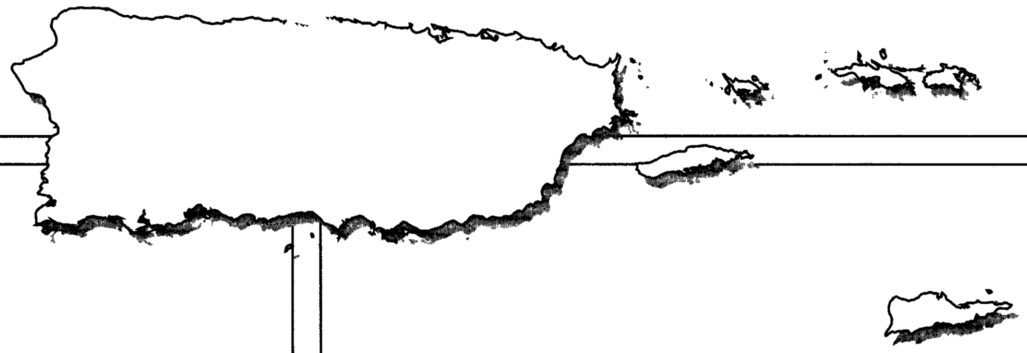

ATLAS OF GROUND-WATER RESOURCES IN PUERTO RICO AND THE U.S. VIRGIN ISLANDS

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4198

Prepared in cooperation with the
U.S. ENVIRONMENTAL PROTECTION AGENCY

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By Thalia D. Veve and Bruce E. Taggart (editors)

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San Juan, Puerto Rico
1996

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNIT, AND AGENCY ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
	Flow	
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09294	meter squared per day
cubic feet per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per day
gallons per day (gal/d)	0.003785	cubic meter per day
inch per hour (in/hr)	25.4	millimeter per hour
inch per year (in/yr)	25.4	millimeter per year
inch per inch (in/in)	25.4	millimeter per millimeter
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter

Abbreviated water-quality unit

microgram per liter (µg/L)

Agency Abbreviations

Puerto Rico Aqueduct and Sewer Authority (PRASA)
Puerto Rico Department of Natural and Environmental Resources (PRDNER)
U.S. Geological Survey (USGS)

Atlas of Ground-Water Resources in Puerto Rico and the U.S. Virgin Islands

By Thalia D. Veve *and* Bruce E. Taggart (editors)

Abstract

This atlas presents an overview of the ground-water resources of the main island of Puerto Rico; two of its larger offshore islands, Isla de Culebra and Isla de Vieques; and the three principal islands of the U.S. Virgin Islands, St. Thomas, St. John, and St. Croix. The atlas presents the most important ground-water information available for these islands, and is written for water managers and the general public. It describes, through the use of maps, graphs, and hydrogeologic sections, the most important aspects of the geohydrology, ground-water flow system, and ground-water withdrawals for the principal aquifers in these islands. Most of the information presented in the atlas is from published reports, although unpublished data from ongoing studies by the U.S. Geological Survey were used to prepare parts of the atlas. This report provides a useful compilation of information concerning major aquifers in Puerto Rico and the U.S. Virgin Islands and provides a first step in gaining a general knowledge of these aquifers. More detailed information is available from the primary sources referenced in the report.

The atlas contains an introductory section and 15 sections describing the ground-water resources of 12 regions within the 7 ground-water areas of the main island of Puerto Rico, Isla de Culebra and Isla de Vieques (described in a single section of the atlas), and the U.S. Virgin Islands (St. Thomas and St. John are described in one section of the atlas and St. Croix in another), and a concluding section describing present and potential problems related to the development of ground-water resources. Information presented in each of 15 descriptive sections of the atlas include the (1) location and major geographic features of the area covered by that section, (2) population and estimated ground-water use within the area, (3) geologic setting, (4) hydrogeology of the area, (5) ground-water levels and movements, and (6) a description of soil permeabilities.

Acknowledgement

The U.S. Geological Survey, Caribbean District wishes to acknowledge the contribution of Thalia D. Veve to the completion of this report. Without her vision and persistence in the face of overwhelming obstacles this report would never have been completed.

1.0 Introduction

This atlas, prepared by the U.S. Geological Survey (USGS) in cooperation with the U.S. Environmental Protection Agency (EPA), presents an overview of the ground-water resources of the main island of Puerto Rico, the offshore islands of Culebra and Vieques, and St. Thomas, St. John, and St. Croix in the U.S. Virgin Islands.

1.1 Purpose and Scope

The atlas was prepared to meet the need for a single publication that presents an overview of the ground-water resources of these areas that can be used by planners, managers, and personnel of various Federal, Commonwealth, and local agencies. The atlas is based largely on published reports that have been prepared during the last 70 years. It does not present a comprehensive description of all that is known about the ground-water resources of these areas, but it does describe the most important aspects of the geohydrology, ground-water flow system, water use, and water-supply or water-quality problems that could affect the future development of water from the principal aquifers. The aquifers selected for description in this report are those that are important sources of water for public and domestic water supply.

The main island of Puerto Rico was divided in five ground-water areas: the North Coast, South Coast, West Coast, East Coast, and East Central (fig. 1.1-1). The North Coast area is underlain by limestone aquifers that are the most productive aquifers in Puerto Rico. These limestone aquifers cover an area of about 600 square miles (mi^2) and are as much as 5,600 feet thick. For purposes of this report, the North Coast area was divided into four regions. From west to east they are the Aguadilla-Hatillo, the Arecibo-Manatí, the Vega Baja-Toa Baja, and the Bayamón-Loíza regions.

The South Coast area is underlain by an alluvial aquifer that averages about 3 miles wide and is about 200 to 300 feet thick in the eastern half, and includes alluvial valleys cut into Tertiary age limestones in its western half. For purposes of this report, this area was divided into three regions. From east to west the areas are the Santa Isabel-Patillas, the Juana Díaz-Ponce, and the Peñuelas-Guánica regions.

The West Coast area includes four small alluvial valleys separated by ridges composed of volcanic rocks, limestone, and some intrusive rocks. The Lajas valley is included in this area, although the origin of this valley differs from that of the other valleys in that it is believed to have been formed by block faulting. For purposes of this report, the West Coast area was divided into three regions. From north to south they are the Añasco, the Guanajibo, and the Lajas regions.

The East Coast area consists of a discontinuous narrow coastal plain and includes several alluvial river valleys. It extends from the Río Grande in the north to Maunabo in the south. However, due to a paucity of published data for the northern part of the area, only the area between Maunabo and Naguabo is described in this report (Naguabo-Maunabo region).

The East Central area, which describes the Aguas Buenas-Juncos region is characterized by mostly mountainous terrain and is underlain by volcanic rocks, intrusive rocks, a few interbedded limestones, and isolated alluvial deposits in river valleys. Although some wells produce ground water from highly fractured volcanic and intrusive rocks, these rocks are important aquifers only locally, and are not described in this report. The Caguas-Juncos alluvial valley, the largest in Puerto Rico is located within the East Central area.

The three largest of Puerto Rico's offshore islands are Isla de Vieques, Isla de Culebra, and Isla de Mona (fig. 1.1-1). Isla de Culebra and Isla de Vieques lie to the east and Isla de Mona to the west of Puerto Rico. Isla de Vieques is underlain by mixed volcanic and intrusive rocks, with some small areas underlain by limestone and alluvial deposits near the coast. Isla de Culebra is underlain mainly by mixed volcanic rocks with some small areas underlain by alluvium near the coast. Isla de Vieques and Isla de Culebra are described in one section of this report. Isla de Mona is an uninhabited island underlain by carbonate rocks and is bounded by a low-lying coastal plain along its south coast. A few shallow wells have been dug on the island, but little is known about the ground-water resources of the area. The hydrology of Isla de Mona is not described in this report.

The U.S. Virgin Islands (fig. 1.1-1) include the islands of St. Croix, St. Thomas, and St. John. St. Croix is underlain by mixed volcanic and intrusive rocks, and carbonate rock with some small areas underlain by alluvium. St. Thomas and St. John are underlain mostly by layered volcanic rocks with some small areas underlain by carbonate rock and alluvium.

Information presented in each of these descriptive sections of the atlas include (1) the location and major geographic features of the area covered by that section, (2) population and estimated ground-water use within the area, (3) geologic setting, (4) hydrogeology of the area, (5) ground-water levels and movements, and (6) a description of soil permeabilities. The amount of detail presented in each of these sections for a particular area is dependent upon the quality and quantity of published data available for that area.

1.1.A Location and Major Geographic Features

This section of the report includes a general topographic map showing the areal extent and boundaries of the area, major streams, and cultural features. The brief text describes prominent geomorphic features in the area.

1.1.B Population and Estimated Ground-Water Use

This section describes the population of the area, presents a map showing approximate locations of known wells, and principal uses of ground water in the area. Population data for the area are from the 1980 and 1990 Census of population and housing (U.S. Department of Commerce, 1982). Water-use data presented are generally for the years 1981-82 and were obtained from various USGS reports. The well location maps were compiled from the USGS Ground-Water Site Inventory, an electronic database maintained in the USGS Caribbean District for Puerto Rico and the U.S. Virgin Islands.

Population data are available by municipio (county) subdivisions, which provides an accurate means of calculating population over specific aquifer areas. Unfortunately, water-use data are not available by municipio subdivisions. In areas where specific studies have determined the use of water from a particular aquifer, information is given. Insofar as possible, all the information in this section is presented by municipio in order to facilitate the comparison of data with other sections of the report.

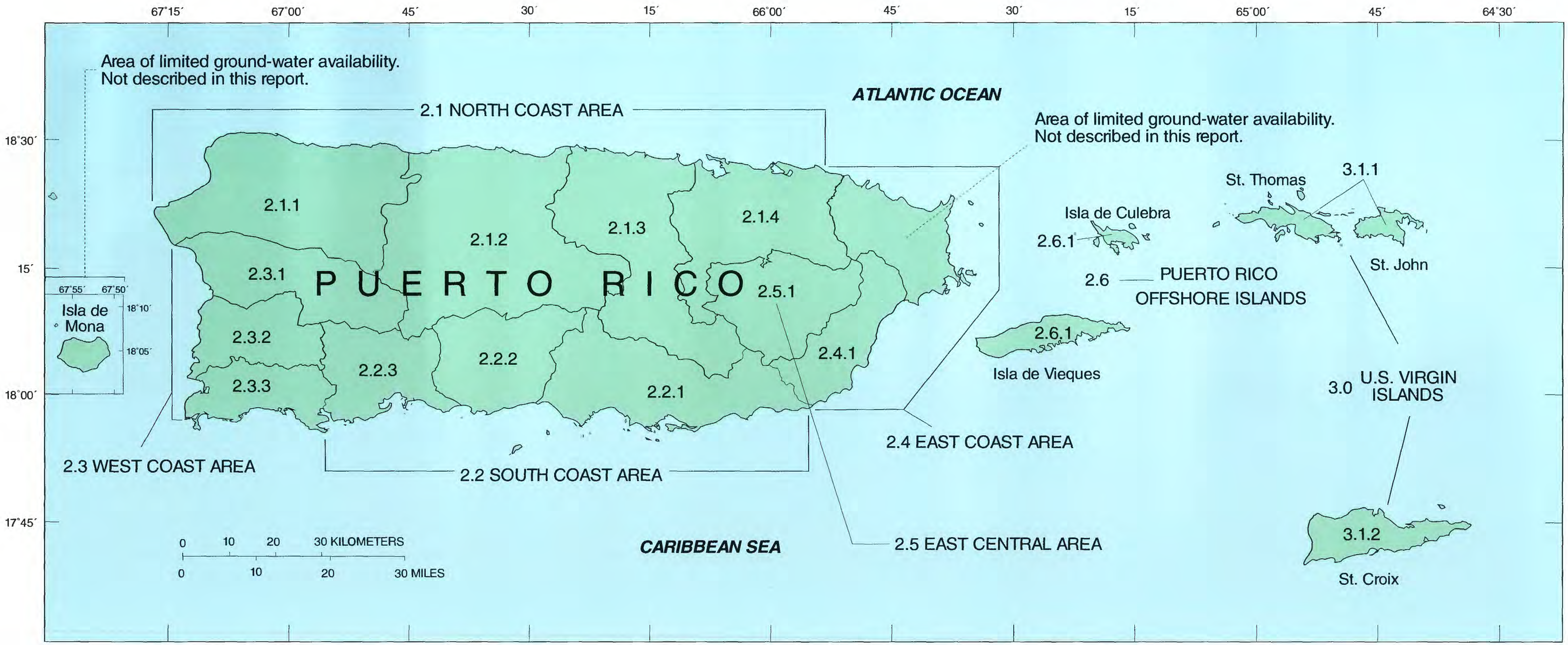


Figure 1.1-1 Index map for sections of the Atlas and ground-water resources areas in Puerto Rico and the U.S. Virgin Islands (the numbers correspond to the section of the report in which each area is described).

1.1.C Geologic Setting

This section includes a map showing the surficial geology and describes prominent rock types within the area. Information presented on the geologic formations include age, composition, and thickness. The age of geologic formations are presented in terms of the Geologic Time Scale (Palmer, 1983), which assigns formal names to specific ranges of geologic time (table 1.1.C-1).

1.1.D Hydrogeology

In this section, the formations that constitute major aquifers are identified and described. Hydraulic characteristics for each of the major aquifers in the area are described. This section generally includes two maps: a map of hydraulic conductivity or transmissivity (the rate of flow of water through a unit cross section of one square foot of a porous rock or sediment), and a map showing aquifer thickness or depth to bedrock. Hydrogeologic cross sections are included where aquifer thickness or depth to bedrock maps are not available.

Table 1.1.C-1 Geologic Time Scale for that period of geologic time pertaining to geologic formations occurring in Puerto Rico and the U.S. Virgin Islands (from Palmer, 1983)
[Ma, millions of years]

Age (Ma)	Era	Period		Epoch	
0. - 0.01	Cenozoic	Quaternary		Holocene	
0.01 - 1.0				Pleistocene	
1.6 - 3.4		Tertiary	Neogene	Pliocene	Late
3.4 - 5.3					Early
5.3 - 11.2				Miocene	Late
11.2 - 16.6					Middle
16.6 - 23.7					Early
23.7 - 30.0			Paleogene	Oligocene	Late
30.0 - 36.6					Early
36.6 - 40.0				Eocene	Late
40.0 - 52.0					Middle
52.0 - 57.8					Early
57.8 - 63.6				Paleocene	Late
63.6 - 66.4					Early
66.4 - 97.5	Mesozoic	Cretaceous			Late
97.5 - 144					Early
144. - 163		Jurassic			Late
163. - 187					Middle
187. - 208					Early
208. - 230		Triassic			Late
230. - 240					Middle
240. - 245					Early

1.1.E Ground-Water Levels and Movement

This section presents a map showing ground-water levels and direction of ground-water flow. Factors such as rainfall and ground-water development that affect ground-water levels are also described in this section.

1.1.F Soil Permeability

This section presents a map showing soil associations and their corresponding permeabilities. The source of data for these maps is the soil surveys of the U.S. Department of Agriculture, Soil Conservation Service. General characteristics of the soil associations and ranges of permeability based on published permeability values for the soil series comprising each soil association are described in this section. Significant differences among soil associations are also described.

1.2 Description of the Area

Puerto Rico and the U.S. Virgin Islands are located in the northeastern Caribbean Sea between latitudes 17°40'N and 18°35'N, and longitudes 64°30'W and 68°00'W (fig. 1.2-1). Puerto Rico is the smallest of the Greater Antilles and, together with its associated offshore islands, has a total area of 3,435 mi^2. The U.S. Virgin Islands include the three main islands of St. Thomas, St. John, and St. Croix with a combined area of 133 mi^2.

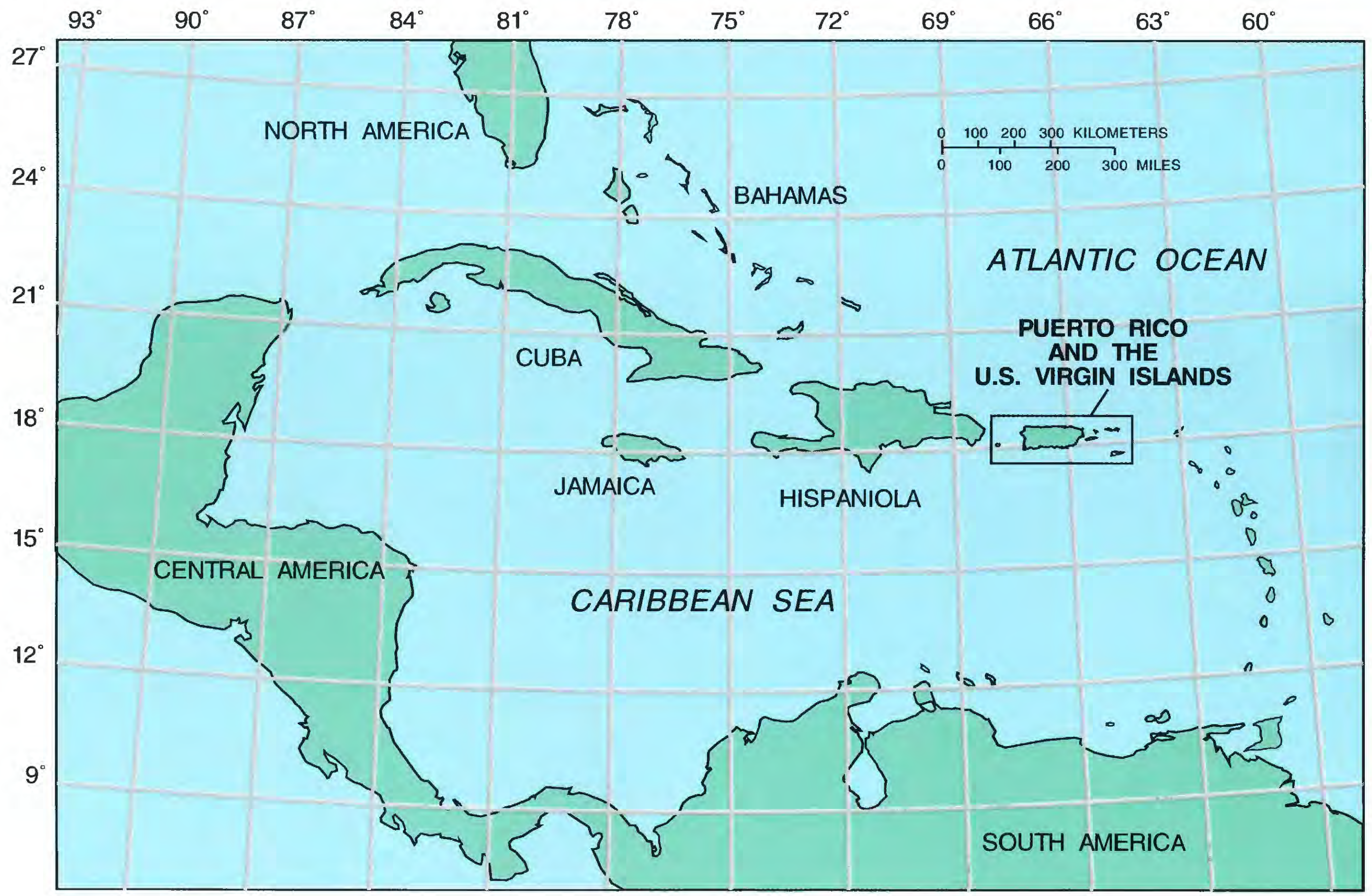


Figure 1.2-1 Location map of Puerto Rico and the U.S. Virgin Islands in the Caribbean.

The main island of Puerto Rico has three principal physiographic areas: the alluvial coastal plains, karst, and the central mountainous interior (fig. 1.2-2). Land-surface elevations range from mean sea level at the coast to 4,389 feet above mean sea level in Cerro Punta at Jayuya. In the offshore islands of Puerto Rico, the highest elevation is in Isla de Vieques where Monte Pirata, at the extreme west end of the island, attains an elevation of 988 feet above mean sea level.

St. Thomas and St. John are characterized by steep topography. The highest land-surface elevations of these two islands are 1,556 feet above mean sea level in St. Thomas and 1,277 feet above mean sea level in St. John (Gómez-Gómez and others, 1984b, p. 409). St. Croix is characterized by low rolling hills. The highest peak in St. Croix is in the Northside Range, where the land-surface elevation is as high as 1,088 feet above mean sea level.

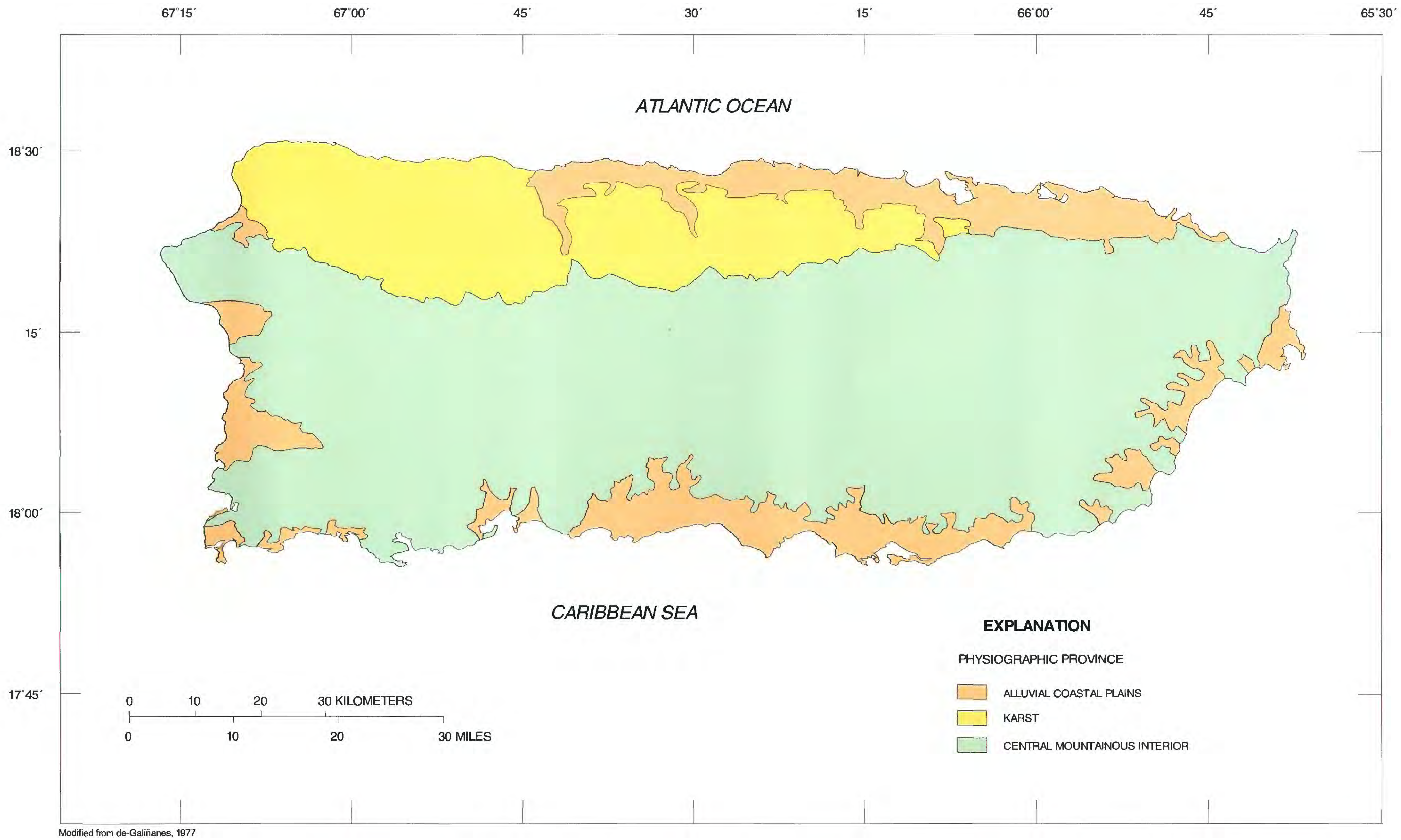
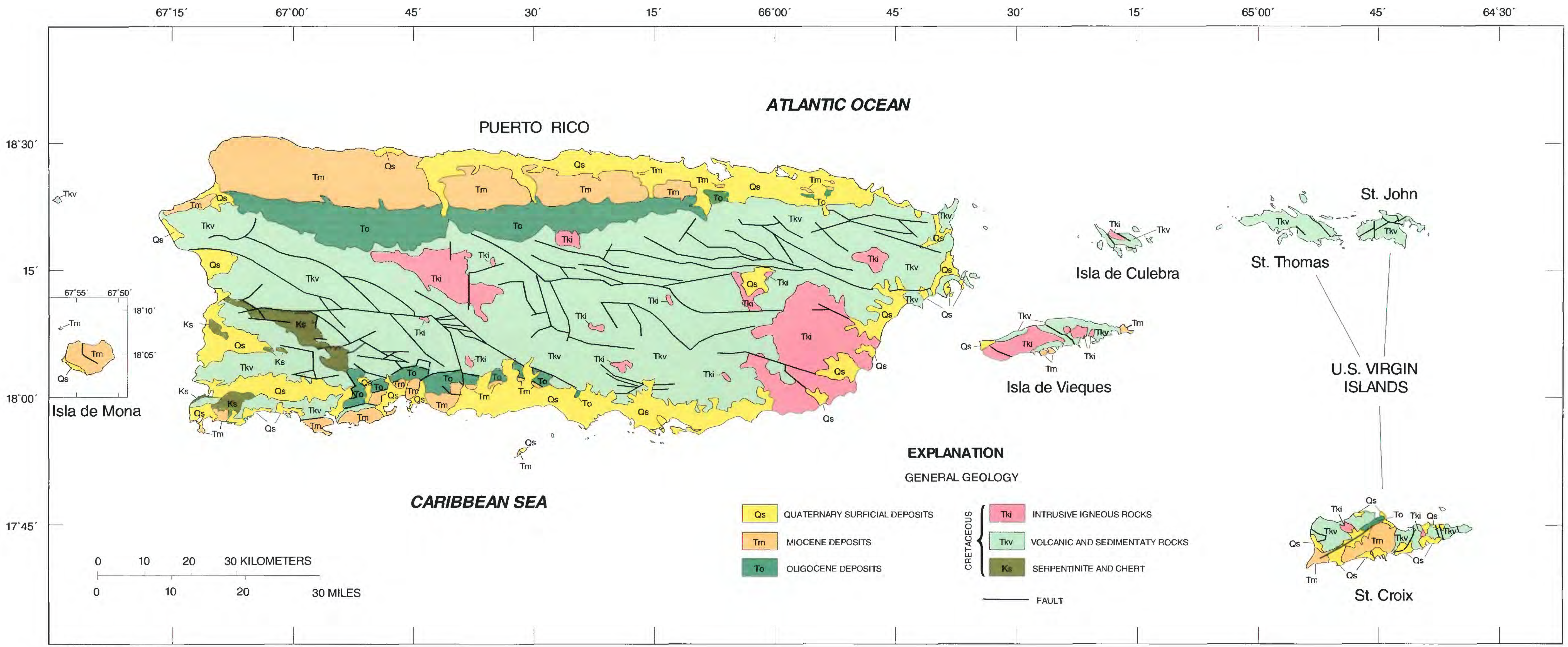


Figure 1.2-2 Physiographic provinces of Puerto Rico.

Puerto Rico and the U.S. Virgin Islands are of volcanic origin. The mountainous interior of Puerto Rico, its offshore islands, and the U.S. Virgin Islands are composed mainly of a mixture of volcanic and sedimentary rocks (fig. 1.2-3). The volcanic rocks include lava, tuff, breccia, and tuffaceous breccia. The sedimentary rocks include siltstone, sandstone, conglomerate, and limestone. Intrusive rocks crop out in several places in the central mountainous interior, especially in the southeastern corner and the western central part of Puerto Rico. These intrusive rocks also crop out in Isla de Culebra and Isla de Vieques. They consist mainly of granodiorite, quartz diorite, and diorite. Minor quantities of quartz porphyry, gabbro, and amphibolite are also present. A large serpentinite and chert deposit crops out in southwestern Puerto Rico.

The Puerto Rico central mountainous interior is flanked by limestone deposits of Tertiary age and by clastic sediments of Quaternary age. The most extensive limestone deposits in Puerto Rico are along the north coast in a band that extends from the northwestern corner of the island to the Río Grande de Loíza in the northeastern corner. This band has a maximum width of 14 miles (Monroe, 1980a, p. 20). In this area along the north coast, a mature karst has developed by dissolution of the limestone. The limestone deposits in the southern part of the island are less extensive and karst features are not as well developed. Limestone rocks similar to those in Puerto Rico are also present in some areas of Isla de Mona, Isla de Vieques, and St. Croix. Clastic sediments that underlie Puerto Rico consist predominately of poorly



Modified from Monroe, 1980a

Figure 1.2-3 General geology of Puerto Rico and the U.S. Virgin Islands.

sorted mixtures of gravel, sand, and finer materials (Quiñones-Márquez and others, 1984b, p. 367). These sediments lie along the north and south coastal plains and in river valleys along the east and west coasts of Puerto Rico. In Isla de Vieques, Isla de Culebra, St. Thomas, and St. John clastic sediments are present in small areas along the coast and within the small river valleys incised by the intermittent streams. In St. Croix, deposits of clastic sediments are more extensive.

Average annual rainfall in Puerto Rico is 70 inches. Rainfall varies geographically and is much more abundant in the northern part of the island than in the southern part, because the latter lies in a rain shadow caused by the central mountain range, which forces the northeasterly trade winds to rise and precipitation to fall on the windward slopes. Annual rainfall ranges from about 30 inches in the western end of the south coast area valleys to about 160 inches near the top of El Yunque (Colón-Dieppa and Torres-Sierra, 1991, p. 475). Rainfall also varies seasonally. The driest month is February and the wettest months are September and October.

Average annual precipitation is 45 inches at St. Thomas and St. John, and 40 inches at St. Croix (Gómez-Gómez and others, 1984, p. 409). Annual rainfall on St. Thomas and St. John ranges from about 40 to 60 inches (Colón-Dieppa and Torres-Sierra, 1991, p. 521). In St. Croix, rainfall patterns are more variable. Annual rainfall averages about 50 inches in northwestern St. Croix and about 20 inches on the eastern end of the island (Colón-Dieppa and Torres-Sierra, 1991, p. 521). Wet and dry seasons are not sharply defined but patterns are similar to those in Puerto Rico. Annual evapotranspiration averages about 45 inches in Puerto Rico and 39 inches in the U.S. Virgin Islands (Gómez-Gómez and Heisel, 1980, p. U1).

1.3 General Land-Use Patterns in Puerto Rico and the U.S. Virgin Islands

The most recent generalized land-use map for Puerto Rico was produced by the Puerto Rico Department of Natural and Environmental Resources (Editorial Cordillera, 1984). The 1977 land-use data has been entered into the Caribbean District Geographic Information System and used to produce a generalized land-use map for Puerto Rico (fig. 1.3-1). This map gives only a general idea of the dominant land uses in the area. For the U.S. Virgin Islands, farmland maps produced by the U.S. Department of Agriculture have been used. These maps show only two land uses: agricultural and residential. The industrial category has been added using USGS topographic maps. The description that follows has been generalized for the purpose of this report.

1.3.A North Coast Area

Agriculture is the predominant land use; largely as pasture and small, family-owned farms. Farmland occupies much of the high, rolling plain in the northern third of the western part of the area and the floodplain of the Río Culebrinas. To the east, farmland predominates where there are small flats or blanket sand filled valleys between limestone hills. Large-scale farming occurs on the flood plains of the Río Grande de Arecibo and Río Grande de Manatí. Sugarcane was once the principal crop in these floodplains. Pineapples are grown on the blanket sands along Highway 2.

Forests occupy most of the karst uplands, which are relatively inaccessible, particularly the area adjacent to the Río Guajataca, and in the southwestern and southeastern North Coast area. Wetlands are not extensive in the western portion of the area. However, large coastal wetlands are common on the coastal plain between Camuy and Manatí.

Most residential areas are near the coast in the towns of Aguadilla, Isabela, Quebradillas, Camuy, Hatillo, Arecibo, Manatí, Barceloneta, Toa Baja, Dorado, and the San Juan metropolitan area. While these urban centers have expanded considerably in recent years, they still occupy a small percentage of the land in the western and central portions of the North Coast area. The only exception to this trend is along the coastal plain from Bayamón to Carolina, where about 90 percent of the land use is residential or urban. Smaller towns and villages are located inland.

Industrial development is not extensive in the western part of the North Coast area, occurring mainly in association with military bases and urban areas. Industrial areas are primarily concentrated in the urban areas along Highway 2 between Arecibo and Manatí and between Bayamón to Carolina near Cataño and along the Bahía de San Juan.

Residential, commercial, and industrial development will probably continue along the more level coastal areas throughout the North Coast area, especially near Guaynabo and Bayamón, as the population in these areas increases and expands into farm land. Changes in land use are unlikely in the more inaccessible karst areas.

1.3.B South Coast Area

Historically, the South Coast area has been one of the most important agricultural areas in the island. As in other agricultural areas in Puerto Rico, sugarcane was the principal crop for many years. However, sugarcane is being replaced by vegetables. The eventual replacement of the sugarcane fields by vegetable crops and the associated changes from furrow to drip irrigation may decrease the water demand for agriculture in an area that depends largely on its ground-water resources. This change from furrow to drip irrigation will also affect the recharge patterns to the alluvial aquifer. Farming is the major activity within the alluvial valleys between Peñuelas and Guánica. Sugarcane production and pastures for dairy cattle have been the most important agricultural activities in this area, with fruits and vegetables generally planted on a small scale.

Forest constitutes the largest land-use category in the mountains in the South Coast area, with agriculture (bananas, citrus fruit, coffee, vegetables, and other crops) a minor land-use category in the region. A xerophytic forest dominates the limestone hills along the coast near Guánica. Wetlands, consisting of both estuarine and palustrine marsh environments, are common along the coast throughout the South Coast area.

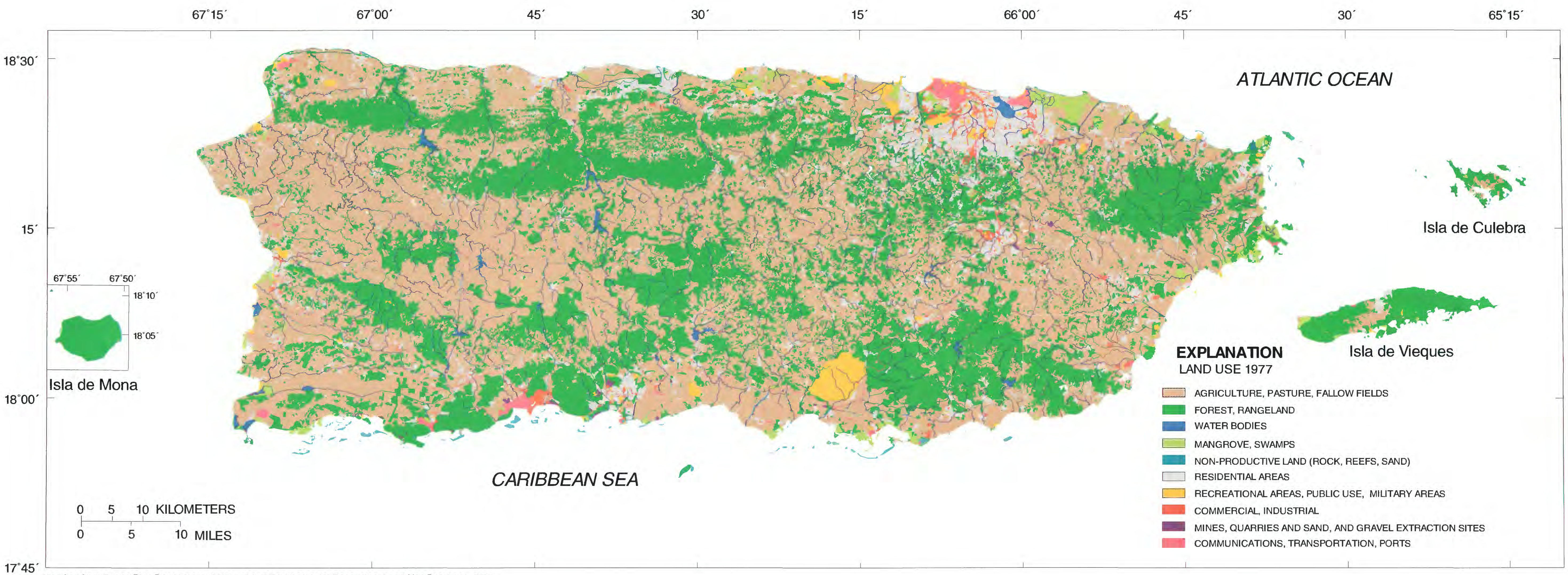
Industrial and urban land use in the South Coast area is most developed between Juana Díaz and Guánica, due to the availability of water sources. The major urban centers in this area are concentrated in the mountains, although rural communities are common throughout the South Coast area. A major industrial center occupies the lower Tallaboa valley, east of Ponce. The Commonwealth Oil Refinery Company was established in the entire lower part of this valley. Other heavy industries were established between Ponce and Guánica in the 1960's. However, many of them ceased operations in the early 1980's, leaving their physical structures behind. A salt industry was also established in this area, which obtains its product from the evaporation of seawater.

1.3.C West Coast Area

The principal land-use category in the West Coast area is agriculture. According to Díaz and Jordan (1987), sugarcane has been the major crop in the Añasco valley in the past. In recent years, however, sugarcane cultivation has decreased. In 1985, almost all of the Central Guanajibo valley was under cultivation with sugarcane, with some cultivation of vegetables and to pasture. In 1972, 19,000 acres of sugarcane were irrigated in the Valle de Lajas for agricultural purposes (Anderson, 1977, p. 3). The next most important land-use category in the Valle de Lajas is pasture, which accounted for 3,500 acres.

Large areas are covered by forest in the hills to the north and northwest of the Central Guanajibo valley. Forested areas are also common in the hills surrounding the Valle de Lajas. Small coastal wetlands are found near the Central Guanajibo valley. The Laguna Cartagena and the Bahía de Boquerón located in the Valle de Lajas, are surrounded by small wetlands.

Major residential areas account for a small percentage of land use in the West Coast area. Principal urban centers include Mayagüez, Añasco, Cabo Rojo, San Germán, Lajas, and Boquerón. Frequent flooding of West Coast area valleys has prevented the establishment of residential communities in low-lying areas. Consequently, the principal urban centers have been built in elevated regions adjacent to the valleys and in their upper reaches, where the effects of flooding are less severe.



Modified from Puerto Rico Department of Natural and Environmental Resources, Land-Use Database, 1977

Figure 1.3-1 General land use in Puerto Rico in 1977.

1.3.D East Coast Area

Historically, the cultivation of sugarcane has been the dominant land use in the alluvial valleys and adjacent highlands of the East Coast area. Sugar mills, to process the sugarcane, were the only sizable industry. Within the last 15 years, an oil refinery, pharmaceutical plants, and light industries, as well as urban areas, have developed. These industries and other agricultural activities such as dairy, livestock, and vegetable farms are replacing the sugarcane economy in the area. Industrial and urban development is concentrated around the towns of Humacao and Yabucoa.

1.3.E East Central Area

In the last several decades, the East Central area has changed from a predominantly agricultural land-use base to industrial, commercial, and residential land uses. Of particular interest is the rapid increase in urbanization in the city of Caguas. Over 90 percent of the Caguas valley falls within the industrial and high-density residential land-use categories. In recent years, the city of Caguas has served as a residential suburb of the San Juan metropolitan area. The main agricultural land-use category has changed from sugarcane cultivation to dairy farms. Although the towns of Gurabo, Juncos, and Las Piedras also have grown, the changes in these areas are less dramatic than the changes in the vicinity of Caguas. The northeastern and southern parts of the East Central area contain the largest forested areas, including the northwestern extremity of the Caribbean National Forest of El Yunque.

1.3.F Puerto Rico Offshore Islands: Isla de Culebra and Isla de Vieques

The interior of Isla de Culebra is primarily used for pasture. The rest of the island is covered by brush or secondary growth forest (fig. 1.3-1). The town of Dewey and surrounding areas are residential and commercial. A number of individual homes and small resorts are scattered throughout the island. The Península Flamenco on the northwest corner of Isla de Culebra was once used as a gunnery impact area by the U.S. Navy. This area has been designated a wildlife refuge.

A large part of Isla de Vieques is devoted to military use. The eastern quarter of the island serves as a gunnery impact area. Adjacent to the impact area, and encompassing an additional fourth of the island, is Camp García, a U.S. Marine Corps training facility. The western quarter of the island is also under military control. About half of this area is covered by brush, with the rest covered by grassland and leased for grazing. There are a number of ammunition bunkers in the area, a few of which are still in use.

Residential land use is concentrated in areas of Isla de Vieques not under military control, particularly around the town of Isabel Segunda on the north coast and Esperanza on the south coast. There is some light industrial development at Isabel Segunda and on a peninsula near Ensenada Honda. Small grazing enterprises occupy the non-residential and the non-military areas of the island.

1.3.G U.S. Virgin Islands

St. Thomas is an urban island (fig. 1.3-2). Charlotte Amalie, the only city, occupies a relatively small area on the south coast. However, in at least six other areas on the island, the density of housing and commercial areas approaches that in Charlotte Amalie. Residential subdivisions are present throughout the island. Agricultural usage is minimal. There are a few small areas in pasture and devoted to truck farming. The remainder of the land is covered by brush and secondary forest.

Two-thirds of St. John is a National Park (fig. 1.3-2). There are some private holdings in the Park area, mostly individual residences. The Park land and much of the privately owned land outside the Park is in brush and secondary forest. The village of Cruz Bay and vicinity make up a lightly populated urban area on the western end of the island. The same is true of Coral Bay, on the eastern end of the island.

In the past, nearly all of St. Croix was under sugarcane or cotton cultivation, or was in pasture. Agricultural usage has declined, but some land is still used for pasture (Jordan, 1975, p. 1; fig. 1.3-3). Although about one third of St. Croix has soil suitable for agriculture, only about 5,000 acres are under cultivation. The remainder of the island is generally undeveloped, except for about 2,000 acres of urban or industrial areas.

