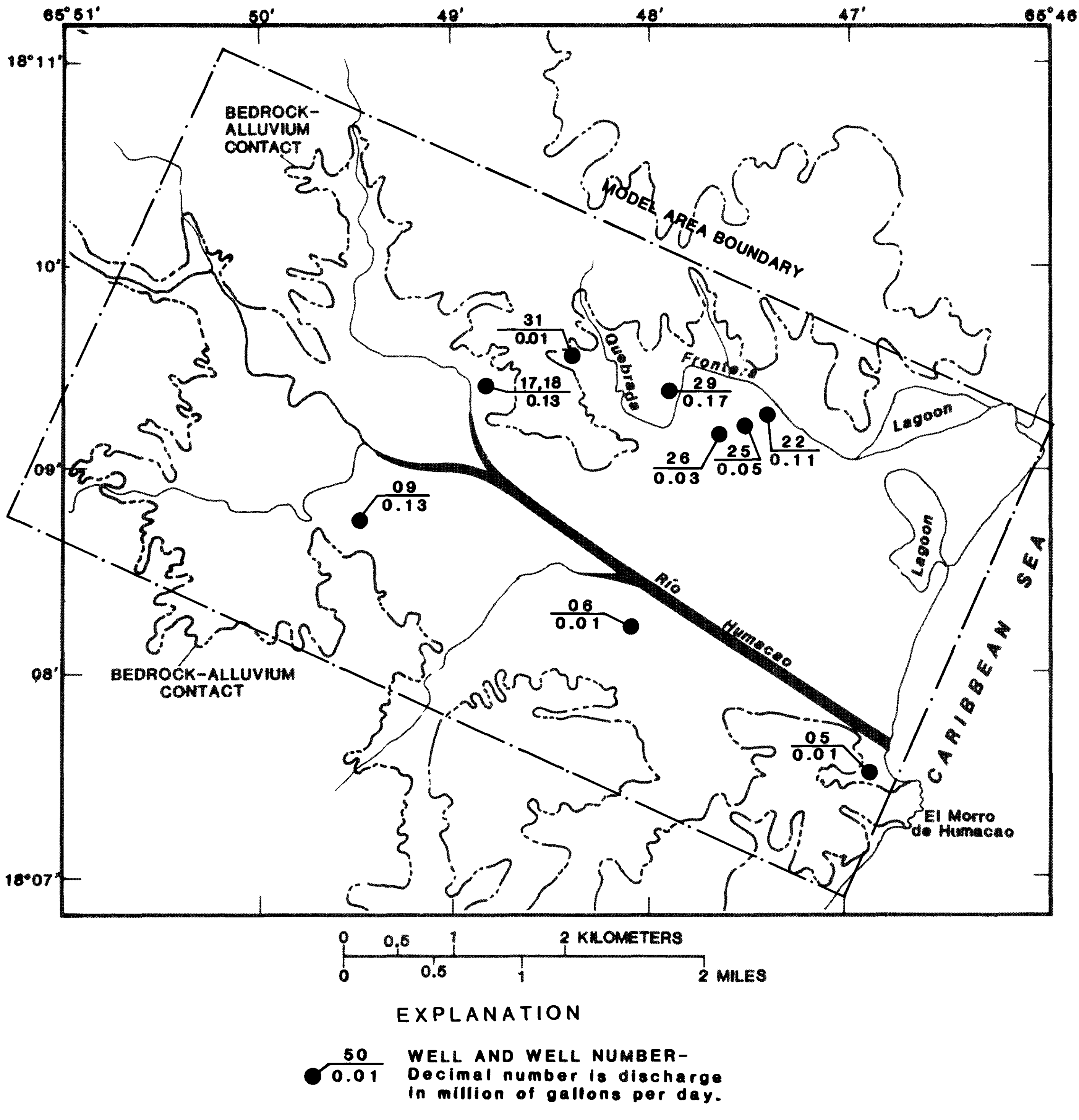


Figure 17.--Location and discharge of wells in the Río Humacao basin, 1984.

Model Calibration

Model calibration is the process by which simulated aquifer properties are modified to obtain a match between the water levels computed by the model and observed ground-water heads. The modeled water-table elevation in the Río Humacao basin was calibrated with water-level data measurements of March 1984, (fig. 16) and the seepage run data collected in April 1984, (table 3) by adjusting, within reasonable limits, values of aquifer hydraulic conductivity, rainfall recharge, and riverbed vertical hydraulic conductivity.

Aquifer Recharge

The initial estimates of rainfall recharge to the aquifer were modified. Although the model was calibrated during a relatively dry period, the original low value of rainfall used neglected the effect of recharge resulting from the average-annual rainfall recharge of the previous year. To match the observed aquifer heads of March 1984 using the initial estimates of rainfall recharge, it was necessary to increase the observed hydraulic conductivity values, which were determined from aquifer tests, by a factor of three. Such a change could not be justified based on field data. Therefore, the initial estimates of rainfall recharge were increased to represent average-annual conditions.

Aquifer recharge by rainfall to alluvial valleys in Puerto Rico has been estimated previously to range from 10 to 30 percent of annual rainfall (Giusti, 1966, 1971; McClymonds, 1972). In the upper to mid reach of the Río Humacao basin (row 1 through 25, fig. 14) rainfall recharge was increased to 20 percent of average-annual conditions or 17 inches. In the lower Río Humacao basin (row 26 through 44, fig. 14) rainfall recharge was increased to 9 inches or 11 percent of average-annual conditions. These increases in rainfall recharge allowed for a better match between modeled and observed ground-water heads without distorting the aquifer hydraulic conductivities beyond field observed values.

