

A HYDROLOGIC EXCURSION TO PUERTO RICO'S SOUTHERN PLAIN

Field Leaders: R.A. Renken, Pedro Díaz, Fernando Gómez-Gómez, and Vicente Quiñones-Aponte

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Conversion Table

For the convenience of readers who may want to use the inch-pound units, the data may be converted by using the following factors:

| Multiply International Systems of Units (SI) | by | To obtain inch-pound units |
|---|----------|--|
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| hectare (ha) | 0.003861 | square mile (mi ²) |
| square kilometer (km ²) | 0.3861 | square mile (mi ²) |
| meter per day (m/d) | 3.281 | feet per day (ft/d) |
| cubic meter per second (m ³ /s) | 35.31 | cubic foot per second (ft ³ /s) |
| cubic meter per second (m ³ /s) | 22.83 | million gallons per day (Mgal/d) |
| cubic meter per second per square kilometer (m ³ /s)/km ² | 91.49 | cubic foot per second per square mile (ft ³ /s)/mi ² |
| liter per second (L/s) | 15.85 | gallon per min (gal/min) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 x °C + 32

Sea Level

In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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ABSTRACT

This report has been prepared for use in conjunction with a hydrologic field excursion to the South Coastal Plain physiographic province of Puerto Rico, commonly called the southern plain, where fan-deltas coalesce to form a narrow (3 to 8 kilometer) plain that extends 70 kilometers across the south-central part of the Caribbean coastline. Poorly consolidated to unconsolidated sand and gravel aquifers underlie the southern plain and supply one-half of all ground-water withdrawals in Puerto Rico and one-half of all water used on the southern plain. Surface water used in the southern plain is obtained from reservoirs located in the central highlands and used mostly for irrigation purposes.

Because flooding in the southern plain is infrequent, development has occurred on many of the relatively flat fan-deltas. Catastrophic floods in these fan deltas may inundate large areas resulting in significant property damage and loss of life. A flood-alert warning system and a channelization project/reservoir in the Ponce area is designed to improve flood prediction and reduce the risk of widespread flooding.

The purpose of the hydrologic field excursion and of this field guide is to familiarize participants with the physical setting of the southern plain of Puerto Rico including the lithologic and hydraulic character of major depositional facies that make-up the principal water-bearing units and provide a tectonic framework that explains the wide variation in thickness of the fan-delta sedimentary sequence.

The route of the excursion provides participants an opportunity to:

- (1) examine a data collection platform that transmits telemetered real-time rainfall-runoff data used to provide advance warning of flash floods;
- (2) examine a channel-improvement project and reservoir designed to provide flood protection; and
- (3) review surface conveyance and ground-water supply systems of the southern plain.

INTRODUCTION

Background

Water-bearing gravel and sand deposits that underlie fan-deltas of the southern plain of Puerto Rico make up the South Coastal Plain aquifer system, and are a principal source of ground water for agricultural, industrial, and municipal users (fig. 1). In this report, the southern plain is used to describe an area within the South Coastal Plain physiographic province. Fan-deltas are defined as alluvial fans that prograde into a body of water from an adjacent highland. The landward part of the fan is the subaerial component and is composed entirely of alluvial fan deposits. A narrow shoreline or transitional zone of beach, tidal flat, supratidal flat, and marsh deposits generally separate this part of the fan from the subaqueous component that include fringing reef, sediment-gravity and inner-shelf deposits.

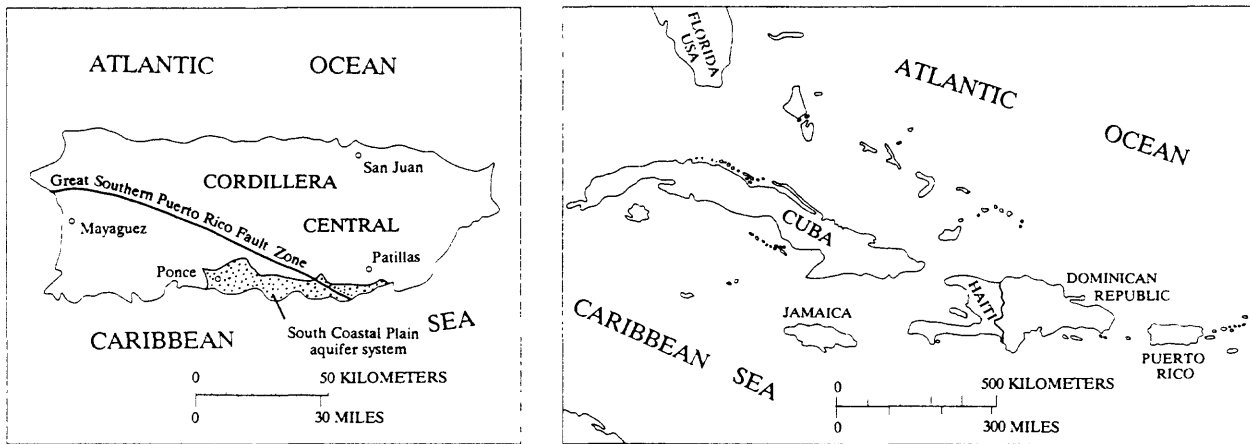


Figure 1.--Location of Puerto Rico's South Coastal Plain.

Nearly one-half of all ground water withdrawn on the island comes from the South Coastal Plain aquifer system (210,000 cubic meters per day (m^3/d)) and one-half of all water used on the southern plain is from the South Coastal Plain aquifer system. About 150,000 m^3/d of surface water is supplied from reservoirs located in the central mountains for irrigation of agricultural lands. An extensive conveyance system of irrigation canals traverses much of the southern plain.

The southern plain is relatively dry and floods are infrequent. However, catastrophic floods have inundated large areas and have resulted in both loss of life and substantial property damage.

Purpose of Excursion and Field Guide

The field excursion and this field guide will focus on helping the participant understand the hydrogeologic setting of Puerto Rico's southern plain. Field stops include the study of a cross-fan exposure that reveals some of the major fan-delta depositional facies and the hydraulic character of sand and gravel aquifers. This and other stops will present a hydrogeologic framework that helps explain region-wide variations in aquifer thickness and hydraulic conductivity. Also, a thermal spring at Coamo, located along a strike-slip fault is visited.

The excursion also will highlight surface-water features of the southern plain. Field stops include a tour of the U.S. Geological Survey (USGS)--Commonwealth of Puerto Rico's Department of Natural Resources (DNR) flood-alert system and a U.S. Army Corps of Engineers (COE) flood-control channelization and reservoir project currently under construction north of Ponce. The excursion examines both surface (irrigation canals) conveyance and ground-water-supply systems of the southern plain.

PHYSICAL SETTING

The southern plain has been formed by a series of coalescing fan-deltas that extend 70 kilometers (km) from Patillas to Ponce over an area of 47,400 hectares (ha) (fig. 2). A view of the fan-deltas shows that they exhibit a characteristic fan-like shape (fig. 3). The apex of a fan-delta develops at the point where the stream emerges from the mountains and is the point of highest altitude of the fan-delta. In Puerto Rico, the altitude at the apex of most fan-deltas does not exceed 50 meters (m) above sea level. The surface of the fan-deltas slopes coastward at a gradient that varies from 25 m per kilometer (m/km) within the apex or upland channel parts of the fan-delta to 2 m/km near the coast. Fan radii average 9 to 10 km from apex to coast. Bedrock hills protrude from the fan-delta plain in several localities, particularly where the overburden thins against the foothills. Subaerial parts of most fan-deltas along Puerto Rico coastline are separated from the Caribbean Sea by a narrow marginal marine or shoreline zone of supratidal or salty-scrub flats, marsh and mangrove swamps, and beach deposits (fig. 3).

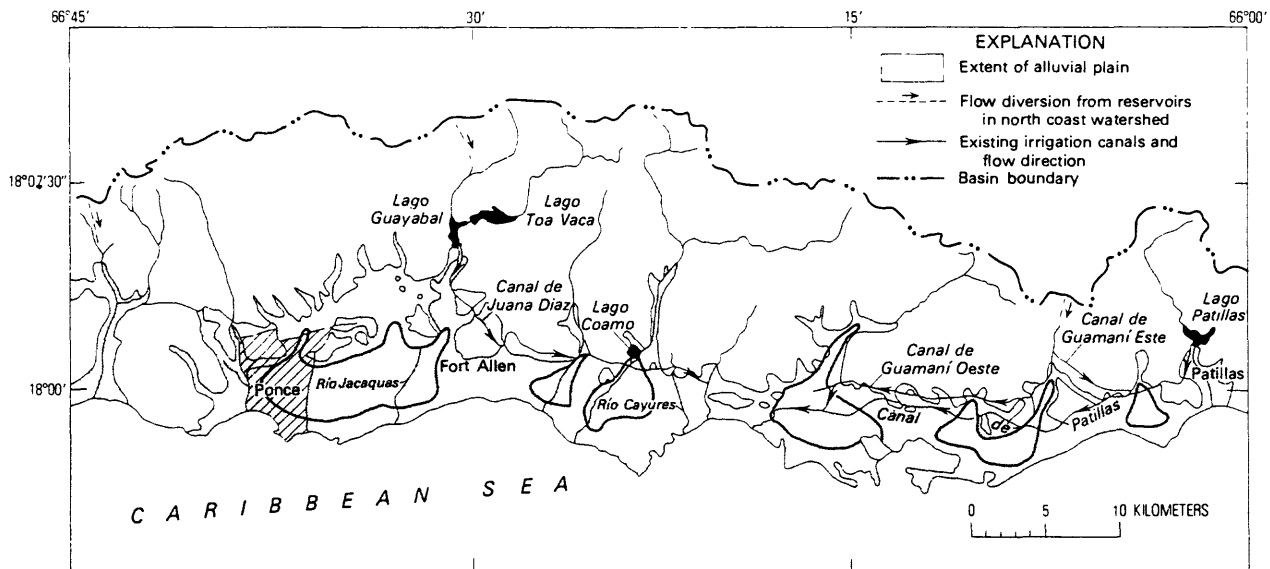


Figure 2.--Major fan-deltas of the southern plain.