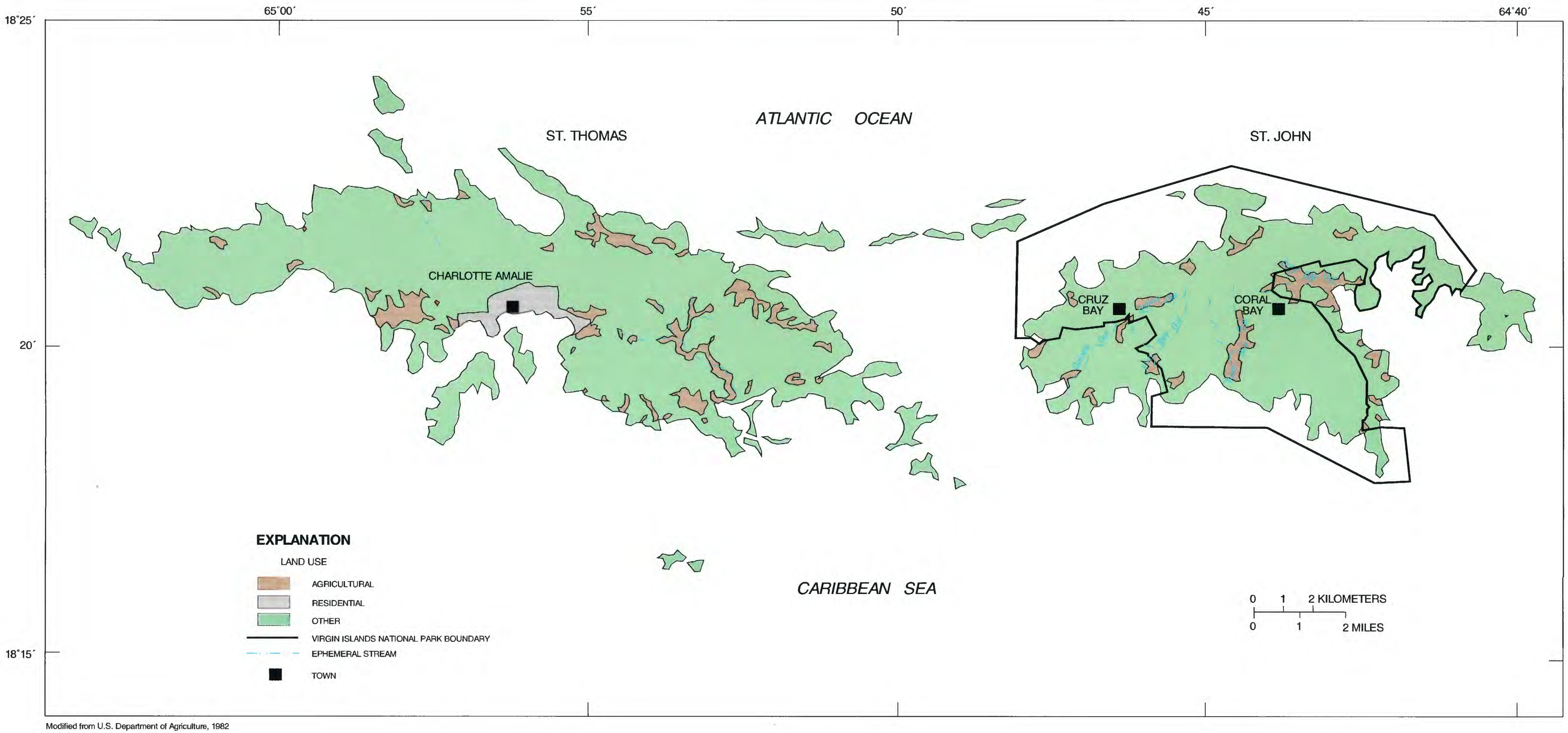
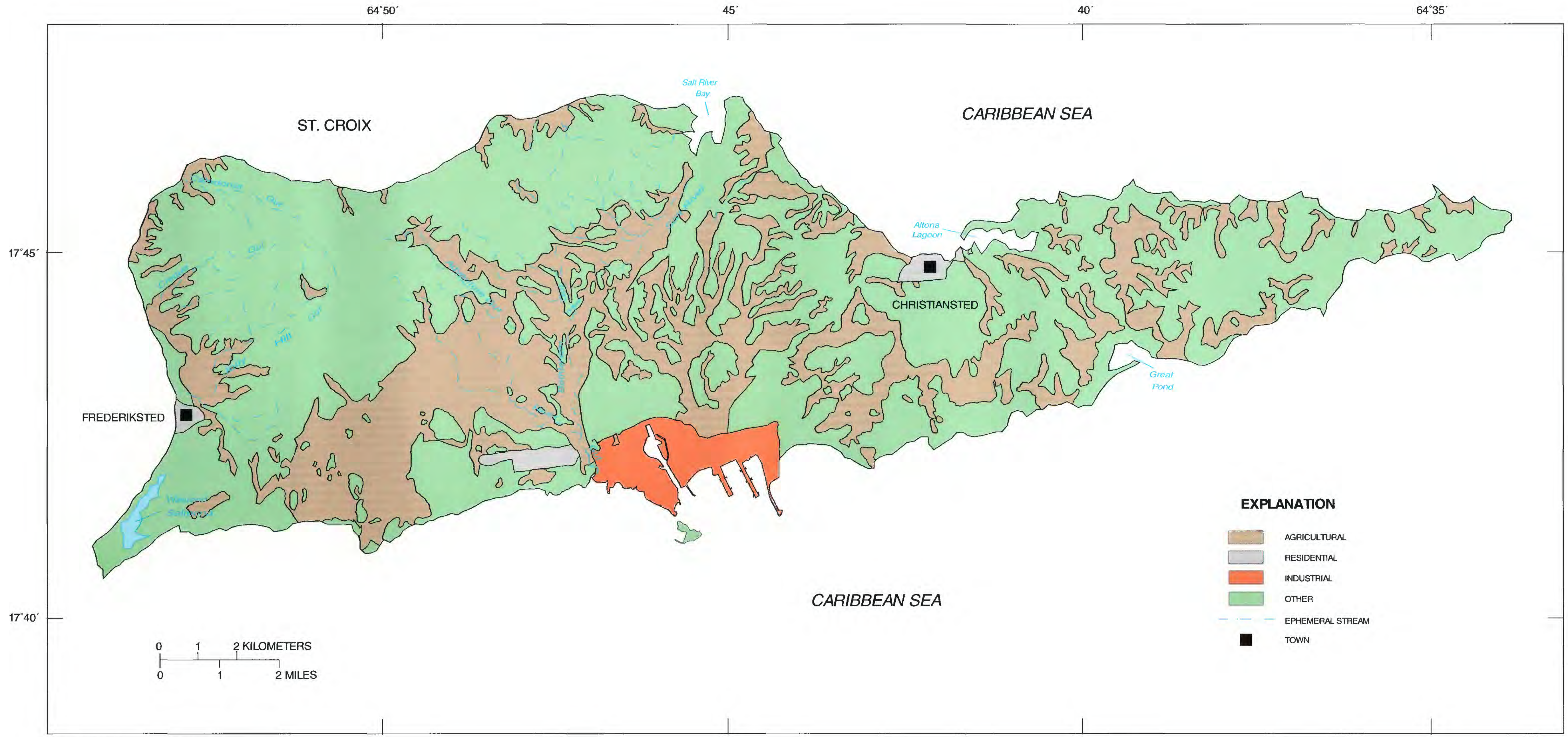


Figure 1.3-2 Generalized land use in St. John and St. Thomas, U.S. Virgin Islands.



Modified from U.S. Department of Agriculture, 1982

Figure 1.3-3 Generalized land use in St. Croix, U.S. Virgin Islands.

2.0 GROUND-WATER RESOURCES AREAS IN PUERTO RICO

2.1 North Coast Area

2.1.1 AGUADILLA-HATILLO REGION

By Patrick Tucci

2.1.1.A Location and Major Geographic Features

The Aguadilla-Hatillo region covers about 400 mi^2 in the westernmost part of the North Coast area. The region extends about 37 miles from the west end of the island to the approximate position of the divide between the Río Camuy and the Río Grande de Arecibo (fig. 2.1.1.A-1). The region is bordered on the south by rocks of the volcanic island core, on the west by the Mona Passage, and on the north by the Atlantic Ocean. Rolling plains and karst features dominate the central and northern areas. The municipios of Rincón, Aguada, Aguadilla, Isabela, Quebradillas, Camuy, and Hatillo are located along the coast, and the municipios of Moca, San Sebastián, and Lares are located inland (fig. 2.1.1.A-1).

The coast is lined by cliffs that, in places, rise more than 200 feet above mean sea level. Much of the south portion of the region is marked by an escarpment of several hundred feet cut by the Río Culebrinas. The northern third of the region is a rolling plain that lies from about 200 to 400 feet above mean sea level, and is bounded on the north by sea cliffs and on the south by karst landforms. Two northward flowing rivers cut across the karst area. The Río Guajataca flows through a deep canyon formed by the collapse of a cave system, and the Río Camuy flows, in part, through a cave system and, in part, through a canyon formed by the collapsed parts of a cave. Lago Guajataca, in the east central part of the region, is a large, man-made reservoir used for public-water supply.

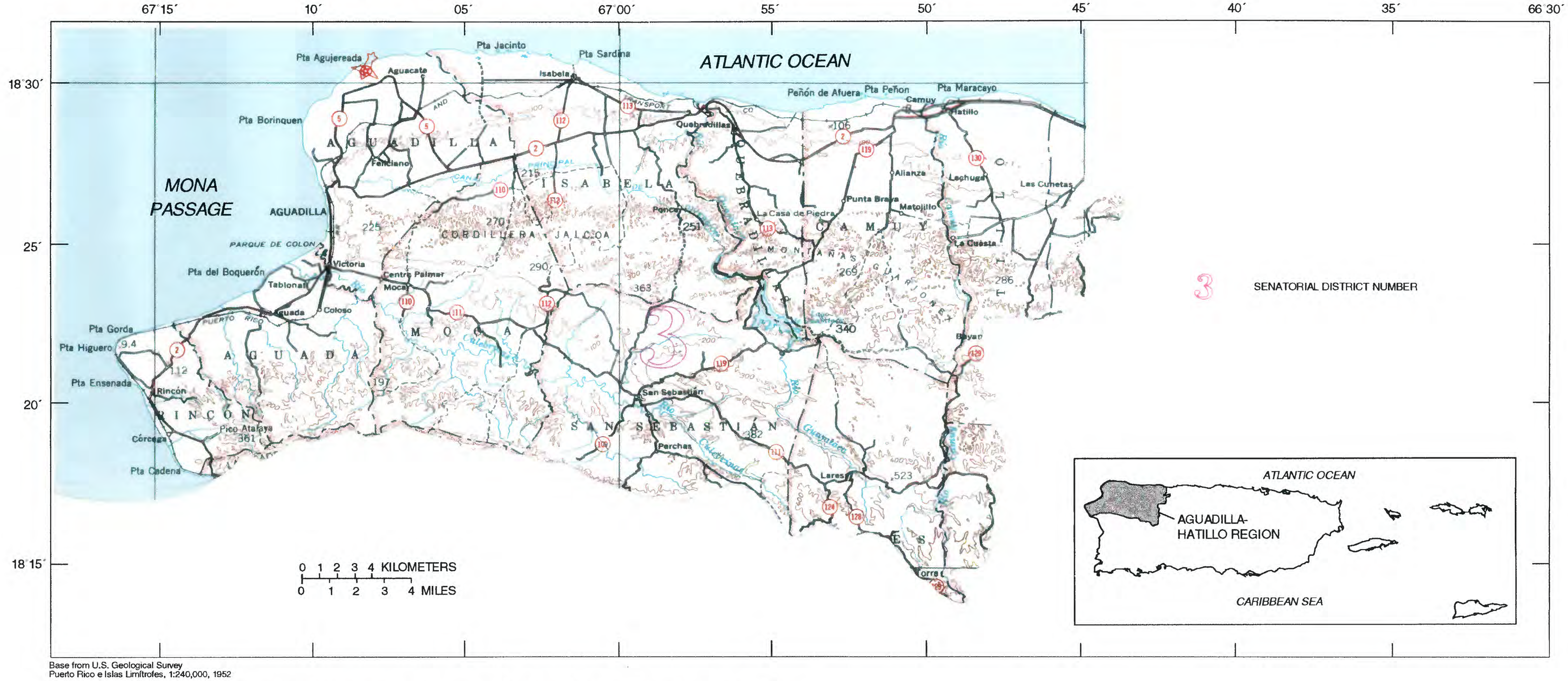
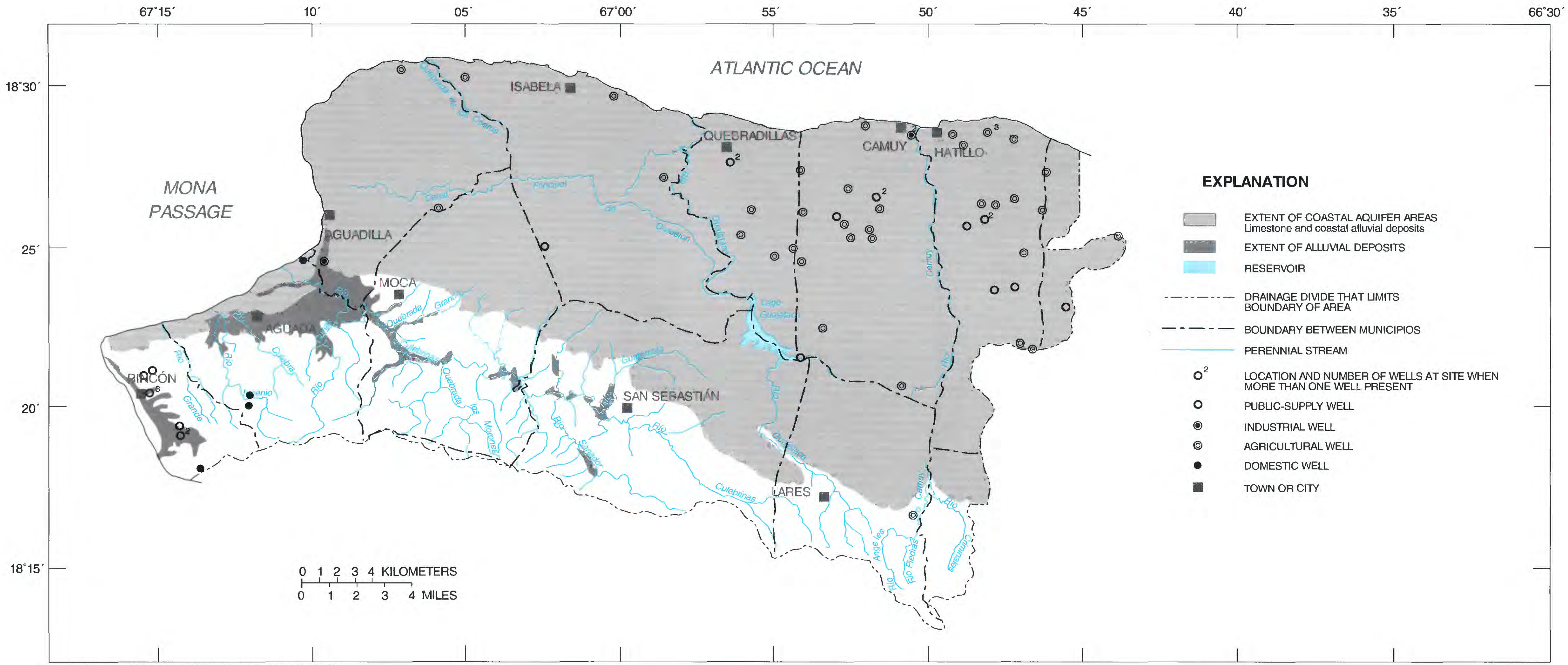


Figure 2.1.1.A-1 Location and major geographic features in the Aguadilla-Hatillo region, Puerto Rico.

2.1.1.B Population and Estimated Ground-Water Use

The population of the Aguadilla-Hatillo region was about 257,000 in 1980 and 282,000 in 1990, an increase of about 9 percent (U.S. Department of Commerce, 1982, 1991; Gómez-Gómez and others, 1984; table 2.1.1.B-1). About 74 percent of the population lives on farms and in rural communities, and the remainder (26 percent) lives in urban areas. The largest municipio is Aguadilla, which had a total population of about 55,000 in 1980 and 59,000 in 1990 (table 2.1.1.B-1).

Ground-water pumpage for domestic use is limited, because most water for public supply is obtained from Lago Guajataca. About 25 Mgal/d of water from Lago Guajataca was used for public supply in 1983 (Gómez-Gómez and others, 1984). Ground water withdrawn in 1983 totalled about 2 Mgal/d, and supplied approximately 12 percent of the population (1980 population estimate; table 2.1.1.B-2). A rural water-supply system in the municipio of Lares uses about 0.01 Mgal/d of ground water. About 6,000 gal/d of ground water was pumped for industrial use in the municipio of Aguadilla. The approximate location of public-supply and industrial wells are shown in figure 2.1.1.B-1.



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.1.1.B-1 Approximate well locations in the Aguadilla-Hatillo region, Puerto Rico.

Table 2.1.1.B-1 Population for the Aguadilla-Hatillo region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Aguadilla	54,606	22,039	32,567	59,335
Moca	29,185	3,960	25,225	32,926
Isabela	37,435	12,087	25,348	39,147
San Sebastián	35,690	10,619	25,071	38,799
Quebradillas	19,728	3,770	15,958	21,425
Lares	26,743	5,224	21,519	29,015
Camuy	24,884	3,680	21,204	28,917
Hatillo	28,958	5,019	23,939	32,703
Total	257,229	66,398	190,831	282,267

2.1.1.C Geologic Setting

Sedimentary rocks are the predominant rock type in the Aguadilla-Hatillo region. They unconformably overlie volcanic rocks (fig. 2.1.1.C-1). The sedimentary rock formations dip northward toward the Atlantic Ocean at an average angle of 3 to 4 degrees. The following description is summarized from Monroe (1980a).

The sedimentary rocks, predominately limestone and calcareous clays of Tertiary age, are probably as much as 5,000 to 6,000 feet thick at the Atlantic coastline. The basal San Sebastián Formation of Tertiary age is primarily a clay in the eastern part of the region, but contains gravel and cobbles in the western part. The San Sebastián Formation ranges in thickness from near zero to about 300 feet. The five overlying formations (Lares Limestone, Cibao Formation, Aguada Limestone, Aymamón Limestone, and Camuy Formation) are predominately limestone, marls, or calcareous clays deposited in a shallow sea, when sea level altitude was higher than in recent geologic times.

The Lares Limestone, overlying the San Sebastián Formation, consists primarily of a fine- to medium-grained limestone. In the western part of the Aguadilla-Hatillo region, the Lares Limestone grades laterally into clastic beds indistinguishable from the San Sebastián Formation. The Lares Limestone ranges in thickness from near zero to about 1,000 feet in this region.

The Cibao Formation overlies the Lares Limestone and is made up of interbedded calcareous clay, limestone, sandy clay, and sand and gravel. In the Aguadilla-Camuy region, the Cibao Formation typically is composed of beds of chalk, marl, and calcareous clay. The Cibao Formation contains significant amounts of sand and gravel near the municipio of San Sebastián, and contains limestone in the lower part of the formation in the Río Camuy area. The Cibao Formation is about 650 feet thick in the Aguadilla-Hatillo region.

The Aguada Limestone, overlying the Cibao Formation, consists primarily of limestone containing chalky beds in the lower part and nearly pure, indurated limestone in the upper part. The Aguada Limestone is about 300 feet thick in the Aguadilla-Hatillo region.

The Aymamón Limestone overlies the Aguada Limestone and consists of a very pure limestone containing almost no sand or clay. In the Aguadilla-Hatillo region, the Aymamón Limestone can be separated into two members. The lower member has been extensively altered, recrystallized, and solution riddled by percolating ground water. The upper member is predominately a chalk interbedded with limestone. The total thickness of the Aymamón is about 600 feet in this region.

Table 2.1.1.B-2 Ground-water withdrawals and estimated population served during 1983 for the Aguadilla-Hatillo region, Puerto Rico
[Mgal/d, million gallons per day; ---, no data available]

[1] Use and supplier		Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use			
[2]A. Puerto Rico Aqueduct and Sewer Authority			
1. Aguadilla		---	---
2. Moca		[3]921	0.058
3. Isabela		[3]112	0.007
4. San Sebastián		---	---
5. Quebradillas		[3]4334	0.273
6. Lares		---	---
7. Camuy		14,399	0.561
8. Hatillo		10,138	0.953
	Subtotal	29,904	1.852
[4]B. Community Systems			
1. Lares		632	0.095
[4]II. Industrial Use			
1. Aguadilla		---	0.006
	Total	30,536	1.953

[1] Municipios not listed under some specific use do not withdraw ground water for the subject use.
[2] Modified from data reported by Gómez-Gómez and others, 1984.
[3] Based on a water consumption of 63 gallons per person per day.
[4] Modified from data reported by a written communication of the Puerto Rico Department of Health.

The Camuy Formation is predominately limestone with sand. The lower members of the Camuy Formation consist of chalk or chalky limestone, and contain appreciable quantities of quartz sand. The upper member of the Camuy Formation is a mixture of chalk, limestone, and calcareous sandstone. The total thickness of the Camuy Formation in this region ranges from about 350 to 550 feet.

The Aguadilla-Hatillo region has more karst features per square mile than any other part of the north coast limestone (Giusti, 1978, p. 9). The greatest karst development is in the Aymamón Limestone and the Lares Limestone. Areas of little or no karst development are primarily limited to the outcrop area of the Cibao and San Sebastián Formations. Relatively little karst has developed on the Camuy Formation. The Camuy Formation forms a rolling plain of 100 to 600 feet above mean sea level in most of its outcrop area. Tertiary and Quaternary blanket sands are widespread and overlie large areas of the Aymamón Limestone and the Camuy Formation.

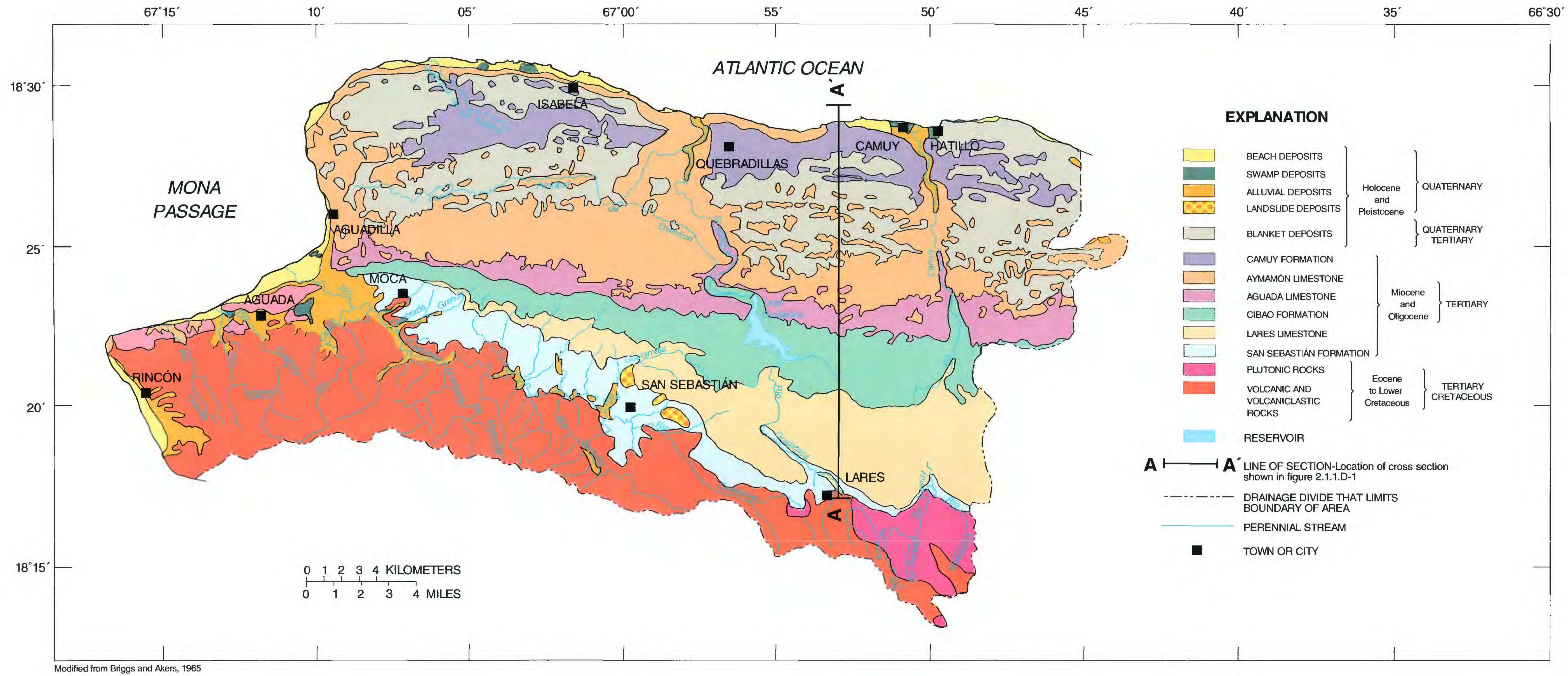


Figure 2.1.1.C-1 Generalized surficial geology in the Aguadilla-Hatillo region, Puerto Rico.

2.1.1.D Hydrogeology

The water-table aquifer, consisting of the saturated parts of the Aguada and Aymamón Limestones (fig. 2.1.1.D-1), is the primary source of ground water in the Aguadilla-Hatillo region. Localized areas of confined ground water may be present within water-bearing zones of the Cibao Formation and Lares Limestone; however, the extent of these zones in the Aguadilla-Hatillo region is unknown. Extensive artesian zones, if present, will likely be located east of the Río Guajataca. Less is known about the hydrogeology of the Aguadilla-Hatillo region than in other areas of the North Coast.

The areal extent and thickness of the water-table aquifer is controlled by the location of the top of the Cibao Formation and the location of the saline-freshwater interface, which forms the base of the aquifer. The maximum thickness of the water-table aquifer is approximately 450 feet, about 4 miles inland from the Atlantic Ocean south of Isabela (Jesús Rodríguez-Martínez, U.S. Geological Survey, written communication, 1991). The aquifer is generally less than 100 feet thick at distances of 2 miles or less from the coast, due to the presence of saline water with depth.

Hydraulic-conductivity values of the limestones along the north coast generally are smaller in the Aguadilla-Hatillo region than in other regions of the North Coast. Limestones in this region may be an order of magnitude less permeable than limestones in the area immediately to the east. Guisti (1978, p. 25) estimated hydraulic-conductivity values of the Lares Limestone, Cibao Formation, Aguada Limestone, and Aymamón Limestone to be 0.6, 1.4, 5.7, and 57 feet per day (ft/d), respectively. Analysis of specific-capacity tests of wells in the region result in similar estimates of hydraulic-conductivity values. Cavernous zones in the limestones, encountered during drilling of test wells, may indicate localized areas of significantly greater

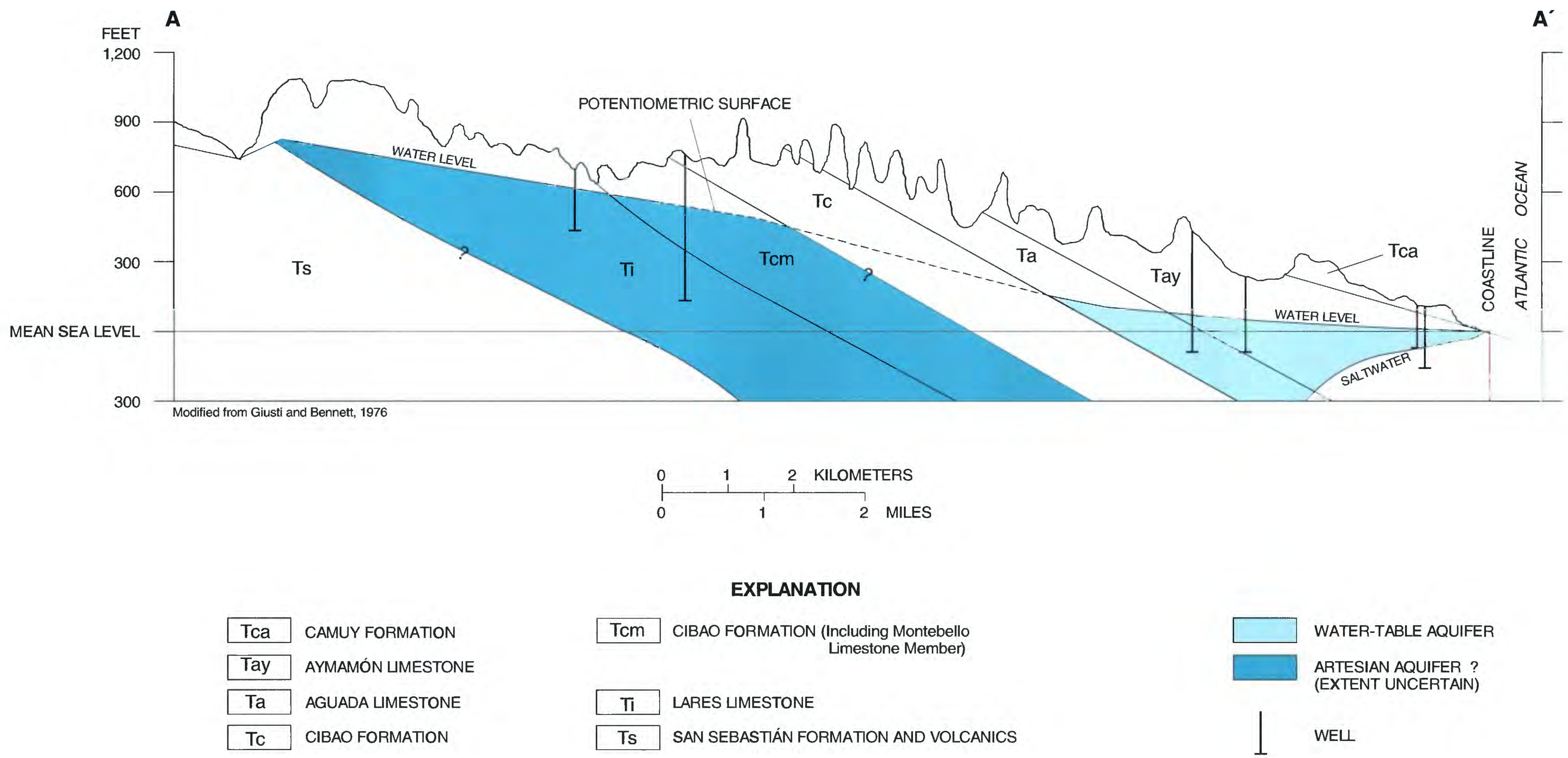


Figure 2.1.1.D-1 Hydrogeologic section in the Aguadilla-Hatillo region, Puerto Rico (line of section shown in figure 2.1.1.C-1).

hydraulic conductivity. The transmissivity of the water-table aquifer generally is less in this region than in other regions of the North Coast area, because of the low hydraulic conductivity and the relatively thin saturated thickness. Transmissivity values generally are less than 5,000 ft^2/d, and range from less than 0.1 ft^2/d where the aquifer pinches out to about 10,000 ft^2/d in areas where the saturated thickness of the Aymamón Limestone and depth to saline water is greatest. Parts of the Aguada and Aymamón Limestones and all of the Camuy Formation are above the water table, and are not part of the aquifer in this region.

The amount of recharge to the ground-water system in the region is unknown. Estimated recharge in a geologically similar region near Barceloneta is about 60 Mgal/d (Torres-González, 1985, p. 26).

2.1.1.E Ground-Water Levels and Movement

Ground-water flow in the Aguadilla-Hatillo region is from recharge areas in the karstic highlands in the center of the North Coast area towards coastal areas to the north and west and towards the Río Culebrinas to the south (fig. 2.1.1.E-1). The water-table map shown in figure 2.1.1.E-1 is for the wet season in November and December 1984. Water levels during that time were somewhat higher than average annual water levels; however, the shape of the water-table contours and the overall pattern of ground-water flow are probably similar throughout the year. Because of the relatively small number of wells available for water-level measurements, the water-table map should be considered only a generalized representation of the water table from which overall patterns of ground-water flow can be estimated.

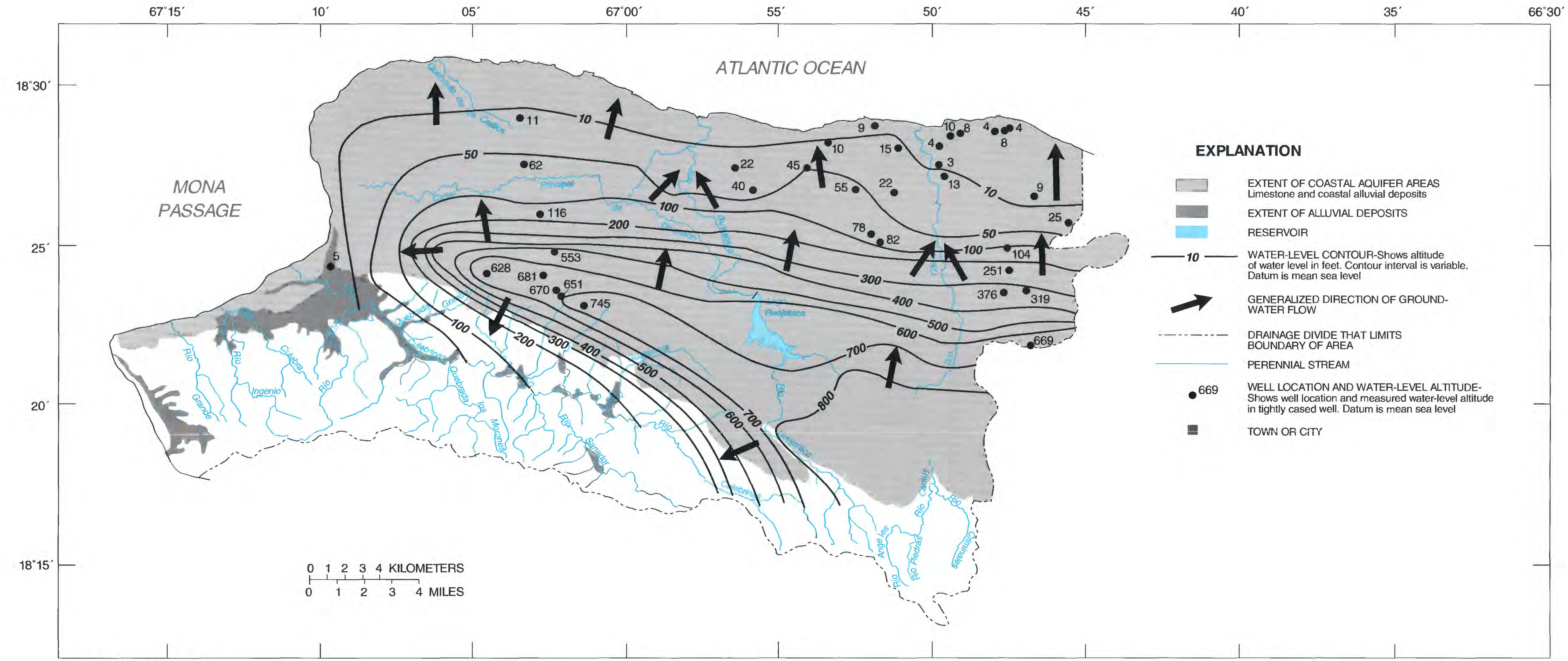


Figure 2.1.1.E-1 Altitude of water-level surface and direction of ground-water flow during November 1984 in the Aguadilla-Hatillo region, Puerto Rico.

Locally, ground water also flows to the Río Guajataca and Río Camuy. This component of flow is not apparent on the water-table surface map (fig. 2.1.1.E-1), because of the large scale of the map and the scarcity of water-level measurements in wells near the rivers. Giusti (1978, p. 35) estimated that from about 30 to 40 percent of the total flow of the lower parts of the Río Camuy and Río Guajataca is base flow, which is the ground-water contribution to the stream. The Quebrada de los Cedros, in the extreme northwestern part of the region, is usually dry and flows only after prolonged rainfall (Giusti, 1978, p. 34). This small stream provides a small amount of ground-water recharge by leakage through the streambed following rainstorms.

The amount of ground water discharging directly to the sea is unknown. A large spring located just 600 feet inland of the coastline in Aguadilla had an average discharge of 1.1 ft^3/s from December 1982 through January 1984 (Guzmán-Ríos, 1988, p.11). Several offshore springs have been documented, or their existence inferred, by remote-sensing techniques (Percious, 1971; Blume and others, 1981), but their discharge is unknown.

Several tributaries on the north side of the Río Culebrinas originate as springflow from the escarpment on the southern edge of the Aguadilla-Hatillo region. The total amount of this springflow and the total amount of ground-water discharge along the southern boundary of the region are unknown.

2.1.1.F Soil Permeability

Soil development can be divided physiographically into five areas: coastal plain, flood plain, limestone upland, volcanic upland, and upland valley (fig. 2.1.1.F-1). These areas are characterized by different morphology and parent material upon which soils developed. Coastal plain soils are developed on level to gently sloping surfaces. Five soil associations are developed on the coastal plain; permeability for these soils ranges from 0.60 to 20.00 in/hr (table 2.1.1.F-1). Two soil associations are developed on the nearly level flood plains, and these are prone to frequent flooding. Soil permeability of the flood plain generally is less than that in the coastal plain, and ranges from 0.06 to 2.00 in/hr. The four soil associations on limestone uplands tend to be thinner than those in other areas (table 2.1.1.F-1) and rock outcrops are common. Slopes are moderate to very steep in these uplands, and soil permeability ranges from 0.60 to 20.00 in/hr. The four soil associations on volcanic uplands are developed on gently sloping to steep slopes, and permeability ranges from 0.60 to 2.00 in/hr. The two soil associations in upland valleys may be on sloping to very steep areas or on ridgetops, and permeability ranges from 0.06 to 2.00 in/hr.

The most permeable soils (2.00 to 20.00 in/hr) in the Aguadilla-Hatillo region are developed along the coast, but are of limited extent (fig. 2.1.1.F-1). The least permeable soils (0.06 to 0.60 in/hr) are found on flood plains or upland valleys. Most of the region is covered by soils of moderate permeability, ranging from 0.6 to 2.00 in/hr.

Table 2.1.1.F-1 Thickness, permeability, and available water capacity for soil associations in the Aguadilla-Hatillo region, Puerto Rico (Modified from Gierbolini, 1975; Acevedo, 1982)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Coastal Plain	42 to 75	0.60 to 20.00	0.04 to 0.20
Bejucos-Jobos	55 to 72	2.00 to 20.00	0.05 to 0.15
Guerrero-Carrizales-Jobos	55 to 60	2.00 to 20.00	0.04 to o.20
Coto-Aceitunas	65 to 75	0.60 to 2.00	0.10 to 0.20
Almirante-Espinosa-Vega Alta	64 to 70	0.60 to 6.00	0.06 to 0.20
Bayamón-Matanzas	42 to 65	0.60 to 6.00	0.06 to 0.20
Flood Plains	60 to 63	0.06 to 2.00	0.12 to 0.20
Coloso-Toa	60 to 63	0.06 to 2.00	0.12 to 0.20
Toa-Coloso-Bajura	60 to 63	0.06 to 2.00	0.12 to 0.20
Limestone Uplands	10 to 60	0.60 to 20.00	0.05 to 0.25
Colinas-Soller	25 to 60	0.60 to 2.00	0.09 to 0.25
Limestone Outcrop-San Sebastián	0 to 55	0.60 to 2.00	0.15 to 0.20
Rock-Tanamá-San Sebastián	16 to 55	0.60 to 2.00	0.15 to 0.20
Soller-San Germán-Rock Outcrop	10 to 25	6.00 to 20.00	0.05 to 0.25
Volcanic Uplands	18 to 62	0.60 to 2.00	0.05 to 0.24
Voladora-Moca	50 to 60	0.60 to 2.00	0.15 to 0.24
Caguabo-Múcara	18 to 27	0.60 to 2.00	0.05 to 0.17
Consumo-Humatas	50 to 56	0.60 to 2.00	0.10 to 0.18
Humatas-Los Guineos-Alonso	56 to 62	0.60 to 2.00	0.10 to 0.18
Upland Valleys	56 to 60	0.06 to 2.00	0.09 to 0.20
Moca-Perchas	58 to 60	0.06 to 0.60	0.15 to 0.24
Colinas-Naranjo-Juncal	0 to 60	0.60 to 2.00	0.09 to 0.20

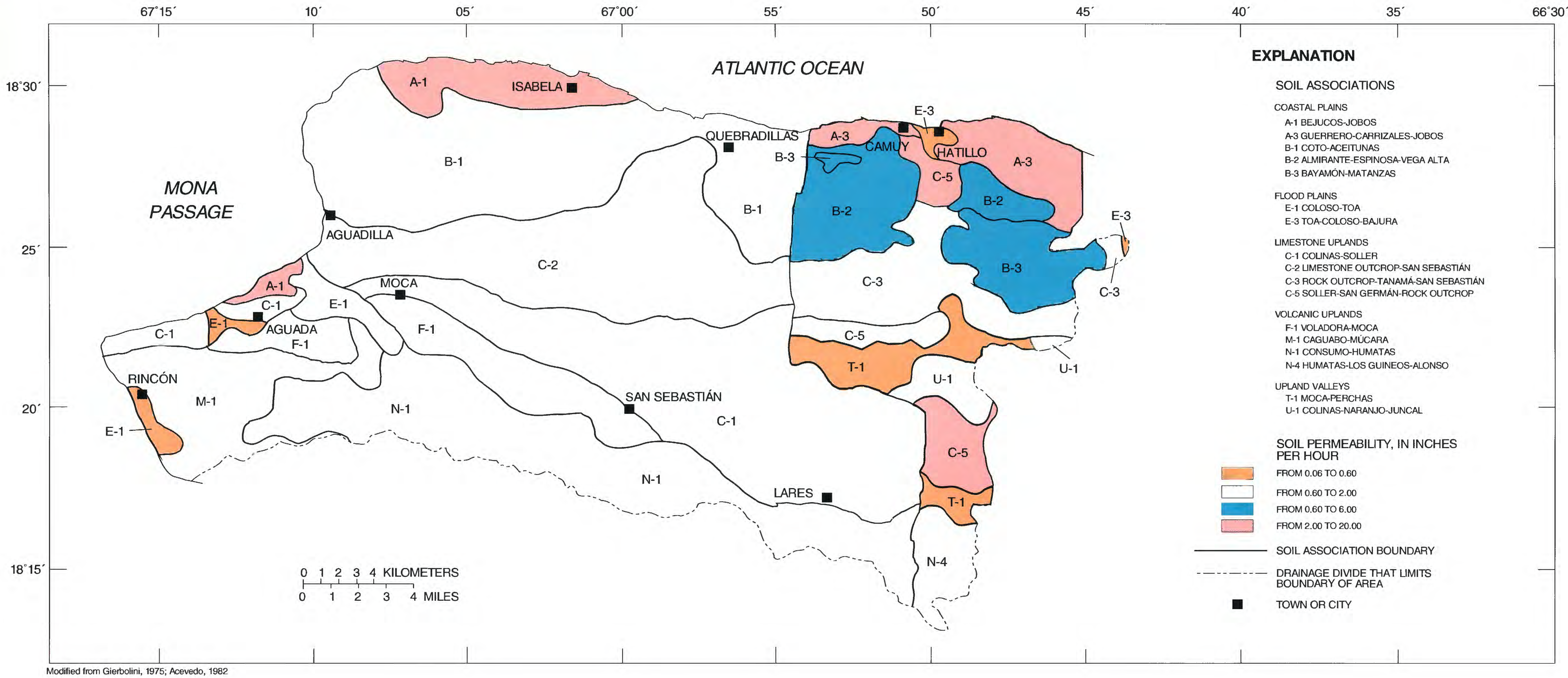


Figure 2.1.1.F-1 Soil associations and permeability in the Aguadilla-Hatillo region, Puerto Rico.

2.1.2 ARECIBO-MANATÍ REGION

By Angel Román-Más

2.1.2.A Location and Major Geographic Features

The Arecibo-Manatí region is located in the west-central part of the North Coast area. The Arecibo-Manatí region extends 23 miles from the western drainage divide between the Río Camuy (fig. 2.1.1.A-1) and Río Grande de Arecibo to the eastern drainage divide, 2 miles east of the Río Grande de Manatí (fig. 2.1.2.A-1). The southern boundary is the contact between the limestone belt and the undifferentiated lower Tertiary and Cretaceous rocks of the island core. The northern boundary is the Atlantic Ocean. The Arecibo-Manatí region is comprised of three major drainage basins, the Río Grande de Arecibo, Río Tanamá, and Río Grande de Manatí. The Río Grande de Arecibo and the Río Grande de Manatí flow northward from the island's mountainous core into entrenched valleys and discharge to the Atlantic Ocean. The Río Tanamá, a principal tributary of the Río Grande de Arecibo, flows to the northeast.

The valley floors of the Río Grande de Arecibo and Río Grande de Manatí have gently sloping surfaces ranging in elevation from mean sea level to about 80 feet above mean sea level at the contact with the limestones. In contrast, the elevation of the limestones range from about 1,200 feet above mean sea level in the southern part of the region to a few tens of feet above mean sea level in the coastal lowlands. The most prominent feature of the coastal lowland is the Caño Tiburones, a sea level swamp that was largely drained for agriculture in 1949.