Hydraulic Conductivity

The first estimates of hydraulic conductivity initially used in the model in nodes where the Río Humacao was simulated were modified. Calibration of the model revealed that an insufficient amount of ground water was flowing between the aquifer and Río Humacao. Further, drill cuttings collected from a test well drilled adjacent to the Río Humacao revealed river deposits of coarse angular sand. Therefore, the aquifer hydraulic conductivity in the Río Humacao nodes was increased to 32 ft/d.

Stream-Aquifer Leakage

The generalized pattern of river gains and losses that was established by the seepage run was matched while calibrating the model, but the quantity of seepage was not matched. The increase in aquifer hydraulic conductivity increased the seepage into and out of the river, but not by a sufficient amount to match the simulated and observed seepage. Therefore, riverbed conductance was increased to achieve a closer match. The initial estimate for the riverbed conductance (one percent of aquifer hydraulic conductivity) was increased to range between 4.5 and 13.5 percent of the aquifer hydraulic conductivity or 1.5 to 4.5 ft/d. With the increase in aquifer hydraulic conductivity and riverbed conductance, a disparity of 3 percent of river gains and 40 percent of river loss between the simulated seepage and observed seepage remained. This difference could be attributed to inaccuracies in open-channel measurements made during the seepage runs.

Altitude of Water Table

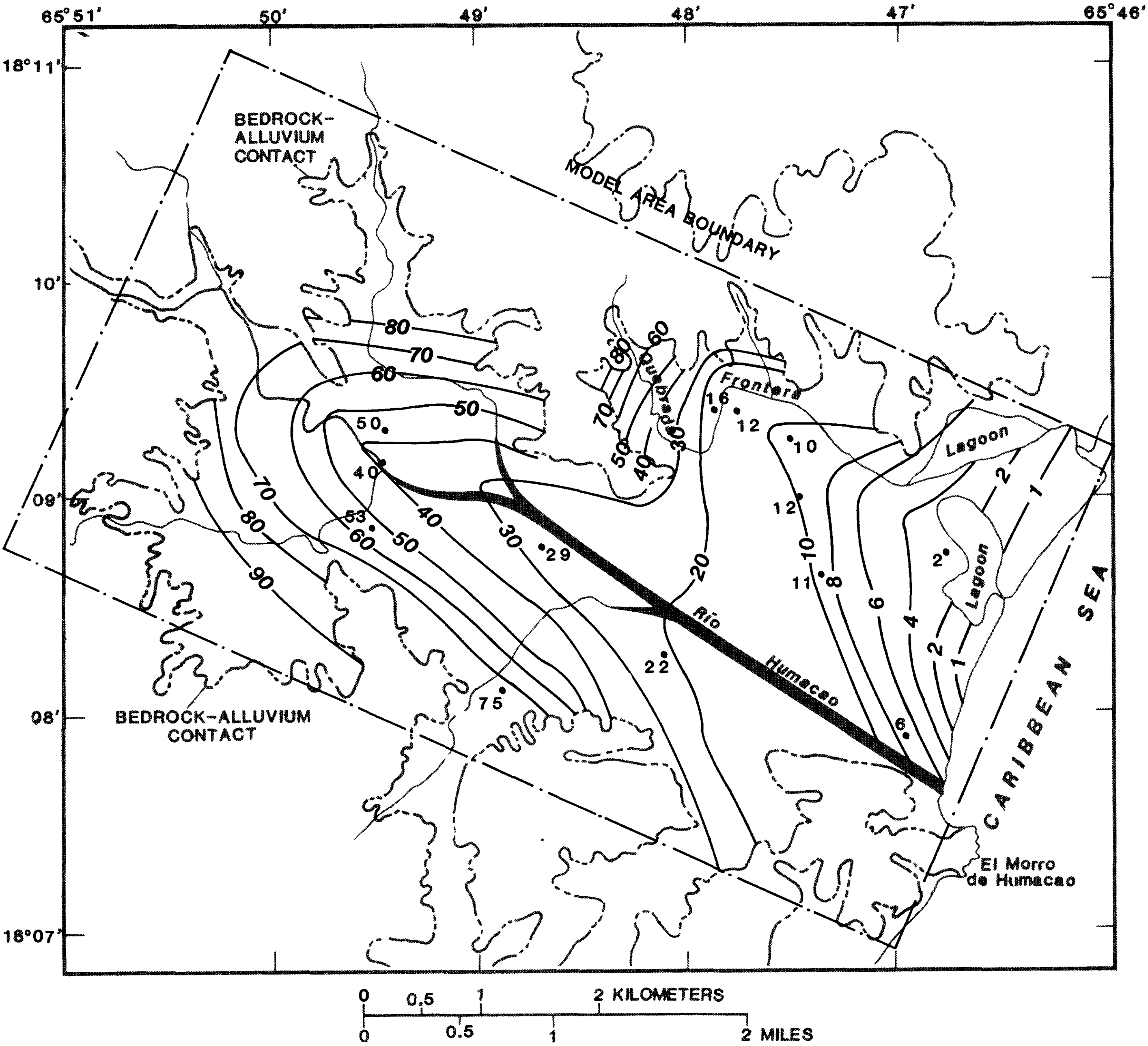
The altitude of the water table simulated by the model (fig. 18) closely approximated the water levels measured in March 1984 (table 14). All of the actual water-levels measured in the field matched within 3 feet of the model computed heads. When a node by node comparison of initial model heads were compared to the ending calibrated model heads the maximum difference was 10.65 feet and the minimum difference was 0.01 feet. The average difference between initial and ending heads when comparing all active nodes was 2.03 feet. The root mean square error for the calibrated model was 3.90 feet.