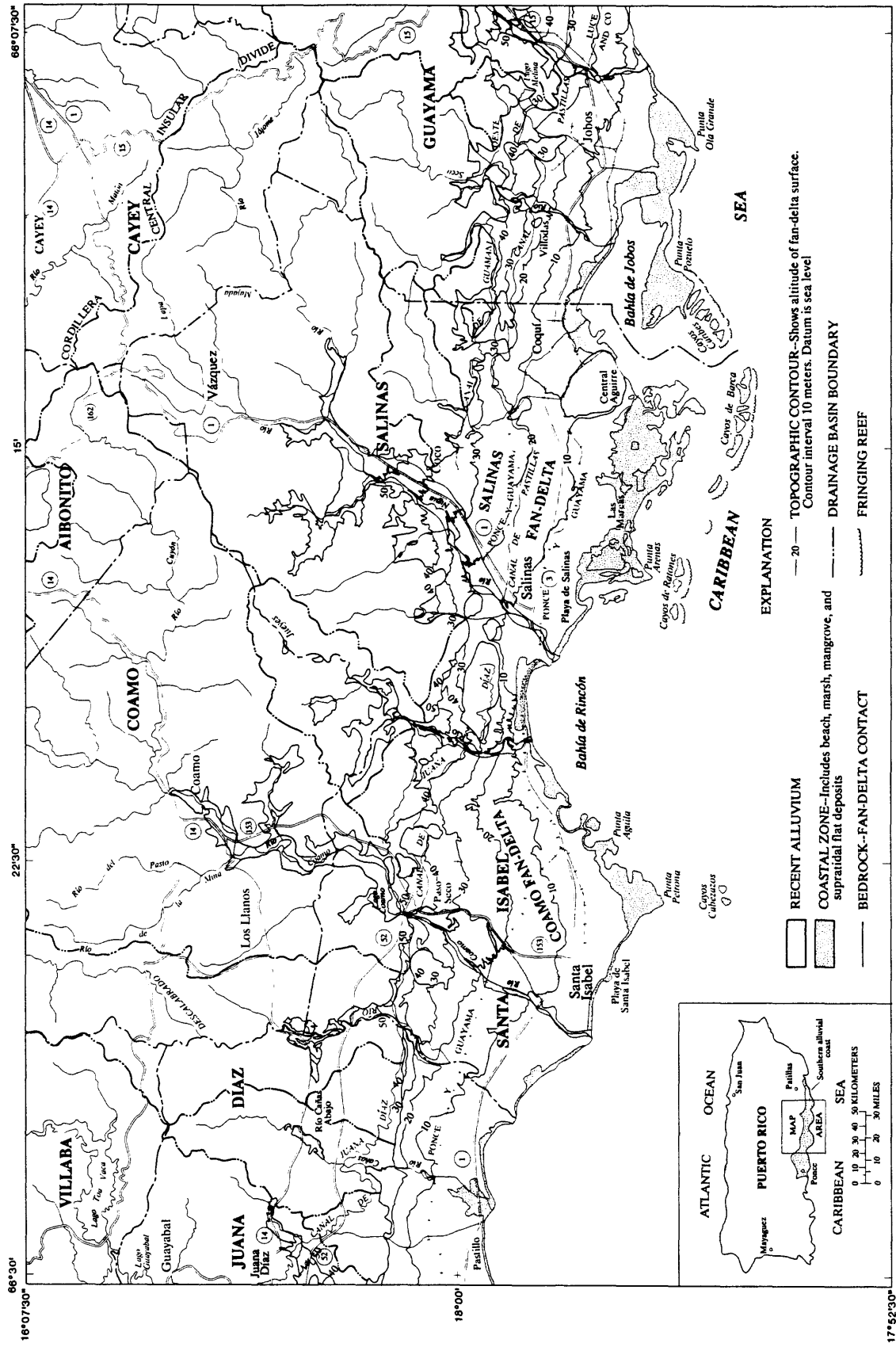


Figure 3.--Surficial morphology of the Coamo and Salinas fan-deltas. (From Renken and others, 1990).

Base from U.S. Geological Survey
Humateo 1:100,000, 1879, unpublished and
Arechivo 1:100,000, 1960, unpublished

Land Use

Man's activities during the last 500 years have considerably changed the type of vegetative cover within the South Coast area. Prior to 1500, the southern plain was covered with a savannah forest of widely-spaced trees, and occasional thorn and brush vegetation (Beishlag, 1955). Natural grasslands were interspersed with trees that lined the rivers, and salty scrub vegetation lay behind the mangrove swamps that bordered the coastline. A dry savannah forest covered a thin soil zone in the foothills and rain forest occupied areas of higher altitude farther inland. By the end of Spanish rule in 1898, most of the savannah forest was logged and the land converted to pasture. Neglected pasture areas reverted to brush fields. The subsequent development of an extensive canal (fig. 2) and ground-water supplied irrigation system provided the infrastructure to develop the present-day sugar cane and vegetable-based agricultural industry. The ground-water resources within the southern plain have been intensively developed as an irrigation water source since 1910. The total cultivated land area has declined from 31,300 ha in 1969 to 13,200 ha in 1987. However, the dominant land use is agricultural. Urban development covers approximately 5,300 ha mostly in the vicinity of Ponce (population 189,046 in 1980) and Guayama (population 40,183 in 1980) as reported by the U.S. Department of Commerce (1982).

Climate

Puerto Rico lies in the path of the northeast trade winds and its climate is greatly influenced by easterly waves, tropical disturbances (May to November), and cold fronts (November to April). Orographic controls create a rainshadow on the leeward side of the island's mountain range and much of the moisture carried by the northeast trade winds never reaches the southern coastal plain. Windward northern slopes receive 2,000 to 5,000 millimeters per year (mm/yr) of rainfall as compared to less than 1,500 mm/yr on the leeward southern slopes (fig. 4). Rainfall along the southern coastal margin and in the western fan-delta averages less than 1,000 mm/yr. Mean monthly temperatures vary from a maximum of 28 degrees Celsius (°C) in September at Central Aguirre to a minimum of 24°C in February at Ponce (U.S. Department of Commerce, 1970).