The major population centers in the Arecibo-Manatí region are the cities of Arecibo, Manatí, and Barceloneta. Industrial development in the region has mainly focused on the establishment of pharmaceutical industries that form one of the largest pharmaceutical manufacturing centers in the world. Urban and industrial development has been concentrated within a few miles of the coast, because of the nearly inaccessible karst terrain further inland.

2.1.2.B Population and Estimated Ground-Water Use

The total population within the Arecibo-Manatí region was about 253,000 in 1980 (U.S. Department of Commerce, 1982). However, total population of the municipios overlying the aquifer areas (Arecibo, Barceloneta, Ciales, Florida, and Manatí) totalled about 166,000. About 53 percent of the population in these municipios lives in the urban areas. The remainder of the population (47 percent) lives in small villages, rural communities, and on farms. Population in these municipios increased by about 8 percent in 1990 (Puerto Rico Planning Board, written communication, 1991). The 1980 and 1990 population distribution in all the municipios within this region is shown in table 2.1.2.B-1. The total ground-water pumpage for the region was about 25 Mgal/d in 1983. The Puerto Rico Aqueduct and Sewer Authority public-water supplies accounted for 76 percent (18.5 Mgal/d) of the total ground-water withdrawals in the region. The estimated population served was about 139,000 (table 2.1.2.B-2). Well location or well fields furnishing water for the different uses are shown on figure 2.1.2.B-1. In this report, domestic use refers to public-water supply and self-supplied users.

The major industries in the Arecibo-Manatí region obtain water from wells. Pumping for industrial use accounts for about 17 percent (4.2 Mgal/d) of the total ground water withdrawn. Most of the ground water used for industrial purposes comes from the deep artesian limestone aquifer. Agriculture accounted for about seven percent of the total ground-water withdrawal in 1983 (1.7 Mgal/d); agricultural use occurs mostly in the Arecibo area where ground water has been used for rice irrigation (Román-Más, 1988).

Table 2.1.2.B-1 Population for the Arecibo-Manatí region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; Puerto Rico Planning Board, written communication, 1991)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Adjuntas	18,786	5,239	13,547	19,451
Arecibo	86,766	48,779	37,987	93,385
Barceloneta	18,942	4,502	14,440	20,947
Ciales	16,211	3,582	12,629	18,084
Florida	7,232	3,641	3,591	8,689
Jayuya	14,722	3,588	11,134	15,527
Manatí	36,562	17,347	19,215	38,692
Orocovis	19,332	1,256	18,076	21,158
Utuado	34,505	11,113	23,392	34,980
Total	253,058	99,047	154,011	270,913

2.1.2.C Geologic Setting

Sedimentary rocks, predominately limestones of Tertiary age, are the principal rocks in the Arecibo-Manatí region (fig. 2.1.2.C-1). These limestones rest on a volcanic base of Early Cretaceous to middle Eocene age and range in thickness from near zero, where they abut the volcanic rocks of the island core, to nearly 6,000 feet at the coastline (fig. 2.1.2.C-2, a). The San Sebastián Formation is the base of the Tertiary rock sequence. In the Arecibo-Manatí region the San Sebastián Formation is predominately clay, sandy-clay, and sandy limestone derived from sediment carried by major rivers to the sea and deposited along a former coastline. The five formations overlying the San Sebastián Formation are mostly limestones deposited in shallow seas (Monroe, 1976 and 1980a). They are the Lares Limestone, Cibao Formation, Aguada Limestone, Aymamón Limestone, and Quaternary deposits.

The Lares Limestone overlies the San Sebastián Formation and consists of a nearly pure limestone containing abundant reef-forming organisms. The Cibao Formation, overlying the Lares Limestone, consists of many members having a heterogeneous lithology varying from limestone to sand, to clay and clayey sand. In the Arecibo-Manatí region, the Montebello Limestone Member of the Cibao Formation, a thick reefal type deposit, overlies the Lares Limestone. In turn, the Montebello Limestone Member is overlain by calcareous clay and sand considered to be typical of the upper Cibao Formation. The Aguada Limestone overlies the Cibao Formation and is a nearly pure limestone probably deposited in a fringing reef-backreef

Table 2.1.2.B-2 Ground-water withdrawals and estimated population served during 1983 for the Arecibo-Manatí region, Puerto Rico
[Mgal/d, million gallons per day; ---, no data available]

[1] Use and supplier		Estimated population served	Average ground-water withdrawals (Mgal/d)
[2]I. Domestic Use			
1. Arecibo		64,705	6.623
2. Barceloneta		20,326	3.725
3. Florida		8,264	1.073
4. Ciales		6,739	0.763
5. Manatí		38,671	6.379
	Subtotal	138,695	18.563
[3]II. Industrial Use			
1. Arecibo		---	0.044
2. Barceloneta		---	2.845
3. Manatí		---	1.750
	Subtotal	---	4.639
[3]II. Agricultural Use			
1. Arecibo		---	1.629
2. Barceloneta		---	0.045
3. Manatí		---	0.052
	Subtotal	---	1.726
	Total	138,695	24.928

[1] Municipios not listed under some specific use do not withdraw ground water for the subject use.

[2] Modified from data reported by Gómez-Gómez and others, 1984.

[3] Modified from Industrial Ground-Water Inventory, November-December 1985.

environment. The Aymamón Limestone, overlying the Aguada Limestone, is also a reef deposit but differs in that much of the Aymamón Limestone is more of a chalk than a crystalline limestone. The Quaternary deposits overlies the Aymamón Formation and are present only in scattered patches in the Arecibo-Manatí region. The Quaternary deposits consist of sandy and silty clays and muck deposits.

The limestones of the Arecibo-Manatí region have undergone significant karstification since their deposition. Prominent karst features in this region include mogotes, cockpits with steep-walled ridges, and steep-sided canyons. The extent of karst development depends on the composition of the limestone. The Cibao Formation, where it is composed of calcareous clay and sandy clay, as in the southeastern part of the region, is the only formation in the Arecibo-Manatí region with little or no karst development.

Alluvial, blanket sand, swamp, and beach deposits of Quaternary age overlie the limestone formations throughout the region (fig. 2.1.2.C-1). Among these surficial deposits, the alluvial and blanket sand deposits play important roles in the hydrogeology of the region. During Pleistocene time, a sea-level stand at more than 300 feet below present sea level, resulted in downward erosion and deepening of the Río Grande de Arecibo and Río Grande de Manatí valleys. Subsequent rises in sea level caused river transported sediments to be deposited within these valleys, filling them to approximately their present level (Gómez-Gómez, 1984, p. 14; Quiñones-Aponte, 1986b, p. 13). The alluvial deposits are composed of moderately well sorted, stratified sand, gravel, silt, and clay (Briggs, 1968). The thickness of alluvial deposits within the Río Grande de Arecibo valley average about 130 feet thick (fig. 2.1.2.C-2, a) in the southeastern part of the valley (Quiñones-Aponte, 1986b, p. 13). In the Río Grande de Manatí valley (fig. 2.1.2.C-2, b), alluvial deposits could be as thick as 300 feet (Gómez-Gómez, 1984, p. 14). The rivers also deposited blanket sands, which are composed of quartz and clay in greatly varying proportions (Briggs, 1966, p. 60).

2.1.2.D Hydrogeology

The Aymamón and Aguada Limestones are the principal geologic units comprising the water-table aquifer in the Arecibo-Manatí region. The alluvium in the river valleys is hydraulically connected to the limestones and, although locally semi-confined by clays, particularly in the Río Grande de Arecibo valley, is considered to be part of the water-table aquifer in the region. Blanket sand deposits, although low yield water-bearing units (aquicludes), are important recharge media to the water-table aquifer underneath.

The artesian aquifer formed by the Lares Limestone and Montebello Limestone Member of the Cibao Formation is confined by the upper member of the Cibao Formation overlying the Montebello Limestone Member, although water-table conditions exist in their outcrop area. The confining layer pinches out towards the south (fig. 2.1.2.C-2, a), causing both the water-table and artesian aquifers to behave as water-table aquifers and to be hydraulically connected (Jesús Rodríguez-Martínez, U.S. Geological Survey, written communication, 1991). Recently collected lithologic and hydrogeologic information indicates that the Lares Limestone and Montebello Limestone Member have a good hydraulic connection. Artesian conditions in both limestones extend beyond the western limit of the Arecibo-Manatí region. East of the Río Grande de Manatí, the Montebello Limestone Member pinches out and is replaced by the Río Indio Limestone and the Quebrada Arenas Limestone Members of the Cibao Formation. The replacement of the Montebello Limestone Member with these members of the Cibao Formation may be at the eastern limit of the Montebello artesian zone. Artesian conditions have been documented in the Lares Limestone beyond the eastern limit of the region (Rodríguez-Martínez and others, 1992). Although artesian conditions occur in the Lares Limestone and the various limestone members of the Cibao Formation throughout the entire North Coast area, the artesian system is most productive in the Arecibo-Manatí region. The relative thickness of the limestone formations, the associated karst development, the larger recharge area, and the large potentiometric heads in the area probably account for the productive artesian conditions already documented.

The hydraulic conductivity of the limestones in the Arecibo-Manatí region varies widely. In general, the older the rocks, the lower the hydraulic conductivity. Giusti and Bennett (1976, p. 23) estimated the average hydraulic conductivity of the Lares Limestone to be 0.7 ft/d; the Montebello Limestone, 9.4 ft/d; the Aguada Limestone, 87 ft/d; and the Aymamón Limestone, 535 ft/d (fig. 2.1.2.C-2, c). Hydraulic conductivity appears to be closely related to the depositional environment, type of depositional material, and the extent of secondary permeability. The highest hydraulic conductivity values occur in the rocks closest to the surface, where the effects of solution by recharge waters are most effective. Giusti and Bennett (1976, p. 21) showed that hydraulic conductivity in the Aymamón Limestone decreases with depth from approximately 2,800 ft/d near the surface to about 2.8 ft/d over about a 1,000 feet depth range (fig. 2.1.2.C-2, d). Hydraulic conductivity for the Río Grande de Arecibo alluvium may range from 25 to 40 ft/d (Quiñones-Aponte, 1986b, p. 22) while the Río Grande de Manatí ranges from 20 to 30 ft/d (Gómez-Gómez, 1984, p. 30).

Transmissivity values in the water-table aquifer were estimated from specific-capacity test data (Sigfredo Torres-González, U.S. Geological Survey, written communication, 1991). Transmissivity increases from less than 100 ft^2/d at the contact between the water table and the artesian aquifers to more than 100,000 ft^2/d immediately west of Barceloneta (fig. 2.1.2.D-1).

Yields to wells tapping the water-table aquifer range from 7 to more than 2,000 gal/min (Gómez-Gómez, 1986). Yields of 1,000 gal/min or more can be obtained from the Aymamón Limestone and from the alluvium in the river valleys. The Aguada, Montebello Limestone Member of the Cibao Formation, and Lares Limestones, comprising the limestone water-table aquifer, usually yield less than 100 gal/min. Maximum yields to wells are from the Aguada Limestone and the upper part of the Montebello Limestone Member where it is artesian. Wells tapping cavernous-limestone zones can yield over 100 gal/min. In artesian zones where the Montebello Limestone Member and Lares Limestone are tapped by wells, yields range from 500 to 1,000 gal/min or more. Yields, however, are not due to the high permeability of these rocks in the artesian zones but to the high pressure heads driving the systems.

2.1.2.E Ground-Water Levels and Movement

The water-table surface map (fig. 2.1.2.E-1) represents the elevation of the water table in the limestone aquifer at the end of the wet season in December 1984. Water levels range from a few feet below mean sea level in the Caño Tiburones area to more than 500 feet above mean sea level near the south-central limit of the limestones. Ground-water flow originating in the Montebello Limestone Member of the Cibao Formation at an elevation of 500 feet moves north, through the Aguada Limestone, to elevations of 100 feet or less in the Aymamón Limestone. Hydraulic gradients associated with this ground-water flow are steeper in the Aguada Limestone than in the Aymamón Limestone.

Ground-water flow is generally from the interior of the island to the sea in the Arecibo-Manatí region. Flow in the water-table aquifer is influenced by coastal wetlands, drainage canals, and the two major rivers that are deeply incised into the limestones. Ground water moves from the limestone units northward into the coastal plain alluvium, discharging from the alluvium into the rivers. Ground water also discharges as springs issuing from the limestone walls of the valleys or from the contact between limestone and alluvium on the valley floors. In the lower reach of the Río Grande de Arecibo, the river losses water to the alluvial aquifer, and that water may discharge at springs in the Caño Tiburones.

When first drilled, heads in the Montebello Limestone Member of the Cibao Formation were as much as 400 feet above sea level. Well location or well fields furnishing water for the different uses are shown on figure 2.1.2.B-1. Withdrawals and possible leakage to the water-table aquifer, through improperly constructed wells, has caused major head declines in the industrial area where withdrawals from the artesian aquifer are concentrated. Discharge from the artesian aquifer probably is diffused by upward leakage through the overlying limestones to the sea floor and offshore (Guisti and Bennett, 1976).

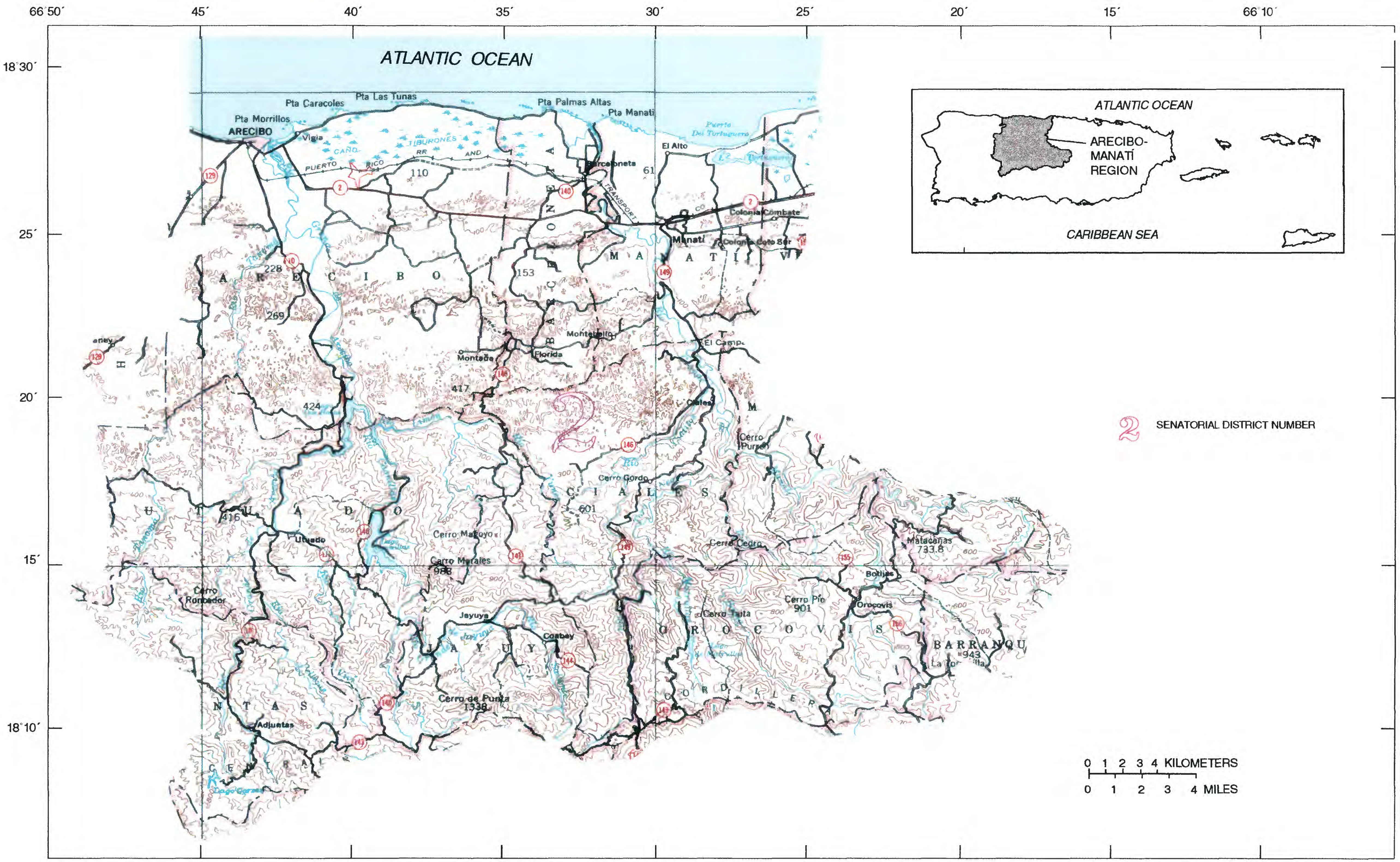
2.1.2.F Soil Permeability

The infiltration rate of the soil zone is an important factor in assessing either recharge to the underlying aquifer or the vulnerability of the aquifer to contamination from certain land-use or waste-disposal practices. Soil-zone permeability as determined by the U.S. Department of Agriculture (Acevedo, 1982) provides an estimate of the water infiltration rate when the soil is saturated. Generalized infiltration rates (fig. 2.1.2.F-1) are derived from soil permeability data (Acevedo, 1982; table 2.1.2.F-1). The values shown in table 2.1.2.F-1 and figure 2.1.2.F-1 are those of the soil zone with the lowest infiltration rate, usually the B horizon that is 3 to 5 feet below land surface in the deep soils of the Arecibo-Manatí region. The overlying A horizon usually is much more permeable.

The most permeable soils, those developed on cemented sand dunes along the coast, are of limited extent. Infiltration rates are high, often exceeding 20 in/hr. In contrast, the deep muck deposits of the Caño Tiburones are the least permeable soils in the region and have infiltration rates as low as 0.06 in/hr. At depth, these soils are underlain by a dense, nearly impermeable clay. Infiltration rates for the greater part of the region range from 0.6 to 2.0 in/hr. Although infiltration rates are similar, the soils are diverse ranging from deep soils developed on river flood-plain alluvium, blanket sand deposits, and adjacent limestones, to thin soils and often bare rock in highly developed karst areas.

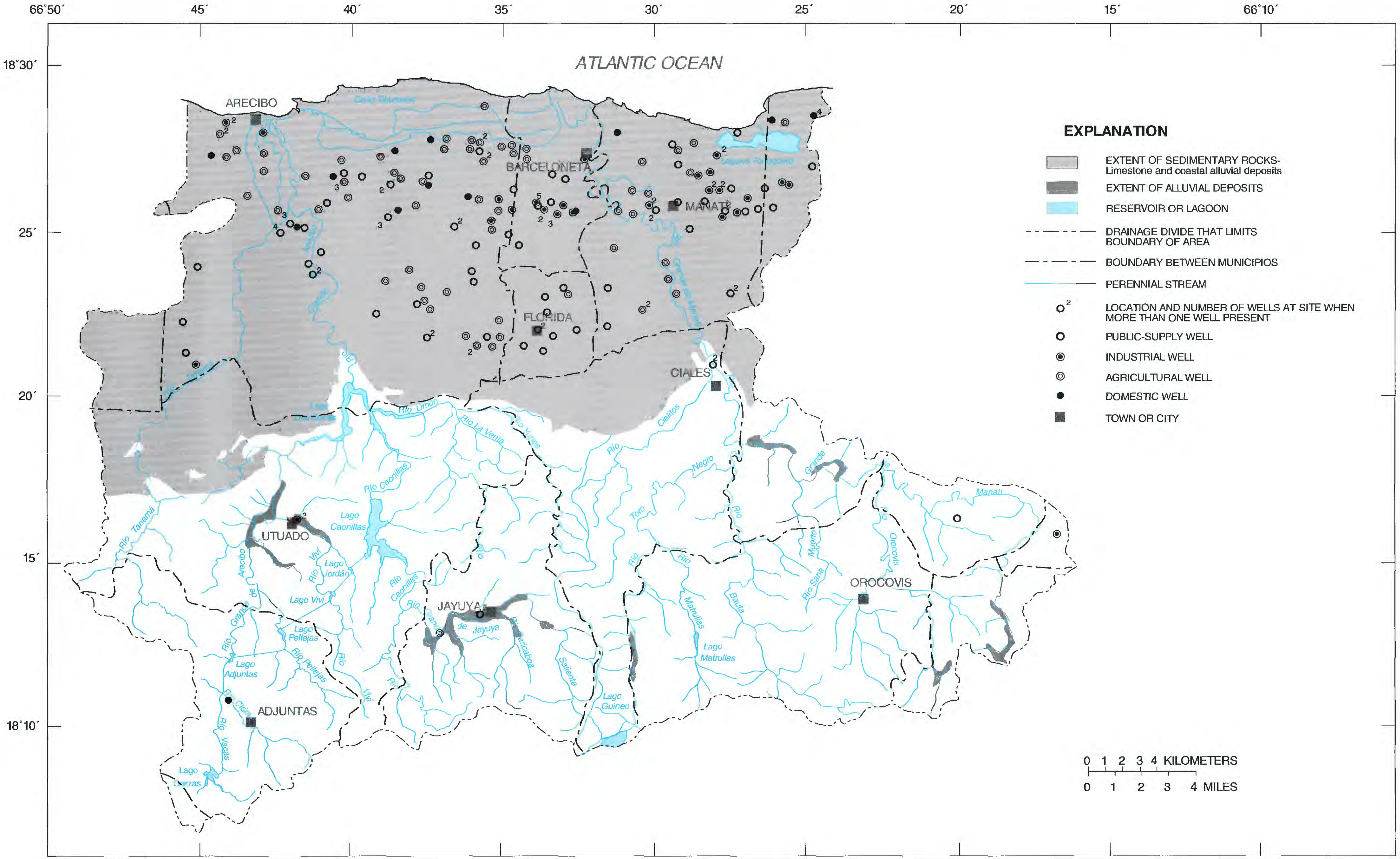
Table 2.1.2.F-1 Thickness, permeability, and available water capacity for the soil associations in the Arecibo-Manatí region, Puerto Rico (Modified from Acevedo, 1982)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Humid Coastal Plains			
Algarrobo-Corozo-Arecibo	0 to 99	0.06 to 0.20	0.02 to 0.20
Guerrero-Carrizales-Jobos	0 to 60	0.60 to 2.00	0.04 to 0.20
Almirante-Espinosa-Vega Alta	0 to 70	0.60 to 2.00	0.06 to 0.20
Bayamón-Matanzas	0 to 65	0.60 to 2.00	0.06 to 0.20
Rock Outcrop-Tanamá-San Sebastián	0 to 55	0.60 to 2.00	0.15 to 0.20
Soller-San Germán-Rock Outcrop	0 to 25	0.60 to 2.00	0.05 to 0.25
Tiburones-Palmar-Garrochales	0 to 84	0.06 to 0.20	0.15 to 0.20
Toa-Coloso-Bajura	0 to 63	0.06 to 0.20	0.12 to 0.20
Moca-Perchas	0 to 60	0.06 to 0.20	0.15 to 0.24
Humid Upland Valleys			
Colinas-Naranjo-Juncal	0 to 60	0.60 to 2.00	0.09 to 0.20
Múcara-Caguabo	0 to 27	0.60 to 2.00	0.05 to 0.17
Humid Uplands			
Múcara-Morado-Maragüez	0 to 60	0.60 to 2.00	0.05 to 0.17
Humatas-Naranjito-Consumo	0 to 60	0.60 to 2.00	0.10 to 0.20
Humatas-Los Guineos-Alonso	0 to 62	0.60 to 2.00	0.10 to 0.20
Humatas-Maricao-Los Guineos	0 to 62	0.60 to 2.00	0.10 to 0.20
Maricao-Los Guineos	0 to 62	0.60 to 2.00	0.10 to 0.20
Pellejas-Lirios-Ingenio	0 to 62	0.60 to 2.00	0.06 to 0.21



Base from U.S. Geological Survey
Puerto Rico e Islas Limítrofes, 1:240,000, 1952

Figure 2.1.2.A-1 Location and major geographic features in the Arecibo-Manatí region, Puerto Rico.



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.1.2.B-1 Approximate well locations in the Arecibo-Manatí region, Puerto Rico.

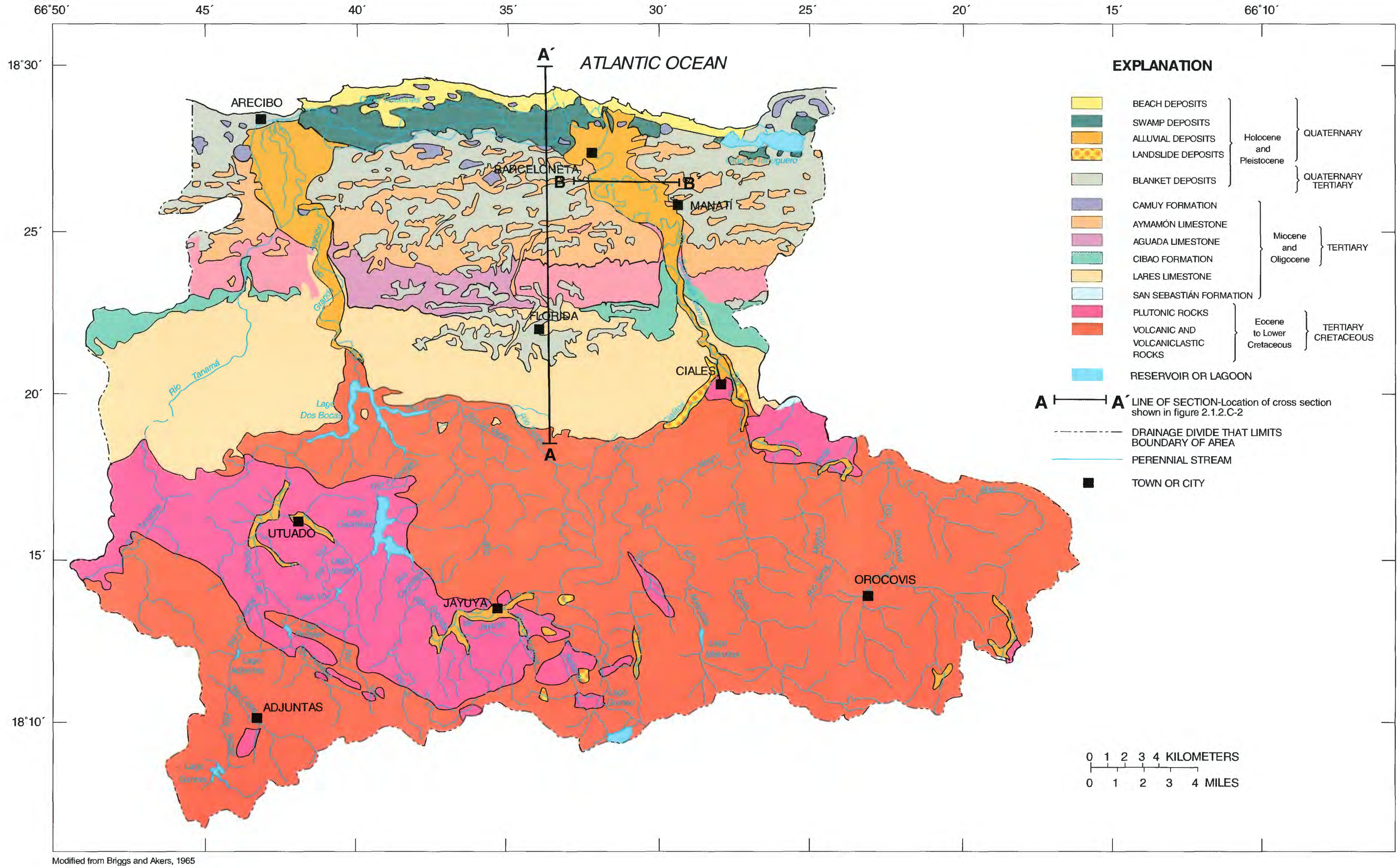


Figure 2.1.2.C-1 Generalized surficial geology in the Arecibo-Manatí region, Puerto Rico.

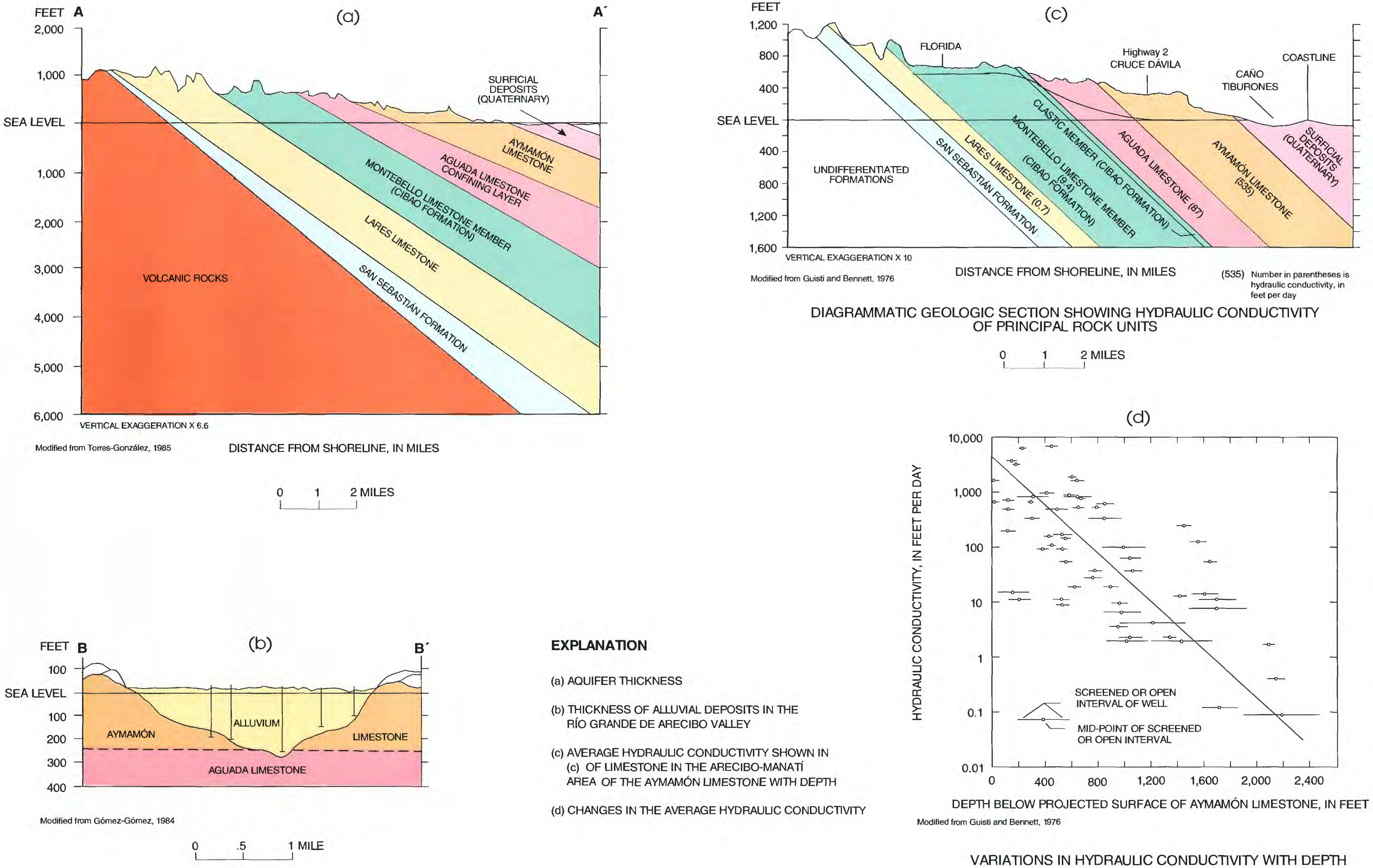


Figure 2.1.2.C-2 Generalized aquifer thickness and hydraulic conductivity in the Arecibo-Manatí region, Puerto Rico (lines of section shown in figure 2.1.2.C-1).

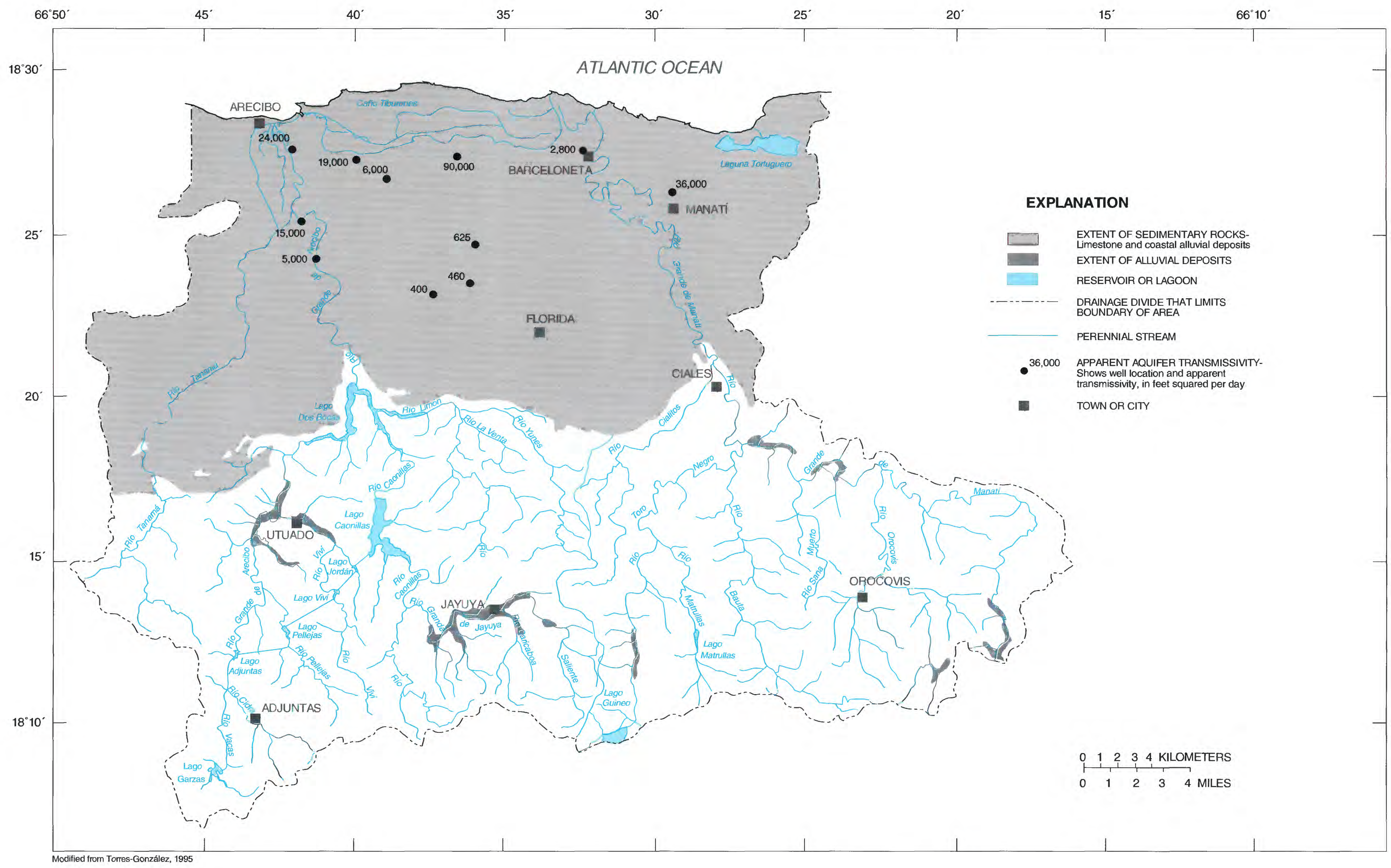
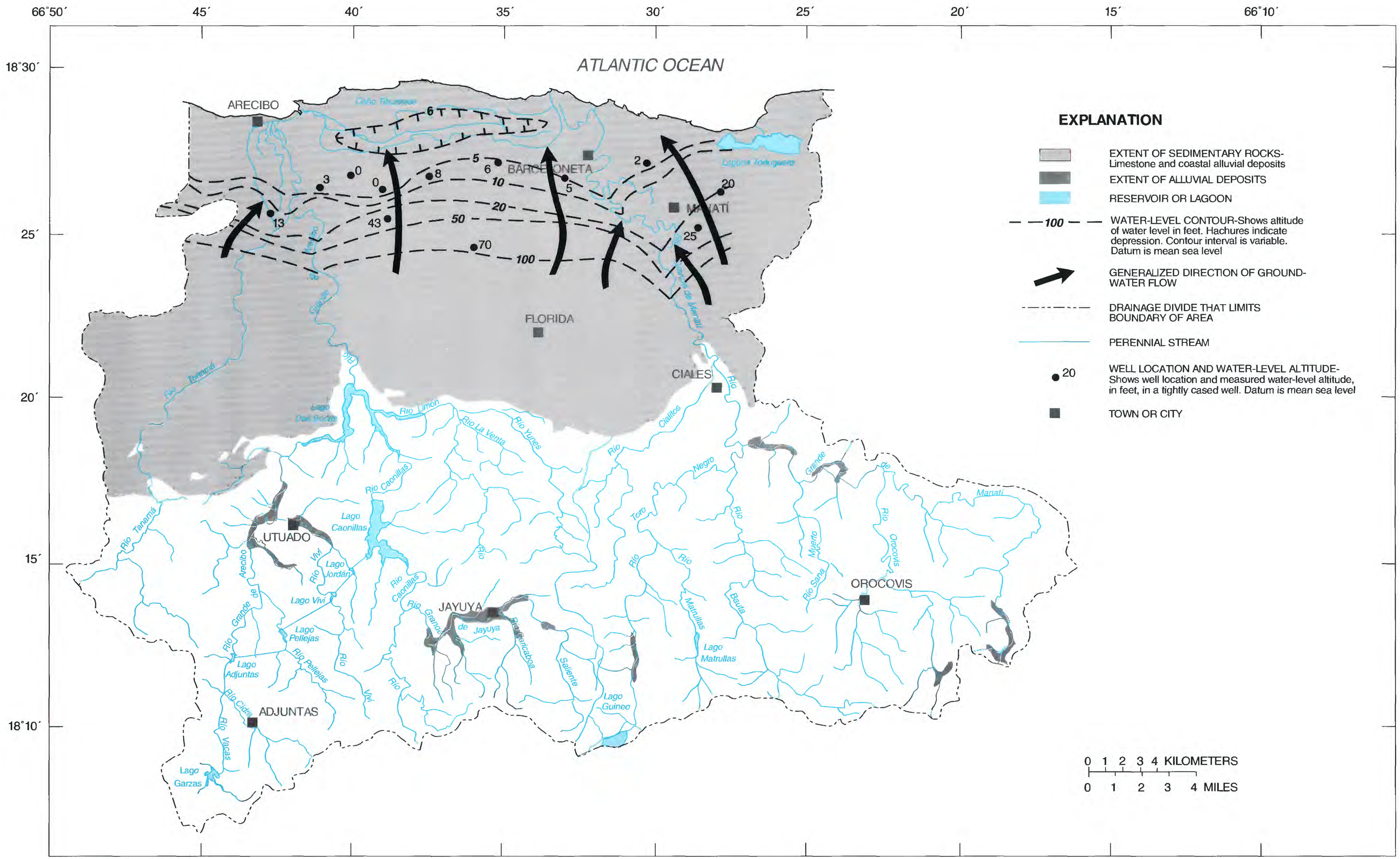


Figure 2.1.2.D-1 Transmissivity in the Arecibo-Manatí region, Puerto Rico.



Modified from Torres-González, 1995

Figure 2.1.2.E-1 Composite potentiometric surface of the upper aquifer of the years 1965 and 1987 in the Arecibo-Manatí region, Puerto Rico.

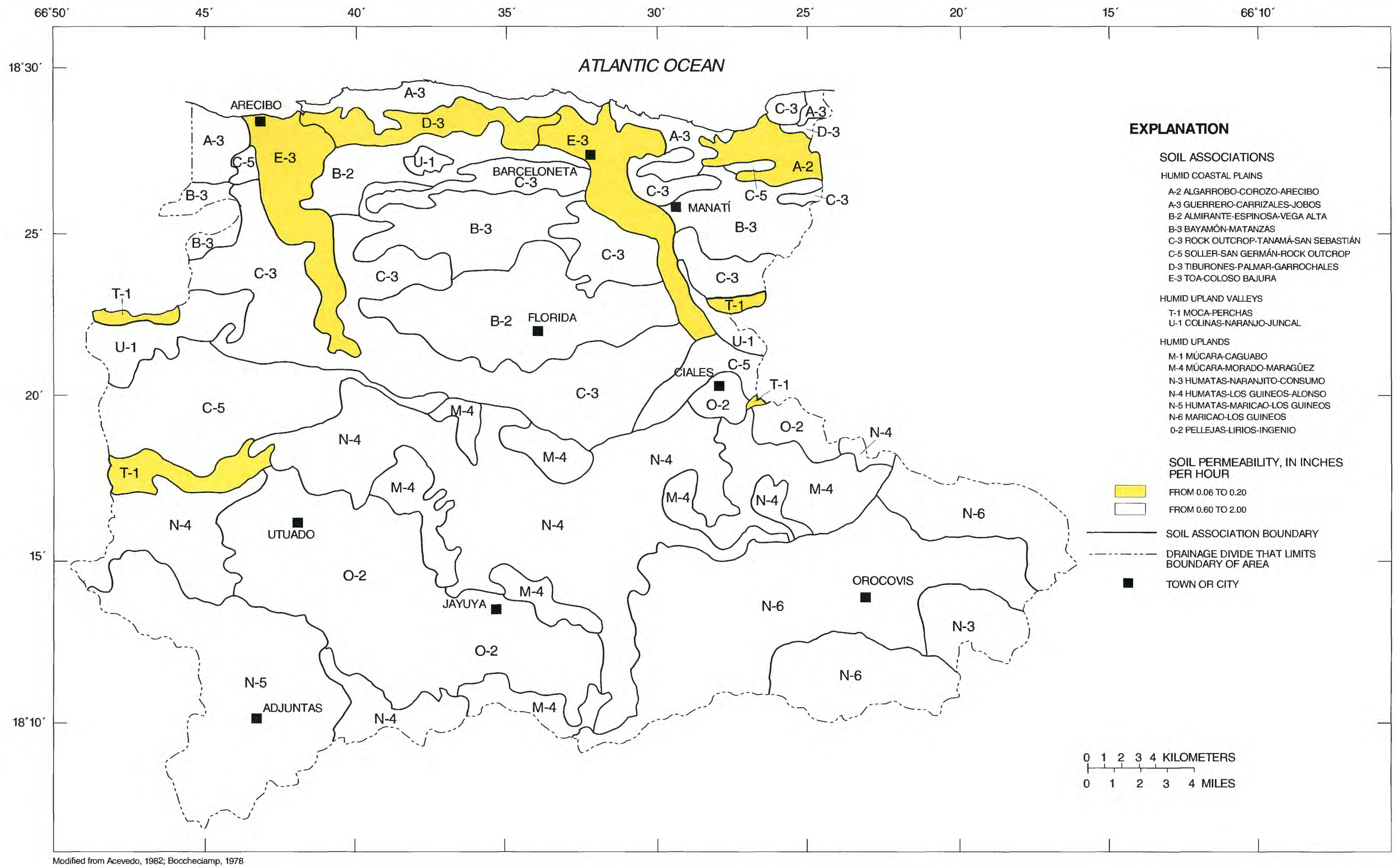


Figure 2.1.2.F-1 Soil associations and permeability in the Arecibo-Manatí region, Puerto Rico.

