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PLANNING REPORT FOR THE CARIBBEAN ISLANDS REGIONAL AQUIFER-SYSTEM ANALYSIS PROJECT

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 86-4074

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By Fernando Gómez-Gómez

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 86-4074

San Juan, Puerto Rico
1987

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

For the convenience of readers who may want to use the International System of Units (SI), the data may be converted by using the following factors:

Multiply inch-pound units	By	To obtain SI units
inches (in.)	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
mile (mi)	1.609	kilometers (km)
square mile (mi^2)	2.590	square kilometers (km^2)
acre	4,047	square meters (m^2)
acre-feet (acre-ft)	1,233	cubic meters (m^3)
gallon per minute (gal/min)	0.06309	liters per second
million gallons per day (Mgal/d)	3,785	cubic meters per day (m^3/d)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (M^3/s)
square feet per day (ft^2/d)	0.0929	square meters per day (m^2/d)

PLANNING REPORT FOR THE CARIBBEAN ISLANDS REGIONAL AQUIFER-SYSTEM ANALYSIS PROJECT

By
Fernando Gómez-Gómez

ABSTRACT

The Caribbean Islands Regional Aquifer-System Analysis (RASA) project includes an area of 3,600 square miles within Puerto Rico and the U.S. Virgin Islands of St. Croix, St. Thomas, and St. John. The principal aquifers are the carbonate rocks of northern Puerto Rico, the carbonate rocks of central St. Croix, (Kingshill aquifer) and the alluvial deposits of the southern coastal plain in Puerto Rico. In 1980, withdrawals from these aquifers were estimated at 210 million gallons per day or approximately 85 percent of all ground-water withdrawals in the region. A comprehensive appraisal of these aquifer systems is required to assess the potential use of this resource without initiating sea-water encroachment.

In October 1984, the U.S. Geological Survey commenced a 5-year study to: (1) provide a regional appraisal of the hydrology, hydrogeology, and ground-water resources of the principal aquifers in Puerto Rico and the U.S. Virgin Islands, (2) provide a detailed analysis of the hydrogeologic framework, ground-water-flow system and geochemistry for the three principal aquifer systems within the region, (3) evaluate the historical hydrologic changes which have led to the present conditions in the principal aquifer systems, and (4) provide means by which to anticipate the effects of future ground-water withdrawals or hydrologic modifications.

A plan of study is presented that describes: (1) The objectives and scope of work, (2) approach, (3) work elements, (4) special studies necessary to achieve the program goals, and (5) the reports that will be produced from the project. Emphasis during the first year will be on the compilation and review of previous literature and the creation of data bases necessary to support the regional analysis. This will be followed by acquisition of new data, development of aquifer models, refinement of data bases, and distribution of information to the general public. The final year will be dedicated to compiling the findings into a regional analysis, and publishing the material in the U.S. Geological Survey Professional Paper Series.

INTRODUCTION

Regional Aquifer-System Analysis Program

The Regional Aquifer-System Analysis (RASA) program represents a systematic effort by the U.S. Geological Survey to study the Nation's major aquifer systems. Twenty-eight aquifer systems have been identified for study, and the Caribbean Islands Regional Aquifer-System Analysis study, which started in fiscal year 1985, is the 19th in the program.

The general objectives of the RASA study are to: (1) Describe the hydrogeology of the principal aquifers, (2) define the hydraulics of the principal ground-water flow systems, (3) define the geochemistry of each principal aquifer system and its relation to the mineral components within the geologic framework, (4) describe the original aquifer systems as they existed prior to development and analyze the changes which have led to their present conditions, (5) combine, in a regional analysis, the results of this and previous studies, and (6) provide the capabilities through which the effects of future changes on the ground- water-flow systems can be estimated.

The purpose of this report is to:

(1) Identify and describe the principal aquifers of Puerto Rico and the U.S. Virgin Islands, (2) explain the importance of ground water in meeting the present water-supply needs, (3) define the problems affecting use and development of the ground-water resource, (4) define the objectives and scope of work of the Caribbean Islands RASA effort, (5) outline the general methods that will be used to develop a regional analysis of results, (6) outline the work elements necessary to meet the objectives of this study, and (7) outline the general scheduling of work and allocation of resources.

Area of Study

The study area is located in the Caribbean Region (Gómez-Gómez and Heisel, 1980) and includes Puerto Rico and its outlying islands (Vieques, Culebra, and Mona), and the U.S. Virgin Islands (St. Croix, St. Thomas, and St. John). These lie within latitude 17°41'N, and latitude 18°31'N, and longitude 64°31'W, and longitude 67°57'W (fig. 1). Puerto Rico and its outlying islands have an overall area of 3,472 square miles (mi^2), and the U.S. Virgin Islands have an area of 136 mi^2.

The total population of the islands is 3.29 million (1980) distributed as follows: Puerto Rico, 3,187,593; St. Thomas, 44,372; St. Croix, 49,726; Vieques, 7,662; St. John, 2,472; and Culebra 1,265. Mona Island is maintained as a natural preserve by the Puerto Rico Department of Natural Resources and has no permanent residents. In Puerto Rico approximately 43 percent of the population is concentrated within 15 miles of San Juan and 12 percent within 15 miles of Ponce, the second major urban center outside of the San Juan metropolitan area. In the U.S. Virgin Islands approximately 20 percent of the population lives within the town limits of Charlotte Amalie in St. Thomas and about 4 percent within the town limits of Christiansted, the main urban center in St. Croix.

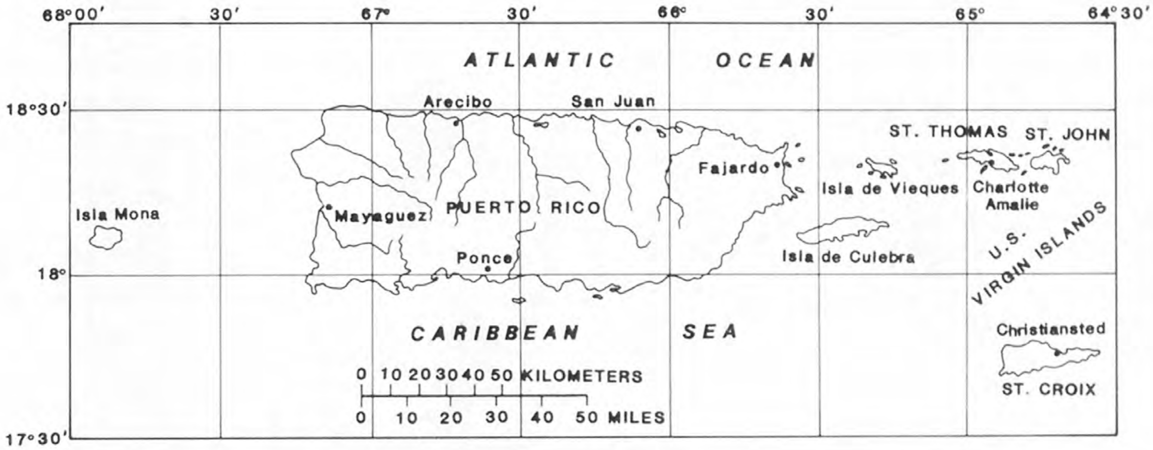


Figure 1.--The Caribbean Islands aquifer-study area.

Hydrologic Setting

Although small in extent, the Caribbean Region has a diverse physical environment. The diversity is caused mostly by the topographic relief and its effect on rainfall distribution more than by any other factor (fig. 2). This is particularly evident on the main island of Puerto Rico where the Cordillera Central mountain chain, which averages 2,800 feet at most peaks with a maximum altitude of 4,400 feet, forms a barrier to the northeast Trade Winds. As a result, most of the south coast lies in a rain shadow averaging less than 45 inches of rainfall per year, while the northern part of the island averages about 80 inches per year. In the smaller islands, the orographic effect is not as pronounced; however, rainfall amounts increase both with altitude and downwind distance from the northeast edge of the islands. As a typical example, in the island of St. Croix, the mean annual precipitation varies from a low of 35 inches at its eastern end to a maximum of 50 inches at 1,000 feet altitude.

Even though the mean annual rainfall in all islands seems high compared to that of temperate climates, much of the rain occurs in short intense showers and is lost to evapotranspiration. Of the 75 inches of rain that Puerto Rico receives in an average year, 45 inches are lost to evapotranspiration, 27 inches are accounted as streamflow, and about 3 inches is ground-water discharge. On the smaller islands, conditions may be similar to results of studies made in St. Thomas, which indicate that of the mean annual rainfall, about 90 percent is lost to evapotranspiration, 5 percent results in streamflow, mostly as storm runoff, and 5 percent may be ground-water recharge.

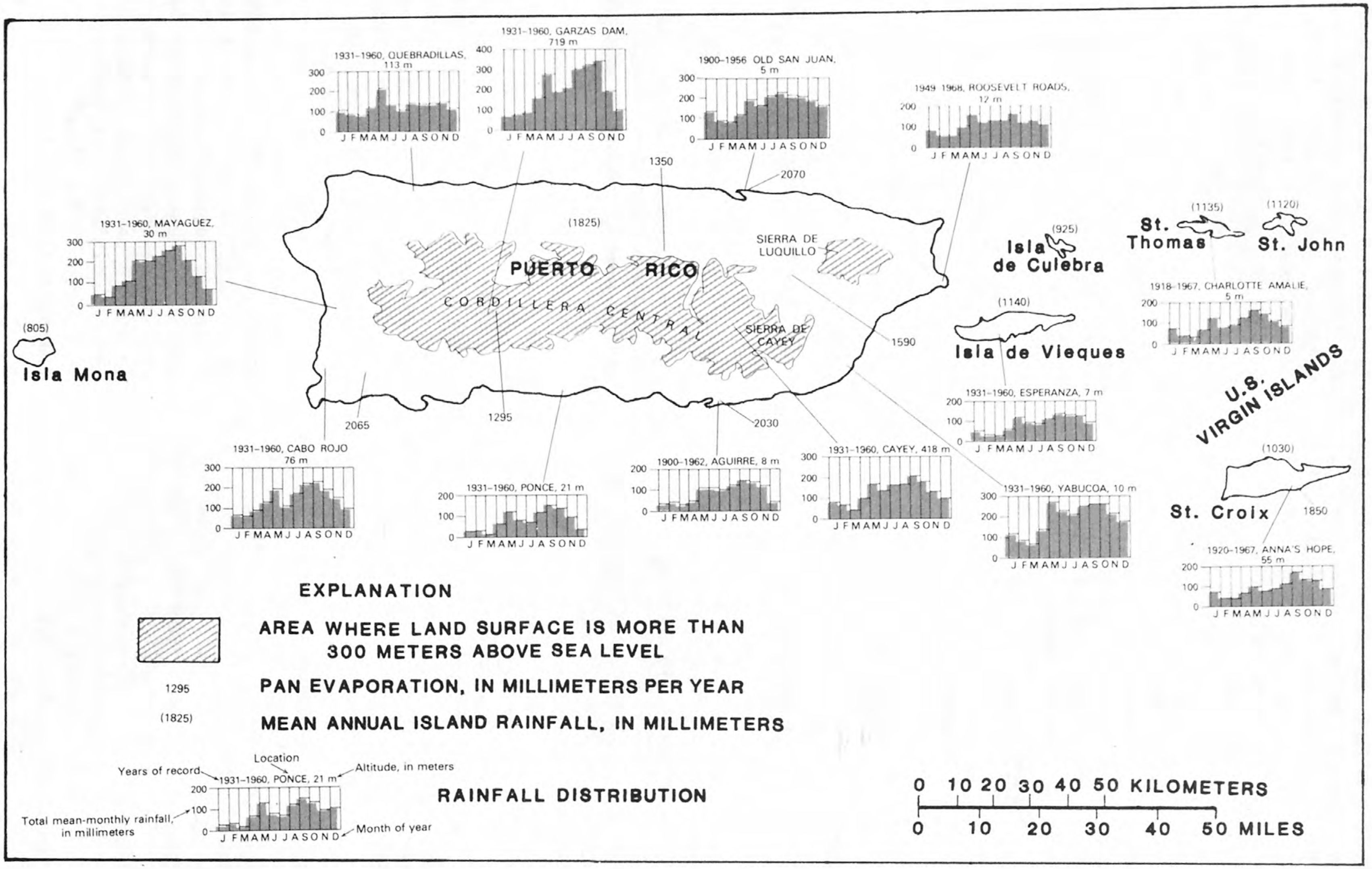


Figure 2.--Rainfall distribution and pan evaporation in the Caribbean Region.

GEOLOGY

The following generalized description of the geology is a summary of more detailed reports compiled by Bogart and others (1964) for Puerto Rico, and by Jordan and Cosner (1973) and Jordan (1975) for the U.S. Virgin Islands. Geologic reconnaissance studies for most of the study area have been prepared by a number of scientists; Meyerhoff (1933); Zapp and others (1948); Cederstrom (1950); Mattson (1960); Briggs (1961); Donnelly (1966); Glover (1971); and Monroe (1980).

The central core of Puerto Rico consists primarily of volcanic and intrusive rocks of Late Cretaceous and early Tertiary age (Plate 1). The volcanic rocks are predominately ashy shale, agglomerate, and tuff, and most of them are thoroughly indurated. These rocks are interbedded with thick, dense lava flows and relatively thin beds of limestone which have been partly recrystallized in many places. The volcanic rocks and interbedded limestone have been complexly faulted, folded, metamorphosed, and intruded by dioritic rocks. The massive, dense dioritic intrusions are exposed by erosion in two large areas and in many small areas on the island. Massive, dense serpentinite and associated silicified rocks underlie large areas in the southwestern part of the island. In the south-central and southwestern parts of the island, the central core extends to the Caribbean Sea and includes rocks of middle Tertiary age resting unconformably on the older rocks and in most places faulted against them. The younger rocks consist of conglomerate, sand, clay, chalk, and limestone.

The central core is flanked on the north and south by clastic sediments and limestones of Oligocene and Miocene age. The older clastic sediments are composed predominately of poorly sorted mixtures of gravel, sand, and finer materials. They grade upward into thick beds of relatively pure limestone. Along the north coast, the limestone has been subjected to extensive solutional activity which has resulted in the formation of a mature karst topography.

Unconsolidated deposits of Pleistocene and Holocene age form a discontinuous coastal plain. The sediments throughout most parts of the north and northeast consist mostly of carbonaceous sandy clay and muck, except at the main stream valleys where these grade inland to a alluvium; at the west coast stream valleys, the deposits are derived from weathered tuff and shale and consist mostly of clay and silt; alluvium deposited at the south and southeast coasts is rich in coarse-grained sand and gravel except near the shoreline where it grades into swamp deposits.

After the deposition of limestone during middle Tertiary time, Puerto Rico was separated from the other major Antillean Islands by block faulting and was arched, uplifted, and tilted to the northeast. The islands of Vieques, Culebra, St. Thomas and St. John are part of the Puerto Rican block, and they are separated from Puerto Rico simply because of the drowning that resulted from the tilting.

Vieques Island is underlain in the eastern half by volcanic rocks of Cretaceous age and the western half by an extensive dioritic rock intrusion (Plate 1). Limestones of Miocene age fringe the south coast and the extreme eastern end, and thin deposits of alluvium form a relatively extensive plain on the southwest.

GEOLOGY

Culebra Island is underlain by volcanic and intrusive rocks of Cretaceous age, and andesite lava and tuff predominate (Plate 1). In the north central part, these have been intruded by diorite. Alluvial deposits are predominately composed of silt and clay, but in the major ephemeral stream courses near the coast they contain some sand and gravel.