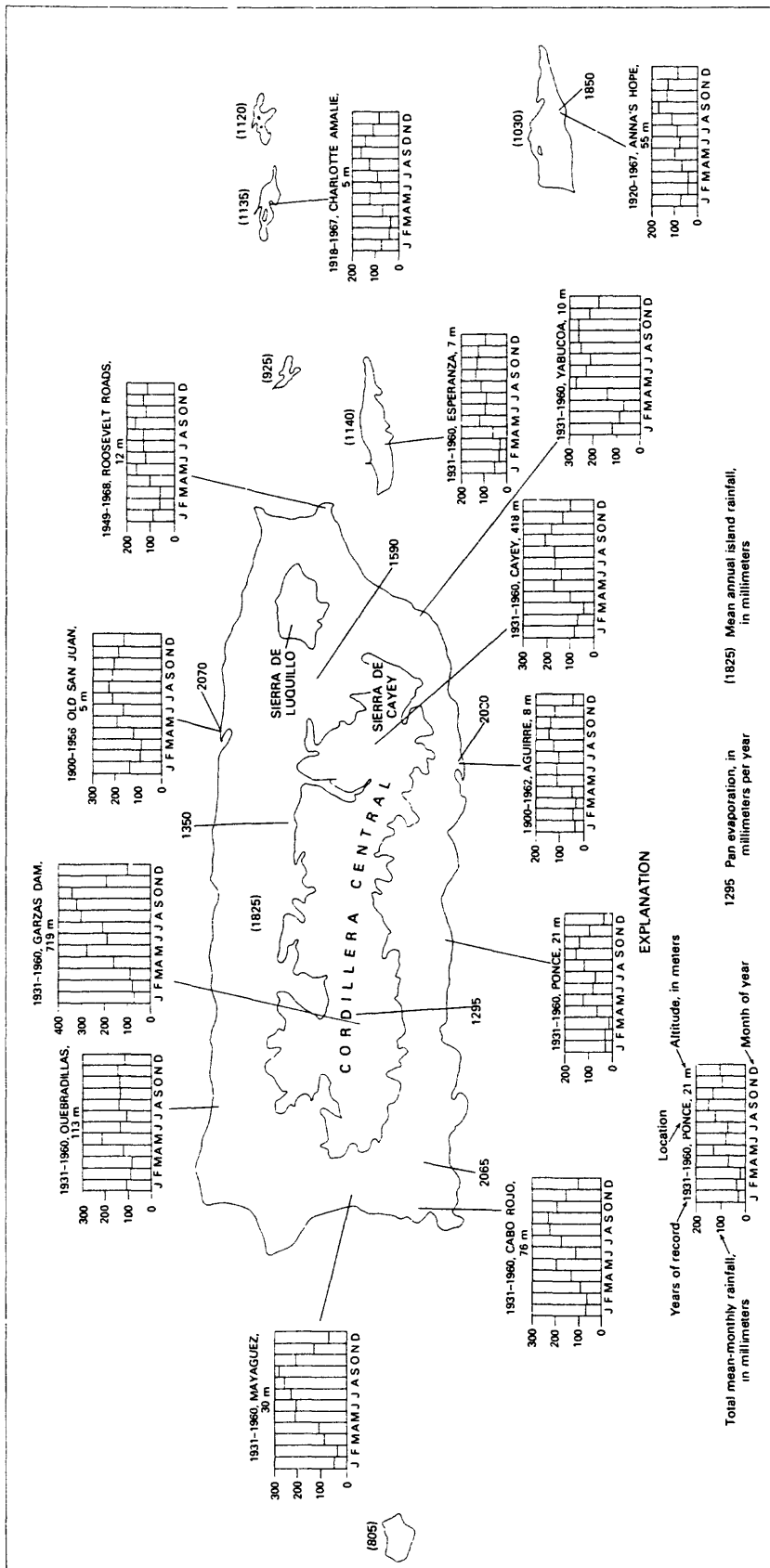


Figure 4.--Rainfall distribution and pan evaporation in the Caribbean region. (From Gomez and Heisel, 1980).

Drainage

Puerto Rico's southern plain is bordered to the north by mountains and foothills of the Cordillera Central. These highlands form steep southward-facing slopes that rise to more than 1,300 m above sea level and constitute the principal drainage divide of Puerto Rico. The Cordillera Central insular drainage divide lies less than 24 km north of the fan-delta shoreline. Tributary streams that flow southward from the Cordillera Central transport the poorly-sorted volcanic and volcanoclastic boulders, cobbles, gravel, and sand that make up streambed deposits. Mountainous streams and rivers are comparatively straight and follow a rectilinear drainage pattern (fig. 2). They have deeply incised valleys in the mountains and in the apex of some fan-deltas. One of the more dramatic examples of incisement is within the apex of a small fan at the Río Jueyes water gap where erosional downcutting is more than 10 m (figs. 2, 3). The principal effect of fan-head incisement is that the incised portion of the fan is inactive and no longer is subject to flooding or sedimentation.

Where the major streams traverse the fan-delta plain, they display a straight to slightly sinuous channel morphology, and in large part, extend southwest from the highland area. For example, the Salinas fan (STOP 3B) is drained by a straight stream, the Río Nigua, which extends southwest from the fan apex. Prior to channelization for flood control (such as in the Ponce area), the confining channels of many streams were lost in the distal areas of the fan-deltas, allowing surface water to spread out as sheetflow onto the coastal lowlands. The size of the bedload material within the dry channel of Río Nigua is varied. Boulders having a diameter greater than 1 to 2 m represent the coarsest waterlain fraction found within the upland stream channel of the Salinas fan-delta. The downstream, midfan channel is floored with smaller boulder- and cobble-size detritus in a coarse to fine sand matrix; other midfan, braided streambed deposits are dominated by pebbly sand and gravel that form longitudinal bars. The wave-built berm found at the Río Nigua channel mouth contains wave-polished gravel, pebbles, and sand.

Debris flow landslide deposits, from the failure of unstable slopes during intense rainfall events, largely are confined to the proximal part of a fan-delta, upland channel, or are deposited immediately adjacent to the mountain front. These deposits provide detritus to the major stream which then is carried downstream and reworked to become part of the fluvial bedload. Narrow debris flow scars, the result of a 1985 storm described below were still visible on the face of Cerro Raspaldo near the Río Jueyes water gap at the time of this writing (1990).

Streamflow is minimal except during flood events. Streamflow in the upstream parts of a fan-delta plain usually is less than 1.0 cubic meters per second (m^3/s) 90 percent of the time (Quiñones and others, 1984), and the midstream reach is often dry. The distal stream channel may be saturated or contain standing water, the result of upward ground-water discharge. Flooding, although infrequent, may be widespread and catastrophic, and is the result in runoff during intense rainfall that may last several days.

In 1985, Puerto Rico was affected by a stationary tropical depression that produced more than 580 mm of rainfall and extensive flooding over much of the southern part of the island during a 24-hour period (figs. 5 and 6). This catastrophic event resulted in additional damage to private and public property estimated at \$125 million. Forty deaths were attributed to extensive flooding, and 130 deaths were attributed to landslides. Peak discharge at Highway 52 (Las Americas Expressway) near the Coamo Dam north of Paso Seco was 2,040 m³/s. Computed discharge at Baños de Coamo, located north of the dam, was 1,870 m³/s. The peak discharge had a recurrence interval of 100 years and exceeded all previously-recorded floods at the site. The flood overtopped the spillway and levee of the Coamo Dam (OPTIONAL STOP 5) just upstream of the highway. The embankment and shoulder on the northern span of the bridge was eroded and the approach slab collapsed into the floodwaters where 24 people lost their lives as their cars fell into the river (Quiñones and Johnson, 1987). Cumulative rainfall near Lago Guayabal, a reservoir northeast of Ponce, exceeded 550 mm during October 6-7, 1985 (Quiñones and Johnson, 1987). During the flood of October 7, 1985, the maximum measured discharge within the Río Jacaguas at Juana Diaz was 360 m³/s, or 3.9 cubic meters per second per square kilometer (m³/s/km²).

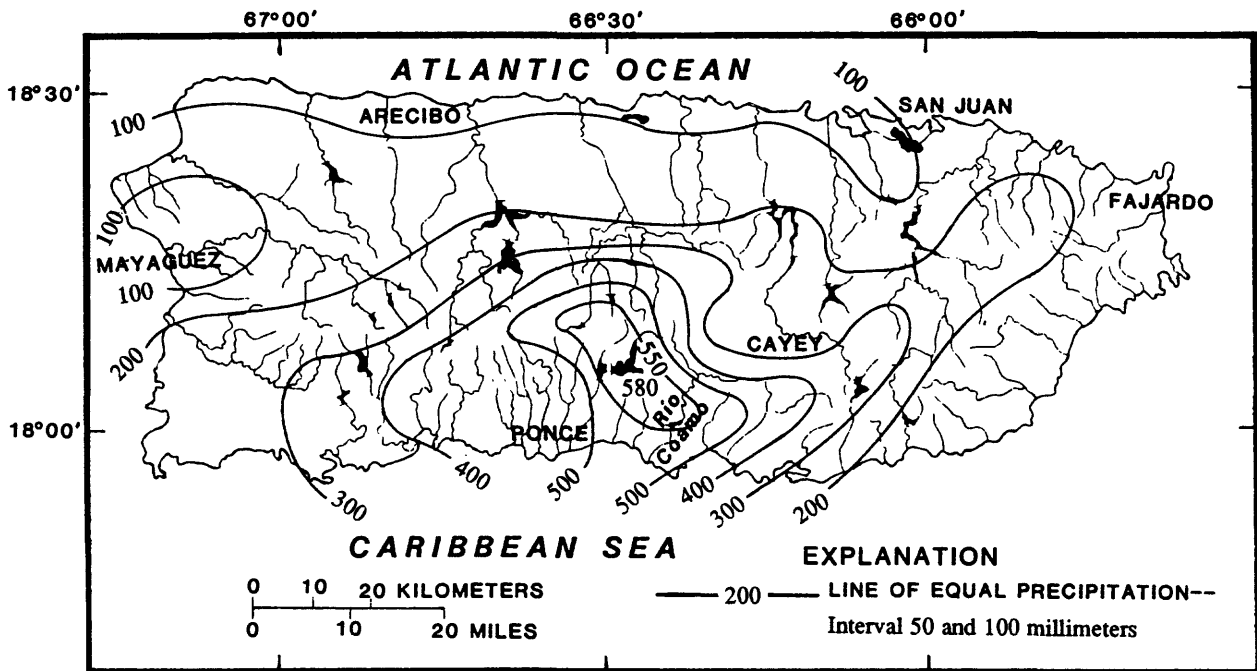


Figure 5.--Cumulative rainfall over Puerto Rico during October 6-7, 1985. (From Quiñones and Johnson, 1987).