Budget

The calibrated steady-state model for the Río Humacao basin alluvial aquifer had a balanced volumetric water budget of 17.62 ft^3/s (table 15). Flow into the aquifer was dominated by ground water contribution across the constant head nodes. The constant head nodes represented flow from the fractured bedrock ridges and the alluvial aquifer where it extends beyond the boundaries of the model. Total ground-water contribution from constant head nodes was 9.57 ft^3/s, or 54 percent of the modeled volumetric water budget of flow into the basin. Of this volume of simulated ground-water flow into the basin, 8.57 ft^3/s was from the fractured bedrock ridges.

To verify the simulated quantity of ground-water contributed to the aquifer from the bedrock ridges the following information was required:

1. Data collected from wells drilled into the fractured bedrock throughout the Humacao-Naguabo area indicated that the elevated water surface in these wells was directly related to the topography, and a ground-water gradient could be assumed to be parallel to the slope of the ridges surrounding the Río Humacao basin.



EXPLANATION

——30—— WATER-TABLE CONTOUR IN FEET--
Shows altitude of simulated water level.
Contour interval variable. Datum is mean sea level.

22• POINT OF MEASURED WATER LEVEL
IN FEET ABOVE MEAN SEA LEVEL.

Figure 18.--Simulated water-table surface with measured water levels in the water-table aquifer, March 1984.

2. At a distance of 500 feet from the bedrock-alluvium contact an average slope (I) of 0.26 was determined.

3. The number of constant-head nodes which represented the bedrock-alluvium contact was 92.

4. The average value of hydraulic conductivity used to control the flow in these constant head nodes was 3 ft/d.

5. Assuming that a 20-foot section of the weathered, fractured rock is in hydraulic contact with the alluvial aquifer and that the width of each node is 500 feet, then:

$A = (500 \text{ ft})\ (20 \text{ ft}) = 10{,}000 \text{ ft}^2$ = perpendicular area through which ground water is moving.

$I = 0.26$ = the gradient parallel to the direction of ground-water flow.

$K = 3.0$ ft/d = horizontal aquifer hydraulic conductivity

Q = rate of ground water flow in ft^3/s

$$Q = K\ I\ A$$

$$= 7{,}800 \text{ ft}^3/\text{d per node}$$

$$= (7{,}800 \text{ ft}^3/\text{d})\ (92) = 717{,}600 \text{ ft}^3/\text{d}$$

$$= (717{,}600 \text{ ft}^3/\text{d})\ (1/86{,}400 \text{ seconds/day}) = 8.30 \text{ ft}^3/\text{s}$$

This value is within 5 percent of the simulated model flow. Verification of simulated ground-water flow from the alluvial aquifer where it extends beyond the boundaries of the model was not attempted. The water-table contour lines from the March 1984 water-table contour map in this area of the model are highly interpretive and subsequently should not be used for estimates of ground-water flow.

Table 14. Comparison of altitude of measured static water levels and simulated water levels, March 1984

Well number (See table 1)	Measured, static water-level (feet)	Simulated water-level (feet)	Difference (feet)
06	22.00	21.51	-0.49
07	75.00	73.08	-1.92
08	30.00	30.09	+0.09
10	52.00	52.25	+0.25
11	40.00	37.38	-2.22
12	53.00	50.36	-2.64
14	6.00	8.33	+2.33
15	2.00	3.21	+1.21
16	11.00	9.95	-1.05
20	12.00	10.17	-1.83
23	11.00	8.42	-2.58
28	16.00	13.45	-2.55
30	18.00	17.85	-0.15

Table 15. Simulated steady-state water budget in the Río Humacao aquifer system, March 1984

	Cubic feet per second
INFLOW	
Stream leakage	2.85
Rainfall recharge	5.20
Constant head boundary	9.57
Total	17.62
OUTFLOW	
Pumpage	0.99
Stream leakage	10.52
Evapotranspiration	5.44
Constant head boundary	0.69
Total	17.64

Ground-water flow out of the aquifer was dominated by river leakage which represented 10.52 ft^3/s or 60 percent of the total ground-water loss. Simulated aquifer loss to the Río Humacao in rows 1 through 25 was 4.61 ft^3/s, which was within 3 percent of the 4.77 ft^3/s of ground-water contribution determined during the April 1984 seepage run. Simulated ground-water contribution to the lagoons in the lower Río Humacao Basin was 0.25 ft^3/s, which was within 16 percent of 0.21 ft^3/s of flow estimated from both the March 1984 water-table contour map and elevation data collected at the lagoons and wells located adjacent to the lagoons.

Simulated ground-water discharge to the Caribbean Sea through the subterranean discharge face was 0.10 ft^3/s. This value was within 9 percent of the 0.11 ft^3/s of ground-water flow estimated from the March 1984 water-table contour map.

Sensitivity Analyses

The Río Humacao basin model was calibrated by using discrete values of aquifer recharge from rainfall, hydraulic conductivity, evapotranspiration, and ground-water seepage into and out of the surface water bodies. Several of these parameters are not precisely known. Limits, as determined from field observations (aquifer tests and seepage run), placed on values of hydraulic conductivity and the amount of water moving in or out of the ground-water regime from surface-water sources require that other parameters used in the model (rainfall recharge and evapotranspiration) be modified to match the field-observed heads and river-aquifer seepage. In order to see what range of values of rainfall recharge and evapotranspiration the model can accomodate, a series of sensitivity analysis was performed.

The model runs for the sensitivity analysis were conducted by increasing and decreasing rainfall recharge and evapotranspiration uniformly over the modeled area by 50 percent (table 16). One steady-state run was made for each parameter change while all other parameters remained unchanged (table 17 and 18). Notable results of the sensitivity runs are as follows:

1. Increasing rainfall recharge improved the match between observed and simulated aquifer heads by increasing the percentage of simulated heads that matched within 1 foot of the observed heads from 30 to 46 percent. The increase in rainfall recharge had a negative effect however on ground water-surface water relations; with a seven percent decrease in accuracy in seepage from the Río Humacao to the aquifer in the lower Río Humacao basin.