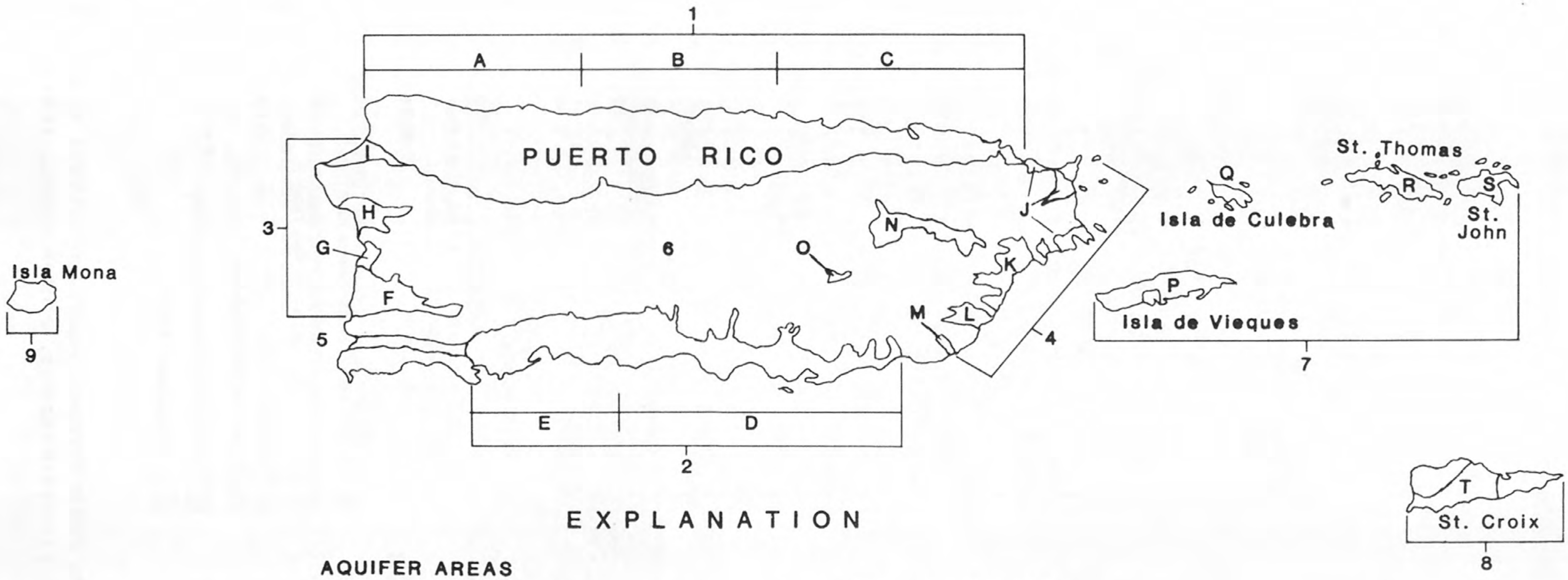
St. Thomas and St. John are underlain by indurated volcanic rock and marine sedimentary rock derived primarily from material eroded from the volcanic core; all these rocks are of Cretaceous age (Plate 2). The only non-volcanic rock is a thin bed of siliceous limestone of Cretaceous age present on both islands. Alluvial deposits are present in the major ephemeral stream courses near the coast and interfinger with beach sand in the coastal embayments.

St. Croix Island is underlain by tuffaceous sandstone, tuffaceous sandstone-mudstone, calcareous mudstone, and siltstone of Late Cretaceous age (Plate 2). These rocks were intruded by crystallized rocks of Late Cretaceous and early Tertiary age and lifted above the sea to form two islands separated by a trough. The trough was later filled with eroded material and mixed with calcareous mud and shallow reef deposits of late Oligocene age. These deposits, in turn are overlain by reef and lagoonal limestone, calcareous mud, and material eroded from the volcanic rocks and deposited in a shallow marine environment in late Oligocene and early Miocene time.

Mona Island is a limestone tableland (Plate 1), bounded by steep to vertical cliffs which rise 200 feet above sea level. Except for a thin soil cover, the entire island consists of limestone and dolomite. Two major units have been identified, these are from oldest to youngest: the Isla de Mona Dolomite, of early or middle Miocene age, and the Lirio Limestone, of Miocene age (Kaye, 1959). A narrow, low-lying coastal terrace exists along its southern perimeter formed by an elevated reef of Pleistocene age with a thin cover of sand.

HYDROGEOLOGY

For the purpose of this report the Caribbean Region has been divided into nine main aquifer areas--six comprising the island of Puerto Rico and three comprising the other island groups (fig. 3). The Puerto Rico areas, which essentially follow the classification of McGuinness (1948), are: (1) North Coast Province, (2) South Coast Province, (3) West Coast Province, (4) East Coast Province, (5) Lajas Valley, and (6) Interior Province. The remaining island areas were divided as follows because of distinct geologic and physiographic similarities: (7) Vieques, Culebra, St. Thomas, and St. John Islands, (8) St. Croix Island, and (9) Mona island.



EXPLANATION

AQUIFER AREAS

1. North Coast Province
2. South Coast Province
3. West Coast Province
4. East Coast Province
5. Lajas Valley
6. Interior Province
7. Vieques, Culebra, St. Thomas, and St. John Islands
8. St. Croix
9. Isla Mona

SUBAREAS

1 A. West Coast to Río Grande de Arecibo
B. Río Grande de Arecibo to Río de la Plata
C. Río de la Plata to Rio Espíritu Santo
D. Patillas to Ponce
2 E. Tallaboa-Guayanilla-Yauco-Guánica
F. Río Guanajibo Valley
G. Río Yaguez Valley
3 H. Río Grande de Añasco Valley
I. Río Culebrinas Valley
J. Fajardo
K. Naguabo-Humacao
4 L. Yabucoa
M. Maunabo
5 Lajas Valley
6 N. Caguas-Juncos Valley
O. Cayey Valley
P. Isla de Vieques
Q. Isla de Culebra
7 R. St. Thomas Island
S. St. John Island
8 T. Kingshill
9 Mona

Figure 3.--Aquifer areas and subareas in the Caribbean Region.

HYDROGEOLOGY

North Coast Province

The North Coast Province covers about one-fifth of Puerto Rico, about 700 mi^2. It is composed primarily of Tertiary limestone and clastic beds extending from the west coast to the vicinity of San Juan, and a coastal plain extending from Río Grande de Arecibo to the Río Espíritu Santo east of San Juan.

The Tertiary rocks have been subdivided into four principal stratigraphic units from youngest to oldest, the Camuy Formation, the Aymamón Limestone, the Aguada Limestone, and the Río Guatemala Group (Zapp and others, 1948). The latter consists of an intertonguing, lenticular sequence of limestone, sand, gravel, and clay. Subsequently , the Río Guatemala Group has been subdivided further into the Cibao Formation, Lares Limestone, Mucarabones Sand, and San Sebastian Formation (fig. 4).

Fresh ground water is contained within two main aquifers--an unconfined aquifer occurring within the Aymamón and Aguada Limestones, as well as the outcrop areas of the Cibao Formation, Mucarabones Sand, and Lares Limestone; and a confined aquifer(s) within the limestone members (bioherms) of the Cibao Formation and the Lares Limestone. Most of the Camuy Formation lies above the water table or has been eroded near the coast. The geologic unit immediately overlying volcanic bedrock consists of sedimentary rocks of Tertiary age, the principal unit being the San Sebastian Formation. It includes clastic strata of clay, sand, gravel and locally of very sandy limestone (Monroe, 1980).

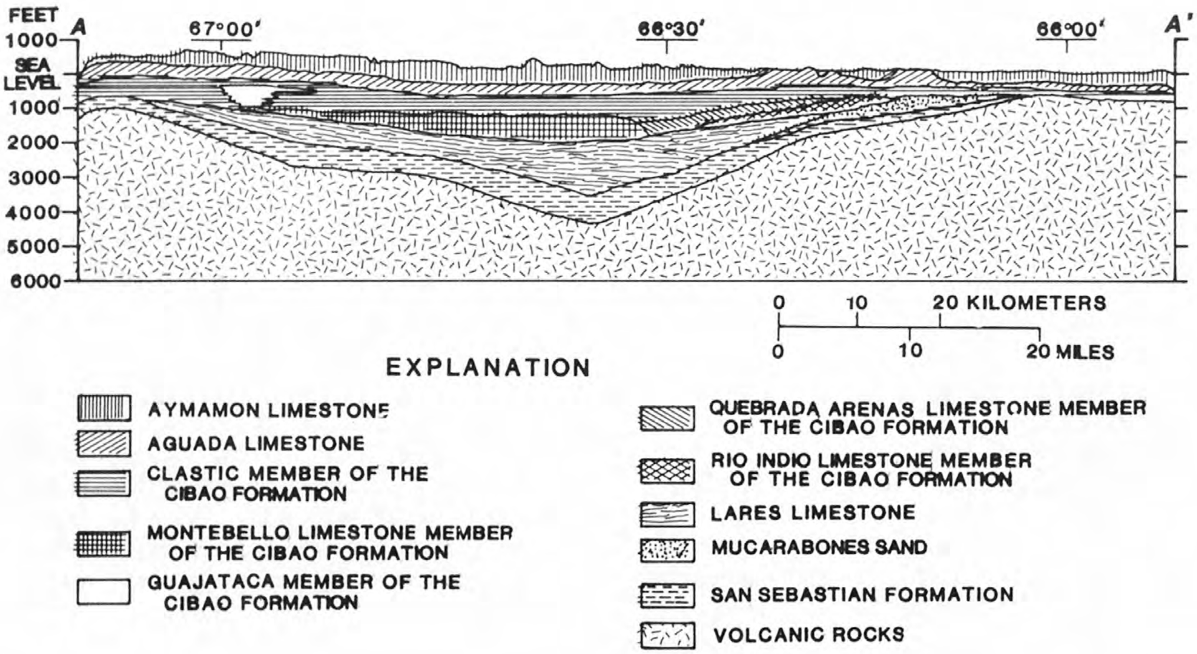


Figure 4.--Hydrogeologic section of North Coast Province aquifer at latitude 18°27'12". (Line of section shown on Plate 1. (Torres-González, written comm., 1985))

HYDROGEOLOGY

North Coast Province - Continued

The limestones and clastic units in the North Coast Province have not been subjected to faulting or deformation since deposition. All the units are exposed in their outcrop areas and have a northerly dip of about 5 degrees with an orientation slightly east of north of about 47 minutes (Giusti, 1976, p.4). The hydrogeologic properties of these carbonate rocks vary greatly as a result of: (a) the tectonic vertical displacement of the islands' platform, eustatic sea level changes, and evolution of north-flowing streams during deposition of the limestone units, and (b) the development of drainage features resulting from solution by rainfall and erosion processes.

Because of the large variation of the hydrogeologic properties, the North Coast Province has been divided into three sub-areas (Gómez-Gómez and Heisel, 1980): (1) West Coast to Río Grande de Arecibo, (2) Río Grande de Arecibo to Río de la Plata and, (3) Río de la Plata to Río Espíritu Santo.

West Coast to Río Grande de Arecibo: This subarea is a limestone tableland characterized by cliffs rising 150 ft above sea level along much of the coast, resulting in a lack of a coastal plain. Ground water exists under unconfined conditions within all the limestone units. Water-table elevations vary from sea level to as much as 900 ft above sea level within the Lares Limestone at a distance about 10 mi from the shoreline. West of Río Guajataca, the maximum water-table altitude is 500 ft within the Cibao Formation and is possibly controlled by Lago Guajataca reservoir which has its spillway at 646 ft. It is unknown if the Montebello or Guajataca Limestone Members of the Cibao Formation contain water under confined conditions; Throughout this area, however, further east in the vicinity of Arecibo, the Montebello Limestone Member is known to contain water under confined conditions.

Hydraulic characteristics of the aquifers are poorly known because very few wells exist within this area. Most of the few existing wells tap the water-table aquifer in the Aymamón or Aguada Limestones and have yields ranging between 50 to 100 gal/min. This quantity represents at least one order of magnitude below typical rates known elsewhere in the North Coast Province. The Aymamón Limestone is generally the most permeable unit containing the North Coast Province water-table aquifer, but in a test hole near Quebradillas, the Aymamón Limestone contained clay within solution cavities throughout most of its saturated thickness (Jordan, 1967). This condition and the hydraulic gradient in the Aymamón part of the water-table aquifer which is approximately one order of magnitude greater than is typically found (.005 versus 0.0007 ft/ft), suggest that the water-table aquifer in this area - may be less permeable.

West Coast to Río Grande de Arecibo – Continued

Recharge to the aquifer occurs from rainfall and possibly from seepage from Lago Guajataca reservoir which was constructed in 1928. Ground-water discharge occurs as spring flow from various springs located along the south-facing escarpment and along the main rivers and offshore, and as as seepage to streams and the seabed. Ground-water development in the area is estimated at less than 5 million gallons per day (Mgal/d).

Río Grande de Arecibo to Río de la Plata: Ground water in this area exists under water-table conditions in the limestone rocks, alluvial valleys, and coastal-plain deposits. An artesian aquifer exists within the Montebello Limestone Member of the Cibao Formation (fig. 5). The artesian zone was discovered in 1968 when wells were drilled through this unit in the vicinity of Barceloneta. At this site, initial heads of 450 ft above sea level were obtained suggesting the existence of leakage through the confining bed and a head loss of about 45 ft per mi, (Giusti, 1976).

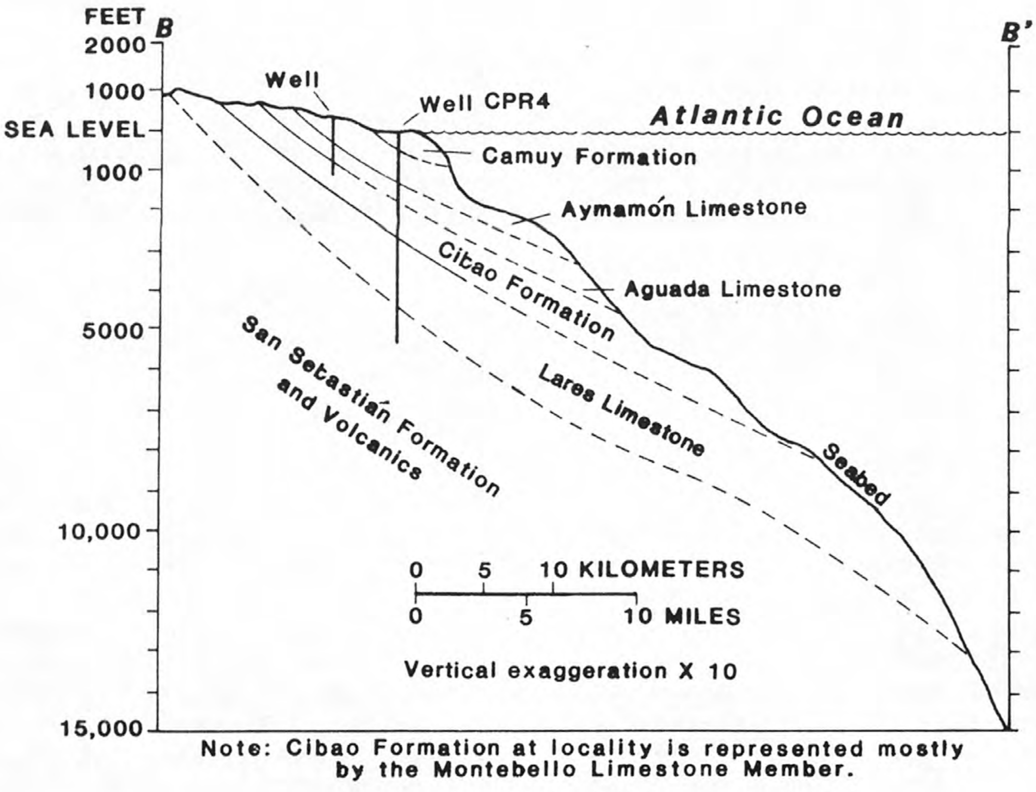


Figure 5.--Hydrogeologic section of North Coast Province showing the extent of the Montebello Limestone Member of the Cibao Formation and dip of units at longitude 66°37'30". (Line of section shown on Plate 1.)

Since 1968, numerous wells have been drilled in the vicinity of Barceloneta and heads in the vicinity of Barceloneta have declined to about 300 ft above sea level. It is unknown whether the Montebello Limestone is in direct hydraulic contact with the underlying Lares Limestone or with the bioherms to the east and west of this unit. Near the eastern part of the area the Cibao Formation is represented by other lithologic units in which artesian conditions have not been reported and only a water-table aquifer is known to exist (fig. 6).