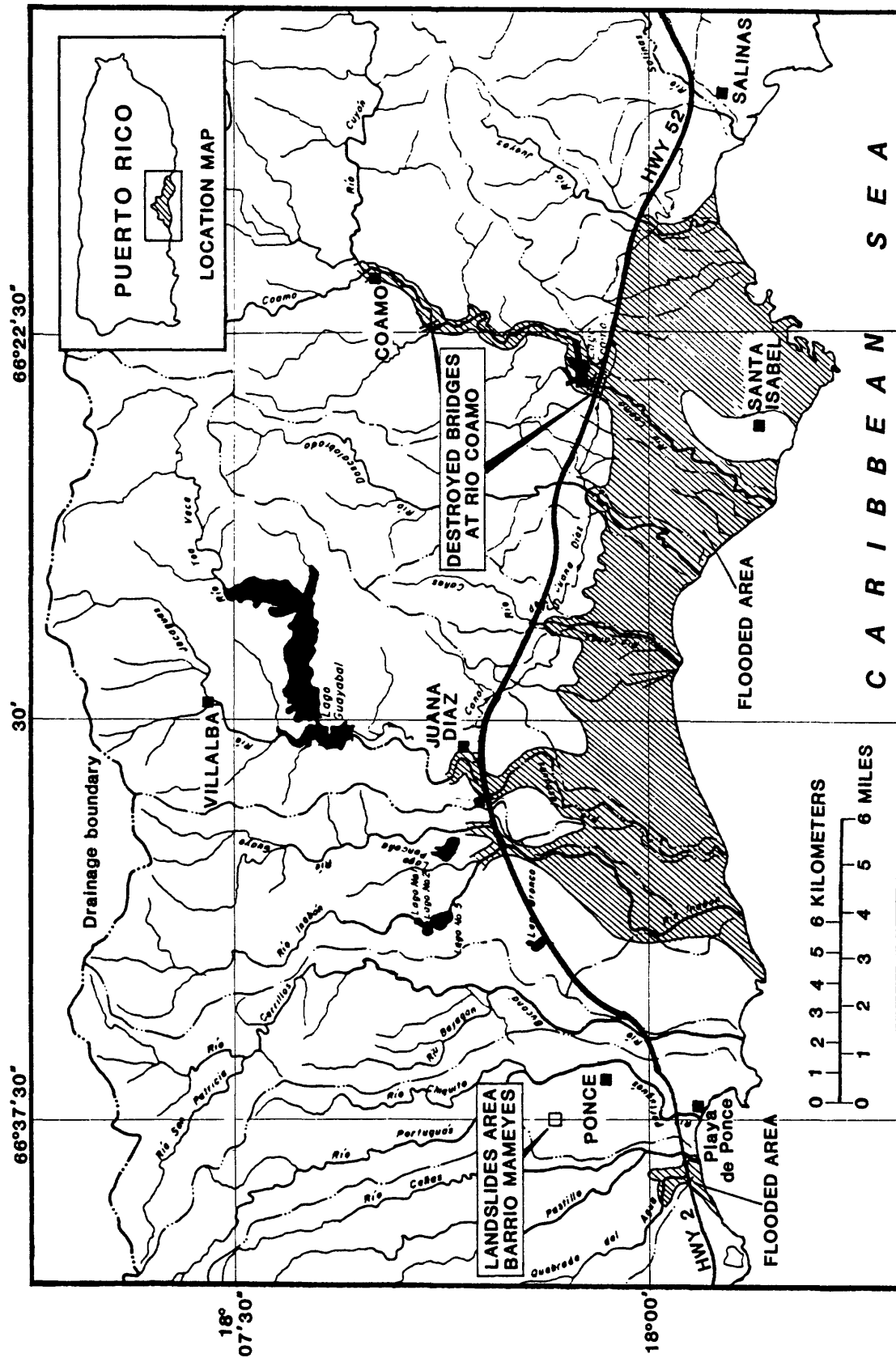


Figure 6.--Areas flooded in the central part of the southern plain during the October 7, 1985 flood. (From Quinones and Johnson, 1987).

Flood Alert System

In response to the October 1985 storm, the Governor of Puerto Rico signed a bill approving funds for the implementation of a Rainfall-Runoff Alert Network. The flood-alert system, developed by the National Weather Service, the U.S. Geological Survey (USGS), and the Commonwealth of Puerto Rico's Department of Natural Resources (DNR), consists of a network of telemetered rainfall and runoff data stations located throughout the island (fig. 7). These telemetered data stations provide real-time rainfall and runoff data that are used to predict flash flooding. The principal objective of the flood-alert system is to provide the Commonwealth of Puerto Rico's Civil Defense Agency with advance notice of flash floods that can occur during intense rainfall.

The equipment used for the stream-runoff gaging network is designed by Synergetics Data Collection Platforms^{1/} and is operated by the USGS. The USGS initiated a real-time data collection program in Puerto Rico in 1984 with the first data collection platform (DCP) transmitting stream stage from the Rio Grande de Loiza to the World's Fair in New Orleans. The network (1990) consists of 60 tipping-bucket rain and stream-stage gages that can be read remotely by using a data interrogation system (fig. 7). River (lake) stages, rainfall and battery voltage sensors transmit information from the DCP to the Geostationary Operational Environmental Satellite (GOES), and from the GOES satellite to the Direct-Readout Ground Station (DRGS) at the U.S. Geological Survey Caribbean District, San Juan, Puerto Rico (fig. 8) (Díaz and Sepúlveda, 1989).

Several different computer programs are used by the USGS's Caribbean District to evaluate the DCP data (Pedro Díaz, USGS, verbal commun., 1980). One computer program (RTLIS) allows users to examine DCP transmissions as they are received from the DRGS. Another computer program (RTPLOT) allows the user to examine processed DCP data graphically. Stream stages, cumulative rainfall, and battery voltage can be displayed for periods that extend up to 60 days. A third program (RTRAIN) can display cumulative rainfall from the DCP unit for up to 7 days. Selected rainfall data can be presented for the entire island or an individual basin.

During a storm, the flood system is accessed by the Commonwealth of Puerto Rico's Civil Defense Agency. Also, personnel from other disaster-response agencies are informed. Real-time data are received by the USGS and the DNR offices are accessed via a computer modem by participating agencies.