2. Decreasing rainfall recharge improved river seepage into the aquifer by 7 percent, but had a negative effect on the match between observed and simulated heads, changing the 100 percent match between simulated and observed heads from 3 to 4 feet.

3. Observed and simulated heads were not affected by changes in evapotranspiration, however increasing evapotranspiration favorably reduced river seepage into the aquifer in the lower Río Humacao basin from 40 to 14 percent of observed seepage.

The results of the sensitivity analysis indicate that, locally, within the Río Humacao basin, rainfall recharge could range from 5 to 26 inches a year, and that evapotranspiration could be as high as 53 inches a year. However, changes in the final calibration of the model based on these results were not made. Discrete localized changes of rainfall recharge and evapotranspiration made in the model, beyond those previously made during the calibration process, did not show the same results as the uniform sensitivity analysis changes. Further, the overall negative effects on the model that were observed when the uniform sensitivity analysis changes were made, justified leaving the calibrated modeled parameters as they were.

Table 16. Aquifer simulations

[units - Mgal/d, million gallons per day; gal/min, gallons per minute]

Simulation	Description
1	Values of evapotranspiration increased by 50 percent.
2	Values of evapotranspiration decreased by 50 percent.
3	Values of rainfall recharge increased by 50 percent.
4	Values of rainfall recharge decreased by 50 percent.
5	Withdrawal rates of 1984 plus a line of five hypothetical wells aligned adjacent to wells 22, 25, and 26 pumping at a rate of 50 gal/min each (1984 pumpage increased by 0.36 Mgal/d).
6	Withdrawal rates of 1984 plus a hypothetical triangular field of 10 wells in the lower Humacao basin pumping at a rate of 25 gal/min each (1984 pumpage increased by 0.36 Mgal/d).
7	Same as simulation 6 except pumpage in the hypothetical well field increased to 50 gal/min in each well (1984 pumpage increased by 0.72 Mgal/d).
8	Same as simulation 6 except pumpage in the hypothetical well field increased to 75 gal/min in each well (1984 pumpage increased by 1.03 Mgal/d).

Table 17. Comparison of simulated and observed water levels in the alluvial aquifer in response to 50-percent change (increase and decrease) in evapotranspiration and rainfall recharge

[Abbreviation - NA, not applicable]

	Steady state		Evapotranspiration				Rainfall recharge			
			50-percent increase		50-percent decrease		50-percent increase		50-percent decrease	
Percentage (A) and number of wells (B) that matched within:										
	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
1	30	4	38	5	38	5	46	6	38	5
2	61	8	53	7	69	9	69	9	38	5
3	100	13	84	11	92	12	100	13	76	10
4 feet of observed field data.	NA	NA	100	13	100	13	NA	NA	100	13

Table 18. Comparison of simulated and observed seepage interaction between alluvial aquifer and Río Humacao in response to 50-percent change (increase and decrease) in evapotranspiration and in recharge

[units - ft^3/s, cubic feet per second]

	Observed aquifer seepage to Río Humacao	Simulated steady state seepage	Evapotranspiration		Rainfall recharge	
			50-percent increase	50-percent decrease	50-percent increase	50-percent decrease
Aquifer seepage to Río Humacao in ft^3/s	4.77	4.60	4.49	4.74	5.16	4.04
Absolute value of percentage error:		4	6	1	8	15

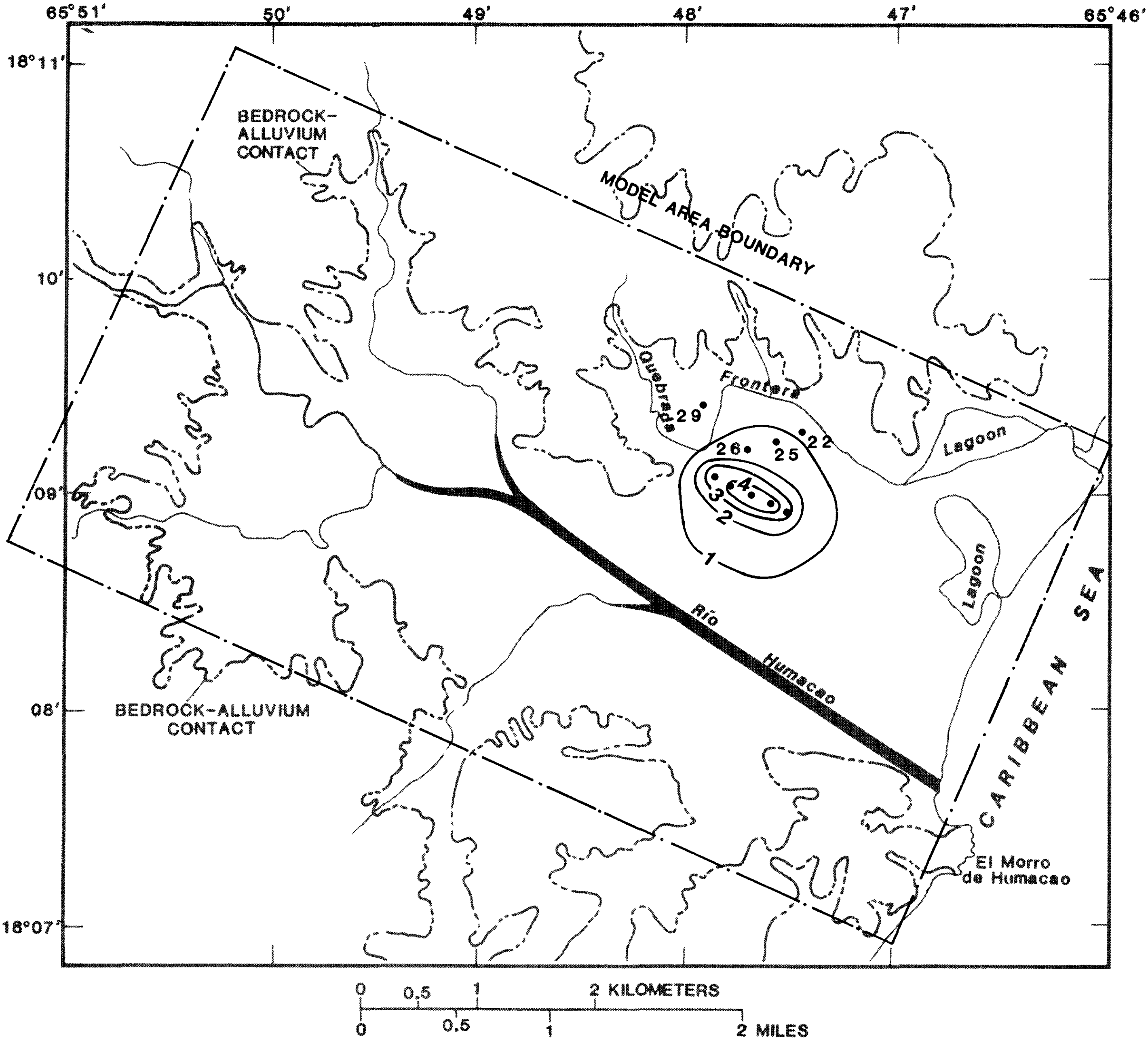
	Observed Río Humacao seepage to aquifer	Simulated steady state seepage	Evapotranspiration		Rainfall recharge	
			50-percent increase	50-percent decrease	50-percent increase	50-percent decrease
Seepage from Río Humacao to aquifer in ft^3/s	2.63	1.58	2.26	0.77	1.39	1.77
Absolute value of percentage error:		40	14	71	47	33