The water-table aquifer within the Aymamón and Aguada Limestones is the most productive aquifer in this subarea. It contains a lens of freshwater overlying saltwater. At about lat 18°26' (3 miles from the coastline), the freshwater lens is approximately 250 ft thick and thins toward the coast (fig. 6). Throughout most of the area, the Aymamón Limestone has been subjected to a high degree of development of solution cavities and locally is cavernous. This is a result of the lithologic nature of the Aymamón which consists of very pure limestone with abundant molds of mollusks and almost no sand or clay. The lack of clastic sediments indicates that no large rivers were carrying sediment from the upland of Puerto Rico to the Atlantic at the time of deposition of the Aymamón Limestone (Monroe, 1980). The Aguada Limestone is less homogeneous, varying from an indurated, relatively pure limestone in the upper part, similar to the Aymamón, to a thick-bedded calcarenite. Locally, the Aguada contains beds of clastic deposits several feet thick. This regional variation is a result of its depositional environment, a fringing reef on a slowly subsiding coastal shelf affected locally by streams.

Further inland, the water-table aquifer exists within the Cibao Formation and the Lares Limestone. In general, these formations have not developed the porosity as that of the Aymamón or Aguada Limestone.

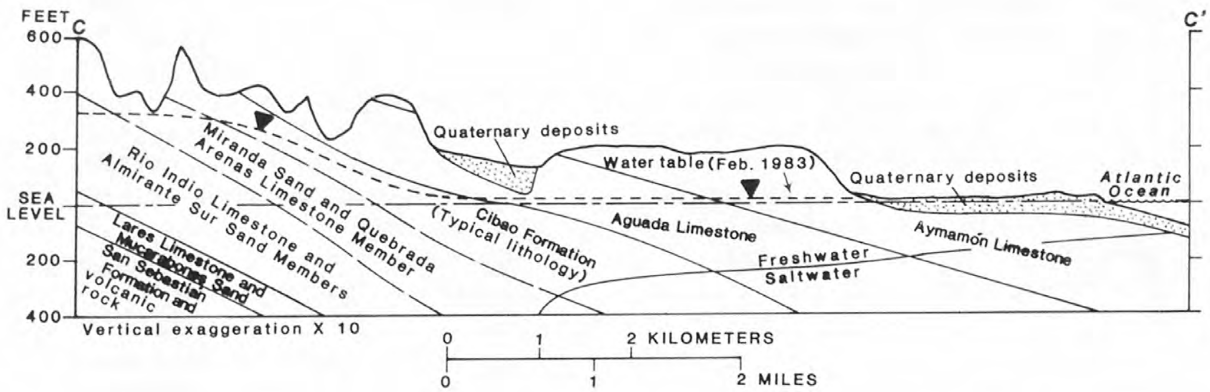


Figure 6.--Hydrogeologic section at Vega Alta area showing coastal-plain surficial deposits and fresh-to-saltwater transition zone. (Line of section shown on Plate 1.)

HYDROGEOLOGY

Río Grande de Arecibo to Río de la Plata – Continued

The Cibao Formation has the most diverse lithology. In this subarea the Cibao is represented by unnamed members of typical calcareous clay or earthy limestone (referred to as the typical lithology by Monroe, 1980), and also the Miranda Sand Member, Quebrada Arenas Limestone Member, Almirante Sur Sand Lentil, Río Indio Limestone Member, and the Montebello Limestone Member. Monroe (1980) described the lithologic characteristics of the members thusly:

> The Miranda Sand Member consists of alluvium deposited near the coast by streams and in ancient river channels cut in the Quebrada Arenas Limestone Member. It varies from coarse sand and silty clay in a noncalcareous matrix, to sandy limestone interbedded with loose sand, and to clayey quartz sand with pebbles and cobbles of quartz and volcanic rock.
>
> The Quebrada Arenas Limestone Member is considered to be an eastward extending tongue of the Montebello Limestone Member. Its greatest thickness is about 200 ft near lat 66°20' (at Vega Alta, fig. 6). In its outcrop, this unit is characterized by numerous sink-holes. Stratigraphically, the unit consists of yellow calcareous clay, locally containing sandstone in a matrix of orange chalky clay, and underlain by hard limestone containing many coral heads.
>
> The Almirante Sur Sand Lentil consists of a locally significant lentil of sand and sandstone, containing pebbly fossiliferous-calcareous sand and glauconitic, slightly sandy calcarenite, within the Río Indio Limestone Member. This unit is exposed in the valley of Río Indio and possibly merges downdip with the Río Indio Limestone Member at about lat 18°23', since it has not been reported in wells north of this latitude. This unit is as much as 130 ft thick and possibly as much as 3 miles wide.
>
> The Río Indio Limestone Member consists of a yellowish-orange limestone and calcarenite interbedded with thin units of chalky limestone. In nearly all outcrops, the basal part contains limestone that is very fragmental, resembling a breccia, and locally layers of large oysters are common. The upper part of the unit is overlain by clayey deposits where overlain by the Quebrada Arenas Limestone Member, and by a coquinoid limestone where overlain by the Almirante Sur Sand Member.

The Montebello Limestone Member is the most extensive limestone unit of the Cibao Formation. It consists of a very pure calcium carbonate, which has been recrystallized into a hard, white, chalky limestone in the upper part. Above its contact with the underlying Lares Limestone, the unit is a weakly indurated, medium to coarse-grained calcarenite which is composed in part of shell fragments. This bed of oyster shells forms a convenient marker between the formations, and is generally from 3 to 15 ft thick. Locally, the calcarenite exists in cross-bedded layers alternating with thin-bedded layers. To the east and west, the Montebello thins rapidly by intertonguing and lateral gradation into soft, chalky limestone and calcareous clay. Its greatest thickness occurs at about longitude 66°35', where it is about 650 ft thick.

The Lares Limestone consists mainly of indurated, very pale orange, fine-to-medium grained calcarenite in stratified beds as much as 3 ft thick. However, significant variation occurs--the upper part (about 500 ft) consists of fine-grained crystalline limestone, and in the basal part (100 to 150 ft) it is thin bedded to flaky limestone with fine to medium grains of limonitic rock which may be derived from fragments of volcanic debris. Locally the limestone is massive and thick-bedded. In such areas extensive cone karst has developed within its outcrop. Cone karst is characterized by many steep-sided cone-shaped hills surrounded by depressions. Where it is thin bedded, the zanjón karst feature predominates. Zanjón karst is a solutional trench ranging from a few inches to several feet in width, as much as 12 ft deep and may extend from several feet to more than 3,000 ft in length.

As has occurred in the western area of the North Coast Province, ground-water flow in this area has been significantly changed from its pre-development conditions. The most significant change to the hydrology has been the dewatering of coastal wetlands particularly the Caño Tiburones, between Río Grande de Arecibo and Río Grande de Manatí, and the construction of a drainage channel connecting Laguna Tortuguero with the Atlantic Ocean. At Caño Tiburones water levels were lowered from about sea level in 1930 to 7 ft below sea level (1980) through construction of extensive drainage canals and pumpage to the sea. At Laguna Tortuguero the ocean outlet lowered the water level in this relatively freshwater lagoon, from about 5 ft (1940) to 3 ft above sea level at present (1985). The large scale effect of these changes on the flow system have never been assessed. In addition, ground-water withdrawals have increased from 10 Mgal/d in the early 1940's to an estimated 60 Mgal/d in 1985, within the water--table part of the limestone aquifer. Since 1968, about 15 wells have been drilled into the confined part of the limestone aquifer mostly within the Montebello Limestone Member. Withdrawals from this artesian zone are estimated at 6 Mgal/d (Torres-González, written comun., 1984). Withdrawals by wells situated within the alluvial valleys are estimated at 8 Mgal/d.

HYDROGEOLOGY

Río Grande de Arecibo to Río de la Plata - Continued

The large scale modifications of ground-water flow within this area make it difficult to establish the regional flow regime prior to these changes. In general, it is known that recharge occurs throughout the entire outcrop areas of the limestones and at topographic depressions throughout the blanket deposits. However, information is not available to assess whether or not the coastal plain wetlands originally recharged the aquifer. Also, the effect of streams and thick alluvial deposits on the flow system has not been adequately defined. The regional impact of all these changes is particularly evident in the lowering of the water table in the Montebello Limestone Member and Lares Limestone between Río Grande de Arecibo and Río Grande de Manatí. The potentiometric surface in this area in 1968 was between 500 and 650 ft (Giusti, 1976) and is between 300 and 650 ft today (Torres-González, written commun., 1985). The apparent 200-foot water-level decline is caused by wells drilled into the Montebello Limestone Member. The aquifer within the Montebello has been intensively developed for industrial water supply near the coast and for public-water supply further inland.

Río de la Plata to Río Espíritu Santo: Ground water in this area exists under water-table conditions within the coastal-plain surficial deposits and alluvial stream valleys, the Aguada Limestone, the Cibao Formation, and the Mucarabones Sand. The basal part of the Cibao Formation (or possibly the basal part of the Aguada Limestone) together with the Mucarabones Sand contain water under confined conditions between Río de Bayamón and Río Piedras (Anderson, 1976). In this area the Aymamón Limestone contains mostly saltwater because of its proximity to the sea (fig. 7).

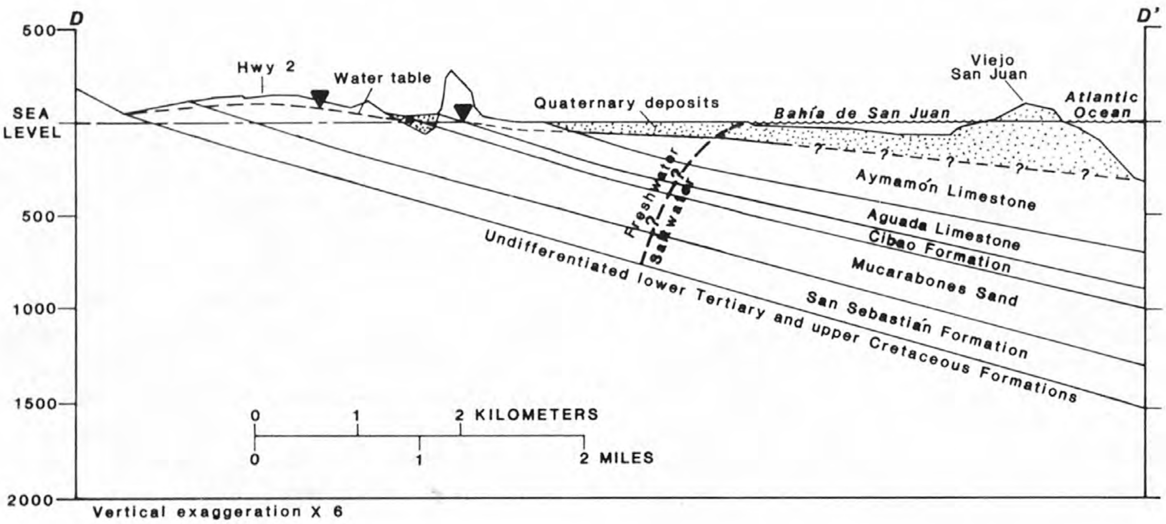


Figure 7.--Hydrogeologic section of San Juan metropolitan area. (Line of section shown on Plate 1.)

Alluvium, terrace deposits, blanket sand, beach, and dune deposits mantle the Aymamón and Aguada Limestones throughout most of the subarea. Thickness of these deposits varies from a maximum of 300 ft within the major stream valleys to about 100 ft or less elsewhere. The Aguada Limestone in this area is similar in lithology to other areas to the west, with the only exception that sand and clay become more common in the formation towards the east. The Cibao Formation in this area consists principally of limestone, sand, and clay. It intertongues and grades laterally eastward with the Mucarabones Sand to slightly west of Río de Bayamón. Similarly, the Aguada Limestone intertongues with chalky beds of the Cibao and becomes indistinguishable from it about half a mile east of Río de la Plata. The Mucarabones Sand consists principally of crossbedded grayish-orange to a yellow fine to medium sand. Near the base of the formation, the sand is coarser and contains gravel and lenses of greenish-gray sandy clay. It extends from the vicinity of Río Grande de Manatí to San Juan, but its greatest thickness is between Río de la Plata and Río de Bayamón where it averages 300 ft.

The Cibao Formation is the principal water-bearing unit in this area, not because of its yield to wells, but because it is the thickest unit containing freshwater (about 200 ft). Coastal surficial deposits are locally important as a source of freshwater mainly at areas east of Río Grande de Loíza. However, freshwater not more than 100 ft thick floats above saltwater as a thin lens, which limits development to domestic supplies. Few wells tap the Mucarabones Sand exclusively, therefore its potential as a water supply is incompletely known.

The ground-water resources of this subarea were among the first to be developed in the North Coast Province, but at present their use is minimal due to widespread saltwater intrusion. Most wells have been abandoned or destroyed except in the western part of the area where saltwater intrusion has been contained by a reduction of ground-water withdrawals. Little remains of the natural ground-water flow regime due to urbanization and destruction of wells open to both the unconfined and confined aquifers. Overall ground-water withdrawals are estimated at less than 10 Mgal/d.

South Coast Province

The South Coast Province covers an area of 230 mi^2. It consists primarily of alluvial and terrace deposits, forming a continuous coastal plain from Patillas to Ponce, and of alluvial stream valleys cut into Tertiary limestones from Ponce to Guánica (Plate 1). This province has been divided into two areas corresponding to the above physiographic differences which are referred to as: the Patillas to Ponce area and the Tallaboa-Guayanilla-Yauco-Guánica area shown in figure 3 (Gómez-Gómez and Heisel, 1980).

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Patillas to Ponce Area: This area extends for approximately 40 mi and averages 3 mi in width. The plain consists of a series of coalescing alluvial fans formed by fast flowing intermittent streams which originate at altitudes above 1,000 ft within 15 mi of the Caribbean Sea. The coastal plain sediments below an altitude of about 150 to 100 ft are of Holocene age. Above this altitude and extending to the foothills are terrace deposits of Holocene and Pleistocene (?) age. The alluvial deposits contain a higher proportion of sand and gravel at the apex of the major fans and become finer grained towards the coast and in the interfluvial areas.

Bedrock consists principally of sedimentary rocks of Tertiary age throughout most of the coastal plain west of Salinas and volcanic rocks of Cretaceous age in the area east of Salinas. The Tertiary rocks from youngest to oldest are the Ponce Limestone and the Juana Díaz Formation (fig. 8). The Ponce Limestone is recrystallized reef limestone that is relatively pure and very resistent to erosion. The Juana Díaz Formation is not as uniform as the Ponce Limestone. It varies locally as a result of its depositional environment much as it exists today (1985) along the south coast "a transgressing sea where alluvial-fan material, composed of sand derived from volcanic rocks, and cobbles and boulders of similar rocks, are worked by the waves into somewhat muddy shingle beach deposits, which commonly have fringing coral reefs nearby" (Monroe, 1980, p. 76). East of Salinas, bedrock consists of massive to thick bedded andesite tuff and welded tuff, porphyritic basalt, volcanic breccia, sandstone and siltstone.

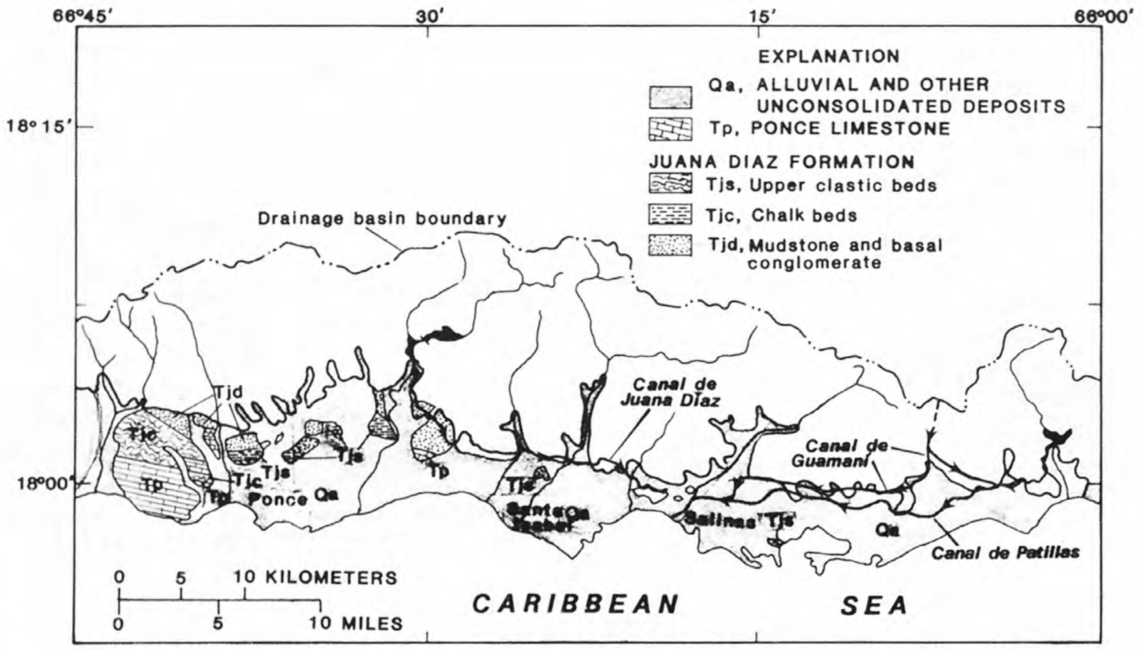

Figure 8.--Surficial geology and principal irrigation canals in the Patillas to Ponce area of the South Coast Province.