^{1/}Use of the brand name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

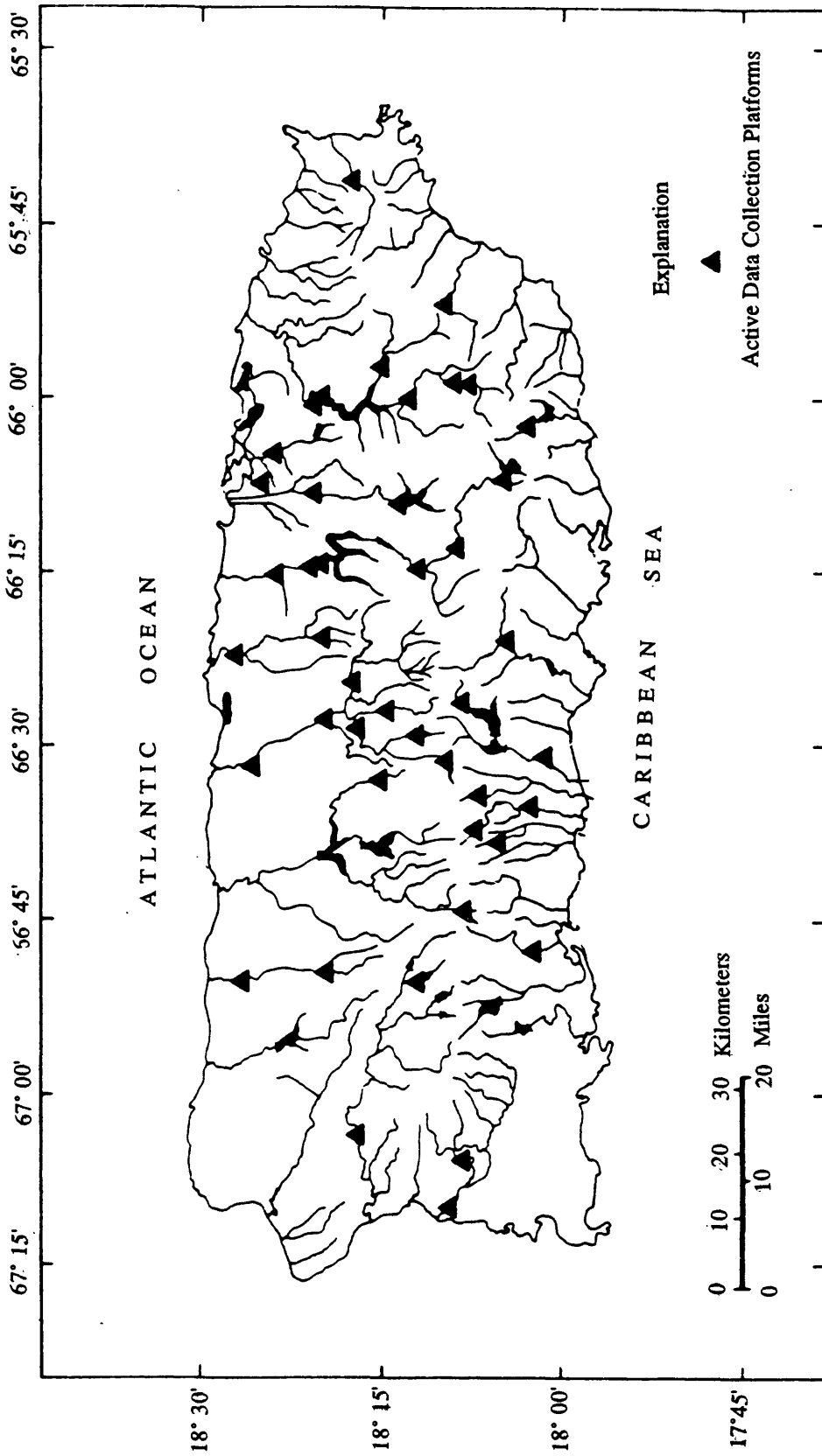


Figure 7.--Location of data collection platform stations in Puerto Rico. (From Diaz and Sepulveda, 1989).

GEOSTATIONARY OPERATIONAL
ENVIRONMENTAL SATELLITE

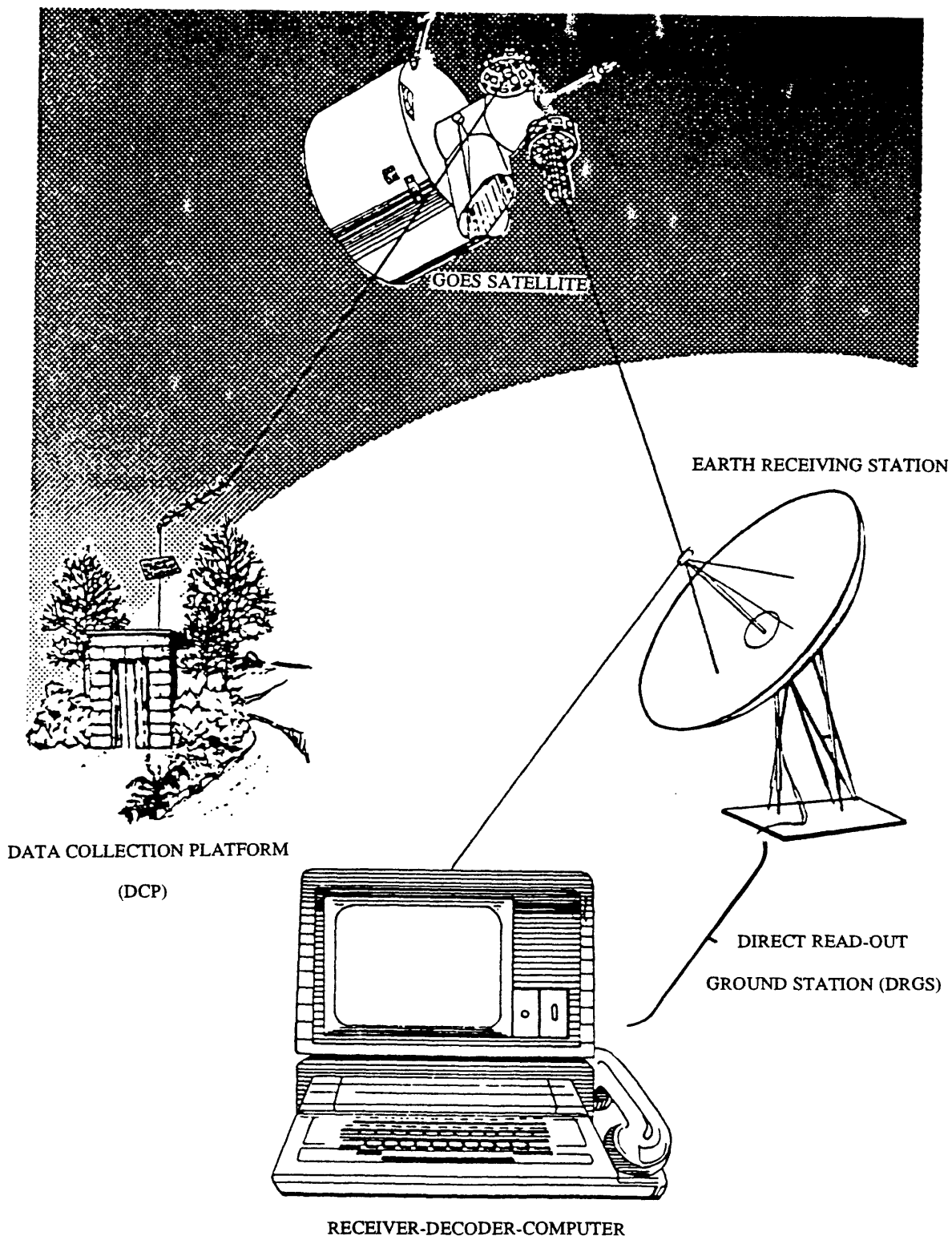


Figure 8.--Real-time data acquisition system. (From Diaz and Spulveda, 1989).

Irrigation Works

Earliest irrigation works (1825) consisted of diversion of baseflow at the principal streams at points at the fan apex. Development of a large-scale irrigation system occurred between 1910 and 1935, and included a 190 km network of irrigation canals and laterals, six reservoirs having a storage capacity of 50 cubic hectometers (hm^3), and two tunnels across the insular divide. These irrigation works made available 300,000 m^3/d of water to 10,800 ha of previously uncultivated land located east of Río Jacaguas. A network of canals and reservoirs was in place by the end of the 1800's diverting most baseflow at streams west of Río Jacaguas (100,000 m^3/d) (Toro-Lucchetti, 1963).

Total surface irrigation deliveries through government-operated irrigation districts east of Río Jacaguas averaged 99,000 m^3/d in 1982. The reduction in deliveries is related to a decline of total sugar cane acreage (principal crop irrigated with surface water) recent preference of ground water for drip irrigation of vegetable crops (Torres-Sierra and Aviles, 1986).

Ground-water development commenced in the early 1900's using steam-powered centrifugal pump systems. By 1925, kerosene-driven motors replaced steam engines. About 50 well fields capable of yielding 80,000 m^3/d were constructed between Ponce and Guayama. Electric powered vertical turbine pumps replaced less efficient pumps beginning in 1930 (Luce and Company, Aguirre, Puerto Rico, written commun., 1986). Ground-water withdrawal increased rapidly after 1930 reaching a peak of 360,000 m^3/d in 1947 (McGuinness, 1948). Ground water withdrawal for irrigation has decreased to a present-day estimate 130,000 m^3/d . Drip irrigation constitutes about 17 percent (60,600 m^3/d) of the total gross irrigation withdrawal. Overall consumptive withdrawal within the southern plain is estimated at 180,000 m^3/d and has decreased by 70,000 m^3/d since 1947.

Portugues-Bucana Flood Control and Water-Supply Project

The Cerrillos and Bucana Multipurpose Project was authorized by the 1970 Flood Control Act. It is designed and being constructed by the COE. The Cerrillos Dam and reservoir and the Portugues-Bucana channel improvement project will provide flood protection and serve as a recreational area and as a water supply for the Ponce area. Channel improvements, designed to alleviate flooding from the Portugues and Bucana Rivers and tributaries, include the enlargement of both river channels and a diversion channel that connects them. The Cerrillos Dam (STOP 9), nearing completion, will be about 100 m tall, and is an earth-rock structure having concrete outlet works and tunnel and an overflow spillway; the storage-capacity of the reservoir is 60 hm^3 . Controlled releases will be used for hydroelectric power generation (Vazquez-Ruiz and Conway, COE, written commun., 1990).

GEOLOGY AND HYDROGEOLOGY OF THE SOUTHERN PLAIN

The total thickness of fan-delta deposits that comprise the southern plain increases irregularly in a coastward direction. The sedimentary section is thickest where fan-delta deposits have infilled cross-cutting graben structures (fig. 9). The sedimentary section is unusually thick beneath the Coamo fan. The reported depth to bedrock exceeds 900 m here as the fan extends coastward. This great thickness of clastic material beneath the Coamo fan is associated with subsidence within a pull-apart basin. In much of the southern plain, depth to bedrock averages less than 100 m. The thinnest fan-delta deposits are found where the sequence lies adjacent to the highlands or near protruding horst structures, prominent as bedrock hills. The complex series of horst and graben structures that underlie the Salinas fan probably are controlled by a fault convergence-divergence mechanism. Overlying sedimentary fan-delta deposits appear to increase in thickness where subparallel strike-slip faults diverge. Fan-delta deposits in the Salinas area appear to thin where these faults converge. The complexity of the structural features that underlie the southern plain can be more fully appreciated by study of outcrop exposures along Puerto Rico Highway 139, the road that extends northward from Ponce to the Río Cerrillos Dam site. Cretaceous and early Tertiary volcanoclastic rocks are tilted, folded, contain numerous fractures, several faults, and fault shear zones.