SIMULATED STRESSES AND RESPONSES

The Río Humacao basin model was designed to simulate the ground-water flow system and to determine the effects of additional ground-water withdrawals on the water-table altitude. Steady-state conditions assume that no water is derived from storage. Simulated effects on the aquifer are immediate, there is no time delay in drawdown as is caused in the actual system when water is derived from storage. Therefore, simulated stresses and responses as modeled show the maximum drawdown in the system.

Ground-water withdrawals as of 1984 in the vicinity of wells 22, 25, 26, and 29 were 0.36 Mgal/d, which represents 55 percent of the total ground water used in the Río Humacao basin. Pumpage in this area was increased from 0.36 Mgal/d to 0.72 Mgal/d by adding a row of five hypothetical wells each pumping at 50 gal/min (table 16, simulation 5). A maximum water-level decline of 7 feet resulted from this increased pumpage (fig. 19).

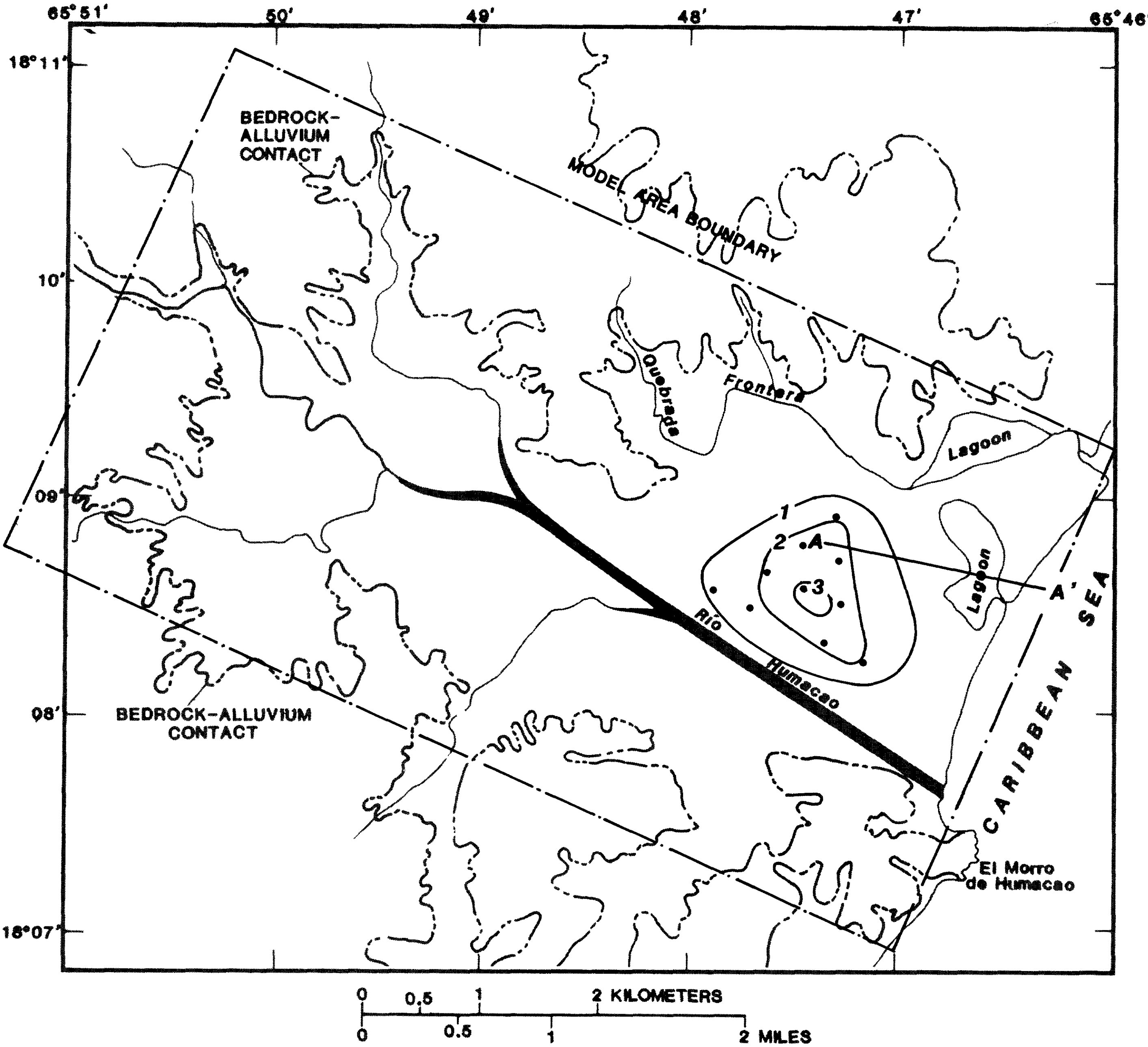
A hypothetical well field was located in the lower Río Humacao basin to simulate various pumping scenarios. Total discharge of the wells in addition to the pumpage of March 1984 (0.65 Mgal/d) was increased to 0.36, 0.72, and 1.08 Mgal/d. Maximum water level declines ranged from 3 feet, when pumpage was increased by 0.36 Mgal/d, to greater than 10 feet when pumpage was increased by 1.08 Mgal/d (figures 20, 21, and 22). It is probable that saltwater intrusion would occur when ground-water pumpage is increased more than 0.72 Mgal/d (fig. 23), particularly if the intakes of the pumping wells were deep within the aquifer.