2.1.3 VEGA BAJA-TOA BAJA REGION

By Fernando Gómez-Gómez and Thalia D. Veve

2.1.3.A Location and Major Geographic Features

The Vega Baja-Toa Baja coastal aquifer area extends across a 9-miles wide segment of the North Coast area (fig. 2.1.3.A-1). It is bounded to the north by the Atlantic Ocean, to the west by the Río Cibuco, to the east by the Río de La Plata, and to the south by a karst tableland (fig. 2.1.3.A-1). Along the coast, sand dunes form an almost continuous ridge, except where the ridge has been breached by the Río Cibuco and Río de La Plata. The coastal dune ridge has an average elevation of about 30 feet above mean sea level and reaches its maximum elevation of 65 feet at Dorado. The dune ridge is less than 2-miles wide, draining to the ocean along its northern slope and to the coastal plain along its southern slope. The karst tableland is generally defined within the 170 feet topographic contour and is about 3-miles wide. This tableland has become the principal area of urban development, and also contains the major highway connecting the San Juan metropolitan area to the western part of the island. High relief topography, dominated by numerous ridges and sinks typical of an immature karst, occurs south of the tableland. The tableland is dissected to the east and west by northward flowing streams that form a well developed alluvial plain, extending inland as much as 6 miles from the coast. Little urban development has taken place within the alluvial plain except for a 0.25 mi^2 urban area within the town limits of Toa Baja. The municipio of Toa Baja, parts of suburban developments on the coastal plain, and parts of Vega Baja are within the flood plain of the Río Cibuco and Río de La Plata. The headwaters of both streams lie within the island's volcanic-rock interior (southern parts of the Vega Baja-Toa Baja region) and have a combined drainage area of 240 mi^2 at the point where they enter the coastal aquifer areas. Most of this drainage area is within the watershed of the 62-miles long Río de La Plata, which has its headwaters at an elevation of 2,960 feet.

2.1.3.B Population and Estimated Ground-Water Use

In 1980, the combined population in the municipios of Dorado and Vega Alta was about 54,200 (U.S. Department of Commerce, 1982). In the 1990 Census (U.S. Department of Commerce, 1991), the population within these municipios was 65,318. This represents an increase of 17 percent from 1980 to 1990. In 1980, 38 percent of the population in the municipios of Dorado and Vega Alta resided within the urban limits of both municipios. The remainder of the population resided within suburban communities (table 2.1.3.B-1). According to the 1980 census, 97 percent of the housing units in the municipios of Dorado, Toa Baja, Toa Alta, Vega Baja, and Vega Alta (approximately 14,800 houses) were served from public-water supply. However, only 38 percent of the housing units were served by public sewers.

Public-water supply within this geographic region is provided principally by ground water. In 1983, there were 24 public-supply wells yielding 12 Mgal/d. Because the Vega Baja-Toa Baja coastal aquifer area public-water supply distribution system is interconnected to the east with the San Juan metropolitan area and to the west with Manatí, part of the well production could have been transferred outside the region. In addition, during 1990 a major public-supply distribution pipeline was completed that connected Dorado with the Enrique Ortega filtration plant. This filtration plant is part of the San Juan Metropolitan area public-water supply and provides approximately 55 Mgal/d from Lago de La Plata. Since 1983, approximately seven public-water supply wells have been taken out of production, either as a result of contamination with organic chemicals (principally trichloroethylene and tetrachloroethylene) or saltwater encroachment. The production lost from these wells has been offset by increasing withdrawals from, and the rehabilitation of, the remaining wells, as well as the construction of new wells. Ground-water withdrawals of 13 Mgal/d in 1991, from a total of 20 public-supply wells, is equal to that estimated for 1983. Ground-water withdrawals for commercial, industrial, and agricultural use could represent less than 2.0 Mgal/d in 1991 (Senén Guzmán-Ríos, U.S. Geological Survey, written communication, 1991; table 2.1.3.B-2). This indicates that between 1983 and 1991 total withdrawals from the coastal aquifer area have remained essentially unchanged. Ground-water withdrawals for irrigation of rice in the vicinity of the Río Cibuco, which accounted for approximately 3 Mgal/d in 1983, were discontinued in 1985. The approximate location of wells in the Vega Baja-Toa Baja region is shown on figure 2.1.3.B-1.

Table 2.1.3.B-1 Population for the Vega Baja-Toa Baja region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Aibonito	22,167	9,331	12,836	24,971
Barranquitas	21,639	3,618	18,021	25,605
Cayey	41,099	23,305	17,794	46,553
Ciales	16,211	3,582	12,629	18,084
Cidra	28,365	6,069	29,532	35,601
Corozal	28,221	5,889	22,332	33,095
[1]Dorado	25,511	10,203	15,308	30,759
Morovis	21,142	2,637	18,505	25,288
Naranjito	23,633	2,849	20,784	27,914
Toa Alta	31,910	4,427	27,483	44,101
Toa Baja	78,246	1,992	76,254	89,454
[1]Vega Alta	28,696	10,582	18,114	34,559
Vega Baja	47,115	18,233	28,882	55,997
Total	413,955	102,717	318,474	491,981

[1] Municipio having geographic limits entirely within the limestone belt.

Table 2.1.3.B-2 Ground-water withdrawals during 1987 in the Vega Baja-Toa Baja region, Puerto Rico
[Mgal/d, million gallons per day; <, less than]

Water-use category	Ground-water withdrawals (Mgal/d)
Public-water supply	12.10
Irrigation	<3.30
Industrial	1.00
Commercial	0.40
Agricultural	0.20
Domestic	<0.05
Mining	0.50
Total	<17.55

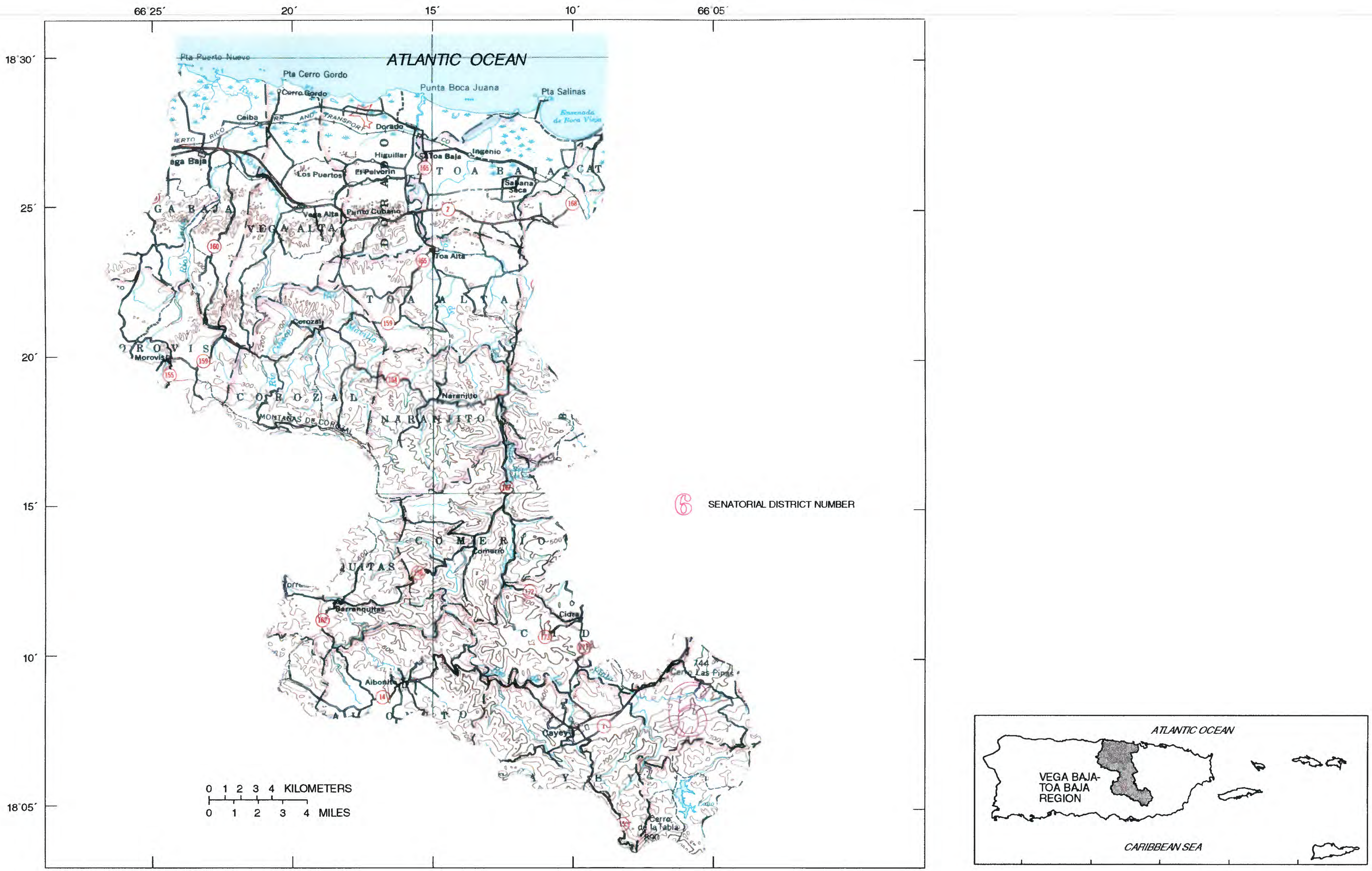
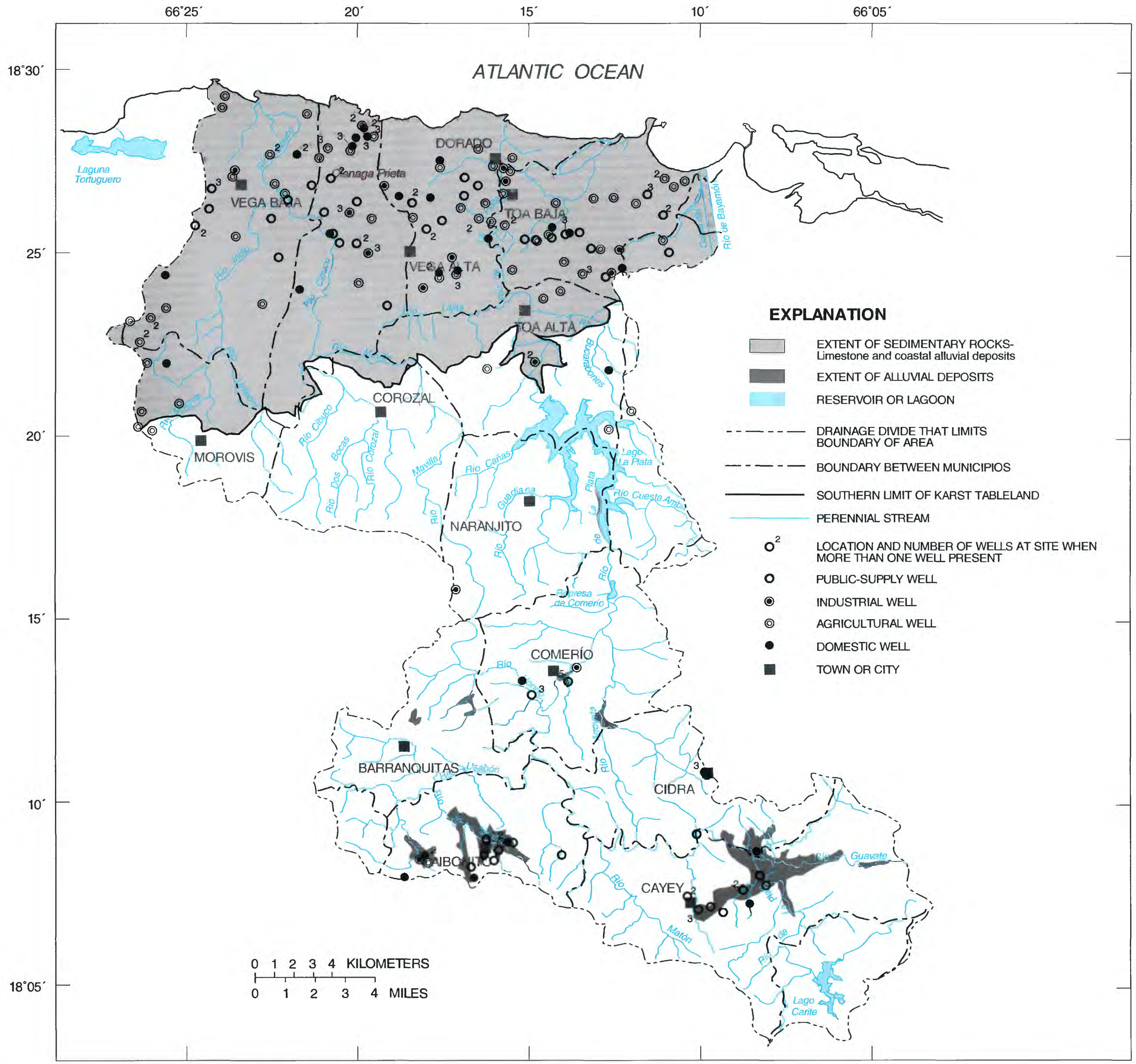
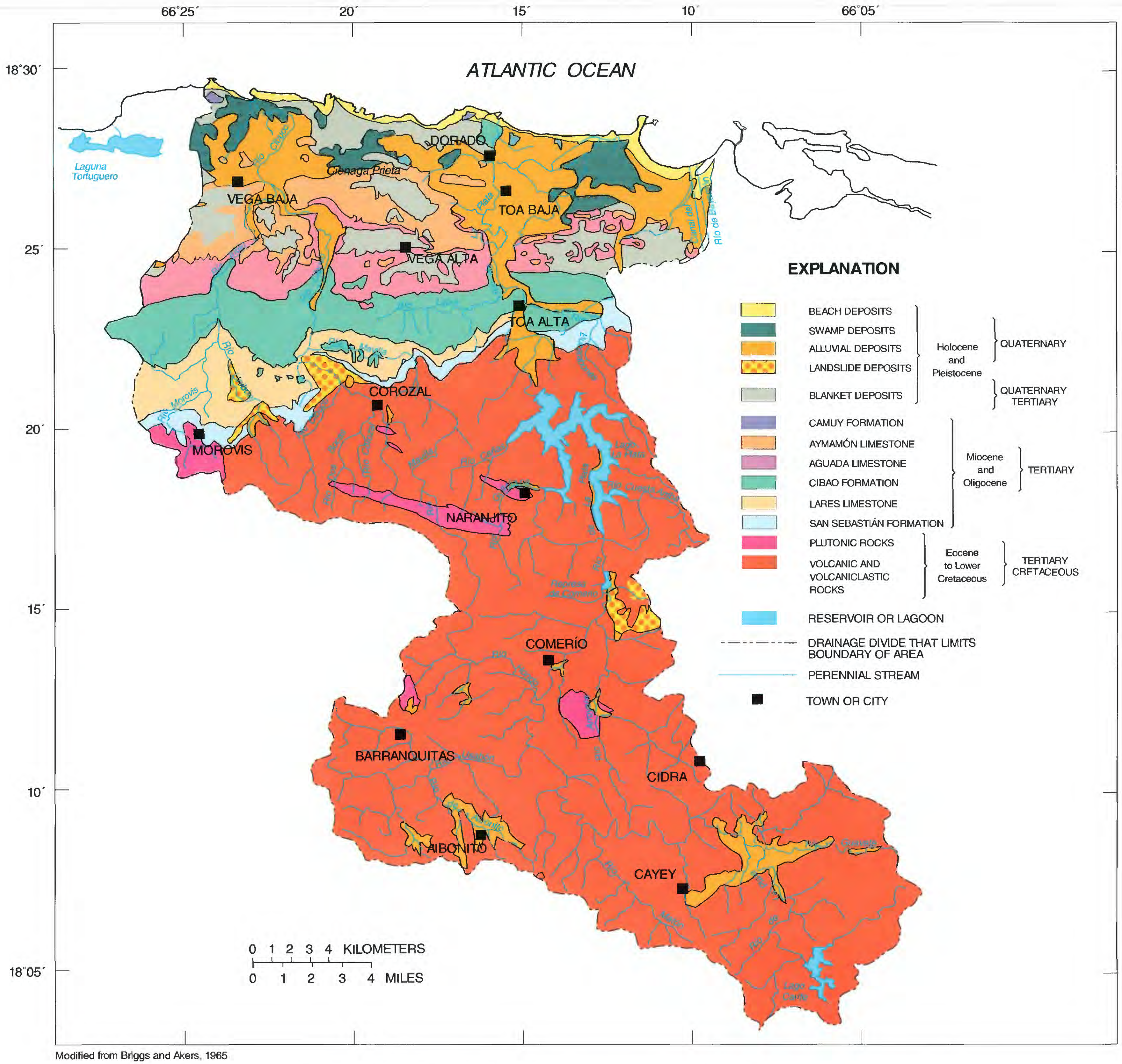


Figure 2.1.3.A-1 Location and major geographic features in the Vega Baja-Toa Baja region, Puerto Rico.



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.1.3.B-1 Approximate well locations in the Vega Baja-Toa Baja region, Puerto Rico.



Modified from Briggs and Akers, 1965

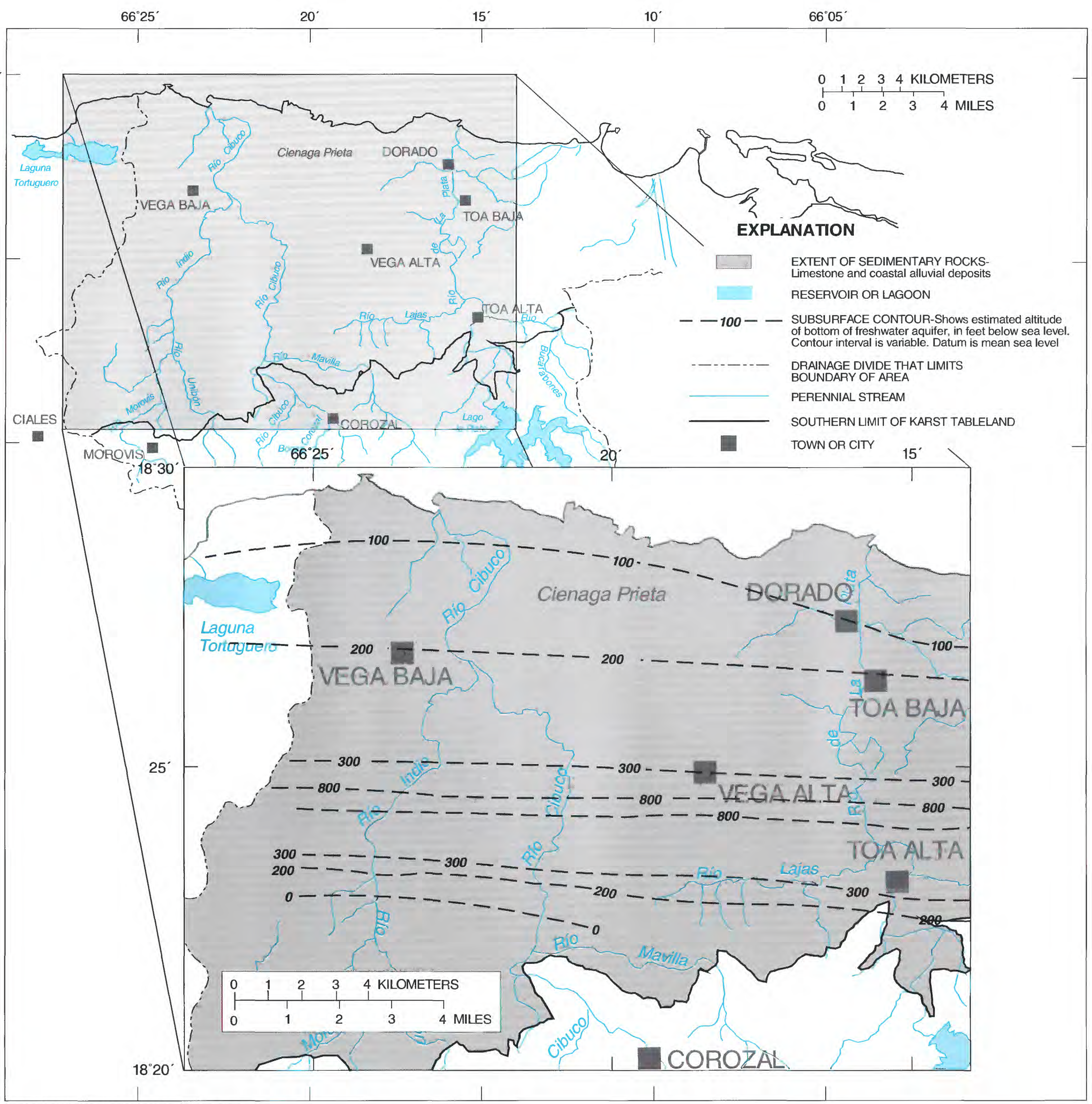
Figure 2.1.3.C-1 Generalized surficial geology in the Vega Baja-Toa Baja region, Puerto Rico.

2.1.3.C Geologic Setting

Sedimentary rocks of Tertiary age underlie the coastal aquifer areas in the Vega Baja-Toa Baja region (fig. 2.1.3.C-1). They are the San Sebastián Formation and Lares Limestone of Oligocene age; the Mucarabones Sand, the Río Indio Limestone, the Quebrada Arenas Limestone, the Miranda Sand Member, and the unnamed upper members of the Cibao Formation of Miocene to Oligocene age; and the Cibao Formation, Aguada Limestone, Aymamón Limestone, and Camuy Formation of Miocene age. Following are brief summaries of the lithology of these geologic units arranged in order from oldest to youngest.

The San Sebastián Formation consists of a sandy carbonaceous clay, locally containing pebbles and cobbles of older volcanic rocks, and beds of fossiliferous-earth limestone. Outcrops are mainly in the southeastern perimeter of the Cretaceous-Tertiary contact.

The Lares Limestone overlies the San Sebastián Formation and consists entirely of calcareous clay in the coastal aquifer areas of the Vega Baja-Toa Baja region. The Mucarabones Sand, overlying the Lares Limestone, is a cross-bedded fine- to medium-grained sand containing lenses of fossiliferous sandy limestone and sandy clay. The Río Indio Limestone Member of the Cibao Formation overlies the Mucarabones Sand and consists of chalky fragmented limestone, weakly bedded to massive, and locally glauconitic. The Quebrada Arenas Limestone Member of the Cibao Formation, overlying the Río Indio Limestone Member, is a finely crystalline to dense limestone locally containing grains of quartz sand and abundant fossil molds. Its main exposure is in the drainage basin of the Río Lajas. The Miranda Sand Member of the Cibao Formation overlies the Quebrada Arenas Limestone Member and consists of angular to subangular fine- to coarse-grained quartz sand in a noncalcareous silty clay matrix. Exposures near Vega Alta contain sand and gravel that grade upward into fossiliferous sand. Only minor exposures of the Miranda Sand Member (less than 0.5 mi^2) have been mapped and lie within the Río Lajas drainage basin. The unnamed upper member of the Cibao Formation, overlying the Miranda Sand Member, is considered to be typical of the Cibao Formation lithology, consisting of beds of calcareous clay, earthy



Modified from Gómez-Gómez and Torres-Sierra, 1988

Figure 2.1.3.D-1 Approximate altitude of the bottom of the freshwater aquifer in the Vega Baja-Toa Baja region, Puerto Rico.

limestone, and marl. The Aguada Limestone overlies the unnamed upper member of the Cibao Formation and consists of hard calcarenite alternating with chalky and rubbly limestone. The Aymamón Limestone, overlying the Aguada Limestone, is a very pure fossiliferous limestone, massive to thick bedded. The Camuy Formation overlies the Aymamón Limestone and consists of chalk and limestone, commonly somewhat sandy and ferruginous. The Camuy Formation is found in isolated outcrops near the coast of less than 0.25 mi^2.

Unconsolidated deposits, regionally referred to as blanket sands, cover most flat areas throughout the outcrop areas of the Aguada and Aymamón Limestones. These deposits are thought to be of Quaternary to Tertiary age and to have an irregular thickness, typically not greater than 100 feet. Along stream valleys, alluvial deposits known to be as much as 280 feet thick in the Río Cibuco drainage basin and as much as 100 feet thick near the Río de La Plata near Toa Baja, interfinger with swamp and marsh deposits of the coastal plain. In the coastal plain area, between the Río Cibuco and Río de La Plata, the unconsolidated swamp and marsh deposits are typically less than 60 feet thick. Along the edges of the coastal plain, Pleistocene age silica sand deposits form most of the ridge of the coastal terrace deposits. Silica sand deposits are also found as terrace deposits along the northern perimeter of the karst tableland. These deposits are locally mined for the manufacture of glass (Briggs, 1965).

2.1.3.D Hydrogeology

Fresh ground water occurs within the carbonate rocks of Miocene and Oligocene age at areas generally inland of latitude 18°25'. Seaward of this latitude, ground water occurs mainly as a lens of freshwater above saltwater. Along a north-south line at approximately longitude 66°19', the depth to the bottom of this freshwater lens varies from about 300 feet at its inland point to about 100 feet at the coast (fig. 2.1.3.D-1). Since 1960, ground-water withdrawals from the coastal aquifer areas have increased significantly. In 1960, total withdrawals were estimated to be less than 2.6 Mgal/d. During 1991, ground-water withdrawals were estimated to be 15 Mgal/d. About 95 percent of this amount was withdrawn within an area that has a transmissivity greater than 10,000 ft^2/d (fig. 2.1.3.D-2). Transmissivity is estimated to be as high as 150,000 ft^2/d.

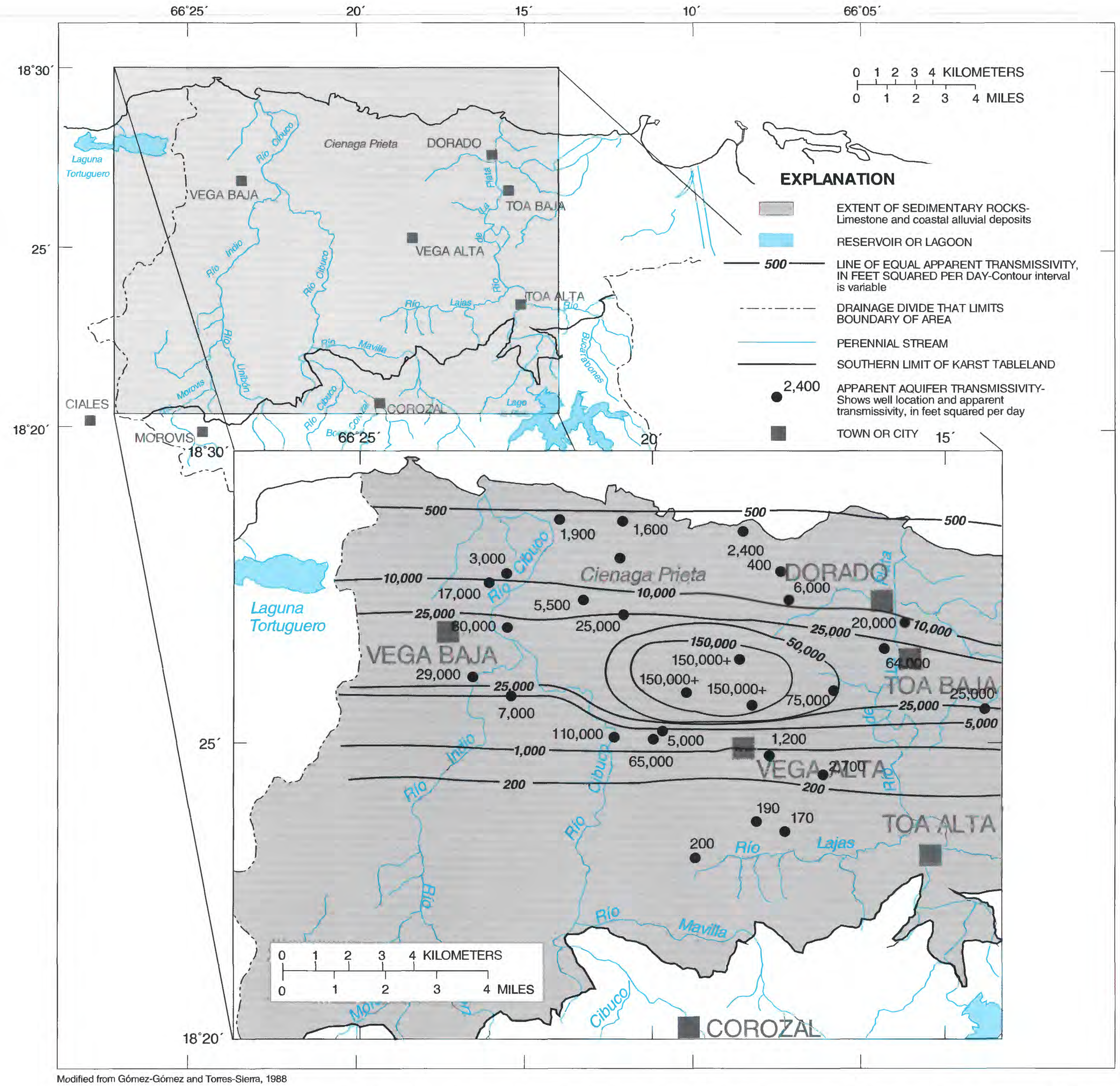


Figure 2.1.3.D-2 Transmissivity estimates at selected wells and the regionalized aquifer transmissivity distribution as obtained through model calibration for the freshwater part of the coastal aquifer in the Vega Baja-Toa Baja region, Puerto Rico.

Ground water within the confined aquifer, consisting of the Lares Limestone and Mucarabones Sand Member of the Cibao Formation (Rodríguez-Martínez, 1991), flows beneath the karst tableland and coastal plain. The total thickness of both units is unknown; however, the thickness of carbonate strata corresponding to the Lares Limestone penetrated by a test well near the coast (latitude 18°27'01", longitude 66°18'22") was 500 feet. A preliminary estimate of the transmissivity of the confined aquifer is 1,000 ft^2/d (Fernando Gómez-Gómez and Sigfredo Torres-González, U.S. Geological Survey, written communication, 1991). Potential for ground-water development from the artesian aquifer in this part of the Vega Baja-Toa Baja coastal aquifer area is limited by the depth at which freshwater is found (1,700 feet below land surface on the coastal plain north of Vega Alta), the lower quality of the ground water (dissolved-solids concentrations greater than 500 mg/L), and the availability of freshwater from the coastal water-table aquifer (fig. 2.1.3.D-3).

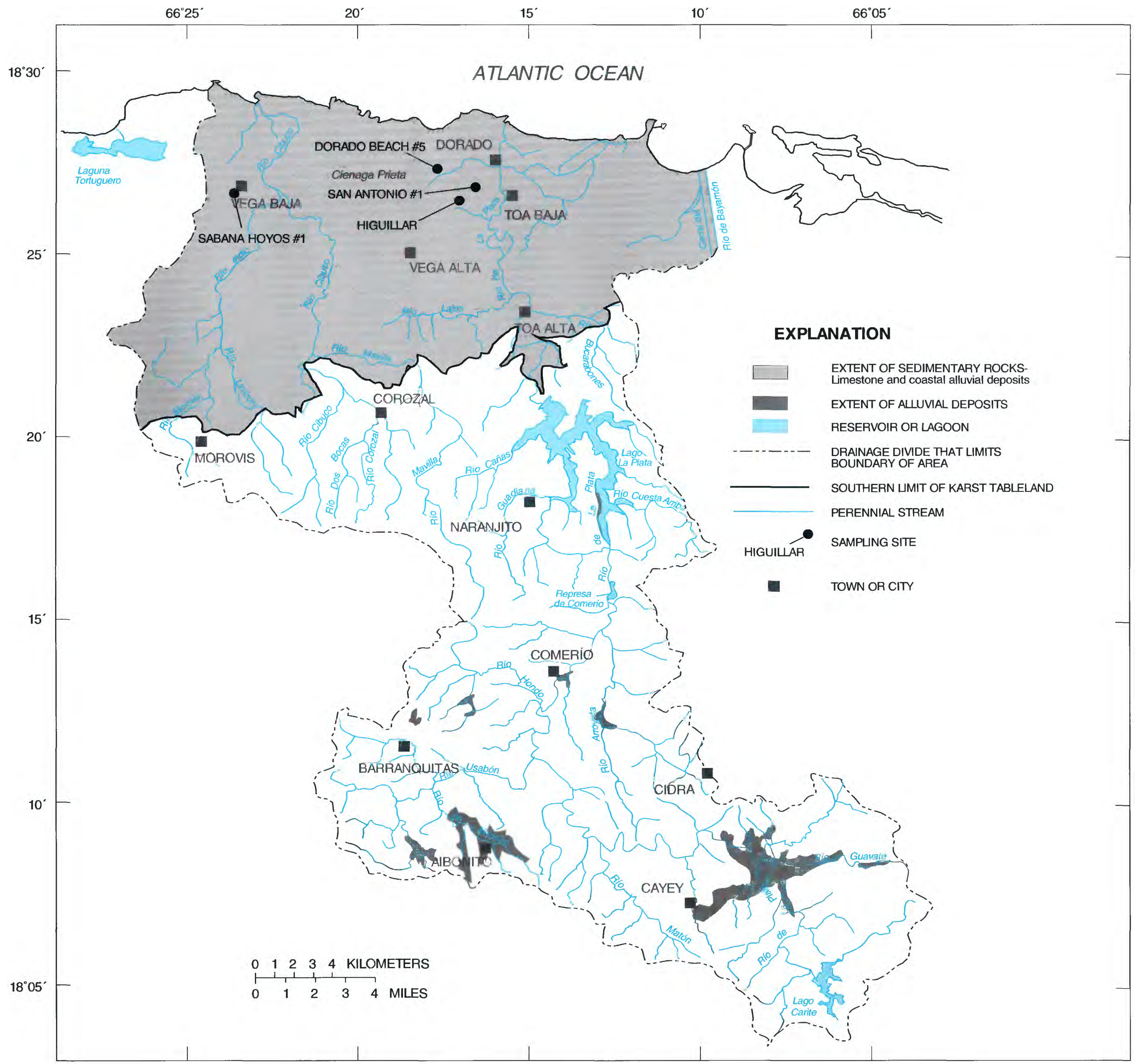


Figure 2.1.3.D-3 Approximate location of wells sampled for dissolved-solids concentration in the Vega Baja-Toa Baja region, Puerto Rico.

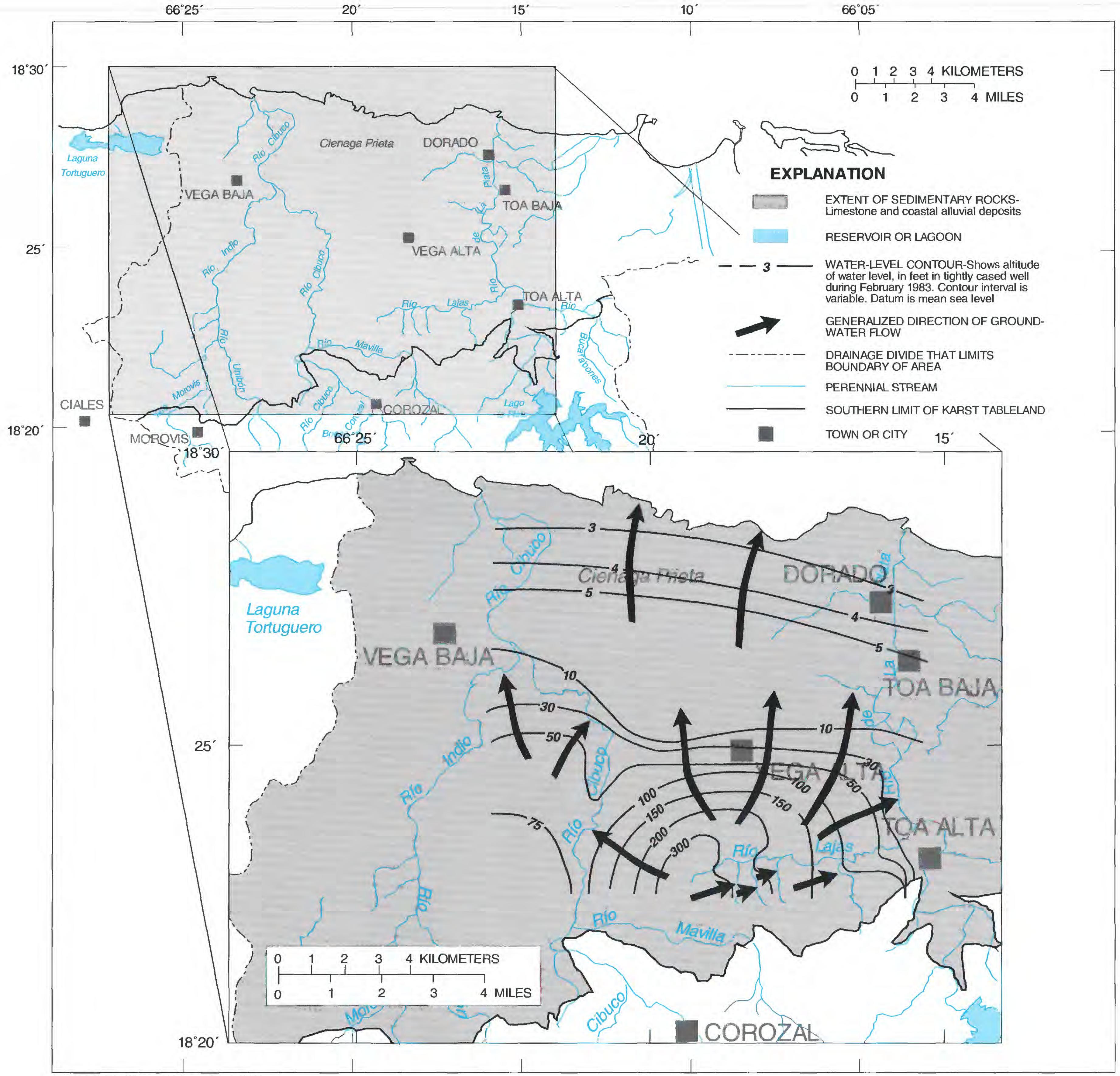


Figure 2.1.3.E-1 Altitude of water-level surface and direction of ground-water flow during February 1983 in the Vega Baja-Toa Baja region, Puerto Rico.

2.1.3.E Ground-Water Levels and Movement

Regional ground-water flow in the coastal water-table upper aquifer is generally toward the ocean coast in the Vega Baja-Toa Baja region (fig. 2.1.3.E-1). A smaller flow component, estimated at less than 3 ft^3/s, discharges toward the Río Cibuco, Río Indio, and Río de La Plata (Gómez-Gómez and Torres-Sierra, 1988). Under pre-development conditions (prior to 1930), most aquifer discharge may have been to the Ciénaga Prieta. Aquifer discharge to this marsh was estimated, by use of a digital ground-water flow model, to be 15 ft^3/s under pre-development conditions, and decreased to about 4 ft^3/s in 1985 (Gómez-Gómez and Torres-Sierra, 1988). Between 1960 and 1970, withdrawals increased from about 3 Mgal/d to about 13 Mgal/d. During this same period, the potentiometric surface throughout the coastal plain could have declined by as much as 10 feet (Gómez-Gómez and Torres-Sierra, 1988). Most of this drawdown could have resulted from increased aquifer withdrawals. However, in about 1960, a drainage channel was dredged from Ciénaga Prieta to the Río Cibuco and part of the decline in the water table could have been caused by dewatering the marsh.

Regional ground-water flow in the confined lower aquifer is toward the east (Fernando Gómez-Gómez and Sigfredo Torres-González, U.S. Geological Survey, written communication, 1991). The head in the lower aquifer was determined to be about 190 feet above mean sea level at a test well drilled about 0.5 miles east of Laguna Tortuguero, and about 10 feet above mean sea level at the possible regional discharge area located 12 miles east of the Río de La Plata.

Rainfall recharge to the upper aquifer occurs throughout the outcrop areas of the carbonate units. In 1983, rainfall recharge constituted about 85 percent of total aquifer recharge (average of 7 inches of rainfall recharge per year), and seepage from the Río Cibuco contributed about 6 ft^3/s (Gómez-Gómez and Torres-Sierra, 1988). Throughout the outcrop area of the lower aquifer, the estimated annual rainfall recharge rate is about 4 inches (Fernando Gómez-Gómez and Sigfredo Torres-González, U.S. Geological Survey, written communication, 1991).

2.1.3.F Soil Permeability

The dominant soil associations overlying the aquifers in this region are the Almirante-Espinosa-Vega Alta, Bayamón-Matanzas, Almirante-Vega Alta-Matanzas, Rock outcrop-Tanamá-San Sebastián, Tanamá-Colinas-Soller, Tiburones-Palmar-Garrochales, and the Toa-Coloso-Bajura (fig. 2.1.3.F-1). Also present to a minor extent are the Algarrobo-Corozo-Arecibo, Martín Peña-Saladar-Hydraquents, and the Pandura-Lirios. These soil associations belong to the humid coastal plains category, except for the Pandura-Lirios association, which is present in the humid uplands.

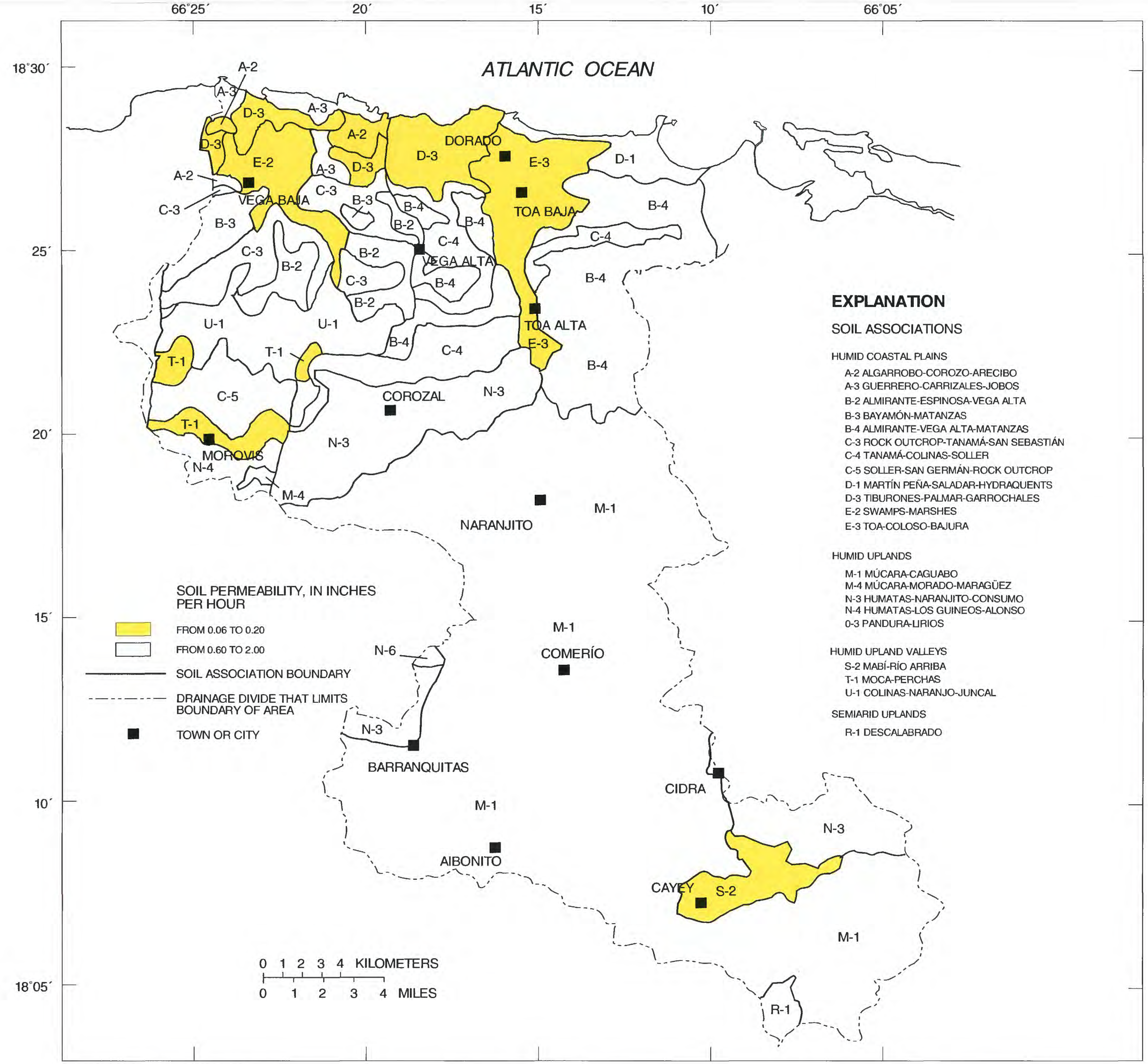
The Almirante-Espinosa-Vega Alta, Bayamón-Matanzas, and the Almirante-Vega Alta-Matanzas soil associations are composed of deep, gently sloping to sloping, well drained and clayey soils (Acevedo, 1982, p. 3; and Boccheciamp, 1978, p. 5). The Almirante-Espinosa-Vega Alta association is mainly located on limestone hills and on terraces along the coast. The Bayamón-Matanzas soils overlie small valleys between limestone hills and on the coastal plains. The Almirante-Vega Alta-Matanzas association is located on terraces and alluvial fans of the coastal plain. These soils formed mainly in clayey sediments of mixed origin and organic materials. The soils that form the Rock Outcrop-Tanamá-San Sebastián association, found in the uplands, are described as rock outcrop and shallow to deep, sloping to very steep, well drained, clayey soils (Acevedo, 1982, p. 4). The Tanamá-Colinas-Soller association is composed of shallow to moderately deep, moderately-to very-steep, well drained soils of the humid mountainous areas (Boccheciamp, 1978, p. 5). These soils are formed mainly in clayey materials weathered from the limestone. The Tiburones-Palmar-Garrochales association is composed of deep, nearly level, poorly drained, acid mucky soils (Acevedo, 1982, p. 4) that overlie flats and depressional areas along the coast and form in organic material. The Toa-Coloso-Bajura association is formed by deep, nearly level, well-to poorly-drained, loamy to clayey soils (Acevedo, 1982, p. 4).