Ground water in the area east of Salinas exists under water-table conditions within alluvial deposits which are from 100 to 150 ft thick near the shoreline, but can be greater than 200 ft in the overdeepened valleys cut into bedrock (fig. 9). West of Salinas to Ponce, the alluvium ranges from 180 to about 300 ft near the shoreline (fig. 10). However, an oil-test well, drilled near the coast at Santa Isabel is reported to have penetrated as much as 3,000 ft of unconsolidated deposits (Glover, 1976). Within these relatively thick unconsolidated deposits, the freshwater part of the aquifer should exist as a lens floating over saltwater. Its thickness at the shoreline is unknown throughout most of the area.

The source of recharge to the aquifer prior to development in the early part of this century was from streamflow seepage and rainfall infiltration through the alluvial and terrace deposits; discharge was to near shore and offshore springs, seepage to the seabed and lower segments of stream channels, and evapotranspiration from the shallow water table near the coast. At present the entire ground water flow system has been considerably modified. Recharge has been augmented by the irrigation canal network (see fig. 8); and discharge occurs mainly through ground-water withdrawals (Bennett, 1976). In 1980, irrigation deliveries from the canal network were approximately 65 Mgal/d (possibly 30 percent of which recharged to the aquifer). Ground-water withdrawals may have been as much as 115 Mgal/d.

Tallaboa- Guayanilla-Yauco-Guánica Area: The main aquifer in this subarea is the alluvium deposited within the stream valleys. The alluvium is principally coarse-grained sand and gravel which grades seaward to fine sand, silt, clay and swamp deposits. Streamflow in all valleys, except at Guayanilla, is regulated by reservoirs supplied mostly from streams north of the drainage divide of the valleys. Bedrock in these valleys consists of Ponce Limestone in the lower part and the Juana Díaz Formation in the upper part. The bedrock contains water in outcrop areas but generally is not considered an aquifer due to the low yield of wells and high dissolved-solids content of ground water. Beneath the valley alluvium the Ponce Limestone has developed secondary porosity, and several wells tap this unit as well as the alluvium.

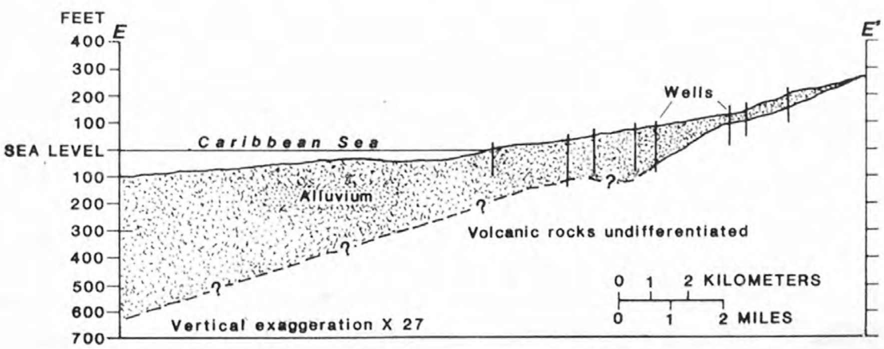

Figure 9.--Hydrogeologic section showing thickness of alluvial deposits at the Salinas area of the South Coast Province. (Line of section shown on Plate 1.)

Tallaboa-Guayanilla-Yauco-Guánica Area: - Continued

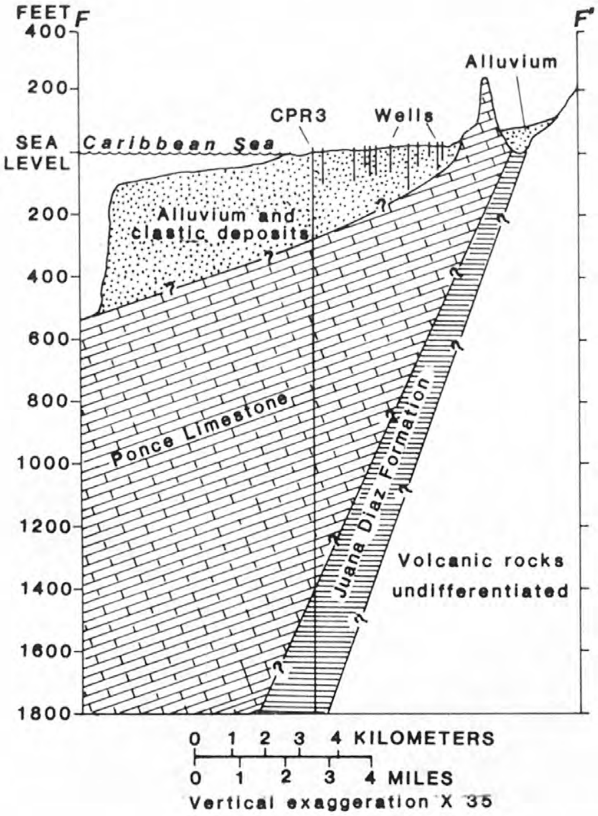

Figure 10.--Hydrogeologic section showing thickness of alluvial and clastic deposits and underlying carbonate rocks in the vicinity of Ponce in the South Coast Province. (Line of section shown on Plate 1.)

Ground water exists under water-table conditions within the alluvial deposits and upper part of the Ponce Limestone. Near the coast freshwater floats above saltwater as a lens, but its thickness is unknown. Both the thickness of the alluvium and its areal extent across the valley vary locally, but in general these increase seaward (fig. 11). Recharge to the aquifer is derived from streamflow, areal application of water for irrigation and occasionally runoff from the bordering slopes. Discharge occurs through ground-water withdrawals at wells, seepage to streams, and evapotranspiration within the nearshore part of the aquifer where the water table is near land surface, and to a lesser extent as subsurface seepage to the seabed. The hydrologic system in these areas has been so greatly modified that the relative importance of any aquifer recharge or discharge process could vary- significantly from year to year. For example, ground-water withdrawals were estimated at about 40 Mgal/d in the early 1970's, but have diminished to about 20 Mgal/d at present (1985) as a result of a complete shutdown of the petrochemical complex in the Tallaboa-Guayanilla area and the sugarcane mill at Guánica.

West Coast Province

Four alluvial valleys form the principal aquifers of the West Coast Province--Río Guanajibo valley (13 mi^2), Río Yaguez valley (2 mi^2), Río Grande de Añasco valley (15 mi^2) and the Río Culebrinas valley (4 mi^2).

Río Guanajibo valley deposits consist of detrital clay, silt, sand, and gravel locally underlain by one or more beds of limestone (limestone units have not been correlated to exposures, fig. 12). Thickness of alluvial and clastic deposits is as much as 100 ft. The thickness of the limestone beneath the alluvium is unknown. Bedrock consists of volcanic and sedimentary rocks of Cretaceous age, predominately basaltic andesite and mudstone indicated by information of wells drilled into the bedrock (Colon-Dieppa, and Quiñones-Márquez, 1984).

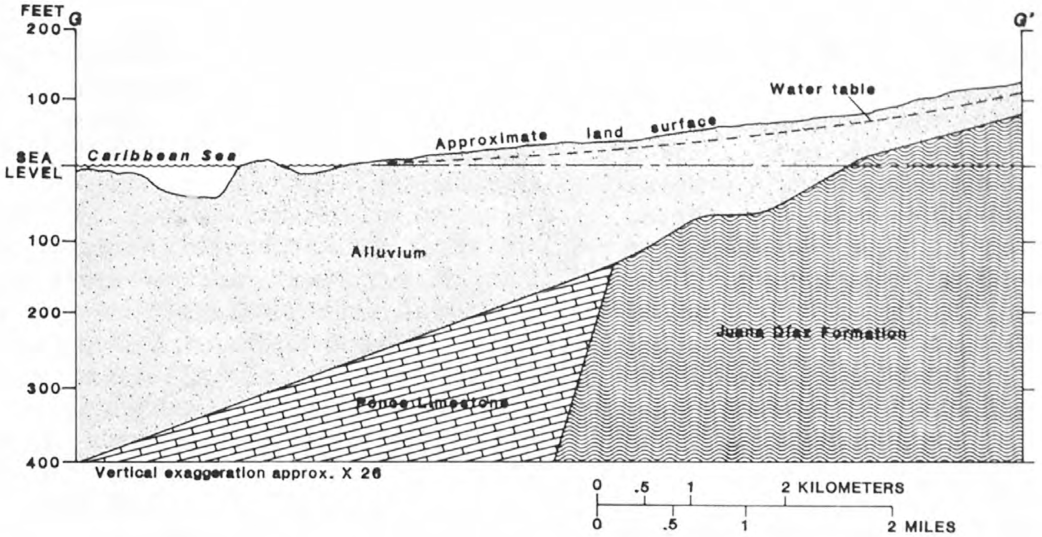

Figure 11.--Cross section showing thickness of alluvial deposits at Río Tallaboa valley in the South Coast Province. (Line of section shown on Plate 1.)

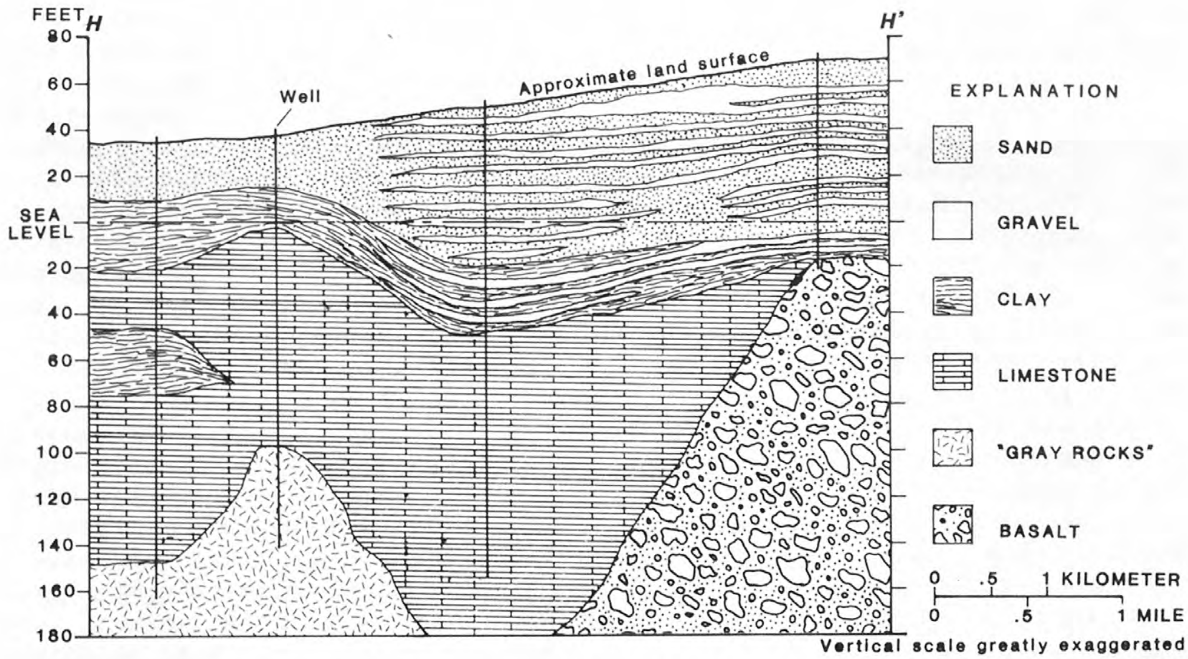

Figure 12.--Hydrogeologic section at Río Guanajibo valley in the West Coast Province. (Line of section shown on Plate 1.)

West Coast Province - Continued

In the Río Yaguez valley, alluvium is the principal aquifer and has a maximum known thickness of 200 ft (Bogart and others, 1964). The alluvial deposits are underlain by alternating layers of clastic sediments and limestone. At the Río Grande de Añasco valley alluvium is as much as 450 ft thick and consists predominately of clay strata interbedded with beds of sand and limestone. No information is available on the Río Culebrinas valley, but the alluvial aquifer is probably similar to that of the Río Grande de Añasco.

Ground-water flow in these stream-valley aquifers under predevelopment conditions should be similar to that at the Río Grande de Añasco (Díaz, U.S. Geological Survey written commun., 1984). Recharge occurs principally from rainfall infiltration, and discharge occurs mostly as seepage to the streambed. At present, extensive drainage works in the Río Guanajibo, Río Grande de Añasco, and Río Culebrinas valley have alleviated water logging problems, but during most of the year the water table remains high due to the high rainfall (fig. 2). In the Río Yaguez valley urbanization has approximately covered the entire area and the use of the alluvial aquifer has been abandoned. The only area where ground-water withdrawal is significant is in Río Guanajibo valley, approximately 5 Mgal/d.

East Coast Province

This province consists of the coastal area extending east of Río Grande on the northeast to the Río Maunabo valley on the southeast (fig. 3). Four major areas make up this province: Fajardo (20 mi^2), Naguabo-Humacao (15 mi^2), Yabucoa (12 mi^2), and Maunabo (3 mi^2).

Fajardo Area - It consists of the interrupted narrow coastal plain and small valleys from Punta Picua on the north to Punta Lima on the east coast. Alluvium, the principal aquifer, consists of lenticular beds of clay, sand and gravel, and rock fragments to a depth less than 100 ft. The best water-yielding units are in the upper alluvial fan of Río Fajardo, where inflow may be induced from the river through the predominating gravel and sand deposits. Elsewhere, ground-water development has induced saltwater encroachment and wells have been abandoned.

Naguabo-Humacao Area - It includes the coalescing alluvial deposits in the lower valleys of Ríos Santiago, Blanco, Antón Ruíz, Humacao, and Candelero. Alluvium in most of this subarea consists of fine sand, silt, clay and swamp deposits. In the upper valley of the Río Antón Ruíz, deposits are coarser grained and consist principally of sand and gravel as much as 165 ft thick.

Yabucoa Area - It consists of the Yabucoa valley, which has been incised in the San Lorenzo batholith, a granodiorite intrusive. Alluvium consists largely of clay, but has appreciable amounts of sand. Thickness of these deposits are as much as 300 ft in the center of the valley and average 100 ft in most areas (Robison and others, 1973). However, the bedrock beneath the alluvium has an irregular surface and along most of the coastline it lies within 160 ft of land surface.

Maunabo Area – The main aquifer consists of alluvium as much as 200 ft thick that contains discontinuous lenticular deposits of sand, gravel, and cobbles. Drilling logs show that the lithology varies widely within the valley, some lenses containing more coarse material than others. In general, the coarser material lies within the main axis of the valley along the Río Maunabo.

Ground water in these stream valley aquifers is under unconfined conditions within the unconsolidated deposits. In the Naguabo-Humacao subarea semi-confined conditions have been found at wells drilled into the weathered-rock zone beneath the overlying clastic deposits in the vicinity of the foothills (Graves, U.S. Geological Survey, written commun. 1984). The importance or extent of the weathered-rock ground-water zone in this or adjacent areas is unknown. In general, ground water flows toward the coast. Recharge occurs along the alluvium- bedrock contact from numerous perennial and ephemeral streams and from areal rainfall infiltration throughout the alluvium. Discharge from these aquifers has been significantly modified by ground-water withdrawals in most valleys except in the Fajardo area where changes to the hydrologic system have been minimal. At Fajardo discharge occurs to the lower segment of streams, as evapotranspiration losses near the coast where the water table is shallow, and as subsurface seepage near shore; at Naguabo-Humacao, discharge occurs principally to coastal swamps. At Yabucoa, most discharge occurs as evapotranspiration (Robison and Anders, 1973); at Maunabo discharge occurs principally to Río Maunabo, contributing nearly 50 percent of its annual flow (Adolphson and others, 1977).