EXPLANATION

——3——	LINE OF EQUAL WATER-LEVEL DECLINE IN FEET.
•	HYPOTHETICAL WELL.
26•	PUMPING WELL AND WELL NUMBER.

Figure 19.--Computed steady-state water-level declines in the Río Humacao basin near wells 22, 25, 26, and 29 for a hypothetical ground-water pumpage increase of 0.36 million gallons per day.



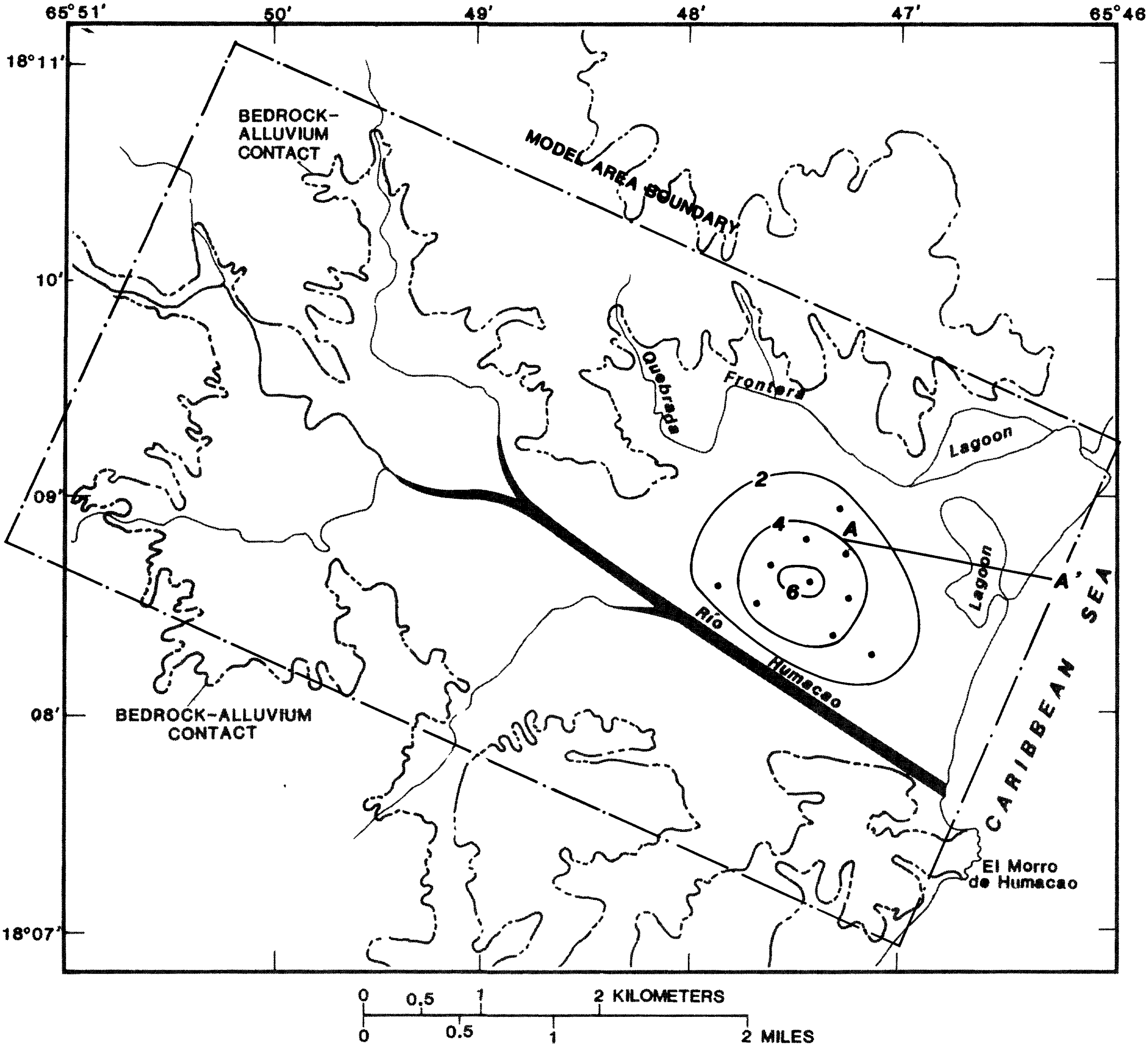
EXPLANATION

—2— LINE OF EQUAL WATER-LEVEL DECLINE IN FEET.