The Algarrobo-Corozo-Arecibo soil association is composed of deep, gently sloping, excessively drained and well drained, sandy soils (Acevedo, 1982, p. 3). The Pandura-Lirios soil association is composed of shallow to deep, moderately- to very-steep, well drained soils of the humid mountainous areas (Boccheciamp, 1978, p. 4). These soils formed in the residuum of granitic rock that is part of the San Lorenzo Batholith. The Martín Peña-Saladar-Hydraquents is composed of deep, nearly level, very-poorly drained soils in low depressions and lagoons of the coastal plain (Boccheciamp, 1978, p. 6).

In general, soil permeability ranges from 0.60 to 2.00 in/hr throughout most of the Vega Baja-Toa Baja region. Only the Algarrobo-Corozo-Arecibo, Tiburones-Palmar-Garrochales, and Toa-Coloso-Bajura associations on the humid coastal plains and the Mabí-Río Arriba and Moca-Perchas associations in the humid upland valleys have lower permeabilities, ranging from 0.06 to 0.20 in/hr. These associations coincide mainly with the alluvium deposits along the main rivers in the region. All of the soil associations have very low available water capacities ranging from 0 to 0.25 in/in. Soil thicknesses range from 0 to 99 inches. Table 2.1.3.F-1 summarizes the information on thickness, permeability, and available water capacity for all the soil associations present in this drainage area including the ones not overlying the aquifers.

Table 2.1.3.F-1 Thickness, permeability, and available water capacity for the soil associations in the Vega Baja-Toa Baja region, Puerto Rico (Modified from Gierbolini, 1975)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Humid Coastal Plains			
Algarrobo-Corozo-Arecibo	0 to 99	0.06 to 0.20	0.02 to 0.20
Guerrero-Carrizales-Jobos	0 to 60	0.60 to 2.00	<0.04 to 0.20
Almirante-Espinosa-Vega Alta	0 to 70	0.60 to 2.00	0.06 to 0.20
Bayamón-Matanzas	0 to 65	0.60 to 2.00	0.10 to 0.20
Almirante-Vega Alta-Matanzas	0 to 70	0.60 to 2.00	0.06 to 0.20
Rock Outcrop-Tanamá-San Sebastián	0 to 55	0.60 to 2.00	0.00 to 0.20
Tanamá-Colinas-Soller	0 to 60	0.60 to 2.00	0.09 to 0.25
Martín Peña-Saladar-Hydraquents	0 to 63	0.60 to 2.00	0.12 to 0.20
Tiburones-Palmer-Garrochales	0 to 84	0.06 to 0.20	0.15 to 0.20
Swamps-Marshes	too variable to be estimated		
Toa-Coloso-Bajura	0 to 60	0.06 to 0.20	0.15 to 0.20
Humid Upland Valleys			
Mabí-Río Arriba	0 to 99	0.06 to 0.20	0.15 to 0.20
Moca-Perchas	0 to 60	0.06 to 0.20	0.15 to 0.24
Colinas-Naranjo-Juncal	0 to 60	0.60 to 2.00	0.09 to 0.20
Humid Uplands			
Múcara-Caguabo	0 to 30	0.63 to 2.00	0.05 to 0.17
Múcara-Morado-Maragüez	0 to 60	0.60 to 2.00	0.05 to 0.17
Humatas-Naranjito-Consumo	0 to 60	0.60 to 2.00	0.10 to 0.18
Humatas-Los Guineos-Alonso	0 to 62	0.60 to 2.00	0.10 to 0.20
Pandura-Lirios	0 to 60	0.60 to 2.00	0.02 to 0.20
Semiarid Uplands			
Descalabrado	0 to 17	0.60 to 2.00	0.10 to 0.20



Modified from Boccheciamp, 1977 and 1978

Figure 2.1.3.F-1 Soil associations and permeability in the Vega Baja-Toa Baja region, Puerto Rico.

2.1.4 BAYAMÓN-LOÍZA REGION

By José M. Rodríguez and Thalia D. Veve

2.1.4.A Location and Major Geographic Features

The Bayamón-Loíza region covers about 280 mi^2 in the eastern North Coast area. It is bounded to the north by the Atlantic Ocean, to the west and south by the drainage basin divide of the Río de Bayamón, and to the east and south by the drainage basin divide of the lower Río Grande de Loíza (below Lago Loíza). Included in the Bayamón-Loíza region are the Río Bayamón, Río Piedras, and lower Río Grande de Loíza drainage basins (fig. 2.1.4.A-1). The San Juan metropolitan area is not only the principal population center of the Bayamón-Loíza region, but also of all Puerto Rico.

The northern section of the Bayamón-Loíza region consists of a coastal plain composed of deposits of sand, silt, clay, and sand muck overlying limestone formations, which form the principal aquifer. The elevation of the land surface in the coastal plain ranges from mean sea level to about 100 feet above mean sea level. An almost continuous strip of swamps and lagoons lies near the coast. The principal coastal lagoons are Laguna San José, Laguna La Torrecilla, and Laguna de Piñones. The southern part of the region is comprised mostly of the foothills of the inner uplands, which range in elevation from about 100 to 1,300 feet above mean sea level.

The principal streams flowing through the region are the Río Bayamón and Río Piedras which flow north, and the Río Grande de Loíza which flows northeast. The Río Bayamón has its headwaters in the mountainous interior of the island and flows across a wide alluvial valley surrounded by swamp deposits near the coast. The Río Piedras, a relatively short river that has its headwaters in the foothills, flows across a wide alluvial plain and discharges into Bahía de San Juan. The Río Grande de Loíza, with headwaters in the interior of the island (section 2.5), is the primary source of water filling Lago Loíza (the principal water-supply reservoir for the San Juan metropolitan area), on its course to the Atlantic Ocean.

2.1.4.B Population and Estimated Ground-Water Use

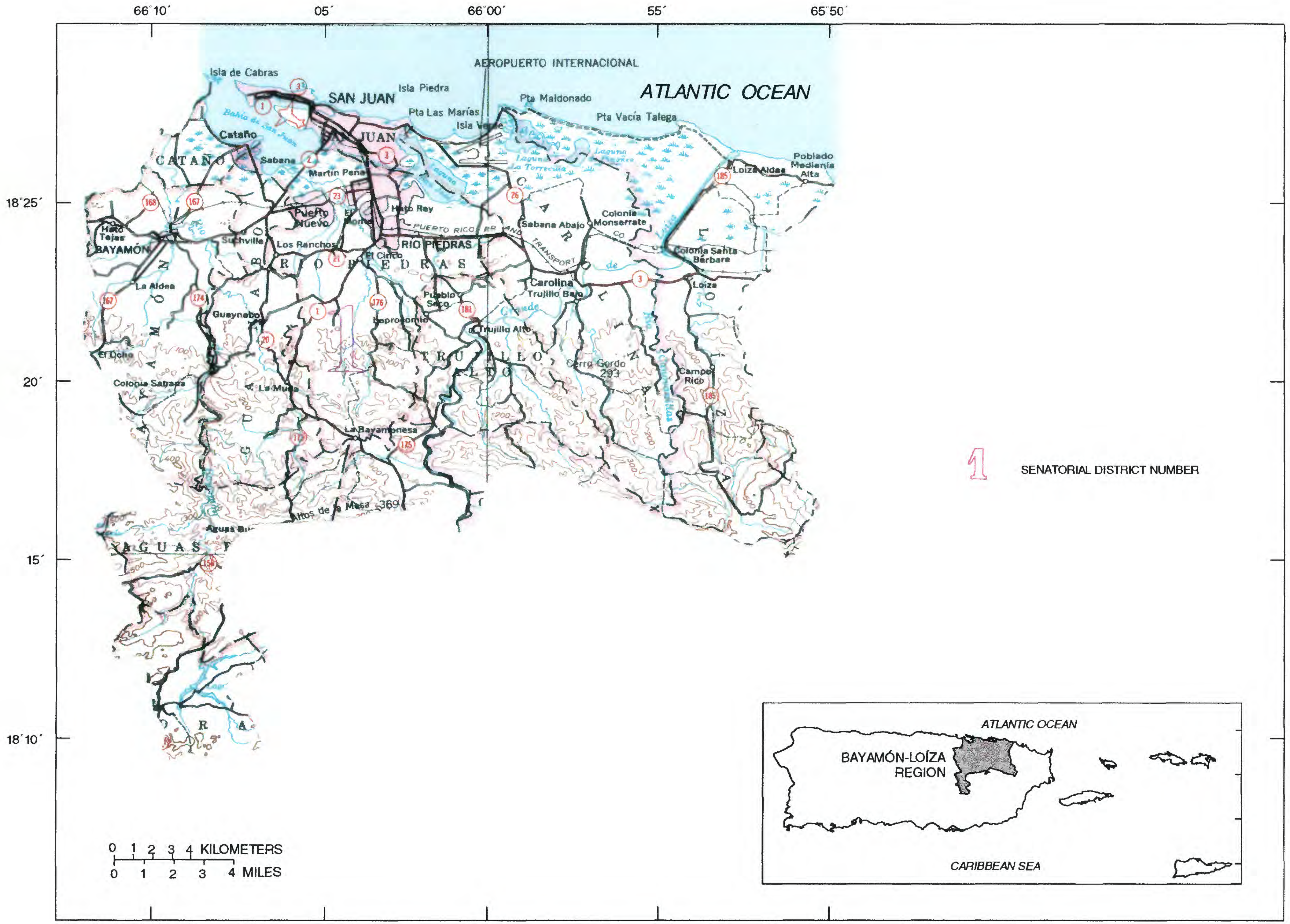
The Bayamón-Loíza region includes the San Juan metropolitan area, which is comprised of the capital city of San Juan, and the municipios of Bayamón, Guaynabo, Carolina, and Cataño (fig. 2.1.4.B-1). It also includes the municipios of Trujillo Alto, Loíza, and Canóvanas. A small area of the municipio of Cidra falls within the southern limits of the Bayamón-Loíza region. The population of the region was about one million in 1980 (table 2.1.4.B-1), which represented 26 percent of the population of Puerto Rico. In 1990, there was a slight increase in population of 7 percent to a total of about 1.1 million. About 89 percent of the total population of the Bayamón-Loíza region live in urban areas, and the remaining 11 percent live in rural areas. The municipios with the greatest percentage of rural population are Loíza and Canóvanas.

Estimated total ground-water withdrawals of 0.94 Mgal/d (table 2.1.4.B-2), were a small fraction of the total of about 158 Mgal/d of surface water distributed for public-water supply in the Bayamón-Loíza region in 1987 (Puerto Rico Aqueduct and Sewer Authority, 1988). Ground-water withdrawals for public use accounted for 0.17 Mgal/d during 1987. Public-water supply wells located throughout the San Juan metropolitan area were in stand-by status most of the time, and were activated only during emergency situations (fig. 2.1.4.B-1).

Table 2.1.4.B-1 Population for the Bayamón-Loíza region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Bayamón	196,206	185,087	11,119	220,262
Canóvanas	31,880	7,260	24,620	36,816
Carolina	165,954	147,835	18,119	177,806
Cataño	26,243	26,243	0	34,587
Cidra	28,365	6,069	22,296	35,601
Guaynabo	80,740	60,706	20,036	92,886
Loíza	20,867	3,932	16,935	29,307
San Juan	434,849	424,600	10,249	437,745
Trujillo Alto	51,389	41,141	10,248	437,745
Total	1,036,493	902,873	133,622	1,126,130

Estimated ground-water withdrawals for industrial, agricultural, and domestic use were 0.59, 0.14, and 0.04 Mgal/d, respectively. Industrial wells are located principally in the coastal plain, but most agricultural and domestic wells are located south of Trujillo Alto and Carolina.



Base from U.S. Geological Survey
Puerto Rico e Islas Limítrofes, 1:240,000, 1952

Figure 2.1.4.A-1 Location and major geographic features in the Bayamón-Loíza region, Puerto Rico.

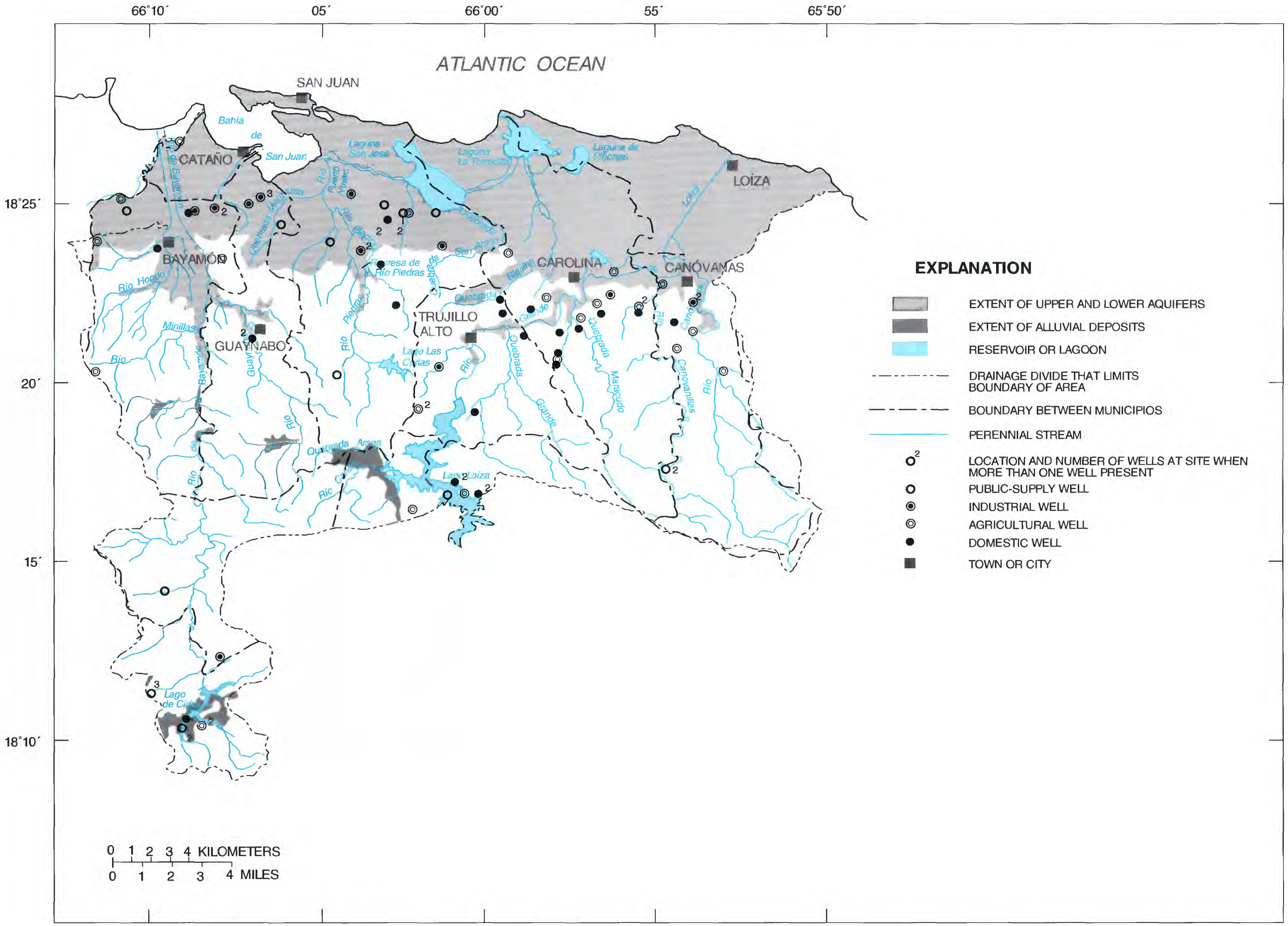
Table 2.1.4.B-2 Ground-water withdrawals and estimated population served during 1987 for the Bayamón-Loíza region, Puerto Rico

[Mgal/d, million gallons per day; ---, no data available]

[1] Use and supplier	[2]Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Public Use		
1. San Juan	529	0.03
2. Bayamón	1,692	0.11
3. Carolina	529	0.03
Subtotal	2,750	0.17
II. Industrial Use		
1. San Juan	---	0.22
2. Bayamón	---	0.25
3. Carolina	---	0.12
Subtotal	---	0.59
[2]II. Agricultural Use		
1. Carolina	---	0.08
2. Trujillo Alto	---	0.03
3. Canóvanas	---	0.03
Subtotal	---	0.14
IV. Domestic Use		
1. Carolina	---	0.01
2. Trujillo Alto	---	0.03
Subtotal	---	0.04
Total	2,750	0.94

[1] Municipios not listed under some specific use do not withdraw ground water for the subject use.

[2] Based on a water consumption of 63 gallons per person per day.



From U.S. Geological Survey Ground-Water Site Inventory Database, 1990

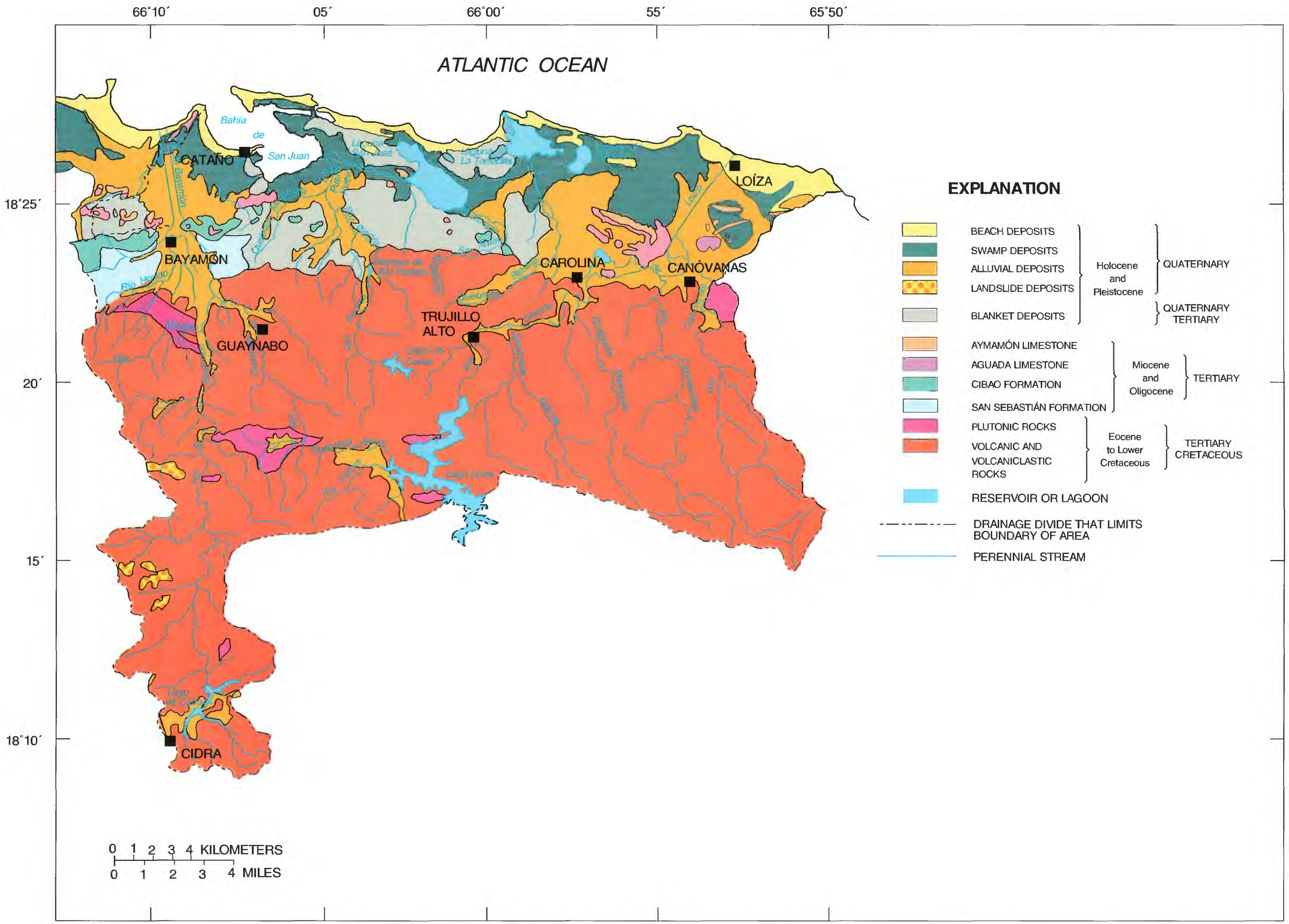
Figure 2.1.4.B-1 Approximate well locations in the Bayamón-Loíza region, Puerto Rico.

2.1.4.C Geologic Setting

Volcanic rocks, consolidated sedimentary rocks, and unconsolidated Quaternary surficial deposits are the three major rock types that occur within the Bayamón-Loíza region (fig. 2.1.4.C-1). Volcanic rocks of Cretaceous age are the most abundant rock type, and are exposed in more than half the region. They are composed of volcanic tuff, breccia and lava, associated sandstone, siltstone and limestone, and some intrusive igneous rocks. These volcanic rocks contain little water except in weathered and fractured zones. Consolidated sedimentary rocks of Tertiary age overlie the volcanic rocks in the northern part of the Bayamón-Loíza region. They are composed of consolidated gravel, sand and clay, and calcareous rocks ranging from marl to indurated limestone. The sedimentary rock formations have a seaward dip of four to six degrees, and are mostly exposed near Bayamón. Unconsolidated surficial deposits overlie the sedimentary rocks in the San Juan to Carolina area.

The consolidated sedimentary rocks have been differentiated into five formations in the Bayamón-Loíza region. In ascending order these formations are: the San Sebastián Formation of Oligocene age, the Mucarabones Sand and Cibao Formation of Oligocene to Miocene age, and the Aguada Limestone and Aymamón Limestone of Miocene age (Monroe, 1980a, p. 9).

The San Sebastián Formation is composed of cross-bedded to massive beds of sand, sand and gravel, and sandy clay, with some thin beds of sandstone and sandy limestone (Anderson, 1976, p. 9). The thickness of the San Sebastián Formation ranges from 165 to 330 feet, attaining its maximum thickness in the western part of the area and becoming thinner to the east. In the San Juan area, the San Sebastián Formation becomes indistinguishable from the overlying Mucarabones Sand and Quaternary deposits.



Modified from Briggs and Akers, 1965

Figure 2.1.4.C-1 Generalized surficial geology in the Bayamón-Loíza region, Puerto Rico.

The Mucarabones Sand overlies the San Sebastián Formation and interfingers eastward with the lower part of the overlying Cibao Formation. East of the Río Bayamón, the Mucarabones Sand is composed of coarse sand interbedded with sandy limestone, coarse sandy clay, and lenses of gravel (Monroe, 1980a, p. 27). Near San Juan, the Mucarabones Sand appears to thin to less than 300 feet, from a maximum thickness of about 400 feet near Bayamón (Monroe, 1980a, p. 27).

The Cibao Formation overlies the Mucarabones Sand and is composed of interlensing beds of calcareous clay, limestone, sandy clay, sand, and gravel (Monroe, 1980a, p. 29). The thickness of the Cibao Formation in the city of Bayamón is about 160 feet.

The Aguada Limestone overlies the Cibao Formation and is a hard thick-bedded to massive calcarenite, and dense limestone interbedded with chalky limestone and marl (Briggs and Akers, 1965). Studies by Monroe (1973) indicate that the lower part of the Aguada Limestone intertfingers with the upper part of the Cibao Formation eastward from the city of Bayamón. The thickness of the Aguada Limestone seems to range from about 80 to 260 feet in most of the area.

The Aymamón Limestone overlies the Aguada Limestone and consists mainly of thick-bedded to massive, commonly quartz free, very pure limestone (Monroe, 1980a, p. 53). This formation is largely covered throughout the area by unconsolidated surficial deposits. The thickness of the Aymamón Limestone is estimated to be as much as 2,000 feet at the coastline (Kaye, 1959).

The surficial deposits of Quaternary age cover the Tertiary age formations in the northern part of the region. These surficial deposits consist of alluvial deposits, blanket sands, beach and dune sands, and swamp deposits. The thickness of the surficial deposits is about 100 feet in the San Juan coastal areas.

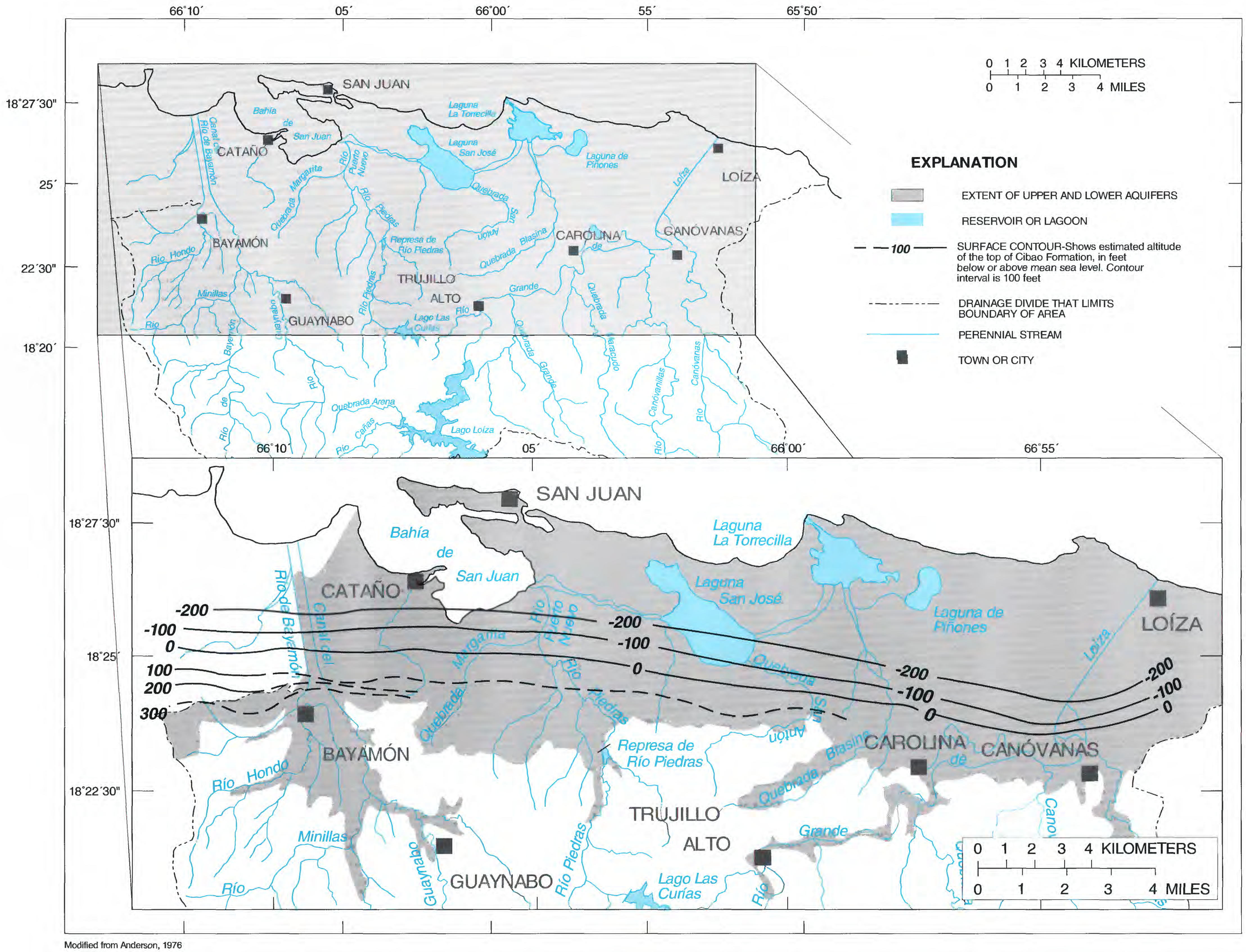
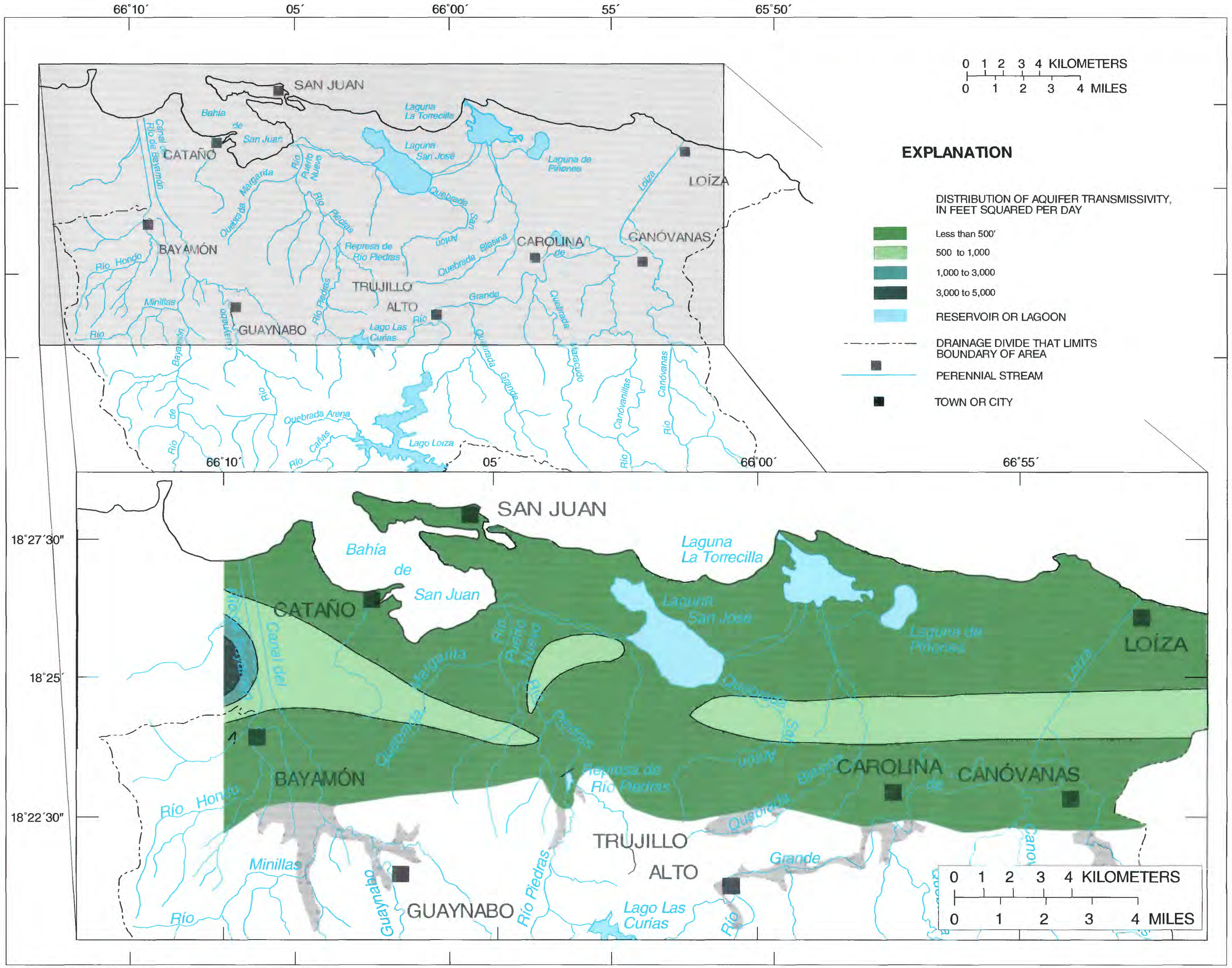


Figure 2.1.4.D-1 Altitude of the top of the Cibao Formation in the Bayamón-Loíza region, Puerto Rico.

2.1.4.D Hydrogeology

Two principal water-bearing units are present in the Bayamón-Loíza region: an upper water-table aquifer comprised of sedimentary rocks of Tertiary age and surficial deposits of Quaternary age; and a lower confined aquifer comprised mainly of sedimentary rocks of Tertiary age. The two units are separated by the upper member of the Cibao Formation, which acts as a confining unit.

The upper aquifer occurs in the uppermost rocks overlying the upper member of the Cibao Formation, the Aguada and Aymamón Limestones, and alluvial deposits. The Aguada and Aymamón Limestones are eroded and covered with alluvial deposits, and the upper part of the Cibao Formation becomes thinner near San Juan. As a consequence, the available freshwater in the upper aquifer around San Juan largely resides in surficial deposits. For the most part, according to Rodríguez-Martínez (1991, p. 12), the upper aquifer is absent in the San Juan metropolitan area, and where present, is thin and contains brackish water. The thickness of the upper aquifer is limited by the location of the saline-freshwater interface and the top of the Cibao Formation (fig. 2.1.4.D-1).



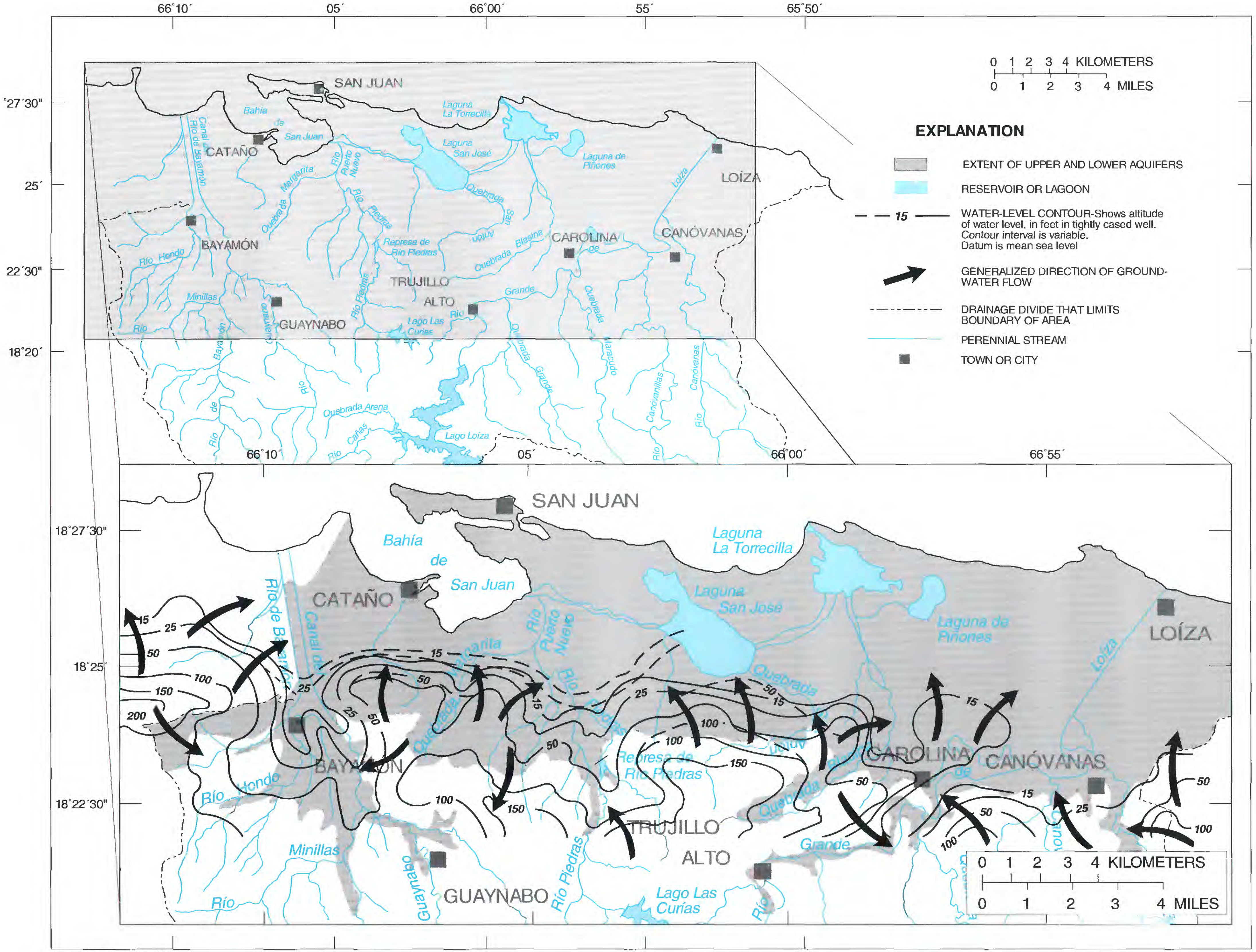
Modified from Ingrid Padilla, U.S. Geological Survey, written communication, 1991

Figure 2.1.4.D-2 Transmissivity in the northern Bayamón-Loíza region, Puerto Rico.

The transmissivity of the upper aquifer ranges from less than 500 to more than 3,000 ft^2/d (Ingrid Padilla, U.S. Geological Survey, written communication,1991; fig. 2.1.4.D-2). Higher transmissivity values are measured west of the Canal del Río de Bayamón in the Toa Baja-Vega Baja region.

The lower aquifer occurs in the Mucarabones Sand and minor limestone lenses within the Cibao Formation (Rodríguez-Martínez, 1991, p.15). The lower aquifer is confined from Bayamón to San Juan, but east of Río Piedras, the formations that comprise this hydrologic unit pinch out. The transmissivity of the lower aquifer ranges from less than 150 to 2,000 ft^2/d (Anderson, 1976, p. 18). The quality of water in the lower aquifer ranges between fresh to brackish in the San Juan metropolitan area (Rodríguez-Martínez, 1991, p.15).

Some wells south of Trujillo Alto and Carolina yield water from the volcanic rocks in small quantities. The water that may be available in the volcanic bedrock flows through cracks and fissures in the weathered zones.



Modified from Anderson, 1976

Figure 2.1.4.E-1 Altitude of water-level surface and direction of ground-water flow during 1971 in the Bayamón-Loíza region, Puerto Rico.

2.1.4.E Ground-Water Levels and Movement

Regional ground-water flow in the upper and lower aquifers within the Bayamón-Loíza region is northward from surficial exposures of the formations of Tertiary age, where the recharge occurs, to eventually discharge into swamps and lagoons along the coast (fig. 2.1.4.E-1). Ground water also moves locally towards the main stream systems of the Río Bayamón, Río Piedras, and Río Grande de Loíza.

Higher ground-water levels are observed during the rainy season, which occurs from August through November and from April to May, than during the dry season. The difference between the highest and the lowest water-level altitude during 1987 in one observation well near Cataño and another near San Juan was about 4 and 9 feet, respectively.

Recharge to the water-bearing formations in the area is primarily from rainfall, but also from infiltration of streamflow. In the highly urbanized San Juan metropolitan area another possible source of recharge to the aquifer is leakage from water and sewer lines (Anderson, 1976, p.15). According to Anderson (1976, p. 27), the Río Bayamón recharges the alluvium and the Tertiary age aquifers when ground-water levels are low, generally from January to April. During the rest of the year the aquifer either is in balance with the stream or contributes water to it.

2.1.4.F Soil Permeability

The soil associations overlying the aquifers in the Bayamón-Loíza region belong to the humid coastal plains group (fig. 2.1.4.F-1). These soil associations are Cataño-Aguadilla, Almirante-Vega Alta-Matanzas, Martín Peña-Saladar-Hydraquents, Swamps-Marshes, Coloso-Toa-Bajura, and Toa-Coloso-Bajura.

The dominant soil association in the Bayamón-Loíza region is the Almirante-Vega Alta-Matanzas, which covers most of the west and west central parts of the aquifer area. The soils of this association are described by Boccheciamp (1978, p. 5) as deep, gently sloping, well drained soils of clayey texture on terraces and alluvial fans of the coastal plain. The Almirante-Vega Alta-Matanzas association ranges in thickness from near zero to 84 inches and has a permeability of 0.60 to 2.00 in/hr.

The second important soil association is the Coloso-Toa-Bajura, which covers most of the eastern part of the aquifer. This association is composed of deep, moderately well- to poorly-drained, nearly level soils on flood plains (Boccheciamp, 1977, p. 3). The Coloso-Toa-Bajura association is derived from fine- to moderately-fine textured sediment of mixed origin. The dominant permeability values in this association range from 0.06 to 0.20 in/hr, although the Toa series within the Coloso-Toa-Bajura association has a permeability of 0.60 to 2.00 in/hr. Thickness of soils in the Coloso-Toa-Bajura association ranges from near zero to 70 inches.