Exposures along escarpments and within entrenched stream channels, driller's log descriptions, and core have been studied to characterize major lithologic and water-bearing units within the southern plain of Puerto Rico. Fan-delta deposits can be divided into two major types

- (1) coarse-grained facies that make-up the principal water-bearing units characterized by massive to bedded boulder- to sand-sized deposits; and
- (2) fine-grained facies dominated by massive to bedded, silt- and clay-sized deposits, which constitute local confining beds.

The proportion of fine sand to bouldery detritus within the coarse deposits varies considerably. Coarse deposits are massive to crudely graded, poorly sorted and have poorly to well rounded clasts. A clast-supported, boulder- to pebble-size channel-fill deposit is well exposed along a coastal scarp near the Central Machete-Puerto Arroyo area (STOP 1). The exhumed channel displays an overall upward-fining nature, and contains large-scale, low-angle cross beds suggestive of lateral migration. The channel at this exposure is 35 m wide, and as much as 3 m thick. The lenticular nature of this channel deposit probably is typical of some water-bearing units within the South Coastal Plain aquifer system. Coarse-grained deposits visible on exposures located along the entrenched channel of the Río Coamo immediately south of the city of Coamo (fig. 2) are characterized by a sand dominated facies. The beds are better sorted and composed mostly of fine to coarse sand and gravel. Horizontal bedding structures and medium-scale, planar cross beds may imply turbulent streamflow conditions during deposition.

Intense weathering and erosion of tuffaceous rocks underlying the foothill and mountain areas to the north provide an adequate supply of fine detritus. The fine-grained facies consists mostly of silt and some clay, and has unstratified to planar units interlayered with thin lenses of gravel and sand, probably associated with sheetflow deposition.

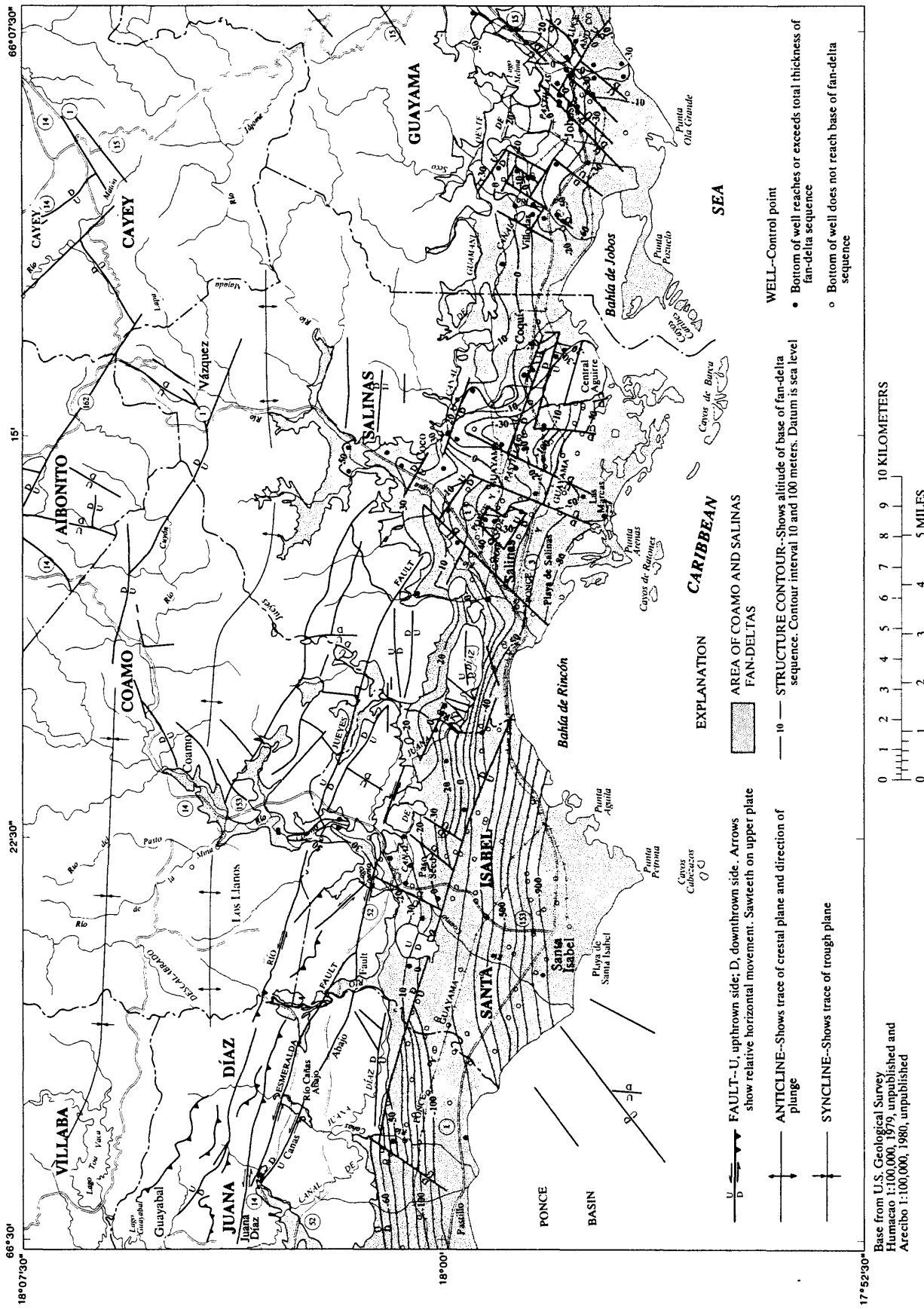


Figure 9.--Configuration of the bedrock surface underlying the central part of the southern plain. (From Renken and others, 1990).

Sand and gravel percent maps of the Salinas and Coamo fans show the spatial variability associated with fan-delta lithofacies (fig. 10). Sand and gravel maps show that the amount of coarse-grained material progressively decreases in a downfan direction. Highest concentrations of coarse detritus are found in proximal parts of the fan or in alluvial channels that reach inland. Where floodwater overflows the bank of the stream channel, it spreads out and covers the midfan floodplain. Coarser detritus is deposited as a midfan lobe and finer material moves downfan where it constitutes more than 80 percent of the depositional sequence.