Withdrawals from the East Coast Province aquifers are estimated at less than 5 Mgal/d. Most ground-water development has been at Yabucoa.

Lajas Valley

Lajas Valley in southwestern Puerto Rico trends east and west and is bound by ridges to the north and south (fig. 3). The valley floor is approximately 35 mi^2 in area, sloping east and west from a maximum altitude of 45 ft at about long 67°04'00". Unconsolidated deposits consist predominately of silt and clay which interfinger with coarser grained material washed into the valley by ephemeral streams. Thickness of these deposits is as much as 300 ft. Beneath these deposits are one or more limestone beds of undetermined thickness or age. Along the highlands several limestone units have been named, aside from the Ponce Limestone which exists near Guánica at the southeast slopes. Among these are the Cotuí Limestone, Parguera Limestone, and Melones Limestone of Late Cretaceous age (Volckman, 1984).

Various aquifers exist in the valley. The most extensive is a leaky-artesian aquifer within the limestone overlain by the unconsolidated deposits. Recharge to this aquifer system is from rainfall infiltration through coarser grained alluvium along the edges of the valley, runoff from ephemeral streams (especially along the more humid north side) and since about 1955, seepage of surface water diverted into the valley for irrigation. Discharge from this aquifer is towards the west coast, as sub-surface flow to the seabed and as evapotranspiration, and towards the east as seepage to the prior Cienaga el

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Lajas Valley - Continued

Anegado (a marsh) and Laguna de Guánica (a brackish-water lagoon). These wetland areas were dewatered during the 1950's by construction of tile underdrains and drainage canals which discharge at Bahía de Guánica.

Ground-water withdrawals in the valley were estimated at 18 Mgal/d for irrigation during the 1940's. At present (1985) withdrawals are essentially nonexistent as a result of the high dissolved solids of ground water at the abandoned high-yield wells tapping the limestones (5,000 mg/L) and availability of better quality water from the irrigation network supplied by surface water. The only withdrawals are from a semi-confined aquifer in limestone (Cotui ? Limestone) at the northeast slopes of the valley (0.3 Mgal/d), and several low-yield domestic wells drilled in alluvial deposits along the sides of the valley.

Interior Province

The only significant aquifers in this province which is mostly igneous rock, 2 are the Caguas-Juncos and Cayey valleys, which cover an area of about 20 mi^2. In the Caguas-Juncos valley (17 mi^2), alluvial deposits consist of clay, sand, and gravel with a thickness of about 60 ft in the vicinity of Caguas and about 120 ft at Gurabo. In the Cayey valley (3 mi^2), alluvium consists predominately of clay and rock fragments with an average thickness of about 25 ft. In both areas the unconsolidated deposits are important principally in retaining recharge from rainfall which eventually infiltrates the underlying weathered or fractured rocks that yield water to wells (average of about 150 gal/min).

No hydrologic studies have been conducted in these valleys, but it can be inferred from well records (Ward and Truxes, 1964) and by comparison to other areas with similar lithology, that the aquifers are leaky-artesian. Withdrawals from these aquifers is estimated to be less than 5 Mgal/d at Caguas-Juncos valley, and about 0.5 Mgal/d at Cayey valley.

Vieques, Culebra, St. Thomas, and St. John Islands

The only significant aquifer in the outlying islands containing water having a dissolved-solids concentration below 1,000 mg/L is the Esperanza-Resolución area on Vieques island (plate 1). The aquifer exists within alluvial deposits which thicken from a featheredge along the volcanic rock outcrops to an average of about 60 ft. Alluvial deposits consist of fine to coarse sand with clay derived from weathering of the granodiorite intrusive. Near the coast, alluvium deposits interfinger with silt, clay and swamp deposits (Torres, S., U.S. Geological Survey, written commun., 1984).

Ground water is under leaky-artesian conditions near the coast and water-table conditions elsewhere. Near the coast, local confinement occurs only where swamp deposits overlie the alluvium. Recharge to the aquifer occurs during periods of intense rainfall -- as direct infiltration through the alluvial deposits or as infiltration of runoff from the upland areas. Discharge is towards the coast as subsurface seepage to the seabed or as evapotranspiration where the water table is near land surface.

Annual pumpage was estimated to be about 0.5 Mgal/d. However, withdrawals during extended dry periods were reduced either by excessive drawdown in wells or saltwater intrusion. Since 1978, water supply on Vieques is obtained via a pipeline from Puerto Rico.

The principal aquifers in Culebra, St. Thomas, and St. John are the volcanic rocks and coastal embayments. Ground water is under confined and leaky-artesian conditions in fractures or in the weathered-rock mantle. In the coastal embayments ground water exists under water table or also under leaky-artesian conditions at places where the weathered-rock zone is capped by relatively impermeable unconsolidated deposits (fig. 13).

Recharge to the aquifers is derived from percolation of rainfall through the soil zone during periods of intense rainstorms when soil- moisture deficiency is satisfied. Within the embayment aquifers, recharge also includes infiltration of runoff and inflow of ground water from the mountain slopes.

In general, yields of wells tapping the volcanic rocks are less than 1,000 gal/d. At most areas on the mountain slopes, depth to water ranges from 50 to as much as 120 ft below land surface. Within the embayment aquifers yield of wells are an order of magnitude greater and depth to water is less than 50 ft. Withdrawals from the volcanic rock and embayment aquifers is estimated at 350,000 gal/d, mostly from St. Thomas and St. John.

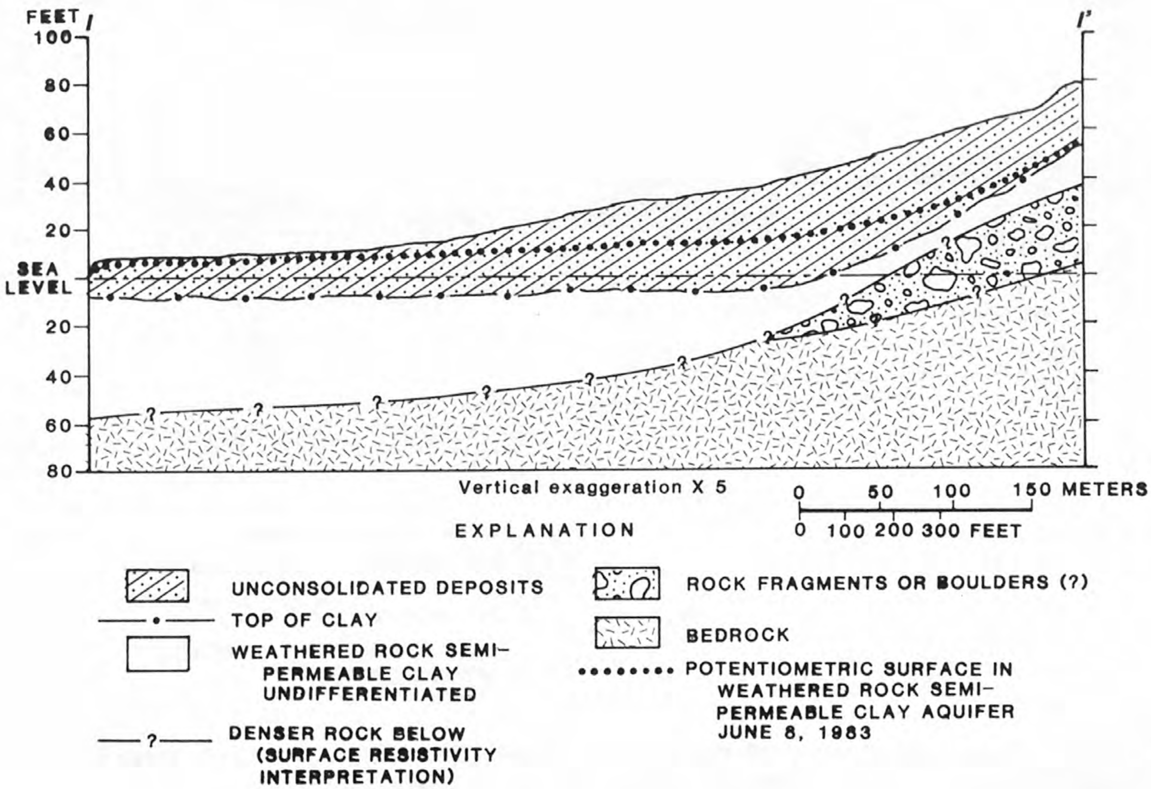


Figure 13.--Hydrogeologic section of a typical embayment aquifer, South Side, St. Thomas Island. (Line of section shown on Plate 2.)

HYDROGEOLOGY

St. Croix

The volcanic-rock and embayment-type aquifers also exist on St. Croix. However, the most important ground-water source is the Kingshill aquifer. The Kingshill aquifer covers an area of about 30 mi^2 in central St. Croix (Plate 2). Alluvial deposits of Holocene and Pleistocene age are associated with filled stream channels cut into the Kingshill Marl of Miocene and Oligocene age which crops out throughout most of the area. Alluvial deposits are generally less than 20 ft thick, but are as much as 100 ft thick along the major stream courses. Alluvial deposits consist of poorly sorted silt, clayey sand, and some gravel. The Kingshill Marl does not have a uniform lithology, varying locally from mostly marl to limestone to sandstone, and does not lie conformably over bedrock. Thickness averages 200 ft, but varies from a maximum of 500 ft to a featheredge along the volcanic-rock outcrops. The Jealousy Formaton forms the bedrock beneath the Kingshill Marl, where it consists of a dark-gray to blue-green clay of indeterminate thickness (fig. 14).

Ground water in the Kingshill aquifer exists under unconfined conditions within the stream alluvial deposits and Kingshill Marl. The water table varies from sea level to a maximum of about 200 ft at the north-south drainage divide, which lies between 1 to 2 mi from the north shore. Maximum saturated thickness is 200 ft; however, large areas exist where the relatively fresh ground water is underlain by water having high dissolved solids whose source is either seawater encroachment or connate water.

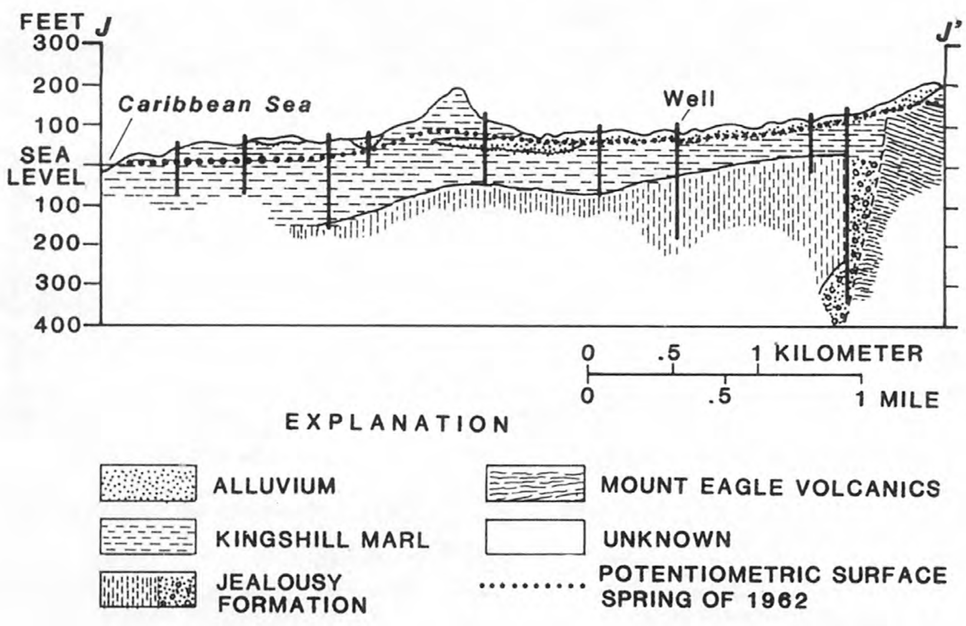


Figure 14.--Hydrogeologic section of Kingshill aquifer, St. Croix Island. (Line of section shown on Plate 2.)

Recharge to the aquifer occurs mainly during the wetter months of the year (May and August to November) from areal rainfall infiltration and seepage from intermittent streams which originate in the volcanic rocks. Discharge occurs as evapotranspiration in the coastal lowlands and withdrawals from wells. Seepage to the seabed could be minimal as a result of increased withdrawals, which have caused a general decline of the water table along the coast of as much as 10 ft in some areas (fig. 15, Robison and others, 1973; Colón-Ramos, 1983). In 1984, withdrawals from the Kingshill aquifer were estimated at approximately 1 Mgal/d.

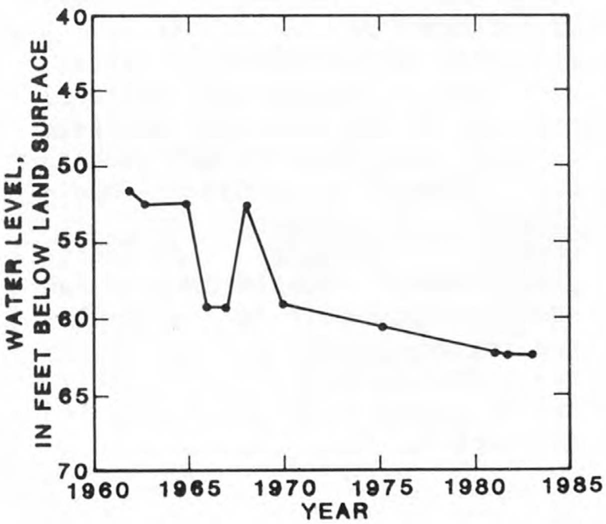


Figure 15.--Graph showing water-level decline at Barren Spot well field in Kingshill aquifer.

Mona Island

Mona Island is considered separately from the other island group because of its peculiar conditions. The island, which has an area of 20 mi^2, is uninhabited and the only knowledge of its ground-water resource is the existence of several shallow dug wells on the southwestern coastal plain. It is speculated that the island could have a freshwater lens floating on saline water with its apex near the island's center, its thickness dependent on recharge and aquifer hydraulic properties (Jordan, 1973). This condition could exist if a north-south trending fault has an insignificant effect on hydraulic characteristics. If the hydraulic conductivity of the limestone rocks is very high, the chances for the existence of a freshwater lens "floating" on saline water are less probable. If a freshwater lens does exist, ground water most likely will contain dissolved solids in excess of 1,000 mg/L, owing to the low rainfall and the effect of sea spray. At a dug well on the southwest coastal plain (Pozo del Portugués) a water sample had dissolved solids of about 3,000 mg/L (Gómez-Gómez and Heisel, 1980).

IMPORTANCE OF AQUIFER SYSTEMS

The principal aquifer systems in the Caribbean Region are those aquifers under the greatest pumping stress--the North Coast Province, the South Coast Province, and the Kingshill aquifers. In these three aquifers, ground-water withdrawals represent a significant portion of the total water use (table 1). Withdrawals from these three aquifers total about 85 percent of all ground-water withdrawals in the region. Without an integrated approach which considers the ground-water flow system as a component of the total hydrologic system (precipitation, surface water, and ground water) it is impossible to evaluate the impact of long-term development on the hydrologic systems.

Although none of the aquifers in the Caribbean Region are areally extensive, their operation and patterns of flow generally are not simple. For most of the aquifer systems, the physical properties of the aquifer matrix, and recharge rates, withdrawal rates, and boundary conditions are insufficiently known. The boundary conditions include not only defining the vertical and horizontal extent of the aquifer, but also the relationship between the aquifer and surface-water bodies (streams, sea, marshes); differentiation of lithologic units within the aquifer system (such as stream alluvial valleys and limestone aquifers); location of the freshwater to saltwater transition zone; and differentiation of aquifers within the overall hydrologic system (artesian overlain by a water-table aquifer). Because of the relatively small size of these aquifers, the effect of local changes in the hydrologic system such as streamflow diversions, or construction of coastal drainage works, leads to relatively fast (within years) regional impact on the entire flow system (such as thinning of the freshwater lens and inland displacement of the freshwater-saltwater transition zone). Without a concerted effort aimed at intensive study of the aquifer systems, the use of the principal aquifers could be imperiled through increased withdrawals or additional modification of recharge and discharge. Drainage projects, ground-water pollution, and pumpage from wells have contributed (or may cause) a reduction in the potential long-term availability of ground water as illustrated in Plate 3.