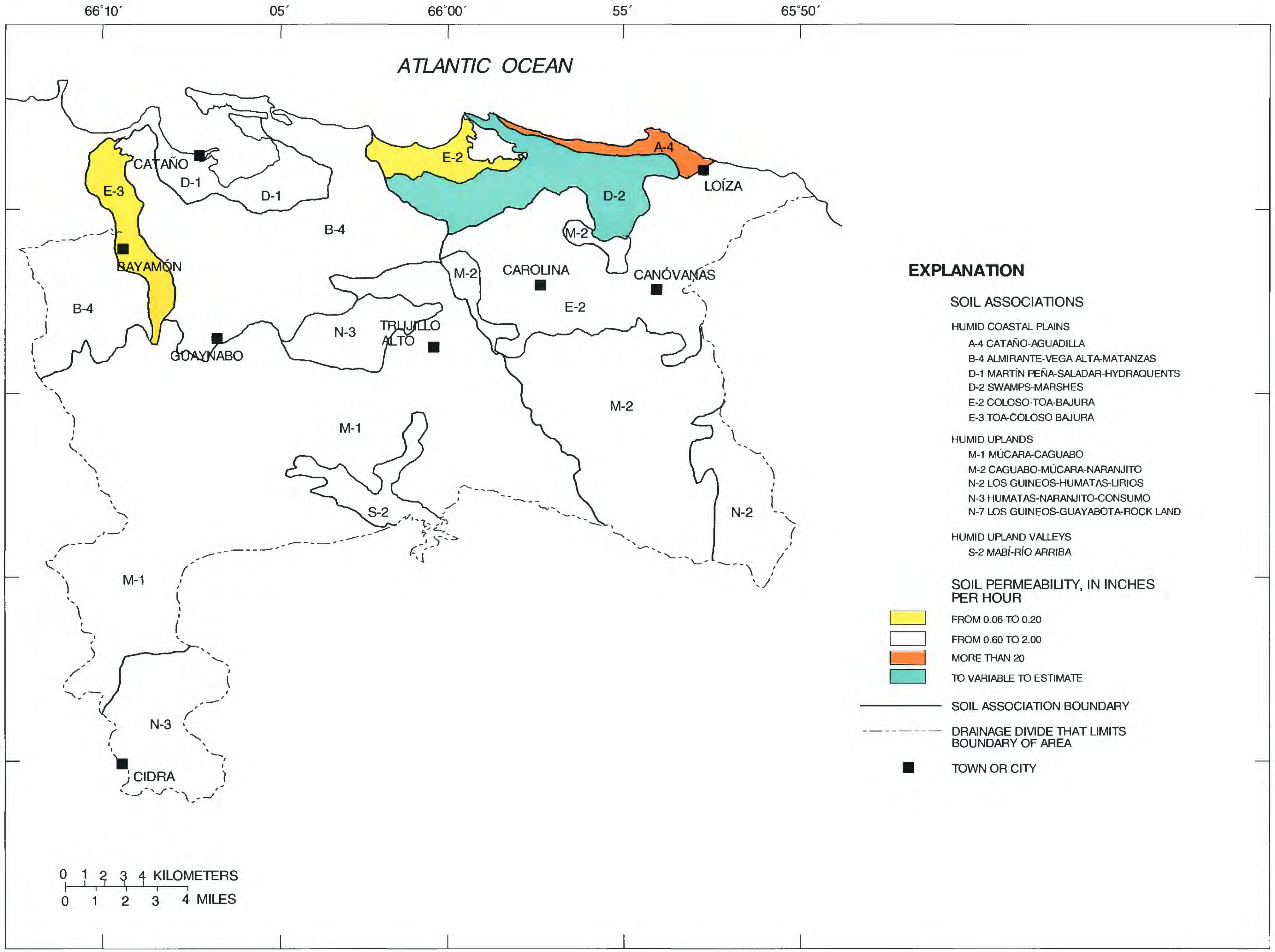
Other soil associations are not extensive in the region. The Swamps-Marshes association covers the northeast, in areas adjacent to the San José, La Torrecilla, and Piñones lagoons. These are deep, very poorly drained soils in the coastal plains, whose characteristics are too variable to be estimated. The Martín Peña-Saladar-Hydraquents association occupies the area surrounding the Bahía de San Juan. These soils are deep, nearly level, and very poorly drained. They are located in low depressions and lagoons of the coastal plains, and permeability generally ranges from 0.60 to 2.00 in/hr. In the Martín Peña series, a permeability at a depth of 18 inches decreases to less than 0.06 in/hr. Thickness of soils in the Martín Peña-Saladar-Hydraquents association ranges from near zero to 63 inches. The Toa-Coloso-Bajura soil association overlies the alluvial deposits located along the Río de Bayamón in the northwestern part of the upper aquifer. This association has a dominant permeability of 0.06 to 0.20 in/hr, although the upper 16 inches in the Coloso series has a permeability of 0.20 to 0.60 in/hr, and the Toa series has a permeability of 0.60 to 2.00 in/hr. Thickness of soils in the Toa-Coloso-Bajura association range from near zero to 70 inches. The Cataño-Aguadilla soil association is present in a fringe bordering the coast in the northeastern part. This soil association has the greatest permeability of any within the region (>20 in/hr); however, the upper 8 inches in the Aguadilla series have a permeability of 6 to 20 in/hr. Thickness of these soils ranges from near zero to 64 inches.

Thickness, permeability, and available water-capacity values are listed for all the soil associations present within the Bayamón-Loíza region (table 2.1.4.F-1). Soil associations present in the upland areas south of the coastal aquifer areas and their characteristics are included in table 2.1.4.F-1.

Table 2.1.4.F-1 Thickness, permeability, and available water capacity for the soil associations in the Bayamón-Loíza region, Puerto Rico (Modified from Boccheciamp, 1977 and 1978)
[>, more than]

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Humid Coastal Plains			
Cataño-Aguadilla	0 to 64	>20.00	0.03 to 0.05
Almirante-Vega Alta-Matanzas	0 to 84	0.60 to 2.00	0.10 to 0.20
[1]Martín Peña-Saladar-Hydraquents	0 to 63	0.60 to 2.00	0.12 to 0.20
[1]Swamps-Marshes		too variable to estimate	
Coloso-Toa-Bajura	0 to 70	0.06 to 0.20	0.12 to 0.20
Toa-Coloso-Bajura	0 to 70	0.06 to 0.20	0.12 to 0.20
Humid Upland Valleys			
Mabí-Río Arriba	0 to 60	0.06 to 0.20	0.15 to 0.20
Humid Uplands			
Múcara-Caguabo	0 to 30	0.63 to 2.00	0.05 to 0.17
Caguabo-Múcara-Naranjito	0 to 40	0.60 to 2.00	0.05 to 0.19
Los Guineos-Humatas-Lirios	0 to 60	0.60 to 2.00	0.10 to 0.20
Humatas-Naranjito-Consumo	0 to 60	0.60 to 2.00	0.10 to 0.20
Los Guineos-Guayabota-Rock Land	0 to 60	0.06 to 0.20	0.15 to 0.20

[1] High water table



Modified from Boccheciamp, 1977 and 1978

Figure 2.1.4-F-1 Soil associations and permeability in the Bayamón-Loíza region, Puerto Rico.

2.2 South Coast Area

2.2.1 SANTA ISABEL-PATILLAS REGION

By Orlando Ramos-Ginés

2.2.1.A Location and Major Geographic Features

The Santa Isabel-Patillas region covers about 90 mi^2 and is located in the South Coast area of Puerto Rico. It is bounded to the north by the Cordillera Central, to the west by the Río Descalabrado drainage basin divide, to the east by the Río Grande de Patillas drainage basin divide, and to the south by the Caribbean Sea. A coastal alluvial plain is the major geographic feature within this region. This coastal plain abuts the Cordillera Central to the north, which reaches elevations of as much as 1,600 feet above mean sea level, and the Caribbean Sea to the south (fig. 2.2.1.A-1). The region includes several small rivers: the Río Grande de Patillas, Río Nigua of Arroyo, Río Guamaní, Río Seco, Río Nigua of Salinas, Río Jueyes, Río Cayures, Río Coamo, Río Cuyón, Río Lapa, and Río Descalabrado. Most of the original vegetation has been removed for agricultural purposes. Nevertheless, a few mangrove swamps remain scattered along the coast. A complex irrigation-canal system constructed between 1914 and 1916 transfers water from Patillas, Coamo, Guayabal, and Carite lakes to the many farms in the region. The principal population centers in the Santa Isabel-Patillas region are Patillas, Arroyo, Guayama, Salinas, Santa Isabel, and Coamo.

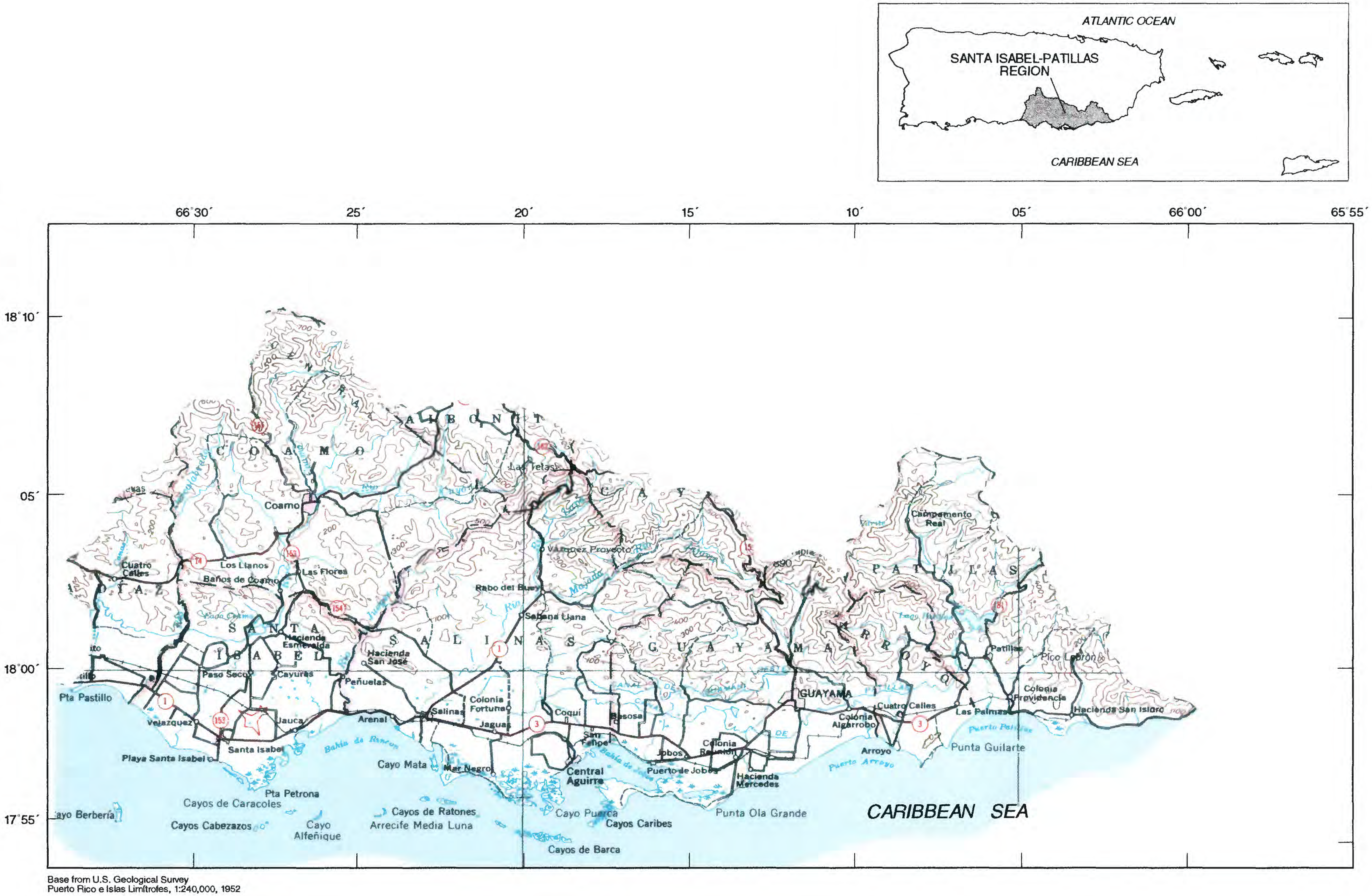


Figure 2.2.1.A-1 Location and major geographic features in the Santa Isabel-Patillas region, Puerto Rico.

2.2.1.B Population and Estimated Ground-Water Use

The population of the Santa Isabel-Patillas region was about 152,000 in 1980 (U.S. Department of Commerce, 1982). The population in the region increased about 6 percent by 1990 resulting in a population of about 162,000 (U.S. Department of Commerce, 1991). About 61 percent of the population lives in rural areas and about 39 percent in urban areas (table 2.2.1.B-1).

Total ground-water withdrawals in the Santa Isabel-Patillas region in 1983 were about 40 Mgal/d, of which approximately 9.4 Mgal/d were for domestic use (table 2.2.1.B-2). The Puerto Rico Aqueduct and Sewer Authority was the major single user, pumping about 9.2 Mgal/d. Private wells and a small community system in the municipio of Santa Isabel, which pumped about 7,000 gal/min, account for the other 0.2 Mgal/d. Ground-water withdrawals represent about 24 percent of the total water for domestic use in this region. Approximate location and use of wells are shown on figure 2.2.1.B-1.

Pumping for agricultural use represented about 64 percent (25.8 Mgal/d) of the total ground-water withdrawn in the region in 1983. About 35 percent of the total water used for irrigation was supplied from ground-water sources; the remaining 65 percent was supplied by streamflow through an irrigation canal and lake system. It is expected that agricultural water supply from streamflow areas west of the Río Jueyes will decrease after 1991, as a result of the conversion from furrow to drip irrigation.

Table 2.2.1.B-1 Population for the Santa Isabel-Patillas region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Arroyo	17,014	8,432	8,579	18,910
Coamo	30,822	12,851	17,971	33,837
Guayama	40,183	21,097	19,086	41,588
Patillas	17,774	3,172	14,602	19,633
Salinas	26,438	6,220	20,218	28,335
Santa Isabel	19,854	6,948	12,906	19,318
Total	152,085	58,720	93,362	161,621

Table 2.1.1.B-2 Ground-water withdrawals and estimated population served during 1983 for the Santa Isabel-Patillas region, Puerto Rico
[Mgal/d, million gallons per day; ---, no data available]

[1] Use and supplier		Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use			
[2] A. Puerto Rico Aqueduct and Sewer Authority			
1. Patillas		13,011	1.0
2. Arroyo		18,900	0.9
3. Guayama		6,890	0.7
4. Salinas		27,912	3.5
5. Santa Isabel		20,711	3.1
6. Coamo		122	0.001
	Subtotal	87,546	9.21
[3] B. Community Systems			
[4] 1. Santa Isabel		111	0.007
	Subtotal	111	0.007
[4] C. Private Supplies			
1. Guayama		[4] 111	0.007
2. Salinas		[4] 285	0.018
3. Santa Isabel		[4] 2,500	0.16
	Subtotal	2,896	0.185
[3] II. Industrial Use			
1. Salinas		---	3.35
2. Santa Isabel		---	1.44
	Subtotal	---	4.79
[3] III. Agriculture Use			
1. Patillas		---	0.09
2. Arroyo		---	1.2
3. Guayama		---	2.64
4. Salinas		---	9.1
5. Santa Isabel		---	12.72
	Subtotal	---	25.75
[3] IV. Commercial Use			
1. Santa Isabel		---	0.009
	Subtotal	---	0.009
	Total	136,358	39.95

[1] Municipios not listed under some specific use do not withdraw ground water for the subject use.
[2] Modified from data reported by Gómez-Gómez and others, 1984.
[3] Modified from data reported by a written communication of the Puerto Rico Department of Health.
[4] Based on a water consumption of 63 gallons per person per day.

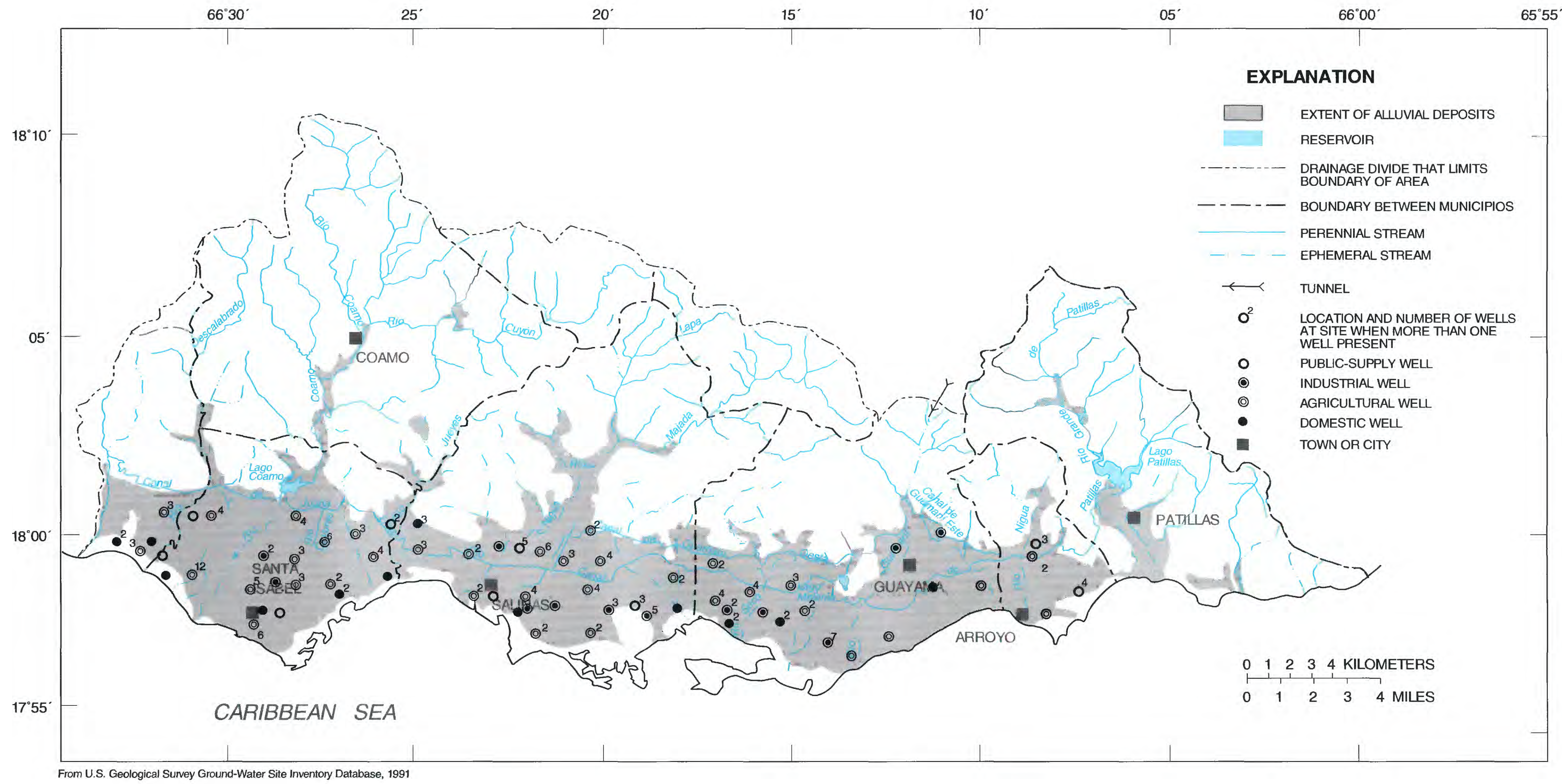


Figure 2.2.1.B-1 Approximate well locations in the Santa Isabel-Patillas region, Puerto Rico.

2.2.1.C Geologic Setting

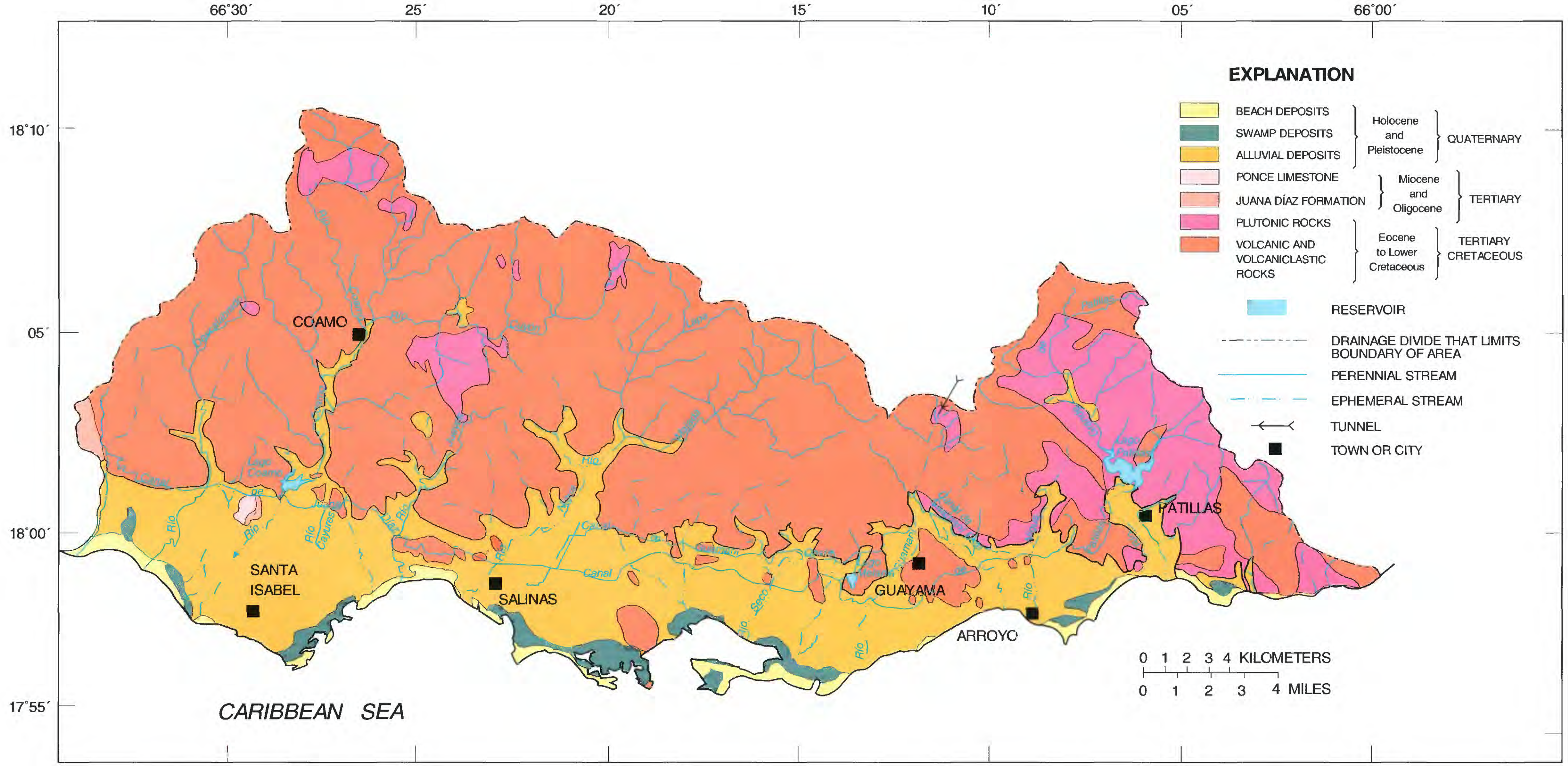
The geology of the Santa Isabel-Patillas region consists of three basic lithologic units. They are, in ascending order, the volcanic-volcaniclastic rocks, the Juana Díaz Formation of Oligocene age, and the alluvial deposits (fig. 2.2.1.C-1).

The volcanic-volcaniclastic and sedimentary rocks of Eocene to Cretaceous age are intensely faulted and constitute almost 67 percent of the Santa Isabel-Patillas region (the uplands), and underly the Quaternary alluvial deposits. According to Monroe (1980a), these rocks are composed of tightly cemented limestone, sandstone and siltstone, tuff breccia, lava, granodiorite, and quartz diorite.

The Juana Díaz Formation of Oligocene age, unconformably overlies the volcanic-volcaniclastic and sedimentary rocks and is highly variable in lithologic character, consisting of conglomeratic sandstone and conglomerate, calcareous arenite, and minor limestone in the Santa Isabel-Patillas region. The thickness of Juana Díaz Formation ranges from 600 to more than 2,400 feet (Monroe, 1980a) and generally thins from east to west.

The Ponce Formation of Miocene age unconformably overlies the Juana Díaz Formation and consists of a tightly cemented, very pale orange to grayish-orange limestone, generally containing abundant molds of mollusks and corals (Monroe, 1980a). Small exposures are observed in the western Santa Isabel-Patillas region.

The alluvial deposits of Quaternary age unconformably overlap the Juana Díaz Formation and are composed of layers or lenses of unconsolidated to poorly consolidated clay, sand, gravel, and rounded to angular boulders. They coalesce to form a gently southward sloping coastal alluvial plain of highly variable thickness, due to extensive bedrock faulting. These deposits are hydrogeologically the most important lithologic unit in the Santa Isabel-Patillas region.



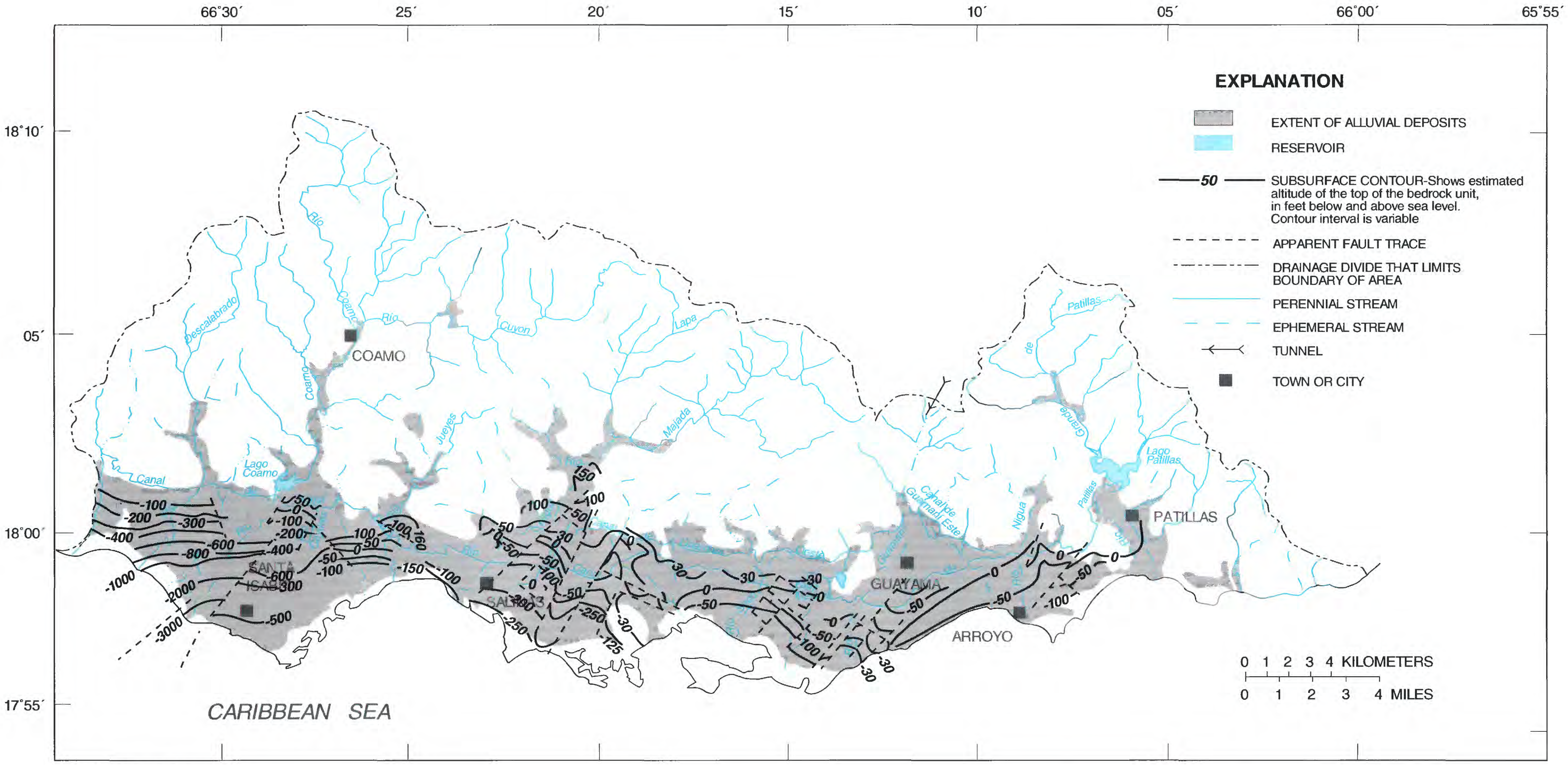
Modified from Briggs and Akers, 1965

Figure 2.2.1.C-1 Generalized surficial geology in the Santa Isabel-Patillas region, Puerto Rico.

2.2.1.D Hydrogeology

The alluvial deposits of Quaternary age are the most important lithologic unit in the Santa Isabel-Patillas region, containing its only sizeable aquifer. This aquifer is generally under water-table conditions, although flowing-artesian conditions have been observed throughout the area. Aquifer thickness may range from zero at the edge of the bedrock-alluvial contact to about 3,000 feet in the vicinity of Santa Isabel (fig. 2.2.1.D-1). East of the Río Jueyes and west of the Río Coamo, aquifer thickness decreases to no more than 300 feet along the shore. The aquifers in the fractured volcanic and plutonic rocks sustain very low yields. Thermal springs near Coamo are used as thermal water pools for recreation.

Hydraulic conductivities, ranging from 100 to 300 ft/d, occur near Santa Isabel, Salinas, and Guayama (fig. 2.2.1.D-2). Elsewhere, hydraulic conductivity is less than 100 ft/d and decreases toward the coast. Transmissivity in the Santa Isabel-Patillas region is highly variable. The highest values, as great as 80,000 ft^2/d, occur in the area between the Río Coamo and Río Jueyes, due to an increase in aquifer thickness. Transmissivities as high as 40,000 ft^2/d are observed between the Río Cayures and the approximate divide between the Río Nigua of Salinas and Río Seco. Transmissivity values in this area increase seaward and toward the interfluvial area. West of the Río Coamo and east of the approximate divide between the Río Salinas and Río Seco, transmissivity values range from 1,000 to 30,000 ft^2/d.



Modified from Renken and others, 1991

Figure 2.2.1.D-1 Altitude of the top of the bedrock unit in the Santa Isabel-Patillas region, Puerto Rico.

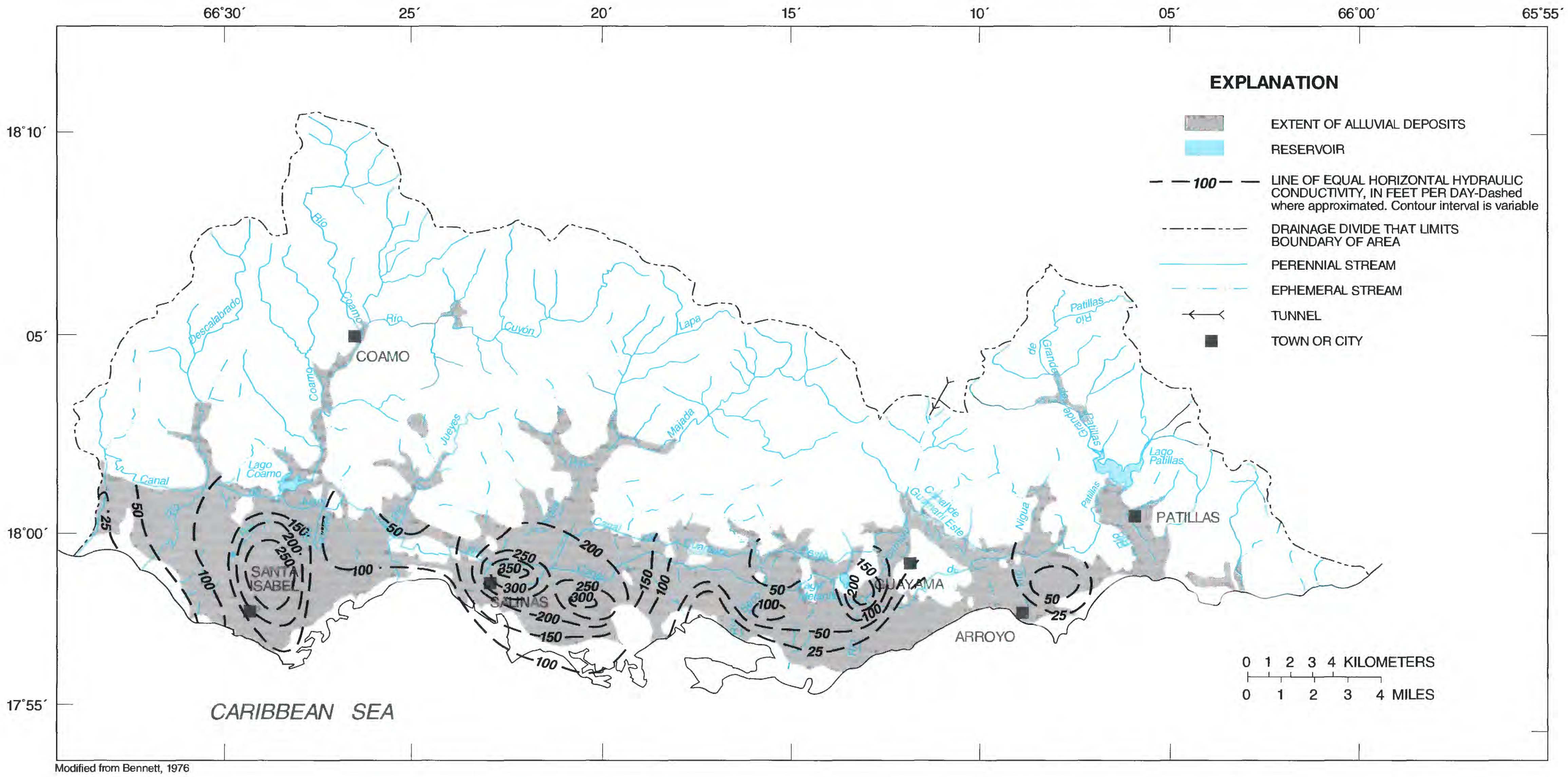
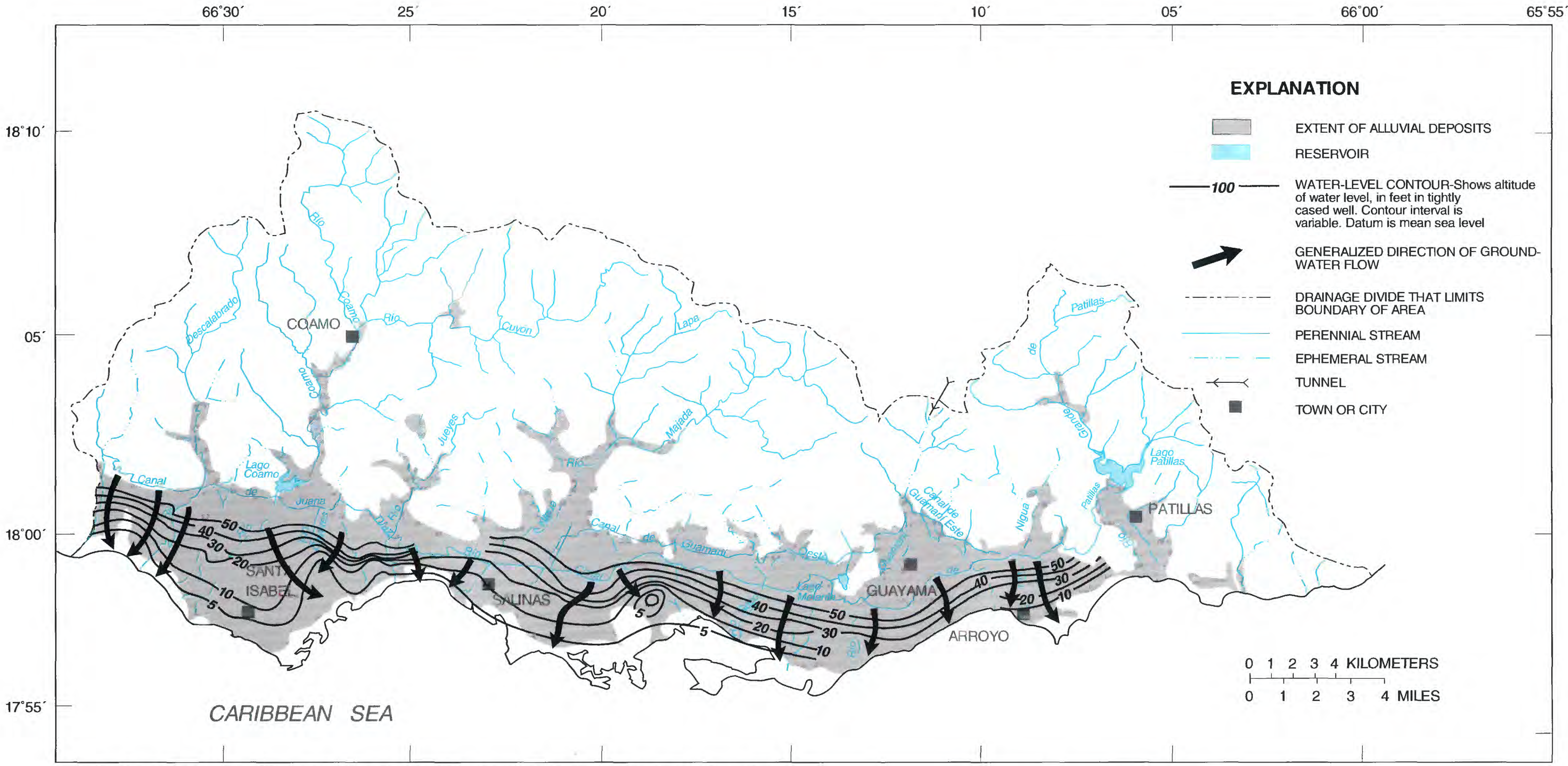


Figure 2.2.1.D-2 Average hydraulic conductivity in the Santa Isabel-Patillas region, Puerto Rico.

2.2.1.E Ground-Water Levels and Movement

Ground-water levels in the Santa Isabel-Patillas region range from 150 to 200 feet above mean sea level near the bedrock-alluvial contact to a few feet above mean sea level near the coast (fig. 2.2.1.E-1). Accordingly, ground-water flows seaward. Where confined conditions occur, ground-water levels may be as high as 10 feet above land surface (Vicente Quiñones-Aponte, U.S. Geological Survey, oral communication, 1987). Ground-water levels may fluctuate as much as 10 feet as a result of seasonal changes.

Sources of aquifer recharge may vary throughout the region. Seepage from rivers and irrigation canals represent the major source of ground-water recharge. Aquifer recharge from precipitation represents only about 10 percent of the mean annual rainfall in the region (Vicente Quiñones-Aponte, U.S. Geological Survey, oral communication, 1987). In the Patillas to Salinas region, aquifer recharge depends primarily on conveyance losses from water diverted from Lago Guamaní and Lago Carite through the Canal de Guamaní and Canal de Patillas. A preliminary ground-water flow simulation of the area has shown that if diversion from Lago Guamaní ceases and actual ground-water pumpage is sustained, the aquifer will undergo an abrupt decrease in water levels (Sigfredo Torres-González, U.S. Geological Survey, oral communication, 1987). West of the Río Jueyes, aquifer recharge comes primarily from streamflow leakage. In general, ground-water discharges to streams in the upland areas and near the coast.



Modified from Torres-González and Gómez-Gómez, 1987; Quiñones-Aponte and Gómez-Gómez, 1987; Rodríguez-del-Río and Gómez-Gómez, 1987

Figure 2.2.1.E-1 Composite altitude of water-level surface and direction of ground-water flow during 1986 and 1987 in the Santa Isabel-Patillas region, Puerto Rico.

2.2.1.F Soil Permeability

The principal soils overlying the aquifer areas in the Santa Isabel-Patillas region are the Coamo-Guamaní-Vives, the Jácana-Amelia-Fraternidad, and the Constancia-Jacaguas-San Antón (fig. 2.2.1.F-1). The Coamo-Guamaní-Vives is composed of deep, well-drained, nearly level to strongly sloping soils on terraces and alluvial fans (Boccheciamp, 1977, p. 4). Its permeability ranges from 0.60 to 2.00 in/hr (table 2.2.1.F-1). The soils composing the Jácana-Amelia-Fraternidad soil association are described as moderately deep and deep, well drained and moderately well drained, nearly level to strongly sloping. They are located on terraces, alluvial fans, and foot slopes and their permeability ranges from 0.60 to 2.00 in/hr. These clayey soils are highly suitable for agricultural use.

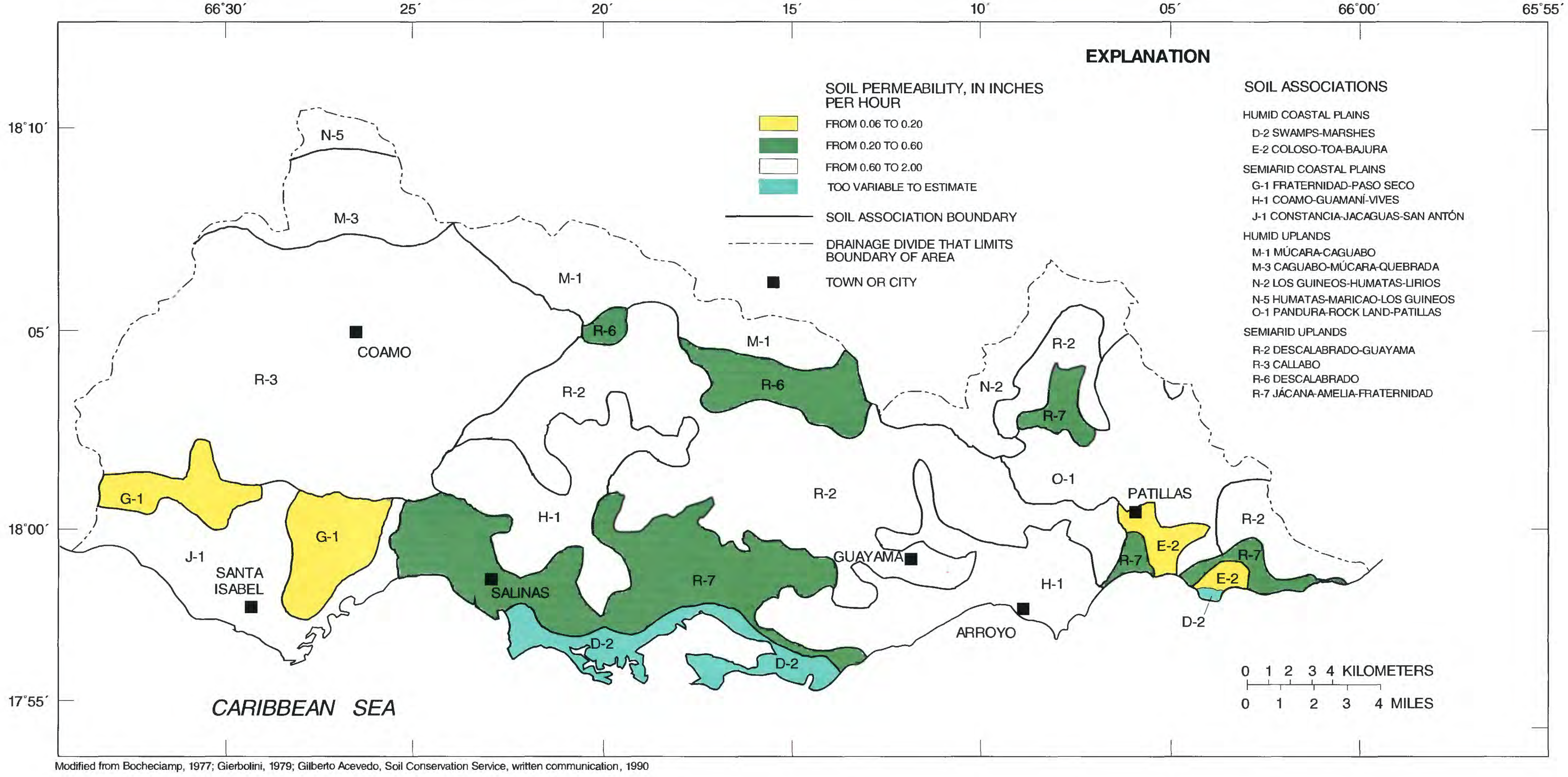


Figure 2.2.1.F-1 Soil associations and permeability in the Santa Isabel-Patillas region, Puerto Rico.