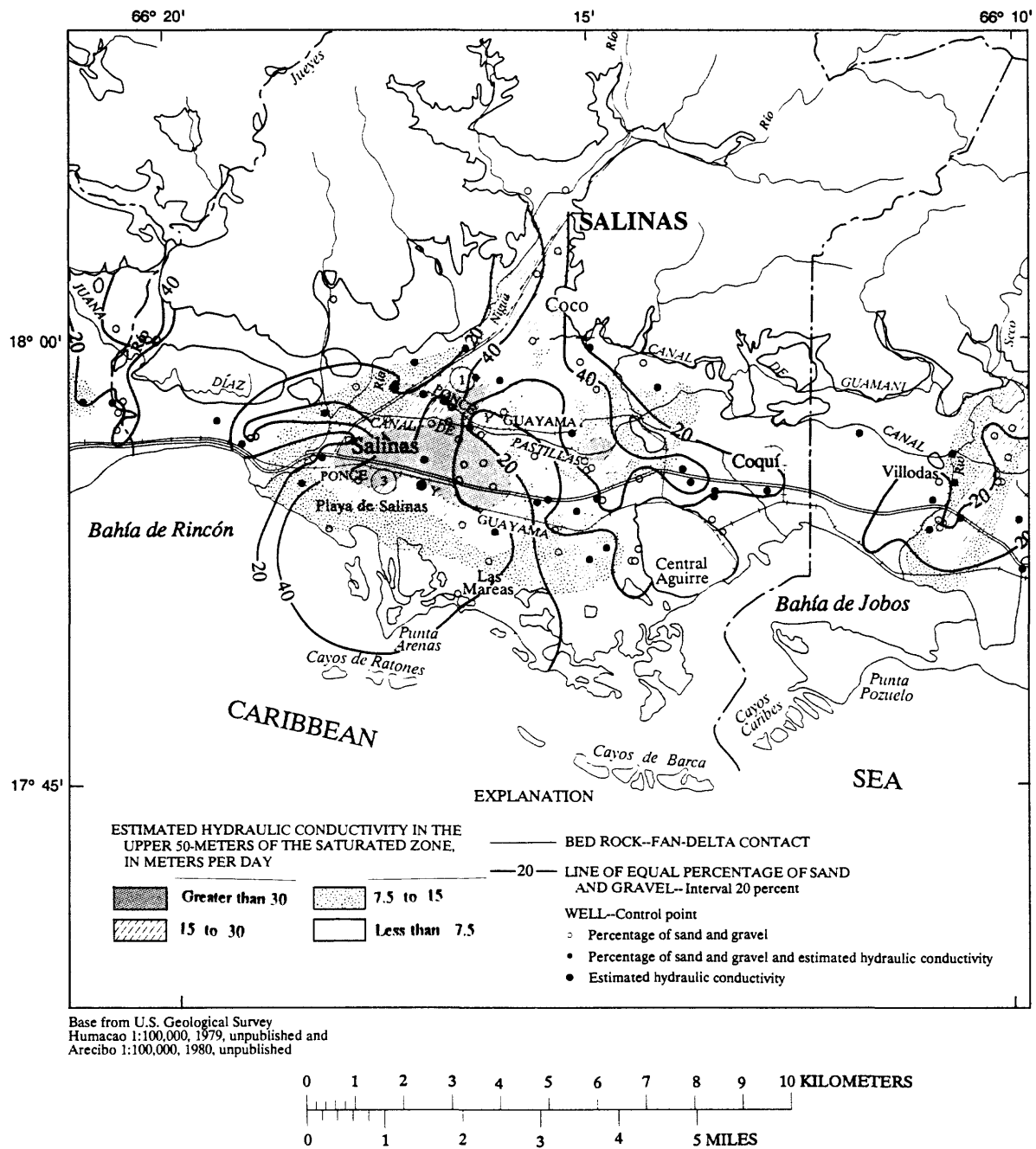


Figure 10.--Percentage of sand and gravel and the distribution of hydraulic conductivity in the Salinas fan-delta. (From Renken and others, 1990).

Ground-Water Hydrology

Ground water within the southern plain occurs under both confined and unconfined conditions. Confined conditions are more prevalent within deeper parts of the plain and near the Caribbean coast where water-bearing strata are overlain by less permeable, fine-grained material. Water-table or unconfined conditions prevail in inland areas. Terrigenous deposits of cobbles, gravel, and sand form the principal water-bearing units. Thick beds of silt and some clay impede vertical movement of ground water and contribute to downfan confined aquifer conditions.

Prior to development, the South Coastal Plain aquifer system principally was recharged by rainfall and stream seepage near the fan apex. Ground water is discharged by seepage at the coast, to the stream channels, or as evapotranspiration. Development of the surface- and ground-water system has modified the hydrologic system considerably. Approximately 30 percent of all surface-applied irrigation water appears to recharge the aquifer. Ground-water discharge under present conditions is principally by large wells. In 1987, consumptive ground-water withdrawal from the South Coastal Plain aquifer system was estimated at 190,000 m³/d; 56 percent was for irrigation and the remainder was mostly for public water supply.

Transmissivity estimates based on aquifer and specific capacity test data were used to map the spatial variation in hydraulic conductivity within the South Coastal Plain aquifer system. A comparison with sand and gravel percent maps shows that the highest hydraulic conductivity (25 to 100 m/d) is found in proximal and midfan areas having large amounts of coarse-grained detritus. Lowest hydraulic conductivity (less than 25 m/d) are associated with distal and interfan deposits (fig. 10).

Fractures and faults serve as conduits for deeper ground-water circulation in the foothills and mountains that lie north of the fan-delta plain. The Baños de Coamo thermal spring (STOP 6), located within the Río Coamo valley and north of the fan-apex, is situated along the Río Jueyes strike-slip fault. Mean daily spring flow ranged from 130 to 300 m³/d between November 1983 and July 1984 (Guzman-Rios, 1988). Discharge data for the Baños de Coamo spring suggests that seismic activity may have increased fracture permeability; springflow increased from an average discharge of 4 to 7 liters per second (L/s) following the June 30, 1984, earthquake (Guzmán-Ríos, 1988).

Ground-Water Quality Trends

Although no significant degradation of the quality of ground water has been reported, the potential exists. Large-scale modification of land use practices may have directly influenced the existing ground-water-flow system. Among these modifications are (1) a decrease in the use of surface water for furrow irrigation and an increase in the use of ground water for drip irrigation; (2) a reduction in aquifer recharge owing to the abandonment of farmland previously under furrow irrigation, and (3) an increase in urban development.

Ground-Water Quality Conditions

The hydrochemical facies of ground water from the southern coastal province (fig. 11) illustrates the wide range of water types. Calcium bicarbonate water largely is associated with ground-water containing less than 600 milligrams per liter (mg/L) dissolved solids. Ground water of this quality commonly is found in the midfan and fan-head areas of the southern plain. Interfan areas and some of the more coastal areas are underlain by water of the sodium bicarbonate (820 mg/L or less) and calcium chloride-sodium chloride type (dissolved solids as great 2,500 mg/L).

Between January and May of 1983, the reported temperature of the Baños de Coamo thermal spring range between 37.6° to 43°C and the specific conductance ranged from 2130 to 2320 microsiemens per centimeter ($\mu\text{S}/\text{cm}$). A thermal well is located nearby along the Río Jueyes fault. The thermal spring at Baños de Coamo discharges water of a sodium-calcium-sulfate type having high concentrations of boron (2,500 mg/L), probably caused by hydrothermal leaching.

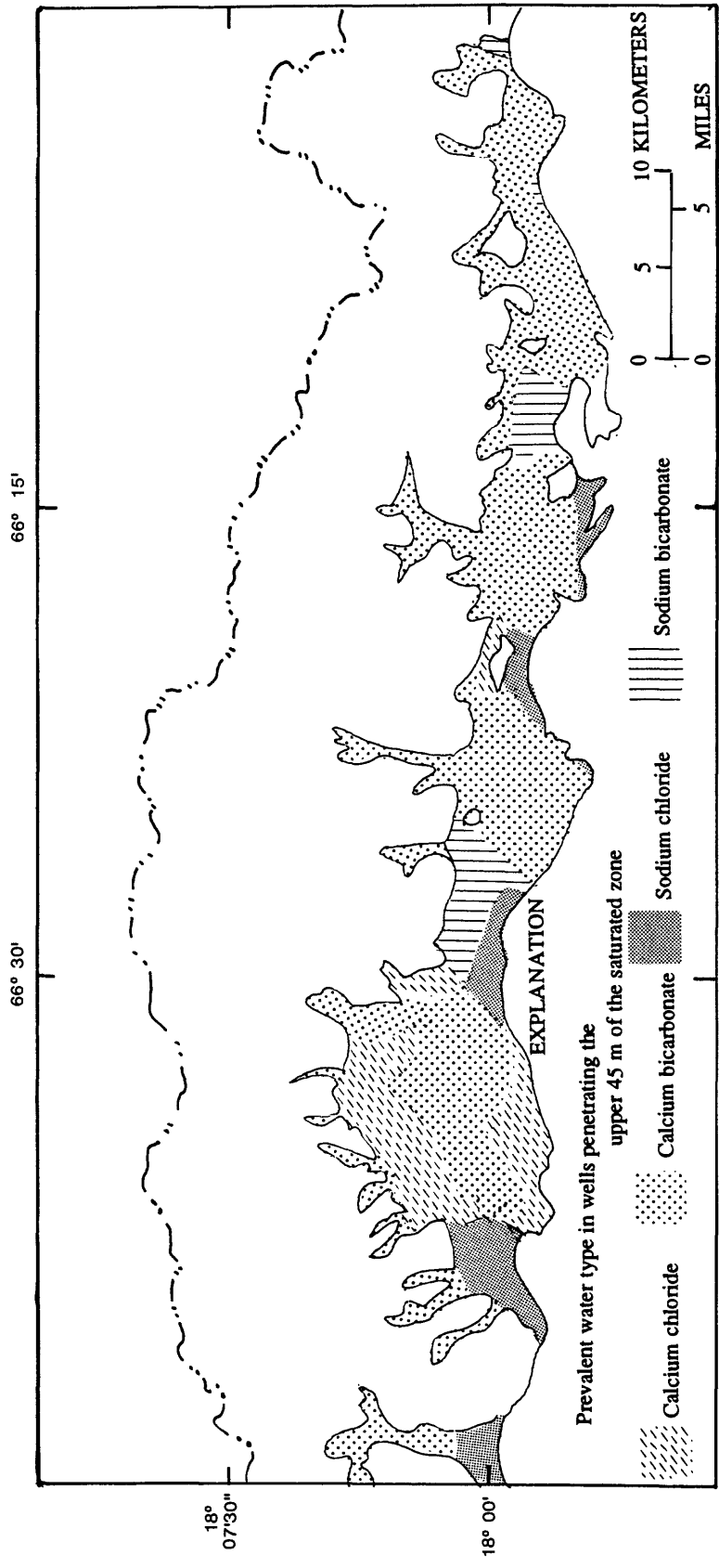


Figure 11. Hydrochemical facies of groundwater in the southern plain.