• HYPOTHETICAL WELL.

A——A' LOCATION OF CROSS-SECTION A-A'.

Figure 20.--Computed steady-state water-level declines in the lower Río Humacao basin and location of cross-section A-A' for a hypothetical ground-water pumpage increase of 0.36 million gallons per day.



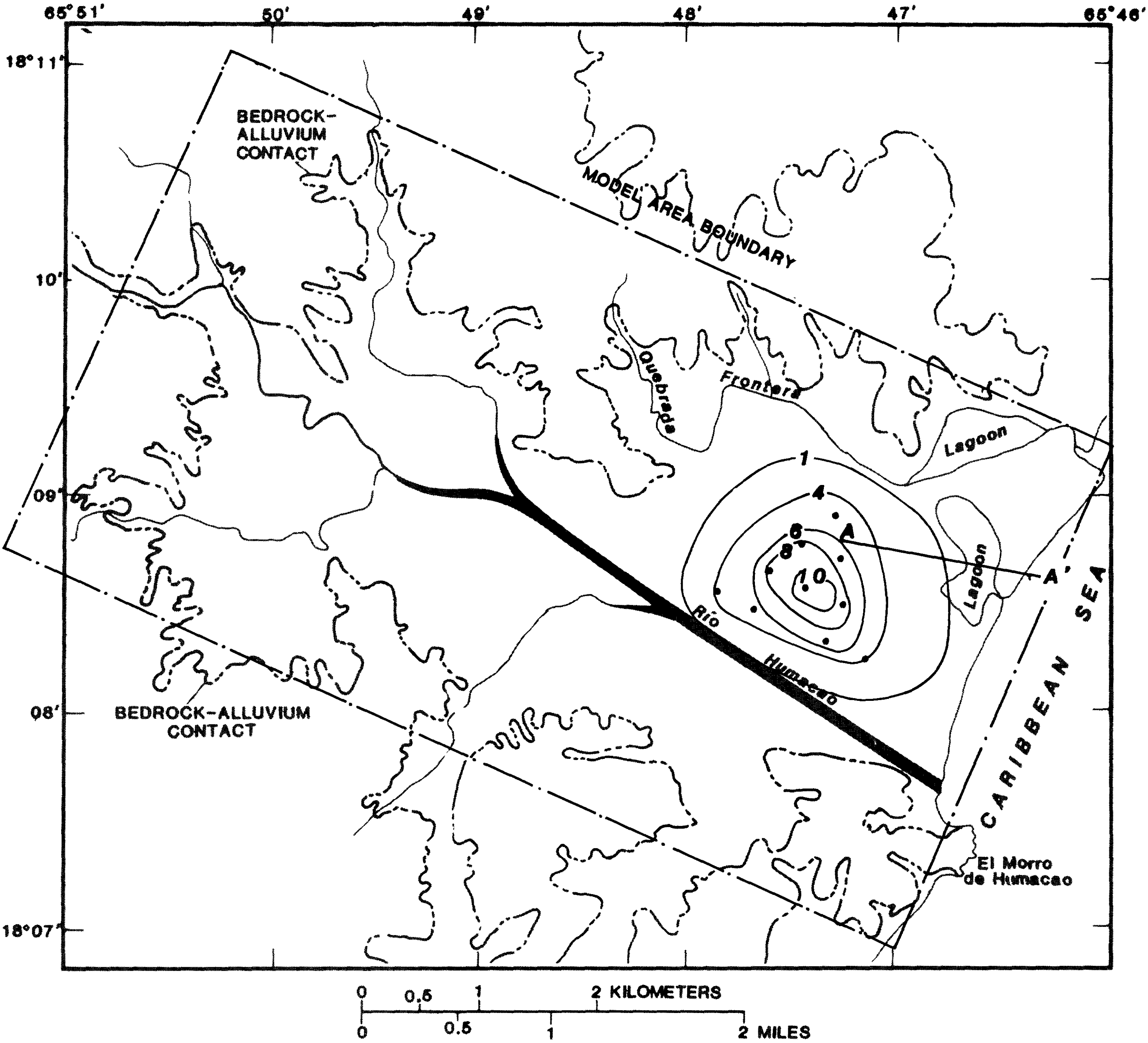
EXPLANATION

—4— LINE OF EQUAL WATER-LEVEL DECLINE IN FEET.

• HYPOTHETICAL WELL.

A——A' LOCATION OF CROSS-SECTION A-A'.

Figure 21.--Computed steady-state water-level declines in the lower Río Humacao basin and location of cross-section A-A' for a hypothetical ground-water pumpage increase of 0.72 million gallons per day.



EXPLANATION

—4— LINE OF EQUAL WATER-LEVEL DECLINE IN FEET.

• HYPOTHETICAL WELL.

A——A' LOCATION OF CROSS-SECTION A-A'

Figure 22.--Computed steady-state water-level declines in the lower Río Humacao basin and location of cross-section A-A' for a hypothetical ground-water pumpage increase of 1.08 million gallons per day.