Table 2.2.1.F-1 Thickness, permeability, and available water capacity for the soil associations in the Santa Isabel-Patillas region, Puerto Rico (Modified from Gierbolini, 1979; Boccheciamp, 1977; and Gilberto Acevedo, Soil Conservation Service, written communication, 1990)
[>, more than]

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Humid Coastal Plains			
Swamp-Marshes		too variable to be estimated	
Coloso-Toa-Bajura	0 to >72	0.06 to 2.00	0.10 to 0.20
Semiarid Coastal Plains			
Fraternidad-Paso Seco	0 to 50	0.06 to 2.00	0.15 to 0.18
Coamo-Guamaní-Vives	0 to 20	0.60 to 2.00	0.10 to 0.15
Constancia-Jacaguas-San Antón	0 to 65	0.60 to 2.00	0.08 to 0.14
Humid Uplands			
Múcara-Caguabo	0 to 30	0.60 to 2.00	0.05 to 0.17
Caguabo-Múcara-Quebrada	0 to 60	0.60 to 2.00	0.06 to 0.17
Los Guineos-Humatas-Lirios	0 to 60	0.60 to 2.00	0.08 to 0.20
Humatas-Maricao-Los Guineos	0 to 72	0.60 to 2.00	0.12 to 0.16
Pandura-Rock Land-Patillas	0 to 48	0.60 to 2.00	0.05 to 0.14
Semiarid Uplands			
Descalabrado-Guayama	0 to 26	0.60 to 2.00	0.10 to 0.15
Callabo	0 to 13	0.60 to 2.00	0.10 to 0.15
Descalabrado	0 to 17	0.20 to 0.60	0.10 to 0.20
Jácana-Amelia-Fraternidad	0 to 50	0.20 to 0.60	0.10 to 0.18

2.2.2 JUANA DÍAZ-PONCE REGION

By Orlando Ramos-Ginés

2.2.2.A Location and Major Geographic Features

The Juana Díaz-Ponce region covers about 80 mi^2 and includes the municipios of Ponce, Juana Díaz, and Villalba. It is bounded to the north by the drainage basin divide in the Cordillera Central, to the west by the Río Cañas drainage basin divide, to the east by the Río Jacaguas drainage basin divide, and to the south by the Caribbean Sea (fig. 2.2.2.A-1). Steep volcanic mountains rising to as much as about 4,500 feet above mean sea level, eroded limestone hills, and a coastal alluvial plain are the predominant types of landforms in the region. The coastal alluvial plain covers about 80 percent of the municipal boundaries of Juana Díaz and about 40 percent of the Ponce municipal limits. The most important surface-water features in this region are the Río Cañas, the Río Portugués, the Río Bucaná, the Río Inabón, the Río Jacaguas, and the Lago Toa Vaca. From Punta Cucharas inland to the valley of the Río Cañas, limestone hill forms constitute most of the southwestern part of the Juana Díaz-Ponce region (McClymonds, 1972, p. 2). There are numerous stream diversions, canals, and storage lakes in the Juana Díaz-Ponce region that are used principally for agriculture (McClymonds, 1972, p. 13). Ponce is the principal population center in this region.

2.2.2.B Population and Estimated Ground-Water Use

The population of the Juana Díaz-Ponce region was about 253,000 in 1980 (U.S. Department of Commerce, 1982). Population in the region increased by about 1.3 percent by 1990, resulting in a population of about 256,000 (U.S. Department of Commerce, 1991). However, the municipio of Ponce experienced a decrease in population from a total of 189,046 in 1980 to 187,749 in 1990. About 74 percent of the population of the Juana Díaz-Ponce region lives in urban areas and about 26 percent lives in rural areas (table 2.2.2.B-1).

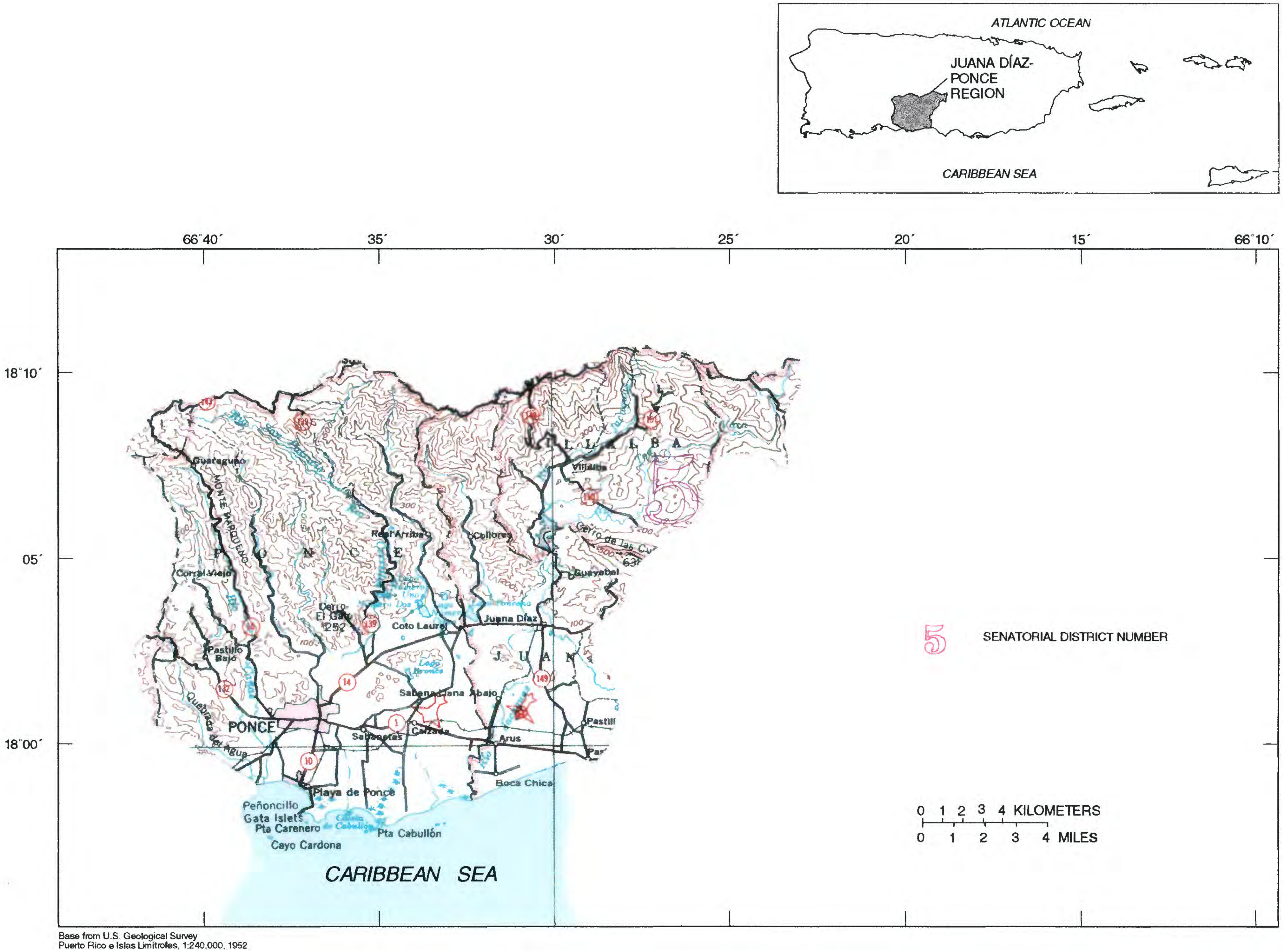


Figure 2.2.2.A-1 Location and major geographic features in the Juana Díaz-Ponce region, Puerto Rico.

Table 2.2.2.B-1 Population for the Juana-Díaz Ponce region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

MUNICIPIO	1980 population TOTAL	URBAN	RURAL	1990 population TOTAL
Juana Díaz	43,505	10,469	33,036	45,198
Ponce	189,046	161,739	27,307	187,749
Villalba	20,734	3,469	17,265	23,559
Total	253,285	175,677	77,608	256,506

In 1983, ground-water withdrawals averaged about 25 Mgal/d, of which 13.1 Mgal/d was for domestic use, 11.7 Mgal/d was for agricultural use, and about 0.1 Mgal/d was for private and commercial use (table 2.2.2.B-2). The Puerto Rico Aqueduct and Sewer Authority was the major single user, pumping about 13 Mgal/d. Private wells for domestic use were only found in the municipio of Juana Díaz and pumped about 0.03 Mgal/d. An estimated 38 percent of the total water demand for domestic use in the region was supplied by ground water.

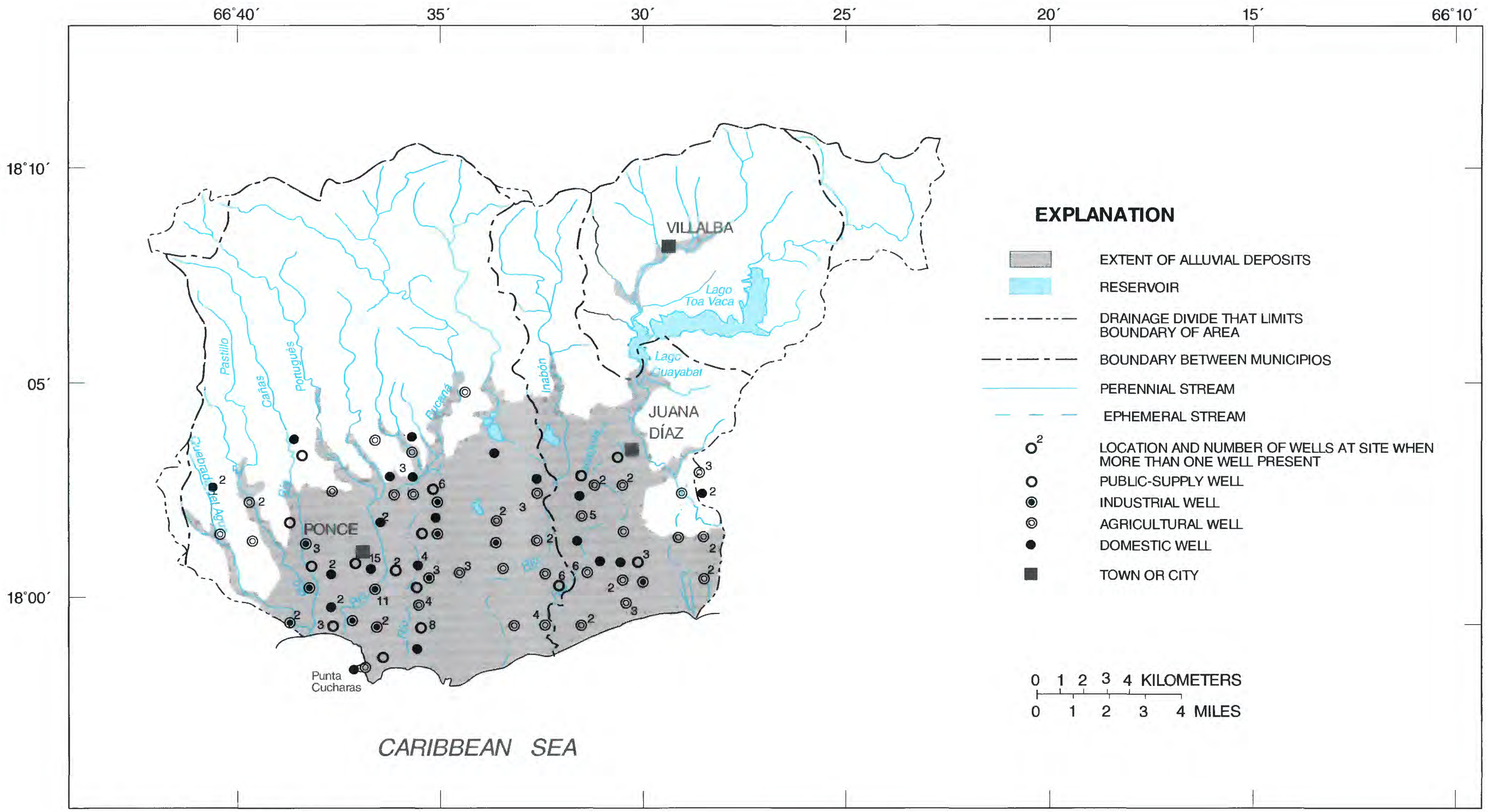
Average ground-water withdrawals for agriculture durind 1983 were 11.7 Mgal/d. In the municipio of Juana Díaz, the total water use for agricultural purposes during 1983 was approximately 23 Mgal/d of which 32 percent was obtained from ground-water sources. The remaining 68 percent was supplied by streamflow through the Canal de Juana Díaz irrigation system. In the municipio of Ponce, 43 percent of the water used for agricultural purposes was supplied from ground water. About 0.06 Mgal/d were pumped for commercial use. Approximate locations and uses of wells are shown on figure 2.2.2.B-1.

Table 2.2.2.B-2 Ground-water withdrawals and estimated population served during 1983 for the Juana Díaz-Ponce region, Puerto Rico

[Mgal/d, million gallons per day; ---, no data available]

[1] Use and supplier	Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use		
[2] A. Puerto Rico Aqueduct and Sewer Authority		
1. Juana Díaz	37,467	3.4
2. Ponce	62,678	9.6
Subtotal	100,145	13.0
[4] B. Private Supplies		
1. Juana Díaz	[3] 460	0.03
Subtotal	460	0.03
[4] II. Agriculture Use		
1. Juana Díaz	---	7.2
2. Ponce	---	4.4
Subtotal	---	11.7
[4] III. Commercial Use		
1. Juana Díaz	---	0.06
Subtotal	---	0.06
Total	100,605	24.8

[1] Municipios not listed under some specific use do not withdraw ground water for the subject use.
[2] Modified from data reported by Gómez-Gómez and others, 1984.
[3] Based on a water consumption of 63 gallons per person per day.
[4] Based on a ground-water survey conducted during March 1986.



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.2.2.B-1 Approximate well locations in the Juana Díaz-Ponce region, Puerto Rico.

2.2.2.C Geologic Setting

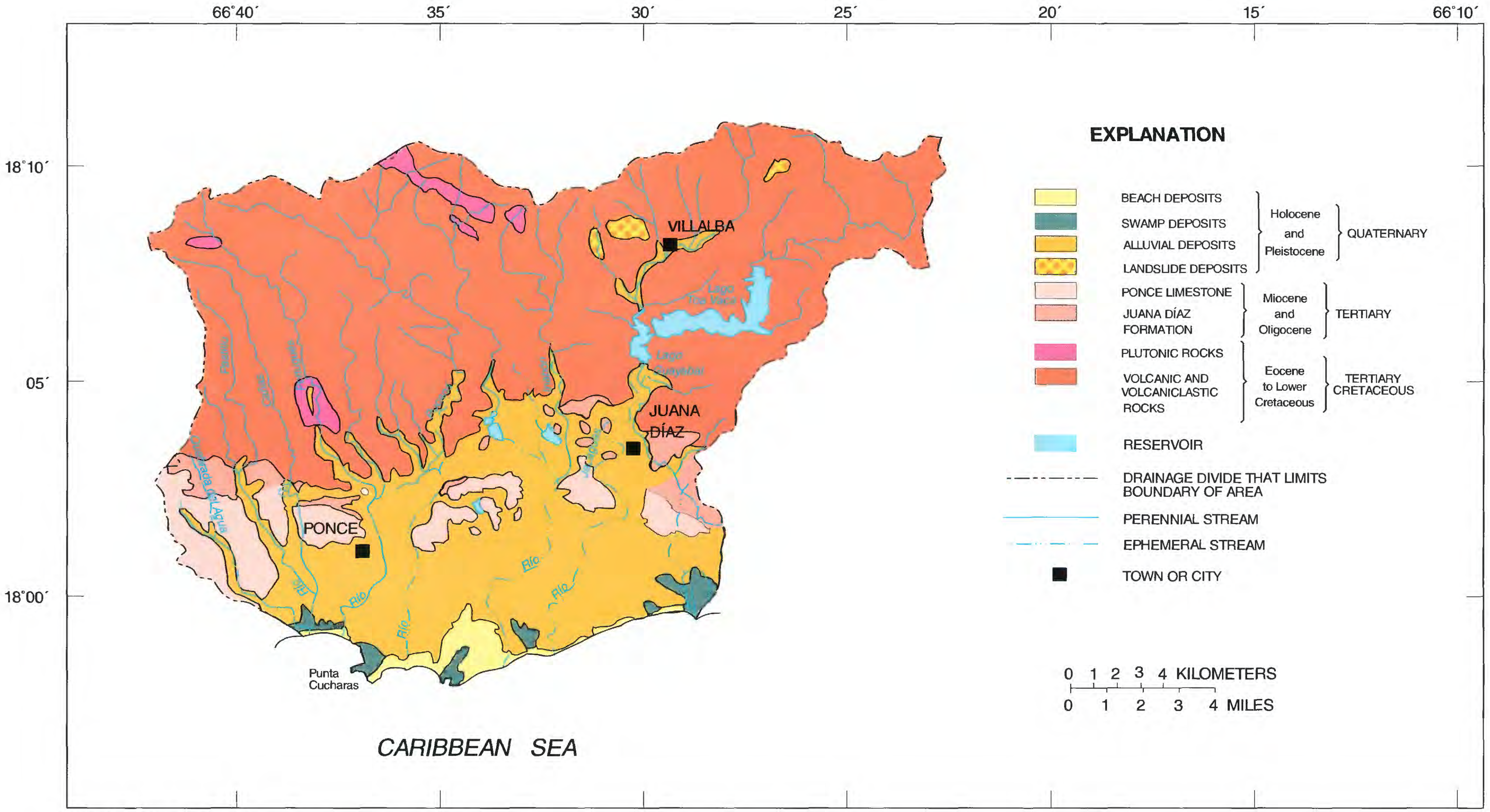
The geology of the Juana Díaz-Ponce region consists of four basic lithologic types. Among these are a suite of volcaniclastic, volcanic, plutonic, and limestone rocks of Early Cretaceous to Eocene age; the Juana Díaz Formation of Oligocene to Miocene age; the Ponce Limestone of Miocene age; and alluvial deposits of Quaternary age (fig. 2.2.2.C-1).

The suite of Early Cretaceous to Eocene age rocks are exposed in the interior upland portions of the Juana Díaz-Ponce region and are composed of volcanic and volcaniclastic-plutonic rocks, tightly cemented limestone, tylaceous sand and siltstone, tuff breccia, lava, granodiorite, and quartz diorite (Monroe, 1980a). These rocks are intensely faulted and are structurally complex.

The Juana Díaz Formation unconformably overlies the suite of Early Cretaceous to Eocene rocks toward the south and consists of limestone in the upper part of the formation and a basal conglomerate of pebbles, cobbles, and boulders in the lower part. It is continuously exposed, except in alluvium-filled valleys, and rests on an eroded and highly irregular surface of the older volcaniclastic-plutonic rocks (Monroe, 1980a, p. 67).

The Ponce Limestone unconformably overlies the Juana Díaz Formation and consists of a tightly cemented very pale orange to grayish-orange limestone, generally containing abundant molds of mollusks and corals (Monroe, 1980a). It too is continuously exposed throughout the Juana Díaz-Ponce region, except where covered by alluvium.

The Quaternary alluvial deposits unconformably overlie the Juana Díaz Formation and Ponce Limestone. These deposits consist of poorly bedded and poorly sorted gravel, sand, silt, and some clay. In general, the amount of gravel diminishes seaward with increasing amounts of silt and clay. The thickness of alluvium deposit exposures in the Juana Díaz-Ponce region range from about 200 to 2,000 feet, though much of this thickness may be due to faulting (Gómez-Gómez and Heisel, 1980).



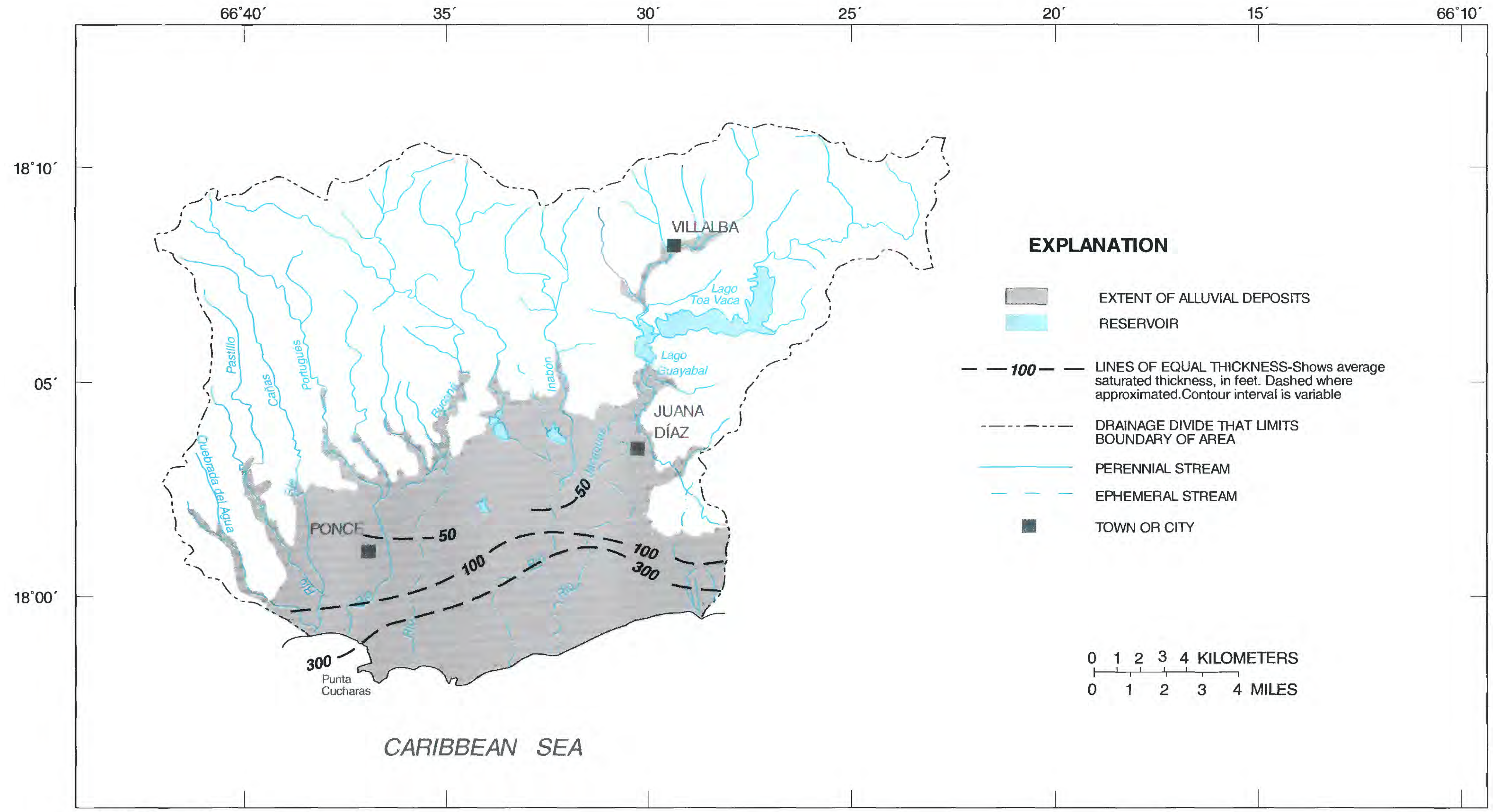
Modified from Briggs and Akers, 1965

Figure 2.2.2.C-1 Generalized surficial geology in the Juana Díaz-Ponce region, Puerto Rico.

2.2.2.D Hydrogeology

The principal aquifer in the Juana Díaz-Ponce region is under water-table conditions in the alluvial deposits, although flowing-artesian conditions have been observed (McClymonds, 1972, p. 19). Aquifer thickness increases toward the coast to about 300 feet (fig. 2.2.2.D-1). In upper valley areas where the alluvium is thinner, ground-water seepage from fractures within the bedrock are an additional source of ground-water recharge. In general, the Ponce Limestone seems to yield more water to wells than the alluvial aquifer in the upper valley areas. The aquifer in the fractured volcanic and plutonic rock is a locally important source of water. The highest well yield in this aquifer, about 200 gal/min, is in the upper Río Portugués (McClymonds, 1972, p. 18). Numerous springs, particularly on formation outcrops, flow in the Juana Díaz-Ponce region. Two thermal springs flow in the upper Río Portugués, and one was developed and used for hot baths (McClymonds, 1972, p.18).

Hydraulic-conductivity values in the alluvial aquifer ranged from 0.1 to 100 ft/d, increasing from east to west toward Ponce and decreasing from the center of the valley toward the shore where amounts of silt and clay increase significantly (fig. 2.2.2.D-2). As a result, most of the deeper water is protected from direct seawater encroachment (McClymond, 1972, p. 5). The Ponce Limestone in the upper valley area may have hydraulic-conductivity values as high as 300 ft/d (Fernando Gómez-Gómez, U.S. Geological Survey, oral communication, 1987). Transmissivity values of the alluvial aquifer near the town of Ponce could be as high as 10,000 ft^2/d. Transmissivity values in the Juana Díaz-Ponce region increase from east to west toward the Río Cañas and decrease seaward.



Modified from Bennett, 1976

Figure 2.2.2.D-1 Aquifer thickness in the Juana Díaz-Ponce region, Puerto Rico.

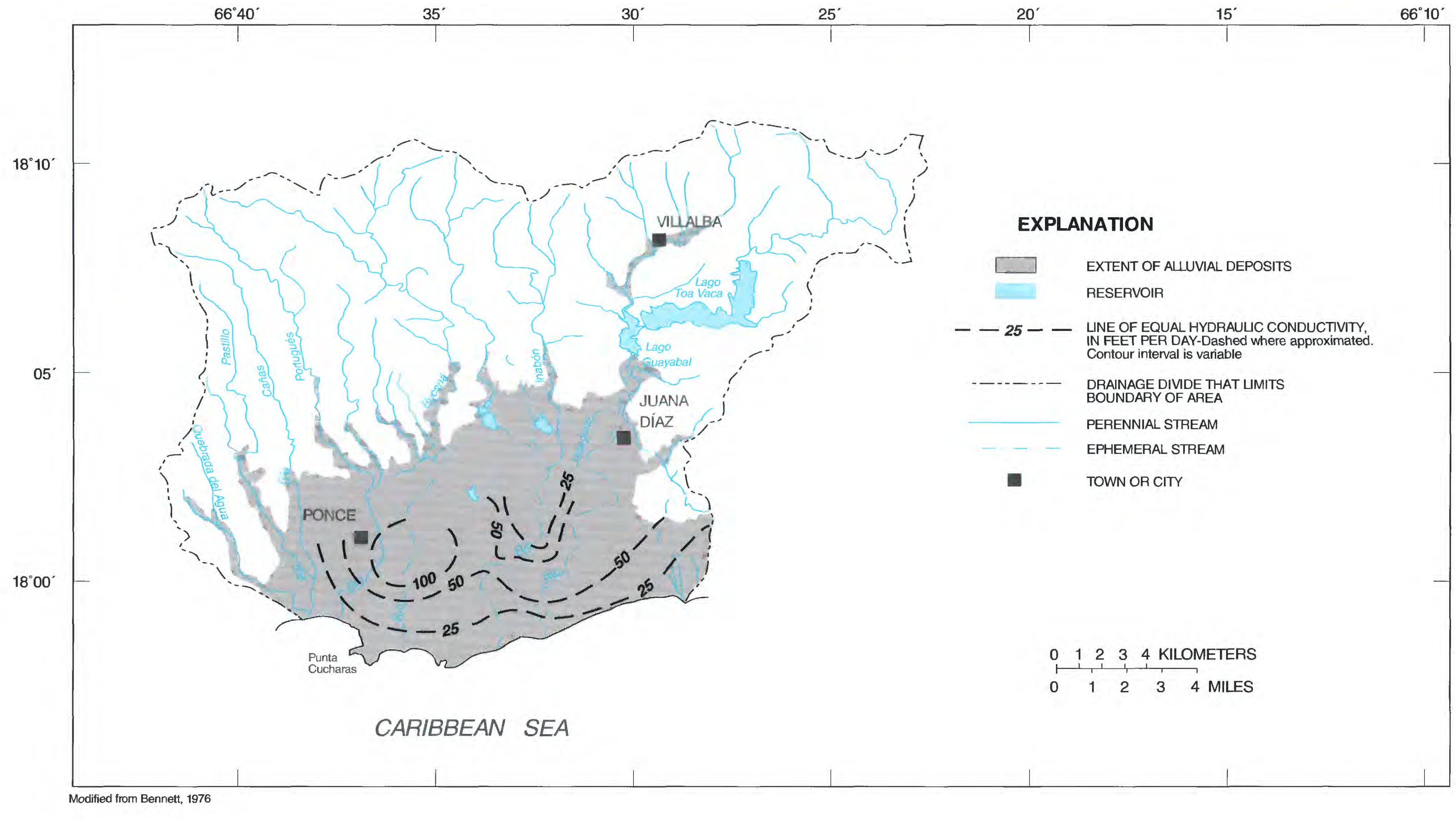


Figure 2.2.2.D-2 Average hydraulic conductivity estimates in the Juana Díaz-Ponce region, Puerto Rico.

2.2.2.E Ground-Water Levels and Movement

Ground-water levels in the Juana Díaz-Ponce region range from more than 100 feet above mean sea level in the upper valley areas to zero near the coast (fig. 2.2.2.E-1). Accordingly, ground-water flows seaward. Ground-water levels may fluctuate as much as 20 feet seasonally.

Seepage from ponds, streams, and irrigation canals represents about 70 percent of ground-water recharge to the alluvium, whereas precipitation contributes only about 30 percent (McClymonds, 1972, p. 15). The quantity of ground water flowing into the alluvial aquifer from the bedrock is probably small compared to the flow in the alluvium. In general, ground-water discharges to streams in the upland areas and near the coast. Commonly, streamflow that has not been diverted seeps into the alluvial aquifer during dry periods. As a result, only peak discharges reach the sea. Small springs issuing from bedrock fractures flow to streams and maintain the flow throughout the year (McClymonds, 1972, p. 5).

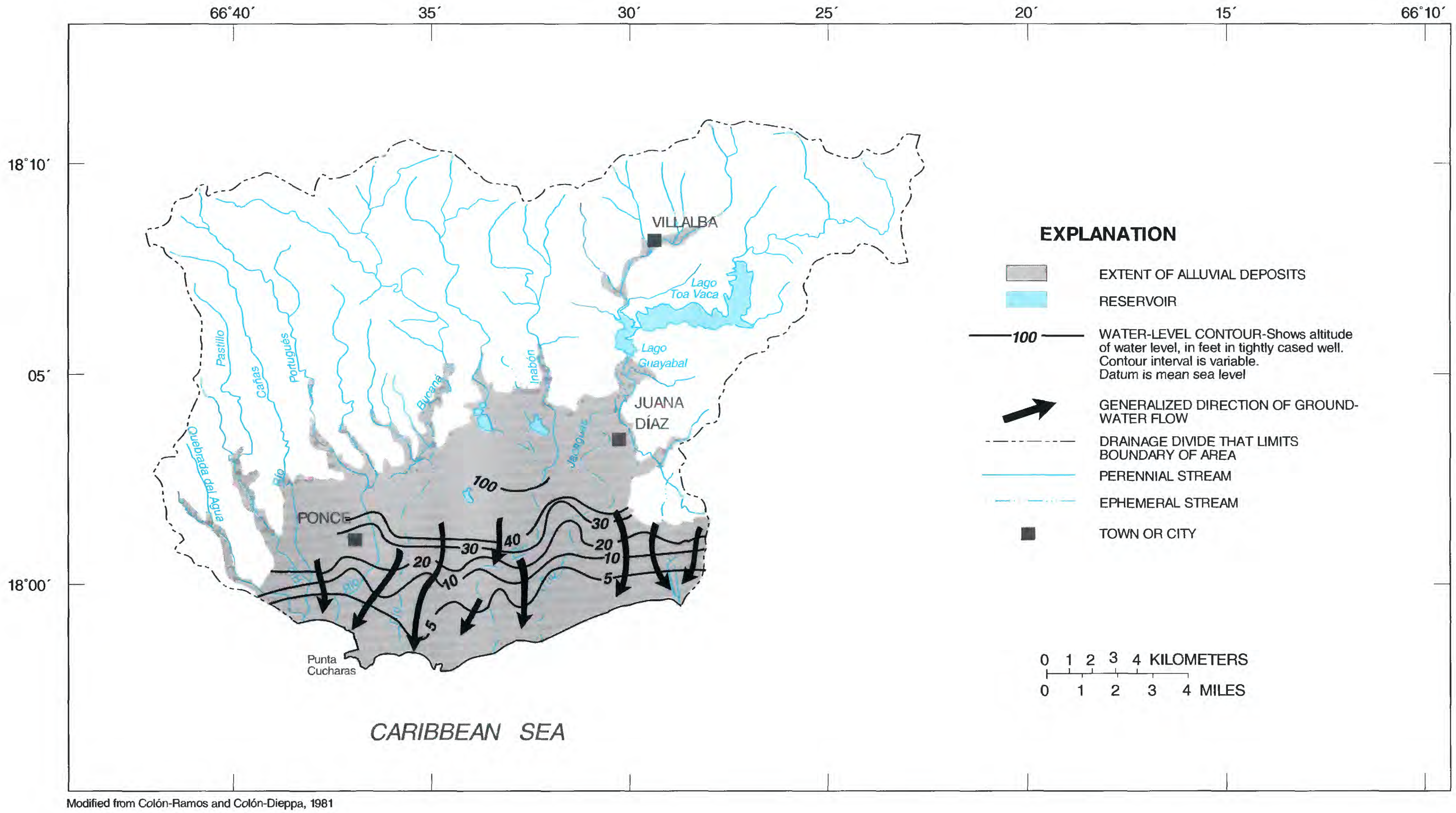


Figure 2.2.2.E-1 Altitude of water-level surface and direction of ground-water flow during 1980 in the Juana Díaz-Ponce region, Puerto Rico.

2.2.2.F Soil Permeability

The most prominent soil associations overlying the aquifers within this region are the Constancia-Jacaguas-San Antón, Fraternidad-Paso Seco, and the Aguilita-Tuque (fig. 2.2.2.F-1). The Constancia-Jacaguas-San Antón soil association is composed of nearly level, poorly- and well-drained, neutral to moderately alkaline, loamy and clayey soils that grade from deep to shallow over sand and gravel (Gierbolini, 1979, p. 5) These soils were formed over the river flood plains and are subject to flooding. The Fraternidad-Paso Seco soil association is composed of gently sloping to strongly sloping, moderately well drained, neutral to moderately alkaline, clayey soils that are deep or moderately deep to sand and gravel (Gierbolini, 1979, p. 5). They have been developed on terraces, alluvial fans, and foot slopes on the coastal plain. The soils in the Aguilita-Tuque soil associations are described by Gierbolini (1979, p. 4) as steep and very steep, well drained, moderately alkaline, loamy and clayey soils that have gravel and pebbles over limestone. They are present on foot slopes, side slopes, and hilltops on the limestone uplands.

Almost all the soil associations in this region have moderate soil permeabilities ranging from 0.06 to 2.00 in/hr (table 2.2.2.F-1). The Fraternidad-Paso Seco association, occurring on the upper valley west of Río Portugués, has the lowest permeabilities in the whole area, ranging from 0.06 to 0.20 in/hr. As a result, small ponds to store water for irrigation occur within this soil association. In general, soils occurring within the Juana Díaz-Ponce region are suitable for agricultural use.

Table 2.2.2.F-1 Thickness, permeability, and available water capacity for soil associations in the Juana Díaz-Ponce region, Puerto Rico (Modified from Gierbolini, 1979)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Semiarid Coastal Plains			
Fraternidad-Paso Seco	0 to 60	0.06 to 0.20	0.06 to 0.18
Constancia-Jacaguas-San Antón	0 to 65	0.60 to 2.00	0.08 to 0.14
Aguilita-Tuque	0 to 60	0.60 to 2.00	0.07 to 0.10
Humid Uplands			
Caguabo-Múcara-Quebrada	0 to 60	0.60 to 2.00	0.06 to 0.17
Humatas-Maricao-Los Guineos	0 to 72	0.60 to 2.00	0.12 to 0.16
Semiarid Uplands			
Callabo	0 to 27	0.60 to 2.00	0.12 to 0.16

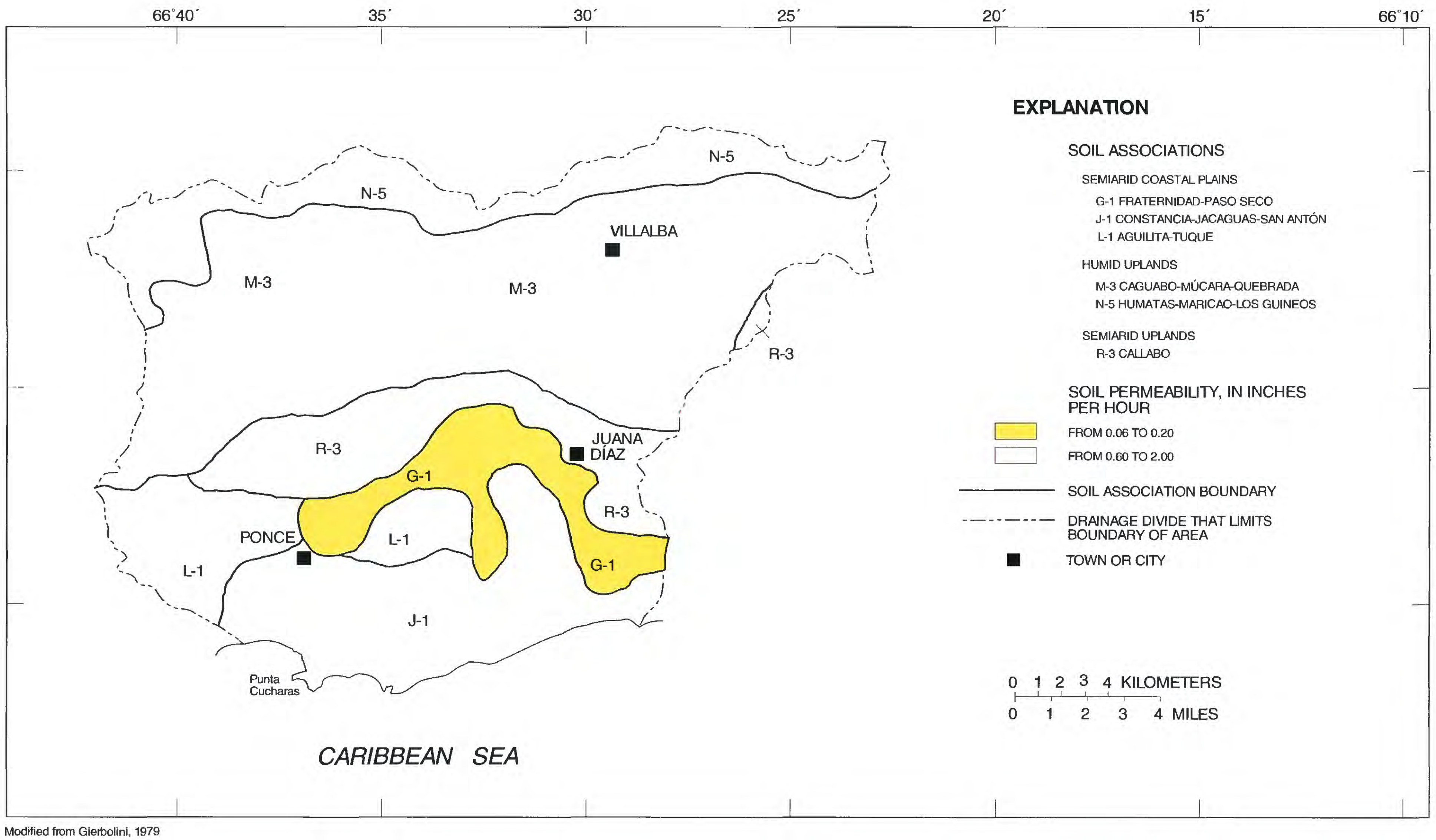


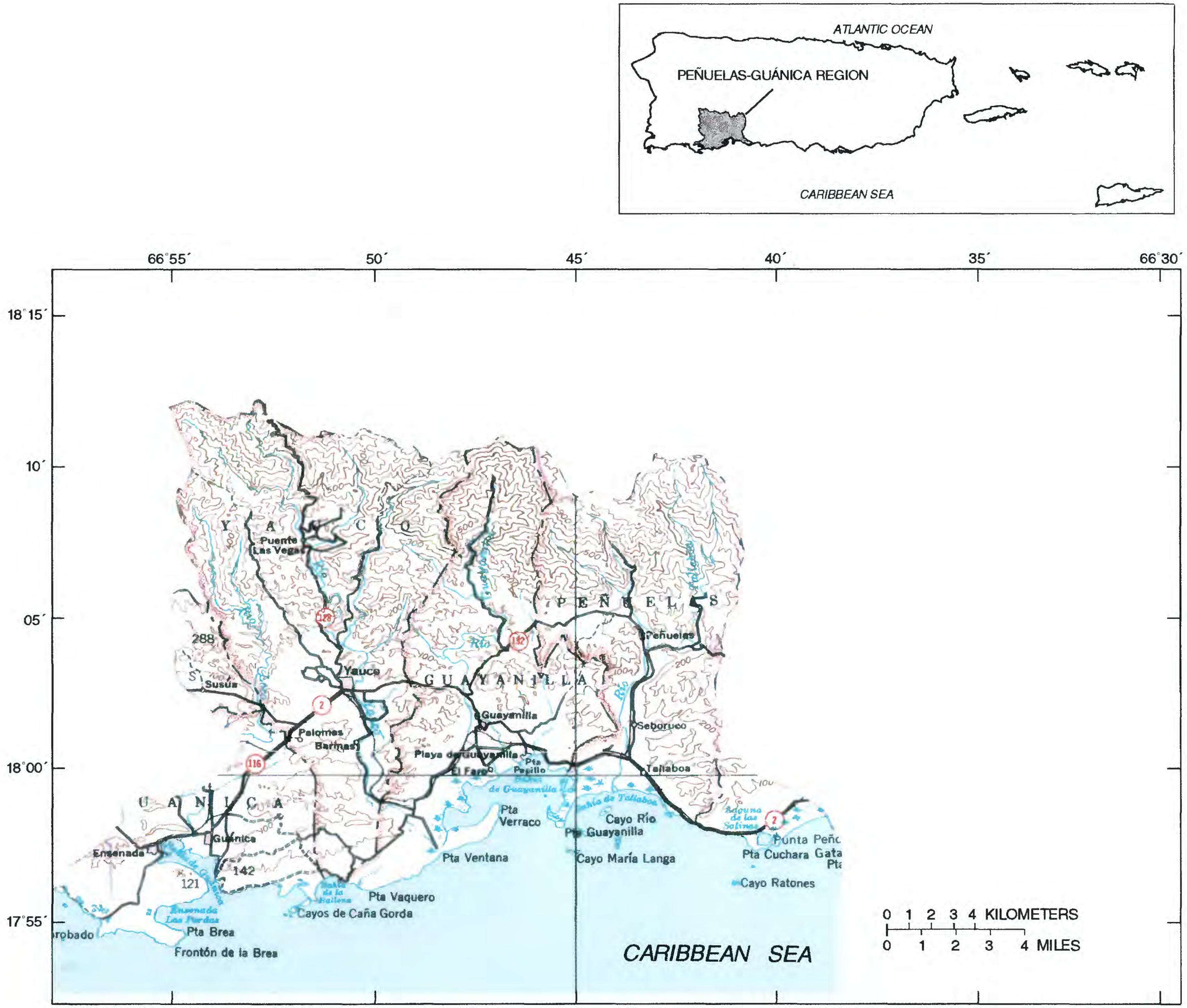
Figure 2.2.2.F-1 Soil associations and permeability in the Juana Díaz-Ponce region, Puerto Rico.

2.2.3 PEÑUELAS-GUÁNICA REGION

By Orlando Ramos-Ginés

2.2.3.A Location and Major Geographic Features

The Peñuelas-Guánica region is located in southwestern Puerto Rico, about 15 miles west of Ponce (fig. 2.2.3.A-1). It covers an area of 30 mi^2 and is bounded to the north by the Cordillera Central, reaching elevations of 3,600 feet above mean sea level, to the west by the Río Loco drainage basin divide, to the east by the Río Tallaboa drainage basin divide, and to the south by the Caribbean Sea. The Peñuelas-Guánica region includes the municipios of Peñuelas, Guayanilla, Yauco, and a portion of Guánica. The Peñuelas-Guánica region includes the drainage basins of the Río Tallaboa, Río Macaná, Río Guayanilla, Río Yauco, and Río Loco. Limestone hills, alluvium filled valleys, and coastal plains are the most typical landforms that occur within the region. The limestone hills, reaching elevations of as much as 1,100 feet above mean sea level, flank the alluvial valleys of the Peñuelas-Guánica region to the north, east, and west. The alluvial valley floors reach elevations of as much as 150 feet above mean sea level and slope gently toward the coast to elevations slightly above mean sea level. The Bosque Estatal de Guánica, a tropical xerophitic forest (a forest composed of plants structurally adapted to grow under very dry or desert conditions) included in the Biosphere Reserve Program of the United Nations, is located in the southwestern part of the region. The principal population centers in the Peñuelas-Guánica region are Peñuelas, Guayanilla, Yauco, and Guánica.