ROAD LOG

| Total mileage (kilo- meters) | Mileage interval (kilo- meters) | |
|---------------------------------------|--|--|
| 0 (0) | 0 (0) | Depart from the Sands Hotel and Casino, Isla la Verde, and travel west (turn right) to San Juan. |
| 1.3 (2.09) | 1.3 (2.1) | Turn left at Calle Jupiter (past Cementerio Memorial de Puerto Pico). |
| 1.5 (2.4) | 0.2 (0.3) | Turn right at light and continue to travel west on Avenida Baldoriory de Castro (Highway 26). |
| 3.4 (5.5) | 1.9 (3.05) | Turn right at entrance ramp for Expreso de Diego (Highway 22) proceeding toward Bayamon |
| 5.0 (8.0) | 1.6 (2.6) | Follow entrance for Expreso las Americas (Highway 18) to Caguas. Proceed south on Highway 18 to Autopista (Highway 52) and continue. |
| 17.2 (27.7) | 12.2 (19.6) | Toll |
| 23.1 (37.2) | 5.9 (9.5) | Toll |
| 28.2 (45.4) | 5.1 (8.2) | Exit off Guavate interchange. Intersection of Highway 184 and Highway 52 (Exit no. 33). Turn left at bottom of exit ramp and follow Highway 184. |
| 31.8 (51.2) | 3.6 (5.8) | Entrance to Guavate State Forest. |
| 35.8 (57.6) | 4.0 (6.4) | View of Carite Reservoir, an earth fill type of reservoir; part of the Southern Coast Irrigation District |
| 41.8 (67.3) | 6.0 (9.7) | View of the Rio Patillas on right hand side of road. |
| 45.8 (73.7) | 4.0 (6.4) | View of U.S. Geological Survey telemetered rainfall-runoff gage station. Continue on Highway 184. |
| 46.3 (74.5) | 0.5 (0.8) | View of Rio Patillas and Patillas Reservoir. Reservoir was completed around 1914. Continue on Highway 184. |
| 47.3 (76.1) | 1.0 (1.6) | Cross Canal de Patillas |

- 48.9 (78.7) 1.6 Turn right at intersection of Highway 184 with Highway 3. Continue on Highway 3.
- 50.4 (81.1) 1.5 Entering the southern plain of Puerto Rico and Arroyo fan-area. View of Central Lafayette Sugar Mill on left hand side of road.
- 52.1 (83.8) 1.7 Entering Municipio de Arroyo and crossing the channelized Rio Nigua.
- 57.2 (92) 5.1 Crossing Quebrada Salada, fed at its headwaters by a thermal spring, Banos de Virella.
- 58.8 (94.6) 1.6 Cross Patillas Canal in Guayama.
- 59.3 (95.4) 0.5 Turn left at intersection of Highway 3 with Highway 744 towards Machete and follow to "T" intersection
- 61.0 (98.1) 1.7 Turn left after crossing railroad tracks and follow road as it turns right toward coast. Turn at first left (unpaved) and follow along the coast.
- 63.1 (101.5) 2.1 STOP 1. Coastal exposure at Central Guayama. A discussion of the exposure seen here is included in text. Exit vehicles and follow path to beach and walk 0.7 miles eastward to next large gully. Follow path to top of scarp and proceed to next field stop.
- 63.8 (102.7) 0.7 Follow unpaved road back in direction of sugar mill, drive on unpaved road along railroad tracks past the sugar mill. Head west to the Phillips Petroleum Refinery along unpaved road.
- 65.6 (105.6) 1.8 Cross dry streambed of the Rio Guamani
- 65.8 (105.9) 0.2 Intersection of the unpaved road and Highways 710 and 3. Follow Highway 3 to the west.
- 67.4 (108.4) 1.6 (Optional detour) Turn left at Highway 710 to view mangroves, tidal and supratidal flats, and compound spit at Punta Pozuelo.
- 69.8 (112.3) 2.4 Jobos Bay in view
- 72.0 (115.8) 2.2 Continue onto unpaved road into mangrove swamp area.
- 72.7 (117.0) 0.7 Circle back to paved road and follow to "T" intersection. Follow Highway 710 back to Highway 3.
- 74.5 (119.9) 1.8 Turn left at intersection of Highway 710 and Highway 3. Proceed west on Highway 3 toward Central Aguirre.

- 80.7 (129.8) 6.2 Turn left at intersection of Highway 3 and Highway 705 and proceed south toward sugar mill. (10.0)
- 81.2 (130.7) 0.5 Turn right onto gravel road and follow along the northern edge of Cerro Central Aguirre. (0.8)
- 81.8 (131.6) 0.6 **OPTIONAL STOP 2A.** Exit vehicles to examine the exposure face at Cerro Central Aguirre. This exposure is located near the projected position of the Esmeralda fault. 10.0
- 83.8 (134.8) 2.0 Continue in vehicles to paved road; turn right on Aguirre Thermo-electric Road. Continue across intersection at Highway 3 onto unpaved road. Continue on unpaved road to Cerro Coqui and follow unpaved road to top of hill (four-wheel drive vehicles only). STOP 2B. View from top of hill provides a panoramic view of the Salinas fan-delta, a well field used for irrigation purposes, Cerro Central Aguirre and Raspaldo, Bahia de Jobos, and the Caribbean Sea. (3.2)
- 85.3 (137.2) 1.5 Return to vehicles, and proceed to Highway 3, turn right at intersection. (2.4)
- 89.3 (143.7) 4.0 Proceed on Highway 3 into Salinas. At Plaza de Salinas, follow Highway 1 westbound. (6.4)
- 90.4 (145.5) 1.1 Proceed on Highway 1 (coastal road) that follows along the Bahia de Rincon coastline. (1.8)
- 90.9 (146.3) 0.5 Pull off road for view of a 10-meter scarp at Hacienda Carolina. This scarp may possibly represent a fault-line scarp. Proceed westward on Highway 1. (0.8)
- 95.4 (153.5) 4.5 Turn right at Highway 541. Follow road. Paved portion of road veers to left with unpaved portion that continues straight. Go straight on unpaved road. (7.2)
- 96.7 (155.6) 1.3 Canal Florida on left. Follow unpaved road until it rejoins paved road at the community of Paso Seco and continue north on Highway 153. (2.1)
- 98.8 (160.0) 2.1 Turn left at Highway 545 (to Gabia) and follow road to headway of the Coamo (**Optional STOP 3**). Turn around and return to the intersection of Highway 545 and Highway 153. Turn left and head northbound to Banos de Coamo. (3.4)
- 103.4 (166.4) 4.6 Turn left at the intersection of Highway 153 and 546 and proceed to Banos de Coamo. (7.4)
- 104.5 (168.1) 1.1 **STOP 4.** Banos de Coamo thermal spring. (1.8)
- 105.6 (169.9) 1.1 Return to vehicles and turn right (south) at intersection of Highway 153 and Highway 546. (1.8)

- 108.9 (175.2) 3.3 Turn right onto Autopista (Highway 52) and head west towards Ponce.
(5.3)
- 114.1 (184) 5.2 View (south) from highway of coast and Isla Caja de Muertos.
(8.4)
- 115.5 (185.8) 1.4 OPTIONAL STOP NO. 5
(2.3) Exposures of the lower clastic facies Juana Diaz Formation of Oligocene and Miocene age. Exposures exhibit alternating boulder, cobble and sand deposits that overlie maroon, burrowed claytone unit. Continue west on Autopista.
- 118.4 (190.5) 2.9 Toll at Juana Diaz interchange.
(4.6)
- 120.6 (194) 2.2 Exit from Autopista (Highway 52) at the Coto Laurel interchange.
(3.5) Turn right at base of exit ramp; head northbound on Highway 506.
- 121.6 (195.7) 1.0 Turn left (west) at intersection of Highway 506 and Highway 14.
(1.6)
- 123.6 (198.9) 2.0 STOP NO. 6. USGS real-time streamflow-rainfall station; part of
(3.2) the flood-alert system (located at improved channel of the Rio Bucana and Highway 14). Return to vehicles and continue westbound on Highway. 14.
- 124.4 (200.2) 0.8 Intersection of Highway 14 and Highway 139. Turn right and follow
(1.3) northbound on Highway 139.
- 125.3 (201.6) 0.9 View of sedimentation pond (part of the Rio Bucana flood
(1.4) channelization project. Follow Highway 139 north to old Highway 139.
- 126.1 (202.9) 0.8 Turn right at old Highway 139 and follow road to the U.S. Corps of
(1.3) Engineers' Rio Cerrillos Dam project site.
- 128.1 (206.1) 2.0 STOP NO. 7 Rio Cerrillos Dam site.
(3.2)
- 131.8 (212.1) 3.7 Return to vehicles and proceed southward on Highway 139 to
(6.0) Highway 14.
- 134.6 (216.6) 2.8 Turn left at the intersection with Highway 506 and head south to
(4.5) Autopista.
- 135.6 (218.2) 1.0 Turn left and head eastbound on Autopista (Highway 52) to San Juan.
(1.6) Return to Sands Hotel in Isla Verde, San Juan.

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