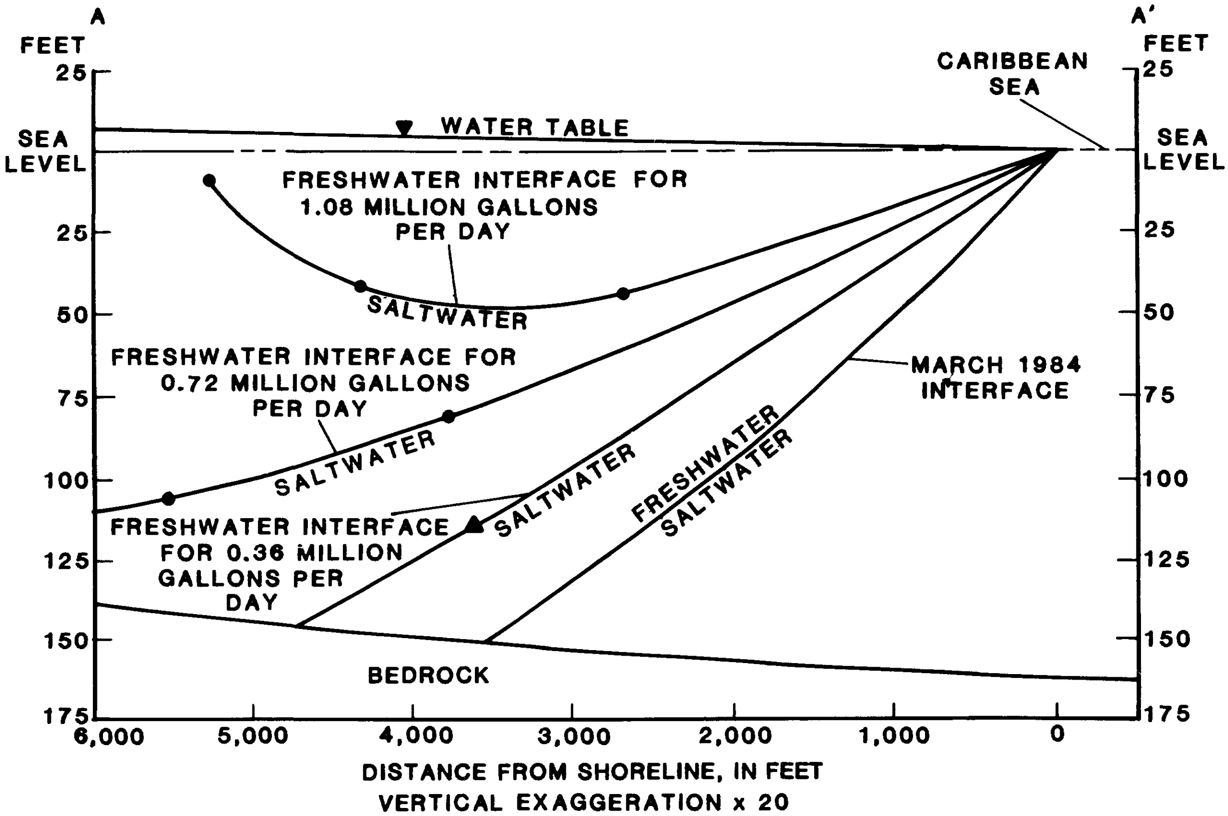


Figure 23.--Freshwater-saltwater interface along cross-section A-A' as interpreted from the Ghyben-Herzberg method for the Río Humacao basin, March 1984 and hypothetical model stresses of increased daily dicharge of 0.36, 0.72, and 1.08 million gallons per day in the Río Humacao basin alluvial aquifer.

SUMMARY

Surface water is the principal water-supply source in the Humacao-Naguabo area, supplying 13.7 Mgal/d. The two major drainage networks are the Río Blanco and Río Humacao. Average annual flow for 1983, which was a normal year for streamflow in the area, was 67.90 ft^3/s for Río Blanco near Florida and 58.80 ft^3/s for Río Humacao at Highway 3 near Humacao. Average annual flow for 1984, which was an abnormally low rainfall year, was 55.80 ft^3/s for the Río Blanco and 38.60 ft^3/s for the Río Humacao at Highway 3.

Presently (1986), aquifers are of minor importance as a water supply for the Humacao-Naguabo area. Daily ground-water use is estimated to be 0.93 Mgal/d. The principal aquifer in the Humacao-Naguabo area occurs within alluvial sediments, under water-table conditions. The alluvial aquifer includes the weathered zone of the bedrock where the bedrock is fractured, permeable, and in hydraulic contact with the alluvium. The alluvial aquifer is wedged-shaped and ranges in thickness from zero at the bedrock-alluvium contact, to more than 170 feet near the coast.

The depth to the water table within the alluvial aquifer varies from 40 feet below land surface near the bedrock outcrops to near land surface in coastal areas. Water level fluctuations in the water table aquifer generally are seasonal and vary within an eight-foot range. Transmissivity values range from 600 to 2,000 ft^2/d; the storage coefficient of the aquifer is approximately 0.02.

Water-quality samples were collected from 18 wells in the study area. Water samples from nine wells had total dissolved solids that exceeded Environmental Protection Agency drinking water standards. Water samples from four wells had concentrations of dissolved iron or manganese that exceeded Environmental Protection Agency drinking water standards. Ground water from wells sampled for concentrations of total recoverable iron and manganese, and that were cased with PVC, had values as high as 25,000 ug/L for iron and 7,600 ug/L for manganese.

Water-quality samples were collected from seven surface-water sites. Water samples from three sites exceeded Environmental Protection Agency drinking water standards for dissolved manganese. These concentrations ranged from 63 to 200 ug/L. Samples from streams were also collected for biological contamination. Counts as high as 10,300,000 cols./100ml for coliform and 1,900,000 cols./100ml for streptococci were measured in samples from Río Humacao.

A two-dimensional, steady-state, digital, ground-water flow model of the alluvial aquifer in the Río Humacao basin was developed to simulate the ground-water flow system and to determine the effects of additional ground-water withdrawals on the water-table altitude. The model was calibrated to observed ground-water levels of March 1984. The model-computed heads were within 3 feet of the observed heads. Model results indicate that if pumpage is increased greater than 0.72 million gallons per day, saltwater intrusion into the aquifer could occur.

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