Table 1.--Estimated ground-water withdrawals in 1980 compared to total water use in areas underlain by the principal aquifers

Aquifers	Ground-water withdrawals, Mgal/d*	Total water use Mgal/d*
North Coast Province		
In west coast to Río Grande de Arecibo area	5	45
In Río Grande de Arecibo to Río de la Plata area	60	65
In Río de la Plata to Río Espiritú Santo area	10	160
South Coast Province		
In Patillas to Ponce area	115	215
In Tallaboa-Guayanilla-Yauco-Guánica area	20	-
Kingshill	0.8	2.8**

* Million gallons per day.
** 2.0 Million gallons per day from sea-water desalination.

PLAN OF STUDY

Objectives and Scope of Work

The goals of the Caribbean Islands Regional Aquifer System study are:

o Provide a general appraisal of the hydrology, hydrogeology, and ground-water resources in Puerto Rico and the U.S. Virgin Islands.

o Establish a data base to support all interpretations including flow-model development. The data base will include information on all aquifers, but will contain more detail on the principal aquifers: North Coast Province, South Coast Province, and Kingshill aquifers.

o Provide a comprehensive appraisal of the hydrogeologic framework and ground-water flow system for the North Coast Province, South Coast Province and Kingshill aquifers,

o Combine efforts with a cooperative project in a test drilling program aimed at obtaining data on aquifer properties (both physical and geochemical) of the North Coast Province aquifer system.

o Develop a better understanding of ground-water recharge, discharge, inter-aquifer flow, and ground-water surface-water relationships in the principal aquifer areas including:

a) flow relationships between streams and stream-valley alluvial deposits and the water-table aquifer of the North Coast Province aquifer system,

b) inter-aquifer flow between coastal-plain surficial deposits and the water-table aquifer of the North Coast Province aquifer system,

c) recharge to the South Coast Province aquifer from surface-water and ground-water irrigation and intermittent streams

d) recharge to the Kingshill aquifer from rainfall infiltration.

o Incorporate the results of aquifer analysis of the North Coast Province with the flow model developed by the cooperative project.

o Develop regional ground-water-flow models of the North Coast Province, the South Coast Province, and Kingshill aquifers.

o Make a comprehensive evaluation of water quality within the Caribbean Island aquifers and a more detailed analysis of the geochemistry in the North Coast Province, South Coast Province, and Kingshill aquifers.

o Evaluate the historical hydrologic changes which have led to the present condition of the principal aquifers.

o Use the regional ground-water flow models to simulate hydrologic changes in the aquifers and to evaluate the potential effects of future ground-water withdrawals or modifications of the hydrologic systems.

Approach

The approach to be taken to achieve the objectives of the study is influenced by the availability of information, complexity of the ground- water-flow systems, and by information provided by other hydrologic investigations which form part of the Caribbean District's cooperative program. However, the general approach will be as follows:

o Examine the existing information to include a literature search and review of data in files.

o Update the existing well inventory and enter data available at other agencies (for example, Puerto Rico Department of Natural Resources, Puerto Rico Aqueducts Authority, Virgin Islands Public Works Department, and Virgin Islands Department of Conservation and Cultural Affairs) into the U.S. Geological Survey's (USGS) data base, Ground-water Site Inventory (GWSI).

o Compile historical data on ground-water quality and enter into the USGS data base, Water Data Storage and Retrieval System (WATSTORE).

o Conduct a water-use inventory to determine ground-water withdrawals and surface-water diversions.

5) Prepare maps of hydrologic parameters (potentiometric surface, transmissivity, etc.) and ground-water quality (concentrations of dissolved solids and specific ions).

o Prepare hydrogeologic maps which portray extent and thickness aquifers, boundary conditions, recharge and discharge areas, etc.

o Conduct areally intensive "snapshot" surveys of principal aquifers to obtain a simultaneous "picture" of ground-water levels, gain or loss of streamflows, withdrawals, and irrigation return flows. The data will be used in ground water flow models.

o Design and calibrate ground-water flow models of the principal aquifers as an aid for in-depth understanding of the ground-water flow systems.

o Obtain additional data as necessary to: refine hydrogeologic maps, ground-water flow models, potentiometric-surface maps, hydraulic properties, maps of ground-water quality and others.

o Make the findings available to the general public through a series of reports.

Work Elements

The Caribbean Islands RASA study was initiated in fiscal year (FY) 1985 and is scheduled to be completed in FY 1989 (table 2). The regional aquifer-system study requires a coordinated effort of staff assigned to four principal work elements:

(1) support functions,
(2) hydrogeology,
(3) water quality and geochemistry, and
(4) ground-water flow simulation.

Table 2.--General time table and principal work elements of the Caribbean Islands RASA study

	1985	1986	1987	1988	1989
Data interpretation	Review of reports, compile historical data, establish data base, develop hydrogeologic maps and construct potentiometric surface maps, and conceptualize flow system	Acquisition of new data; revision of hydrogeologic, hydrologic, and geochemical maps; geochemical flow-path modeling	Regional analysis		
Digital flow models	Model design for South Coast Province, Kingshill, and North Coast Province aquifers	Calibration of models	Evaluate the regional development impact on the North Coast Province aquifer by flow-model simulations.		
Report preparation	Preliminary reports (Open-file, WRI, HA and Journal Articles).				Professional Paper Series
		FUNDING AND PERSONNEL			
Budget	$528,000 *	$475,000 *	$350,000	$350,000	$175,000
Hydrologists (man years)	7.0	6.0	4.5	4.5	3.0

* Includes $125,000 for deep drilling contract.

PLAN OF STUDY

Work Elements - Continued

The work to be accomplished within each work group is as follows:

Support Functions

Support functions are related to data compilation, management of the data base(s), and field acquisition of new data. The bulk of this effort is scheduled for the first two years. During the first year (FY 1985) data were reviewed to identify major deficiencies and determinations were made with respect to the acquisition of new data.

The types of information to be compiled and coded are:

1. well-inventory data,
2. water levels and trends,
3. quality of water and trends,
4. aquifer characteristics, hydraulic conductivity, saturated thickness, areal extent, recharge/discharge areas, anisotropy, and storage,
5. ground-water withdrawals and trends,
6. delineation of ground-water flow systems,
7. delineation of aquifer units,
8. surface-water diversions and historic hydrologic changes,
9. stream-flow records, and
10. rainfall distribution and seasonal trends.

The code will vary according to data need. Site-specific data related to well or aquifer characteristics will be stored in the Geological Survey data base, GWSI; data related to quality of water in the data base, WATSTORE. Other data, such as aquifer thickness, recharge areas, and delineation of the ground-water flow system, will be stored in the District's data base.

Field acquisition of new data will be conducted mostly during the second and third year of the study (FY 86 and 87). However, various data-collection efforts (ie. geophysical surveys, selective test drilling) will be initiated during the first year in order to complement ongoing District cooperative studies. Most of the data will be collected on the principal aquifers: North Coast Province, South Coast Province, and Kingshill. Data will be obtained from other aquifer areas to the level necessary to accomplish the study objectives. Types of data to be collected are outlined below.

1) Aquifer hydraulics

- areal analysis of specific capacity and aquifer tests to obtain regional estimates of transmissivity using techniques described by Bentall (1963).

- slug tests at selective depths especially in unconsolidated surficial deposits of the North Coast Province aquifer and near shore in the South Coast Province aquifer using methods described by Ferris and Knowles (1954) or by Cooper and others (1967).

- controlled drawdown aquifer tests, especially at Salinas fan in South Coast Province aquifer, to evaluate the horizontal anisotropy.

Support Functions - Continued

2) Down-hole geophysical logging.

- at test holes and cased or partly cased wells to corroborate driller's logs in files, or to assess lithologic conditions in areas where limited data exist by comparing logs. The District is equipped with a multi-conductor unit with capabilities for natural gamma, gamma-gamma density, neutron porosity, temperature, specific conductance, long and short-normal electric resistivity, spontaneous potential, acoustic velocity, caliper, flow meter, brine injection and point sample collection.

3) Test drilling.

- the Caribbean District's CME-75 rotary drill rig will be used to construct piezometers to define water levels and water quality in data-deficient areas, and to obtain shallow cores and lithologic data for calibration of surface resistivity soundings. This drilling capability will be used mainly for depths less than 300 ft.
- several test holes in excess of 300 ft will be drilled. The deep drilling will be accomplished by combining efforts with a cooperative project in the North Coast Province aquifer (Torres- González and Wolansky, 1984).

4) Surface-resistivity surveys.

- resistivity surveys will be conducted along the shoreline to define the depth to saline water, mostly in the South Coast Province and Kingshill aquifer areas. These surveys also will be used to define depth to bedrock and depth to water table. Interpretation will be accomplished through computer analysis of sounding data (Zohdy, 1973), and comparison of results with reliable lithologic logs. Soundings near the north coast shoreline have been done in a previous study (Torres-González and Wolansky, 1984).

5) Ground-water withdrawals.

- initial estimates of withdrawals will be obtained from data in the GWSI file. More intensive surveys will be conducted in the South Coast Province and Kingshill aquifer areas because it is anticipated that withdrawals constitute the principal aquifer discharge.

6) Surface-water diversion for irrigation.

- a series of stream gages (10 to 12) will be installed in the irrigation-canal network of the South Coast Province aquifer area. These gages will be used for areal water balance analysis and for quality assurance of data collected by other agencies. In past studies of the South Coast Province aquifer (Giusti, 1968, 1971; McClymonds, 1972; and McClymonds and Díaz, 1972) it was estimated that the irrigation canal network could supply as much as 50 percent of the total aquifer recharge.

7) Synoptic measurements.

- intensive areal surveys in which "snapshot" measurements will be made of ground-water levels, withdrawals from wells, streamflow, etc. The data obtained will be used in ground-water flow-model development. Intensive data collection efforts of this type are planned for the South Coast Province and Kingshill aquifers.

Hydrogeology

The hydrogeologic framework will be delineated on the basis of surficial geologic maps, areal hydrologic studies, drillers' well logs, and aquifer properties. Surficial-geologic maps are available for the main island of Puerto Rico and Mona Island at 1:20,000 scale. Most are from the Geological Survey's "Miscellaneous Map Series" except for the southwest part of the island. Other sites have been mapped at smaller scales (fig. 16).

Hydrologic studies varying from general reconnaissance to more localized assessments have been conducted by previous investigators. Regional appraisals have been made by McGuinness (1948), Bogart and others (1964), and Gómez-Gómez and Heisel (1980).

A large amount of data which can be used in defining the hydrogeology and flow systems is available from investigations undertaken by the cooperative programs of the District. A preliminary list of hydrogeologic reports by aquifer areas follows:

North Coast Province - The regional hydrogeology including water-budget analysis and areal estimates of aquifer hydraulic properties was described by Giusti (1976). More site-specific studies include: estimates of vertical to horizontal anisotropy and location of the fresh-to-salt-water transition zone near Vega Baja by Bennett and Giusti (1972); assessments of surface water and ground water in the Lower Río Grande de Manatí Valley by Goméz-Goméz (1984), at the Vega Baja to Sabana Seca area by Torres-González and Díaz (1984), at the Lower Río Grande de Arecibo valley by Quiñones-Aponte (1985), at the San Juan metropolitan area by Anderson (1976), and in the area east of San Juan by Torres-González (1984).

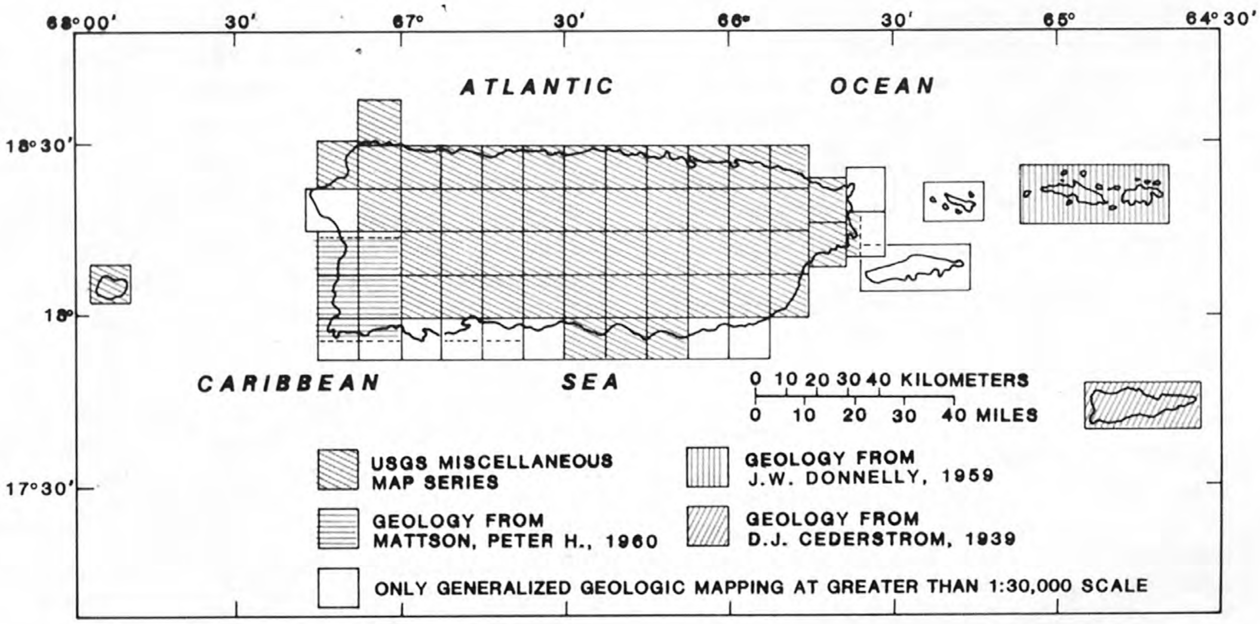


Figure 16.--Status of surficial geologic mapping in the Caribbean Region.

PLAN OF STUDY

Hydrogeology – Continued

South Coast Province - Water resources investigations have been made for the entire province. In the area from Patillas to Ponce, Giusti (1968, 1971), McClymonds (1972), and McClymonds and Díaz (1972) described the hydrogeology, the ground-water flow system and developed preliminary water budgets for each major alluvial fan. Similar analyses were made for the stream valley areas between Ponce and Guánica by McClymonds (1967), Crooks and others (1968), and Grossman and others (1972).

West Coast Province - The only hydrologic investigations made were preliminary surface and ground-water resources assessments on thewestern part of Río Guanajibo valley (Colón-Dieppa and Quiñones- Márquez, 1985) and at the Lower Río Grande de Añasco valley (Díaz, U.S. Geological Survey, written commun., 1984).

East Coast Province - Ground-water investigations were conducted at the Naguabo-Humacao area (Graves, U.S. Geological Survey, written commun., 1985), at Yabucoa valley (Robison and Anders, 1973), and at Maunabo valley (Adolphson and others, 1977).

Lajas valley - A general description of the flow system was presented by Anderson (1977). Most of his analysis is based on data collected by others (Israelson, 1954; Reeve, 1956; Bonnet and Brenes, 1958; Willardson, 1958; Gordon, 1961; Vázquez and Ortiz-Velez, 1967)for the purpose of solving salinity problems in the valley and construction of drainage works.

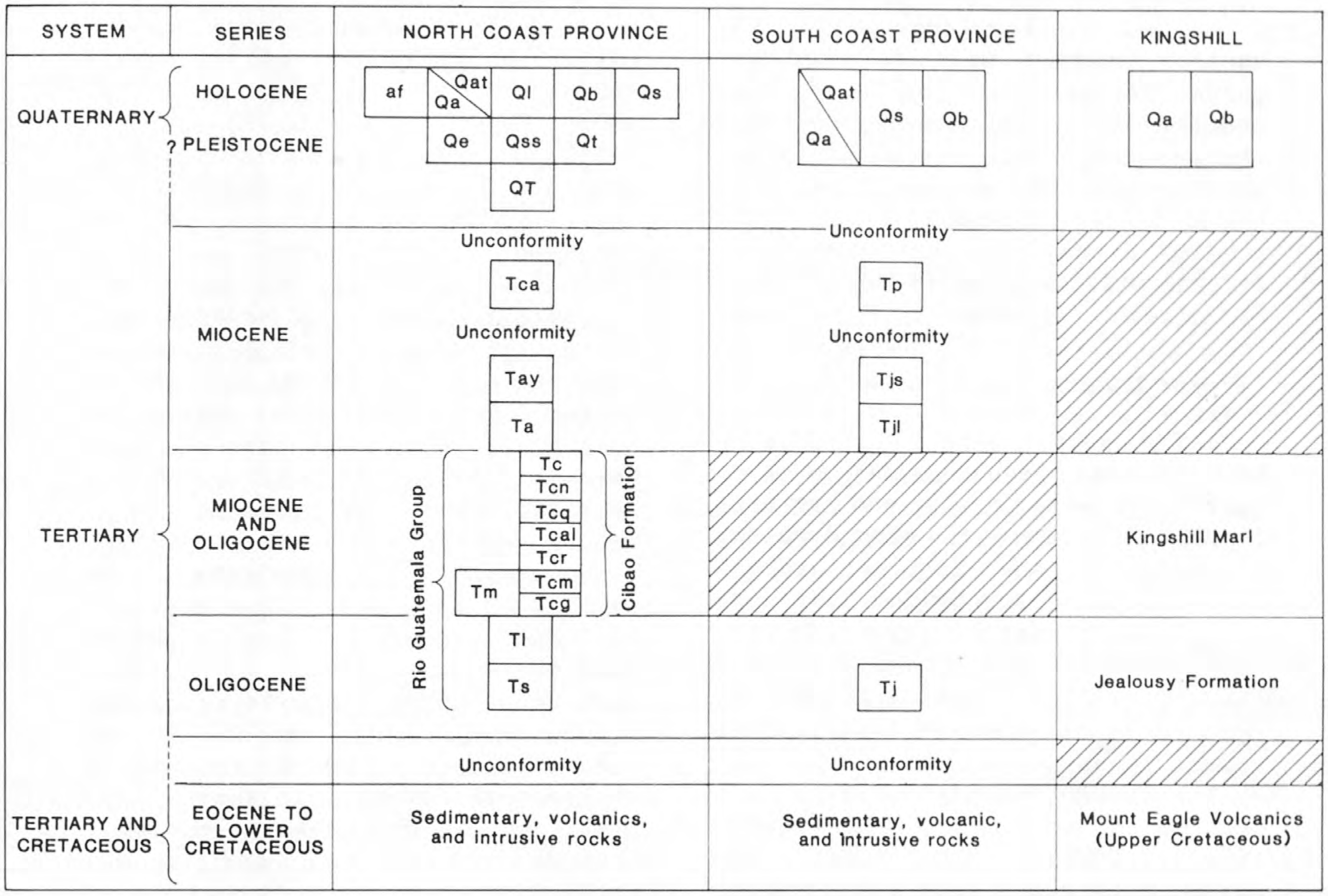
At other areas only general descriptions of hydrologic conditions exist. Most of the analyses made for the islands are to a large part based on more detailed studies at St. Thomas (Jordan and Cosner, 1973) and St. Croix (Jordan, 1975).

Information from these studies will be used to prepare a preliminary analysis of the aquifer systems by isopleth maps showing,

- thickness of aquifer units,
- potentiometric surface,
- recharge and discharge areas and rates,
- altitude of top and bottom of aquifers (and confining units?),
- lithofacies, and,
- hydraulic conductivity (or transmissivity) within each aquifer unit,

for the South Coast Province and Kingshill aquifers. This effort is not necessary for the North Coast Province aquifer because it has been included in an ongoing District cooperative investigation (Torres-González and Wolansky, 1984). Information for other aquifer areas will be compiled and stored in the respective data bases and analyzed to the degree necessary to support the project objectives. Both the regional maps and the data bases will be revised continually as new data become available during the execution of the project. A summary of the preliminary hydrogeologic framework for the Caribbean Islands, principal aquifers is given in table 3.

Table 3.--Generalized stratigraphic correlation chart of the North Coast Province, South Coast Province, and Kingshill aquifers



EXPLANATION

af - Artificial fill

Qa - Alluvium, deposited in stream valleys

Qat - Alluvium, undifferentiated and terrace deposits

Ql - Landslide deposits

Qb - Beach deposits

Qs - Swamp deposits

Qe - Eolianite

Qss - Silica sand deposits

Qt - Terrace deposits

QT - Undifferentiated surficial deposits

Tca - Camuy Formation

Tay - Aymamón Limestone

Ta - Aguada Limestone

Tc - Cibao Formation, typical lithology

Tcn - Miranda Sand Member

Tcq - Quebrada Arenas Limestone Member

Tcal - Almirante Sur Sand Member

Tcr - Río Indio Limestone Member

Tcm. - Montebello Limestone Member

Tcg - Guajataca Member

Tm - Mucarabones Sand

Tl - Lares Limestone

Ts - San Sebastian Formation

Tp - Ponce Limestone

Tjs - Juana Díaz Formation, upper clastic beds

Tjl - Juana Díaz Formation, limestone beds

Tj - Juana Díaz Formation, lower clastic beds

(North Coast Limestone and South Coast Province from Monroe, 1980, Kingshill from Cederstrom, 1960.)

Hydrogeology –Continued

Present knowledge of the aquifer systems will be used to guide efforts in improving the understanding of recharge/discharge quantities and mechanisms. This will be accomplished by actual field studies at four aquifer areas. The scope of this effort will be described in the "Special Studies" section.

Water Quality and Geochemistry

The main objective of this work element is to interpret the quality-of-water data and relate it to the regional ground-water flow system and general hydrogeology. To accomplish this a major effort must be expended to:

- compile existing ground-water quality data,

- perform basic quality-assurance tests to ensure consistency of data,

- segregate data into that which meets quality assurance standards, that which represents partial analyses, and that which fails the quality-assurance tests,

- correlate sampling sites which meet the quality-assurance standards with site-identification number in GWSI and enter into WATSTORE file, and,

- perform statistical analyses of major constituents per geologic unit.

Major sources of ground-water quality data are the Puerto Rico Aqueducts and Sewers Authority (PRASA), which operates and maintains all public water-supply wells, and the Puerto Rico Department of Natural Resources (PRDNR), which requires industrial users to submit quality-of-water analyses on a regular basis. In 1984, the PRASA maintained 413 public-supply wells (Gómez-Gómez and others, 1984). PRASA and PRDNR may have more than 2,000 water-quality analyses. About 500 additional complete water quality analyses of major cations and anions can be compiled from reports or data maintained in files by the U.S. Geological Survey. A preliminary check of the available data indicates most analyses were made between 1950 and 1984. Because analytical techniques have changed through the years, it will be necessary to review the laboratory procedures used by the various organizations to evaluate the quality of the data. In addition, most analyses are of samples which were not processed at the collection site according to current procedures. As a result, these data will be used mainly to assess regional differences in geochemistry, gross ground-water-quality changes with time, and areal variability within the same aquifer.

After the historical data have been examined statistically, it will be "matched" with the preliminary hydrogeologic-framework and aquifer flow-system analysis. At this stage preliminary regional isopleth maps can be prepared of the distribution of major ionic species or dissolved solids. These maps will assist in identifying recharge/discharge zones, or differentiating aquifers or anomalous areas within a given aquifer. At sites for which long-term water-quality data are available, trend analysis will be made and correlated with regional aquifer stresses. At this stage, areas can be identified for collection of samples to corroborate interpretations derived from the preliminary geochemical maps, and data can be obtained at areas where major data voids exist.

This sampling effort will essentially be limited to common chemical constituents and basic physical field measurements (ie. pH, alkalinity, temperature, specific conductance, cations, anions, and selected trace constituents). This sample collection effort will be conducted late in FY 1985 and early FY 1986.

Most of the effort between fiscal years 1986 to 1988 will be oriented toward relating geochemical processes to the flow system as conceived in the hydrogeologic analysis. This will require collection of samples from specific aquifer units and analyses of a larger array of constituents, in addition to those listed previously. Among these are: stable hydrogen and oxygen isotopes to define areas of recharge and discharge, carbon-14 or tritium analyses for time of travel estimates, dissolved gases, and other stable isotopes for mass-balance calculations. In addition it will be necessary to obtain cores for mineralogic analysis by optical means or X-ray diffraction.

Development of geochemical flow-path models are scheduled to be made principally in the three major aquifers: The North Coast Province, the South Coast Province, and the Kingshill. Computer programs such as WATEQF (Plummer & others, 1978), BALANCE (Parkhurst and others, 1982), and PHREEQE (Parkhurst and others, 1982) will be used to: (1) determine mineral speciation and saturation indices; (2) specify kinds and amounts of minerals which dissolve or precipitate; and (3) calculate changes of speciation, redox, and isotopic ratios along the flow path.

Ground-Water Flow Simulation

The main objective of this work element is to develop digital ground-water flow models of the principal aquifer systems. The basis for model development will be the hydrogeologic-framework maps and the aquifer-properties data.

Several different computer programs will be used, depending on the extent of information and use of the model. Initially a two-dimensional (2-D) finite-difference model (McDonald and Harbaugh, 1984) will be used to estimate reasonable values of aquifer properties areally. This approach will be used throughout simulated areas to determine the general configuration of the water table, recharge/discharge rates and areas, areal estimates of aquifer transmissivities, and to test aquifer boundary conditions. Indirectly these preliminary models will be used to determine where (and what type) of data are needed. The same computer program can also be used to prepare cross-section models of the flow system.

For aquifers with significant vertical anisotropy, intensive ground-water development, or where salt-water encroachment exists, it will be necessary to use other models, such as the three-dimensional (3-D) code of the McDonald and Harbaugh model (1984), or 2-D solute-transport models developed by Konikow and Bredehoeft (1978) or Voss (1984).

Models of these extensive areas will be completed as part of this study. These will be, in order of development, of the South Coast Province, the Kingshill, and the North Coast Province aquifers.

PLAN OF STUDY

Ground-Water Flow Simulation - Continued

The South Coast Province aquifer will be simulated initially using two models: one covering the south coast alluvial plain from Río Patillas to a line slightly east of Río Cayures (near Salinas), the second covering the area west of this boundary to a line about 2 mi west of Ponce (see Plate 1). A preliminary 2-D finite-difference model (McDonald and Harbaugh, 1984) of each area will be constructed with grid spacing of 1,000 ft in each direction. Initial estimates of aquifer properties will be obtained from an electric-analog model previously constructed by Bennett (1976). These preliminary models will be the framework for developing a detailed 3-D model. A detailed sub-area model of the Salinas fan will be developed using actual field data collected as part of a study described in the "Special Studies" section. The detailed 3-D model of Salinas fan will serve as the basis for developing the two regional models of the South Coast Province aquifer. It may not be necessary to use a 3-D aquifer model to simulate the displacement of the freshwater-saltwater transition zone. This is due to the fact that the estimated horizontal to vertical anisotropy near the coast is 1,000: 1 (Bennett, 1976), and the general absence of evidence of salt-water encroachment. The effect of reduced recharge or increased withdrawals on the freshwater- saltwater transition zone will be evaluated through the use of steady-state, cross-sectional models depicting various scenarios.

For the Kingshill aquifer, a preliminary 2-D model with a grid spacing of 1,000 ft in each direction will be developed. After preliminary testing, it will be decided whether a 3-D model is needed or a 2-D model incorporating the ability to deal with variable-density ground water (AQUISALT-Voss, 1984, (MOC-Konikow and Bredehoeft, 1978; or SATRA-Voss, 1983) is required.

For the North Coast Province aquifer, a regional 3-D model will be constructed from subarea models developed under a District cooperative program (Torres-González and Wolansky, 1984). A refinement of the estimates of recharge/discharge processes in alluvial stream valleys and throughout the coastal-plain surficial deposits is needed for the development of the 3-D regional model. During the District cooperative project, only net recharge or discharge will be estimated, however, it will be necessary to quantify water flowing to and from the streams or coastal-plain deposits in order to support geochemical interpretations. Details of these activities will be described in the "Special Studies" section.

A major problem in the process of developing useful ground-water flow models is the quantification of aquifer recharge and discharge. Techniques for improving estimates of recharge and discharge will be conducted in three areas:

1. The North Coast Province aquifer.

   a - Obtain values of streambed leakage.

   b - Define the interrelationship between the water-table aquifer in alluvial valleys and the regional aquifer.

   c - determine flux of water between the regional aquifer and the alluvial deposits and between the latter and the streams.

   d - define the interrelationship between the water-table aquifer within the coastal unconsolidated deposits and the regional aquifer.

2. The South Coast Province aquifer.

   a - Determine net aquifer recharge from each of the following major sources: leakage from irrigated fields, stream leakage, and areal rainfall infiltration.

3. Vieques Island.

   a - Determine net aquifer recharge which can be ascribed to areal rainfall infiltration and to runoff from mountain slopes.

   b - Obtain values of ground-water discharge by evapotranspiration.

Information obtained will be used in development of the regional ground- water flow models for the three principal aquifers. Further details of the "Special Studies" effort are given below for each selected study area.

Río Grande de Manatí Alluvial Valley

This area was selected for detailed study principally because local conditions can be extrapolated to the other stream valleys dissecting the North Coast Province aquifer. Other important considerations are that: the stream is unregulated, gaging stations are maintained as part of the District's data program, and a baseline hydrologic study was made in the lower valley (Gómez-Gómez, 1984).

PLAN OF STUDY

Río Grande de Manatí Alluvial Valley - Continued

The Río Grande de Manatí valley study (fig. 17) will be designed to define conditions described in item 1a through 1c. The information for a and b will be obtained by construction of three to four piezometers arrays perpendicular to the stream in at least three different locations above highway PR-2. Data obtained from these piezometer arrays will be evaluated along with the river stage and the hydraulic gradient to obtain aquifer diffusivity values and estimates of ground-water flux. Analysis of these data most probably will use techniques described by Pinder and others (1969) in combination with a three dimensional flow model (McDonald and Harbaugh, 1984).

Item 1c is intended to define the migration of water across the alluvial valleys. The results will be used in the development of geochemical flow-path models of the North Coast Province aquifer. In the lower valleys of Río Grande de Arecibo, Grande de Manatí and Cibuco, hydraulic gradients are toward the northeast. This seems to be the result of the northwest orientation of stream valleys (Plate 1) and the differences in hydraulic conductivity between the underlying limestone units and the alluvium. Specifically, within the lower part of the valleys where the alluvium rests on Aymamón or Aguada Limestone, the thick alluvial deposits (as much as 300 ft) could form "barriers" to ground-water flow toward the valley along the left bank. The large difference in hydraulic conductivity between the alluvium (range of 1 to 30 ft/d) and the limestone units (50 to 500 ft/d) probably contributes to a "dewatering" of the alluvium along the opposite side.

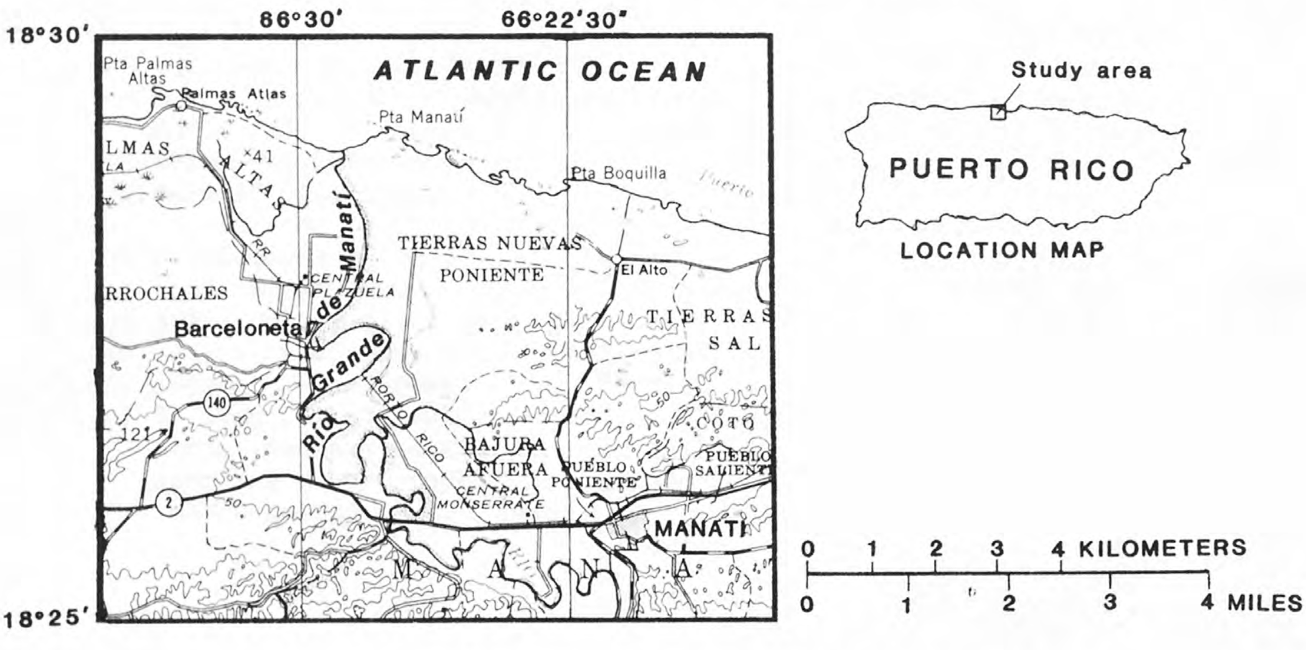


Figure 17.--The Río Grande de Manatí area of study.

In order to assess item 1c, information obtained in items 1a and 1b will be complemented with geochemical data. Geochemical data will consist of stable isotopes of oxygen and hydrogen and tritium analyses for use in mass-balance calculations (Muir and Coplen, 1981), and radon gas tracer studies (Jacoby, 1979) to define recharge zones along the stream. Although the results of these activities cannot be extrapolated to the other stream valleys, they will serve to document the application of these techniques.

Vega Alta Coastal Plain

The Vega Alta coastal-plain study (fig. 18), presently underway, will result in definition of the ground-water flow system within this subarea. In most of the studies the coastal plain is defined as a ground-water discharge area. However, a recent reconnaissance study of the Vega Alta area indicates that locally the coastal plain is a recharge zone. The apparent cause is the higher hydraulic conductivity of the underlying limestone aquifer.

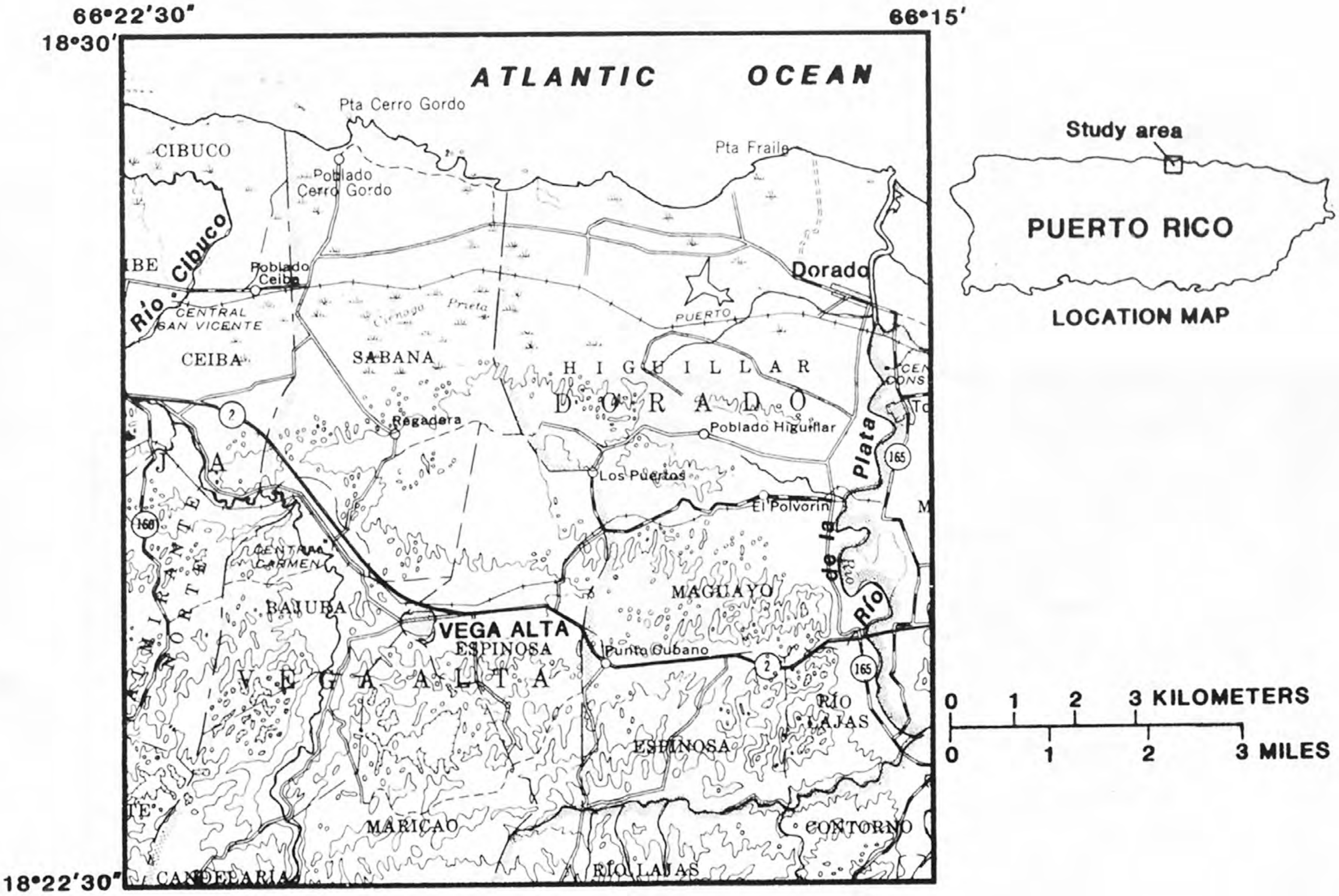


Figure 18.--The Vega Alta area of study.

PLAN OF STUDY

Vega Alta Coastal Plain - Continued

This area was selected for study because it is the only part of the North Coast Province aquifer with a minimal modification of the natural discharge features of flow system (other coastal areas have been modified through drainage works). The study will focus on determining: (1) whether a regionally extensive, high secondary-porosity zone occurs at a depth of approximately 80 to 100 ft below sea level (this interval has been identified in various drillers' logs as a large-yield zone and may be related to the eustatic sea level of about 10,000 years ago (Fairbridge, 1960)); and (2) the amount of recharge. Data will be obtained from piezometer nests at about six locations, and water samples will be collected from different depths within the vertical profile and analyzed for stable oxygen and hydrogen isotopes. The area will be monitored for one year. Other complementary data will be obtained as part of the regional analysis.

Salinas Area

The Salinas study (25 mi^2) will define the recharge as given in item 2a. This area (fig. 19) was selected for study because all the major recharge and discharge features of the South Coast Province aquifer exist in the area, and also because the aquifer is relatively thin (see fig. 9). Data will be obtained by installation of 10 to 12 observation wells, three rain gages, and an evaporation pan on the Río Salinas fan. Information on ground-water withdrawals and surface-water irrigation will also be obtained.

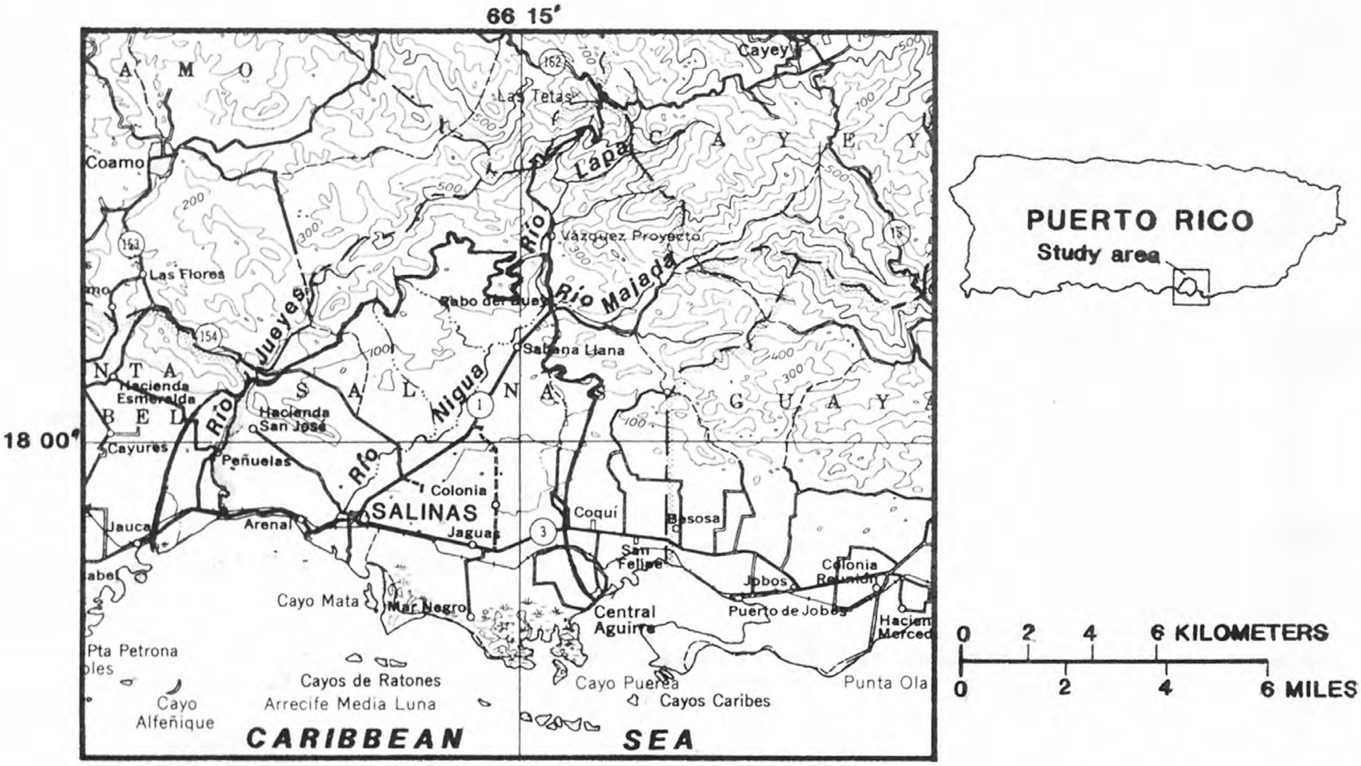


Figure 19.--The Salinas area of study.

The data will be analyzed by techniques previously used on data from the Río Coamo fan (Giusti, 1971), but the analysis will be extended using a 3-D ground-water flow model. The results of this study will improve of estimates used in the South Coast electric-analog model described by Bennett (1976). Previous areal recharge-discharge analyses for the South Coast Province aquifer were made on the basis of the Río Coamo fan study. The major advantage in this study compared to the Río Coamo fan study is that the lower aquifer boundary is well defined (volcanic bedrock).

Vieques Island

The Vieques Island study will be concerned with the aquifer in the Esperanza area (fig. 20). The main objective is to obtain data on aquifer recharge from rainfall and discharge by evapotranspiration as described in items 3a and 3b. This aquifer was selected for study because: (1) no withdrawals are presently being made; (2) aquifer boundaries can be defined accurately; (3) it is representative of aquifer areas in the sub-tropical climate zone, similar to the Kingshill aquifer area in the island of St. Croix, where recharge occurs only during intensive rainstorms; and (4) a 2-D ground-water flow model has been developed. Data collection and analysis for this subarea will be similar to that for the Salinas area.

Results of this study will be used in development of the ground-water flow models for the Kingshill and parts of the South Coast Province aquifers.

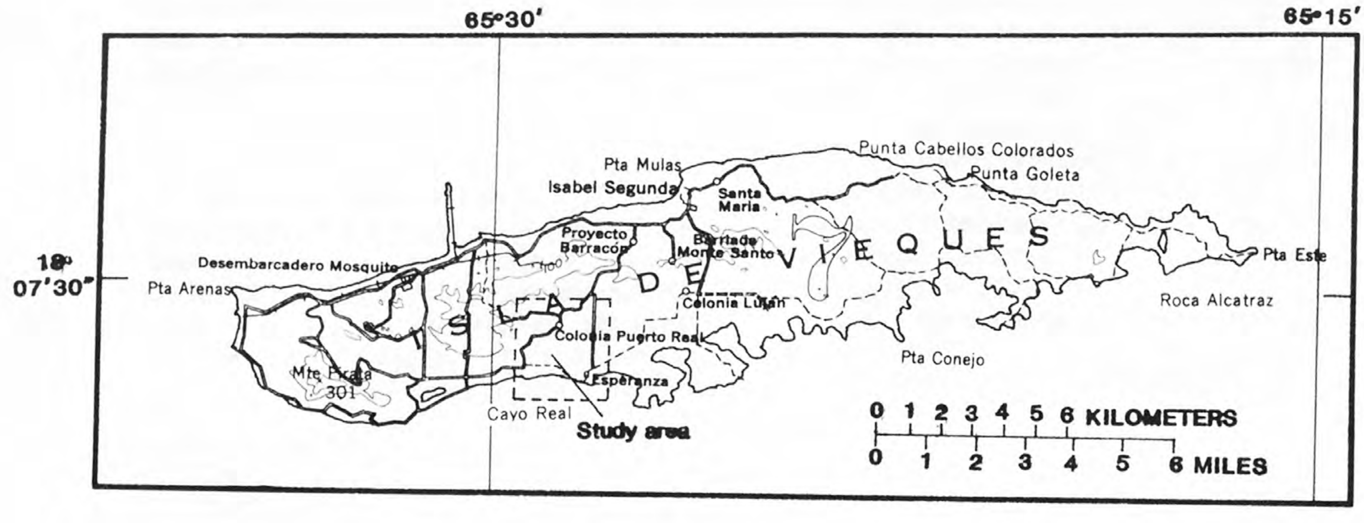


Figure 20.--The Esperanza area of study at Vieques Island, PR.

PLANNED REPORTS

Findings of the Caribbean Islands RASA study will be made available in publications. Most publications will be in the Geological Survey's Open-File Reports (OFR), Water-Resources Investigations Reports (WRIR), or Hydrologic Atlas (HA) series. Journal articles and symposium reports are also possible. The final findings will be presented in the U.S. Geological Survey Professional Paper (PP) series. Tentative titles for the planned Professional Paper series are:

Chapter A - Hydrogeology and hydrology of the Caribbean Islands Regional Aquifer System in Puerto Rico and U.S. Virgin Islands - A Summary.

Chapter B - Hydrogeologic framework of the principal aquifers in the Caribbean Islands Regional Aquifer System - the North Coast Province and South Coast Province aquifers in Puerto Rico, and the Kingshill aquifer in U.S. Virgin Islands.

Chapter C - Geochemistry of the Caribbean Islands Regional Aquifer System in Puerto Rico and U.S. Virgin Islands

Chapter D - Simulation of ground-water flow in the Caribbean Islands Regional Aquifer System in parts of Puerto Rico and U.S. Virgin Islands

Other planned publications are:

Open-File Reports

1. Compilation of historical ground-water-quality data for the North Coast Province aquifer, Puerto Rico.

2. Compilation of historical ground-water-quality data for the South Coast Province aquifer system, Puerto Rico.

3. Compilation of historical ground-water-quality data for the Kingshill aquifer system of Central St. Croix, U.S. Virgin Islands.

4. Compilation of chemical analyses of samples of precipitation, surface water and ground water obtained during the Caribbean Islands RASA study.

Water-Resources Investigations Reports

1. Delineation of saltwater in the unconfined part of the North Coast Province aquifer, Puerto Rico.

2. Delineation of saltwater in the South Coast Province aquifer, Puerto Rico.

3. Conceptualization of controlling geochemical processes in the South Coast Province aquifer of Puerto Rico from preliminary water quality and hydrogeologic data.

4. Conceptualization of controlling geochemical processes in the North Coast Province aquifer of Puerto Rico from preliminary water quality and hydrogeologic data.

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10. Hydrogeology of the South Coast Province aquifer, Puerto Rico.

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6. Potentiometric surface of the Kingshill aquifer, central St. Croix, U.S. Virgin Islands.

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