Base from U.S. Geological Survey
Puerto Rico e Islas Limítrofes, 1:240,000, 1952

Figure 2.2.3.A-1 Location and major geographic features in the Peñuelas-Guánica region, Puerto Rico.

2.2.3.B Population and Estimated Ground-Water Use

The population of the Peñuelas-Guánica region was about 96,500 in 1980 (U.S. Department of Commerce, 1982). From 1980 to 1990 population increased by 10 percent to about 106,000 (U.S. Department of Commerce, 1991). About 64 percent of the population in this region live in rural areas, whereas only 36 percent of the population live in urban areas (table 2.2.3.B-1). Surface water has been the major water source for the Peñuelas-Guánica region. In 1983, public-water supply in the municipio of Peñuelas came exclusively from surface-water sources.

Total ground-water withdrawals in 1983 were about 8.82 Mgal/d (table 2.2.3.B-2). The Puerto Rico Aqueduct and Sewer Authority was the major single user, pumping about 5.2 Mgal/d, which provided water to 43 percent of the population in the area for domestic use. Ground-water use for agriculture was about 41 percent (3.62 Mgal/d) of the total pumpage in 1983. About 30 percent of the total water demand for irrigation came from ground-water sources; the remaining 70 percent was diverted from streamflow. Approximate locations of wells are shown on figure 2.2.3.B-1.

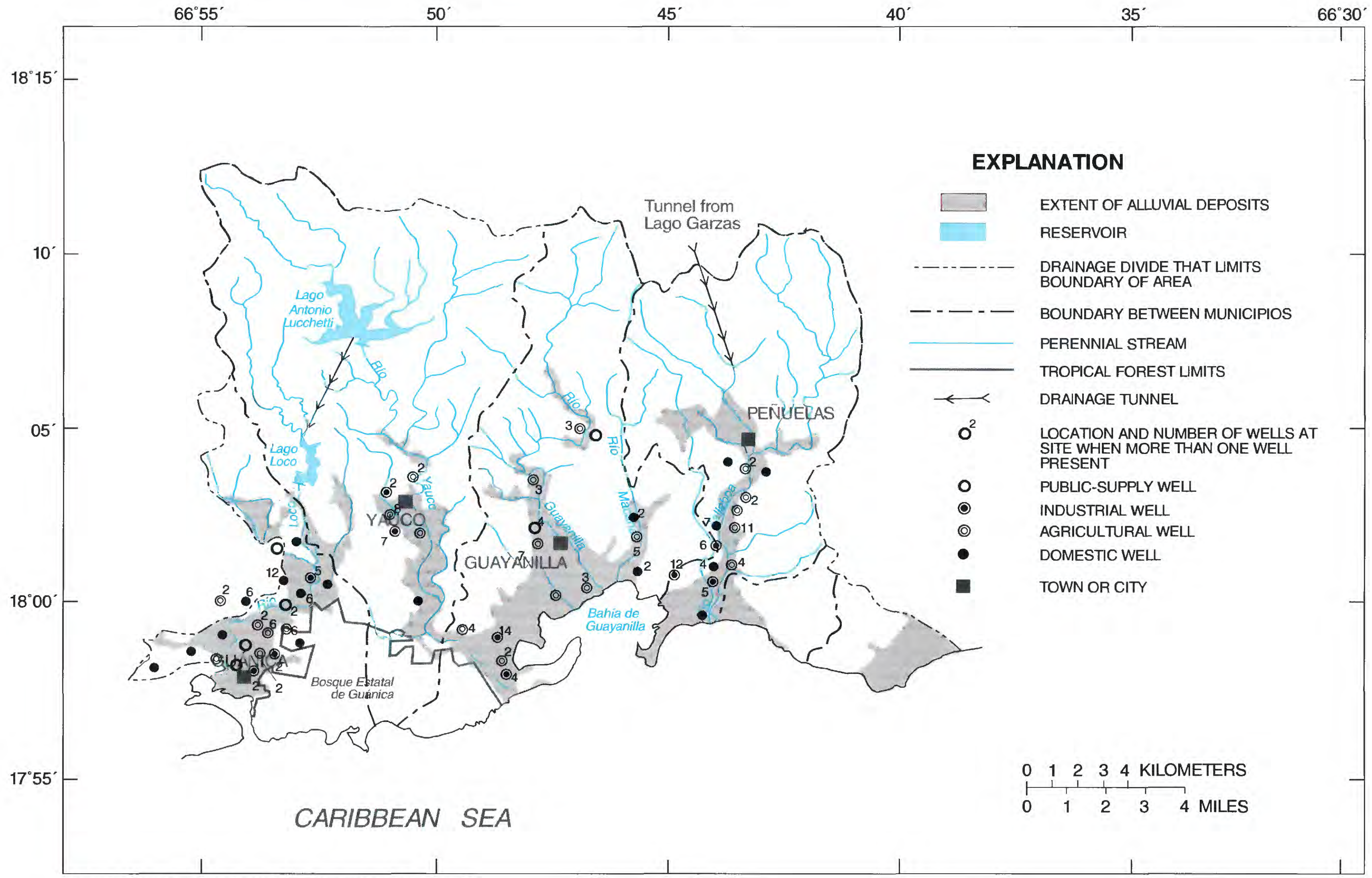
Table 2.2.3.B-1 Population for the Peñuelas-Guánica region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

MUNICIPIO	1980 population TOTAL	1980 population URBAN	1980 population RURAL	1990 population TOTAL
Peñuelas	19,116	4,235	14,881	22,515
Guayanilla	21,050	6,163	14,887	21,581
Yauco	37,742	14,594	23,148	42,058
Guánica	18,799	9,628	9,171	19,984
Total	96,707	34,620	62,087	106,138

Table 2.2.3.B-2 Ground-water withdrawals and estimated population served during 1983 for the Peñuelas-Guánica region, Puerto Rico
[Mgal/d, million gallons per day; ---, no data available]

[1] Use and supplier	Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use		
[2] A. Puerto Rico Aqueduct and Sewer Authority		
1. Peñuelas	---	---
2. Guayanilla	14,339	1.3
3. Yauco	[3] 7,334	0.5
4. Guánica	20,003	3.4
Subtotal	41,676	5.2
II. Agriculture Use		
1. Peñuelas	---	0.17
2. Guayanilla	---	0.95
3. Guánica	---	2.5
Subtotal	---	3.62
III. Commercial Use	---	---
Total	41,676	8.82

[1] Municipios not listed under some specific use do not withdraw ground water for the subject use.
[2] Modified from data reported by Gómez-Gómez and others, 1984.
[3] Based on a water consumption of 63 gallons per person per day.



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.2.3.B-1 Approximate well locations in the Peñuelas-Guánica region, Puerto Rico.

2.2.3.C Geologic Setting

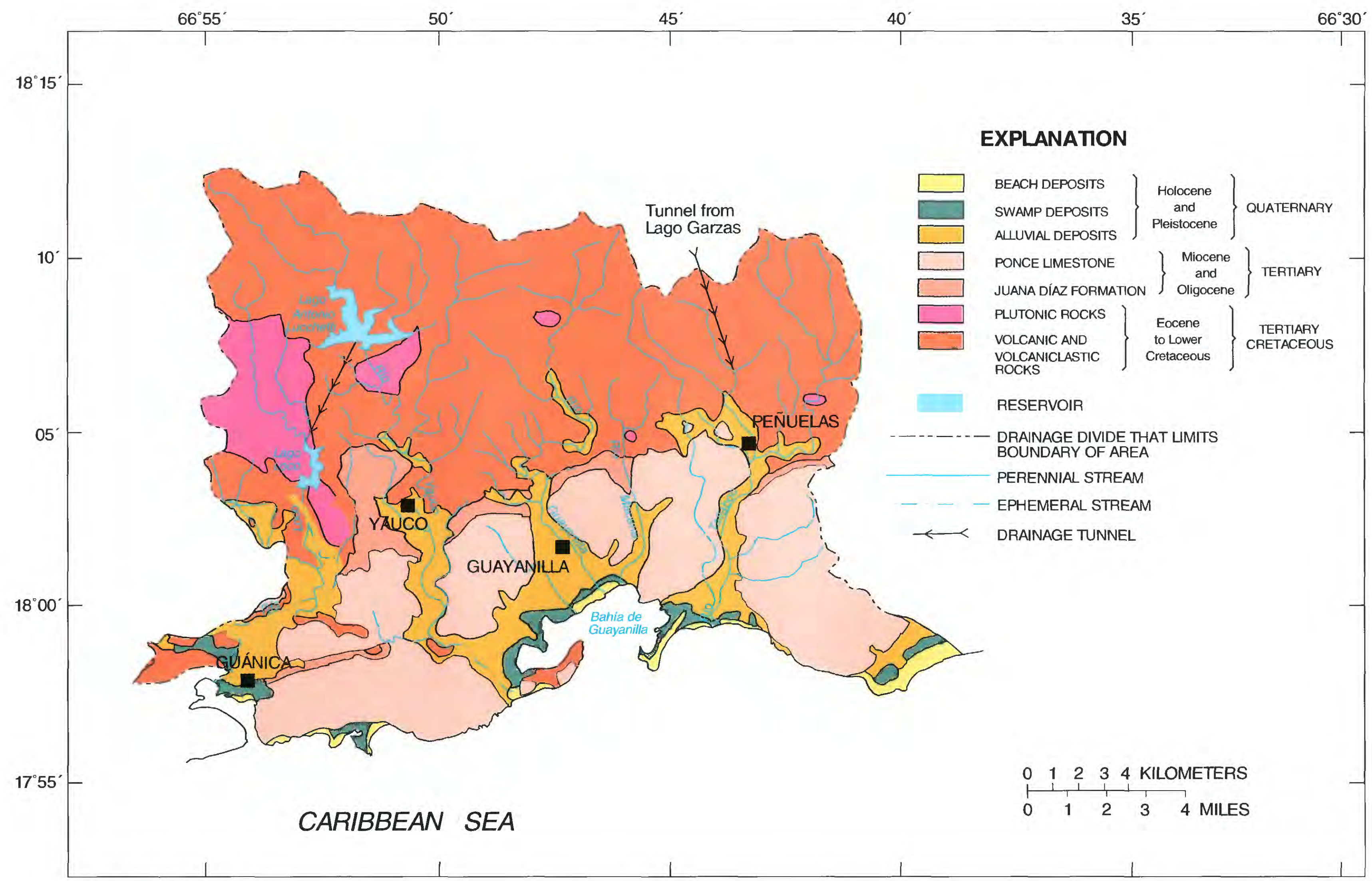
The geology of the Peñuelas-Guánica region consists of four basic lithologic units. They are: a suite of volcaniclastic, volcanic, plutonic, and limestone rocks of Early Cretaceous to Eocene age; the Juana Díaz Formation of Oligocene to Miocene age; the Ponce Limestone of Miocene age; and alluvial deposits of Quaternary age.

The suite of Early Cretaceous to Eocene age rocks in the uplands consists of tuffaceous sand and siltstone, tuff breccia, lava, granodiorite, and quartz diorite (Monroe, 1980a) (fig. 2.2.3.C-1). These rocks are intensely faulted and are structurally complex.

The Juana Díaz Formation overlies the suite of Early Cretaceous to Eocene age rocks and crops out in upper valley areas (Monroe, 1980a). It consists of a stratified chalky, clayey, white to very pale orange limestone in the upper part of the formation and of sand, gravel, and cobbles of various types of volcanic rocks, and very fossiliferous mudstone in the lower part. It is continuously exposed, except in alluvium-filled valleys, and rests on an eroded and highly irregular surface of the older volcaniclastic-plutonic rocks (Monroe, 1980a).

The Ponce Limestone, overlying the Juana Díaz Formation, is a very pale to grayish-orange, tightly cemented, and fossiliferous limestone. It is continuously exposed throughout the Juana Díaz-Ponce region, except where covered by alluvium (section 2.2.2).

The Quaternary alluvium in the river valleys and coastal plains unconformably overlies the Juana Díaz Formation and Ponce Limestone and is the most important lithologic unit in the Peñuelas-Guánica region, because it contains the most productive aquifers. These deposits are composed of layers or lenses of poorly consolidated clay, silt, sand, gravel, and boulders. In general, particles decrease in size toward the coast where the amount of silt and clay is higher. Beach and swamp deposits of Quaternary age are scattered along the shore (fig. 2.2.3.C-1).



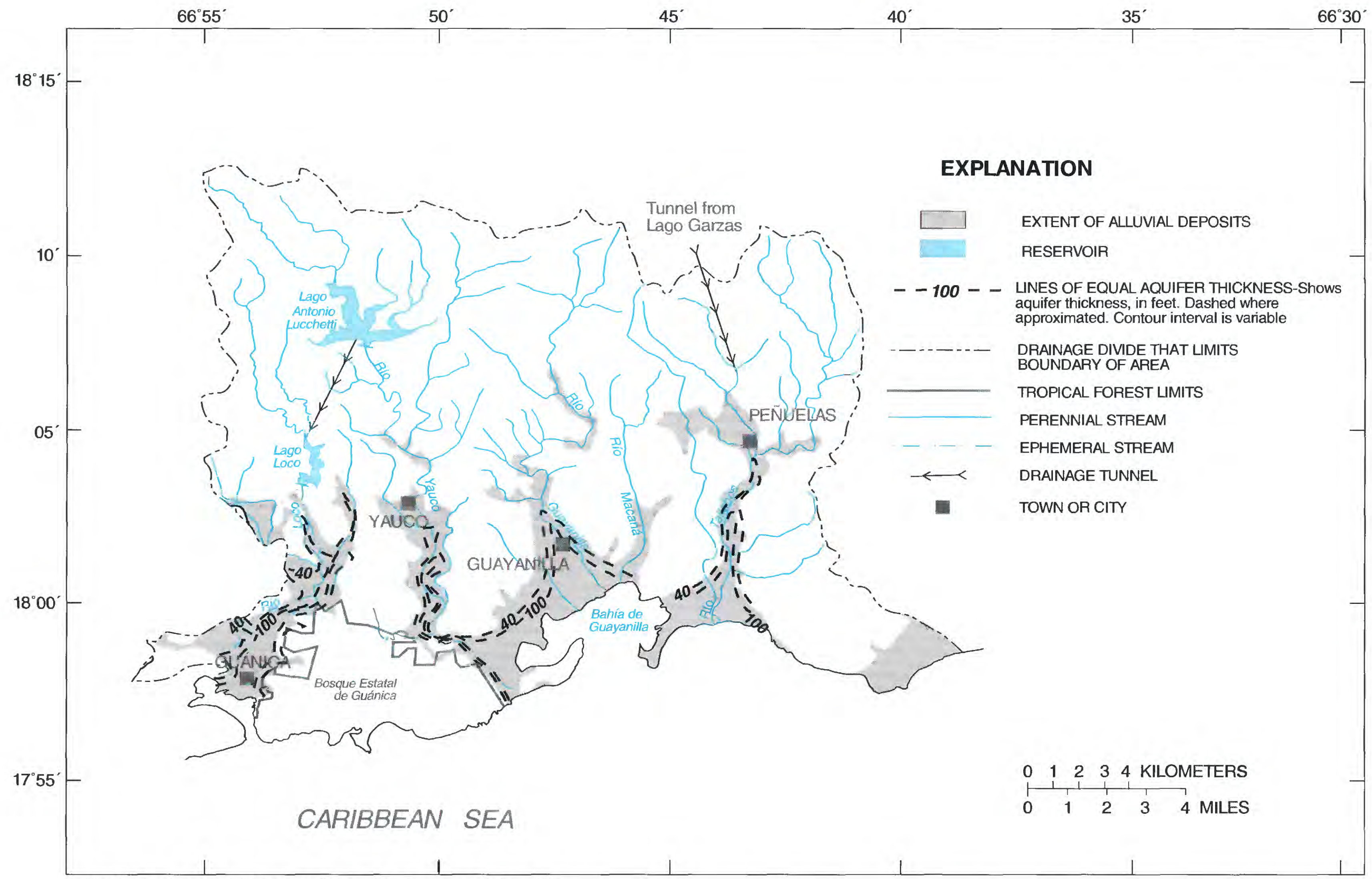
Modified from Briggs and Akers, 1965

Figure 2.2.3.C-1 Generalized surficial geology in the Peñuelas-Guánica region, Puerto Rico.

2.2.3.D Hydrogeology

The principal aquifers in the Peñuelas-Guánica region occur in the alluvial deposits under water-table conditions. The thickness of alluvial deposits range from less than 1 foot along the valley sides to more than 200 feet along existing stream courses (fig. 2.2.3.D-1). Hydraulic-conductivity values were estimated from specific-capacity tests of wells in the Río Loco and Río Yauco valleys (fig. 2.2.3.D-2). In these valleys, the hydraulic-conductivity values could be as high as 300 feet, decreasing seaward with increasing silt and clay content. The transmissivity of the alluvial aquifer in the Peñuelas-Guánica region may, in general, increase inland and streamward as aquifer hydraulic conductivity increases (Bennett,1976).

Aquifers in both the Ponce Limestone and the Juana Díaz Formation may yield more water in upper valley areas. Estimates of apparent hydraulic conductivity at wells tapping the aquifer in the Ponce Limestone and the Juana Díaz Formation range from 2.7 to about 270 ft/d (Bennett, 1976, p. 17).



Modified from McClymonds, 1967; Crooks and others, 1968; Grossman and others, 1972

Figure 2.2.3.D-1 Aquifer thickness in the Peñuelas-Guánica region, Puerto Rico.

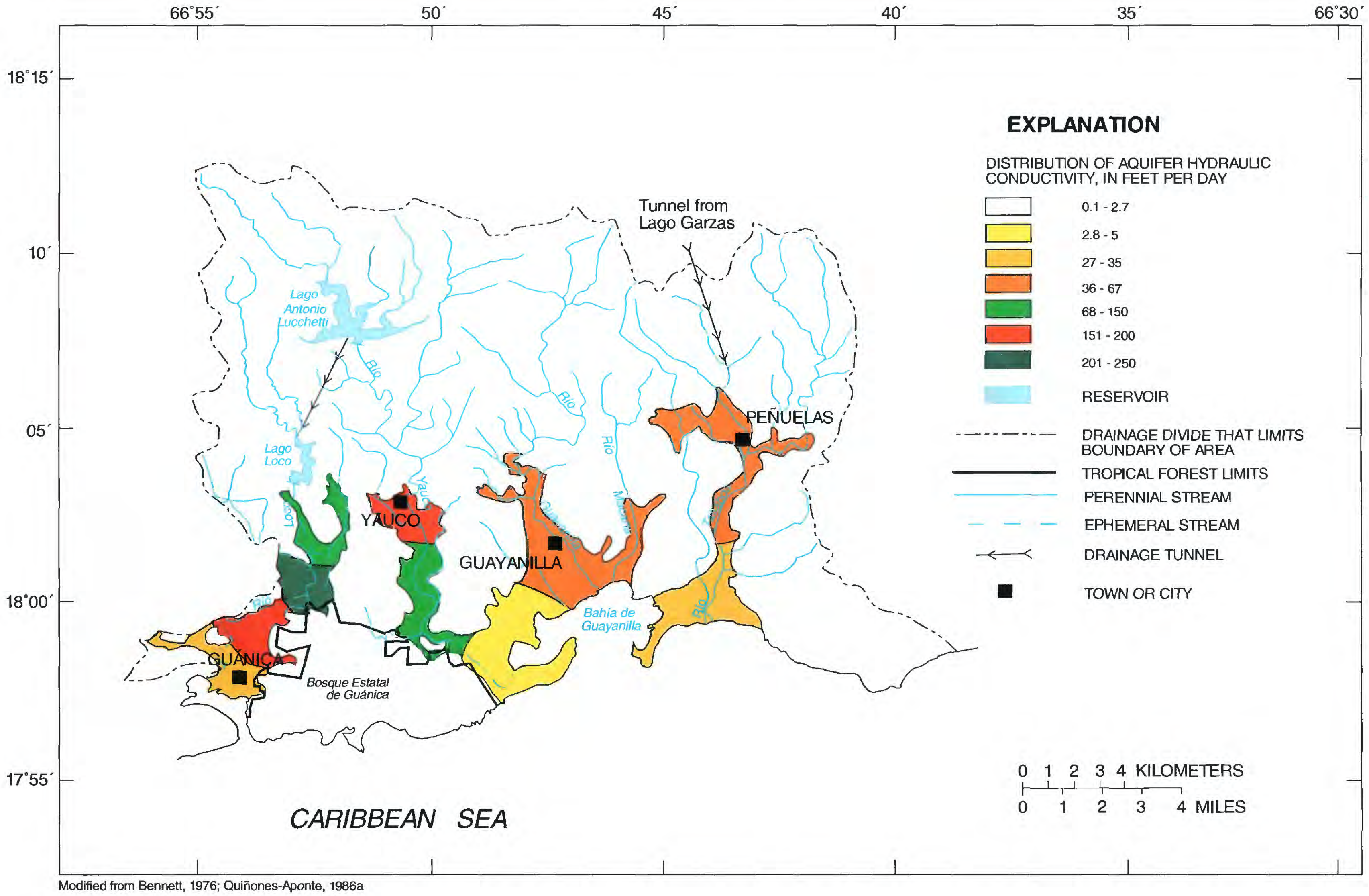
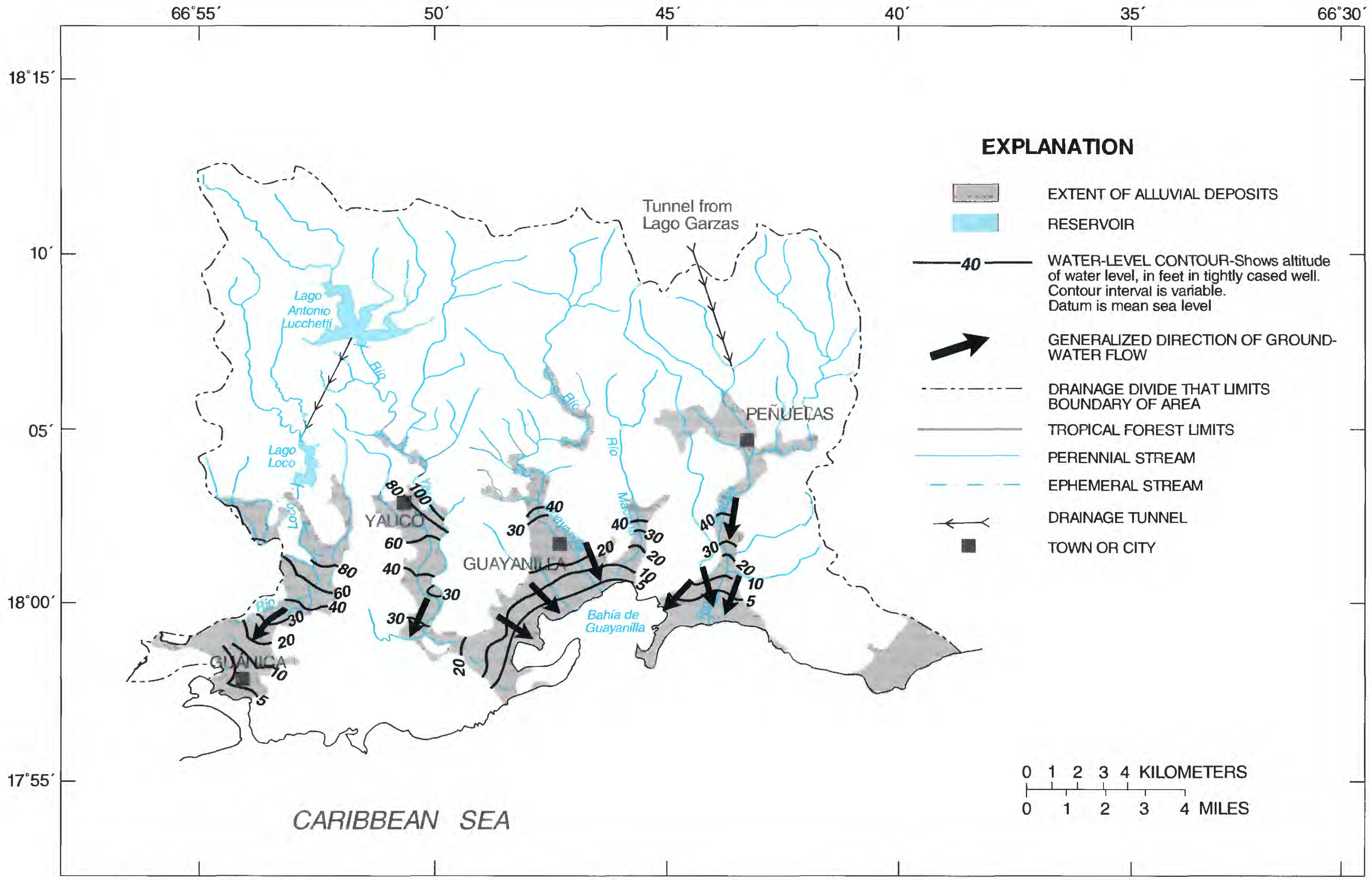


Figure 2.2.3.D-2 Regional distribution of apparent hydraulic conductivity in the Peñuelas-Guánica region, Puerto Rico.

2.2.3.E Ground-Water Levels and Movement

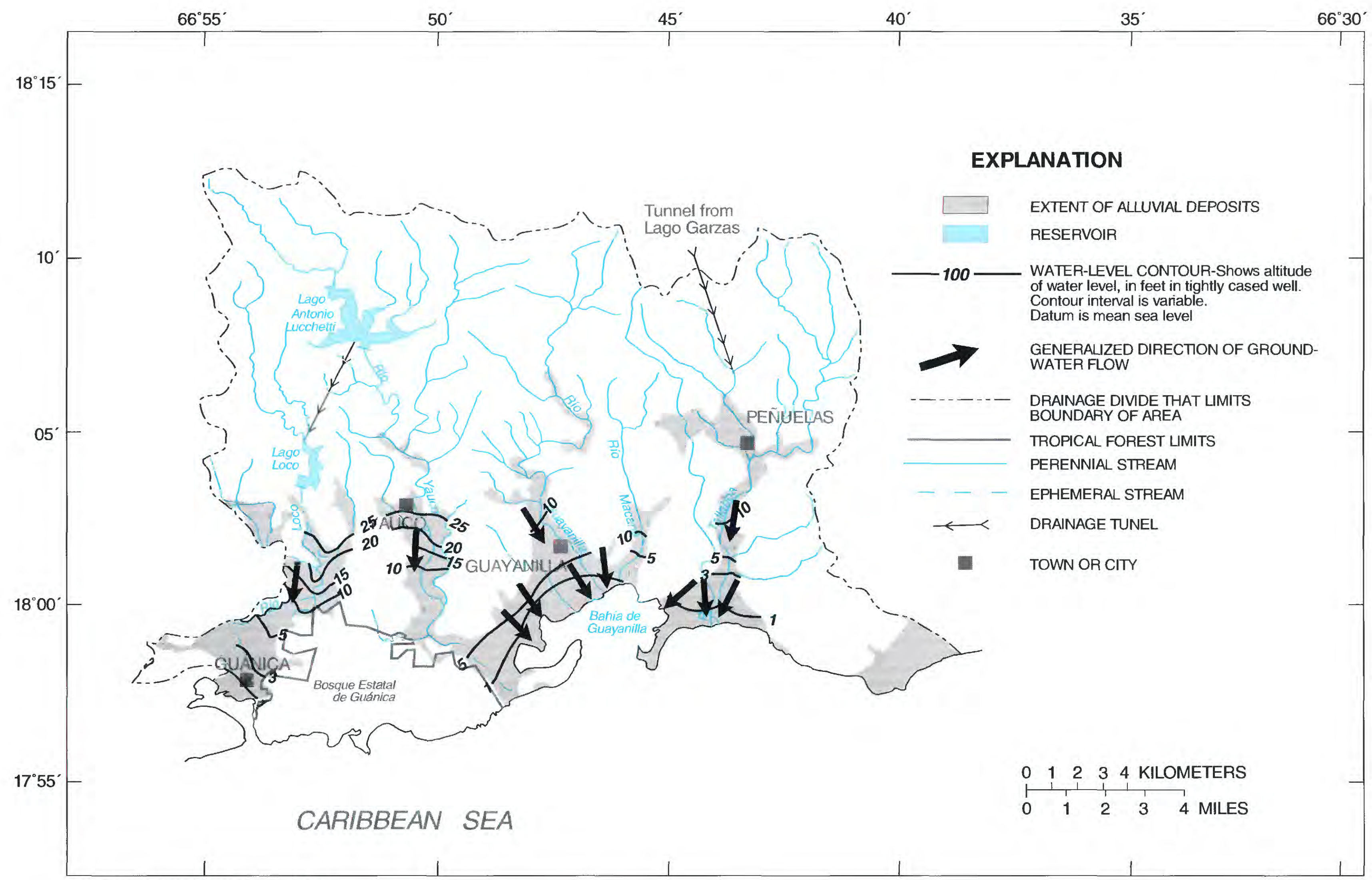
Ground-water levels in the alluvial deposits range from 100 feet above mean sea level in the upper valley areas to near mean sea level along the coast (fig. 2.2.3.E-1). In the Río Guayanilla, Río Macaná, and Río Tallaboa, ground-water levels are as high as 40 feet above mean sea level in upper valley areas during average dry periods (fig. 2.2.3.E-1) and 10 feet above mean sea level during very dry years (fig. 2.2.3.E-2). Ground-water levels in the upper parts of the Río Yauco and Río Loco valleys are as high as 100 feet above mean sea level during dry periods and 25 feet above mean sea level during droughts. Average seasonal ground-water level fluctuations in the Peñuelas-Guánica region are as high as 40 feet in the Río Yauco valley. Throughout the Río Yauco valley, ground-water levels fluctuated from 10 to 36 feet below land surface during 1975 to 1985 (Quiñones-Aponte, 1986b, p. 8). Seasonal ground-water level fluctuations in the Peñuelas-Guánica region are affected by pumpage. The water table is generally at its lowest level during February.

Ground-water recharge and discharge in the Peñuelas-Guánica region vary throughout the year in response to precipitation, pumping, and streamflow diversions. Greater stream seepage into the aquifer was observed in upper valley areas during low streamflow conditions (Grossman and others, 1972, p. 48; Quiñones-Aponte, 1986b, p. 8), although streams are generally gaining, rather than loosing, water in lower reaches. Aquifer recharge from stream seepage is affected by the regulation of streamflow at headwaters and diversions to irrigation channels in the Río Tallaboa, Río Yauco, and Río Loco valleys. Aquifer recharge by rainfall in the Peñuelas-Guánica region is minimal, because of high evapotranspiration rates and low rainfall frequency, intensity, and duration. Ground-water flows predominantly toward the sea, from recharge to discharge areas, following the general topography and drainage of the alluvial valley floors.



Modified from Gómez-Gómez and Heisel, 1976

Figure 2.2.3.E-1 Altitude of water-level surface and direction of ground-water flow during February 1976 in the Peñuelas-Guánica region, Puerto Rico.



Modified from Gómez-Gómez and Heisel, 1976

Figure 2.2.3.E-2 Water-level contour during February 1968 and direction of ground-water flow in the Peñuelas-Guánica region, Puerto Rico.

2.2.3.F Soil Permeability

The most prominent soil associations overlying the aquifer areas in the Peñuelas-Guánica region are Aguilita-Tuque, Constancia-Jacaguas-San Antón, and the Fraternidad-Aguirre-Cartagena (fig. 2.2.3.F-1). The Aguilita-Tuque soils are steep to very steep, well drained, moderately alkaline, loamy and clayey soils with some gravel and pebbles (Gierbolini, 1979). These soils occupy foot slopes, side slopes, hilltops, and overlie the limestone and alluvial deposits in the Río Tallaboa valley. The Constancia-Jacaguas-San Antón association overlies the alluvial deposits in the Río Guayanilla valley and coastal plain. They are nearly level, deep to shallow, somewhat poorly- to well-drained, neutral to moderately alkaline, loamy and clayey soils. These clayey to loamy soils are the best for farming in the area. Both the Aguilita-Tuque and the Constancia-Jacaguas-San Antón soil associations have permeabilities ranging from 0.60 to 2.00 in/hr (table 2.2.3.F-1). The Fraternidad-Aguirre-Cartagena soils are moderately well drained to poorly drained, nearly level to sloping, calcareous alluvial soils. This soil association has the lowest permeability for this region ranging from 0.06 to 0.20 in/hr.

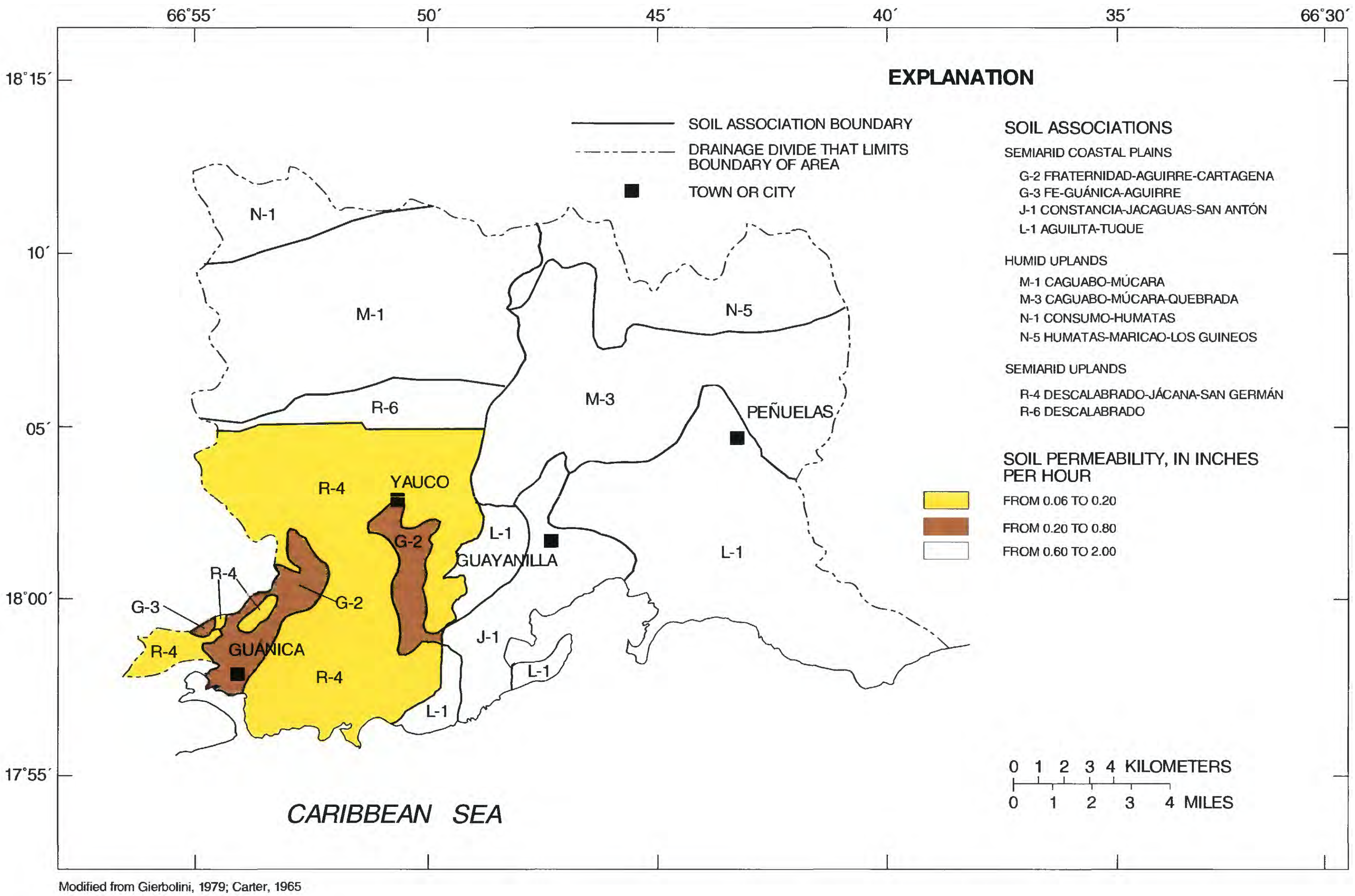


Figure 2.2.3.F-1 Soil associations and permeability in the Peñuelas-Guánica region, Puerto Rico.

Table 2.2.3.F-1 Thickness, permeability, and available water capacity for the soil associations in the Peñuelas-Guánica region, Puerto Rico (Modified from Gierbolini, 1979)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Semiarid Coastal Plains			
Fraternidad-Aguirre-Cartagena	0 to 70	0.06 to 0.20	0.10 to 0.18
Fe-Guánica-Aguirre	0 to 56	0.06 to 0.20	0.12 to 0.18
Constancia-Jacaguas-San Antón	0 to 65	0.60 to 2.00	0.08 to 0.14
Aguilita-Tuque	0 to 60	0.60 to 2.00	0.11 to 0.14
Humid Uplands			
Caguabo-Múcara	0 to 36	0.60 to 2.00	0.03 to 0.17
Caguabo-Múcara-Quebrada	0 to 60	0.60 to 2.00	0.03 to 0.17
Consumo-Humatas	0 to 60	0.60 to 2.00	0.09 to 0.18
Humatas-Maricao-Los Guineos	0 to 72	0.60 to 2.00	0.12 to 0.16
Semiarid Uplands			
Descalabrado-Jácana-San Germán	0 to 28	0.60 to 2.00	0.08 to 0.17
Descalabrado	0 to 20	0.60 to 2.00	0.09 to 0.11

2.3 West Coast Area

2.3.1 AÑASCO REGION

By Thalia D. Veve

2.3.1.A Location and Major Geographic Features

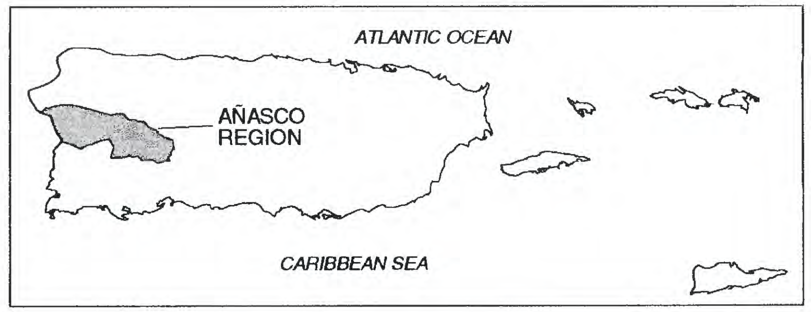
The Añasco region is located on the west coast area of Puerto Rico between latitudes 18°20'N and 18°05'N and longitudes 67°15'W and 66°45'W. The two principal river basins in the region are the Río Grande de Añasco and the Río Yagüez (fig. 2.3.1.A-1).

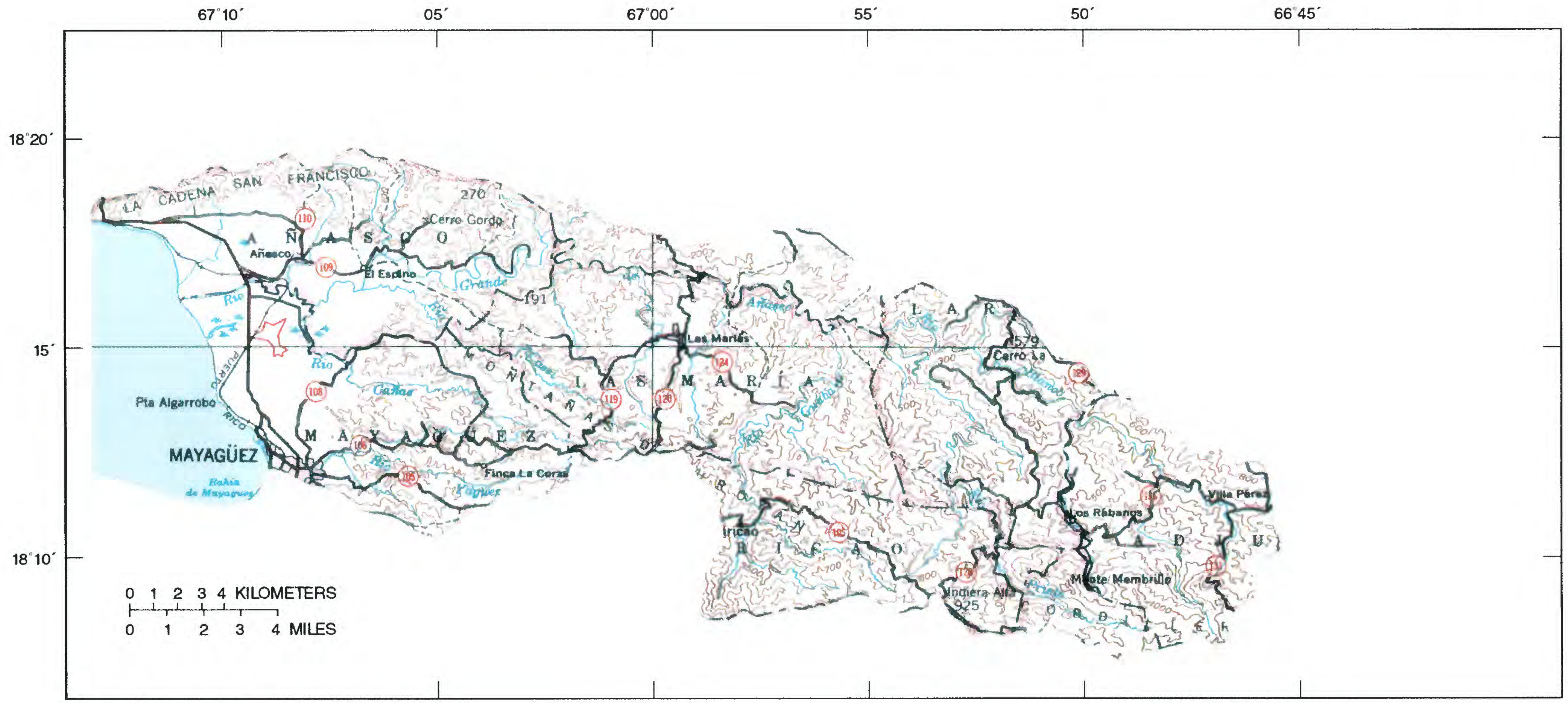
The Río Grande de Añasco originates near the Cordillera Central, flows west, and discharges into the Bahía de Añasco. The upper reaches of the basin contain four reservoirs connected by pipelines; the Lago Toro, Lago Prieto, Lago Guayo, and Lago Yahuecas. The Río Grande de Añasco alluvial valley covers an area of approximately 18 mi^2. It is bounded by hills to the north, east, and south, and by Bahía de Añasco to the west. The two prominent mountain ranges are the Cadena de San Francisco and the Atalaya mountains to the north, and the Colinas de Uroyán to the southeast. The tributaries of the Río Grande de Añasco that flow into the lower valley are the Río Dagüey and the Río Cañas. The Caño La Puente and Caño Boquilla are smaller streams within the valley.

The Río Yagüez originates near the town of Maricao, flows west, and discharges into the Bahía de Mayagüez. The Río Yagüez alluvial valley covers an area of about 2 mi^2. The valley is bounded by hills to the north, east, and south, and by Bahía de Mayagüez to the west.

Elevations within the alluvial valleys range from mean sea level to 65 feet above mean sea level. The highest elevation in the mountains located within the Añasco region is Monte Guilarte in the Cordillera Central at 3,953 feet above mean sea level.

The two principal population centers in the Añasco region are the town of Añasco and the city of Mayagüez. Añasco is located upstream of the confluence between the Río Dagüey and Río Grande de Añasco. Mayagüez is located on the coast and is much larger than Añasco, covering almost all of the Río Yagüez alluvial valley.





Base from U.S. Geological Survey
Puerto Rico e Islas Limítrofes, 1:240,000, 1952

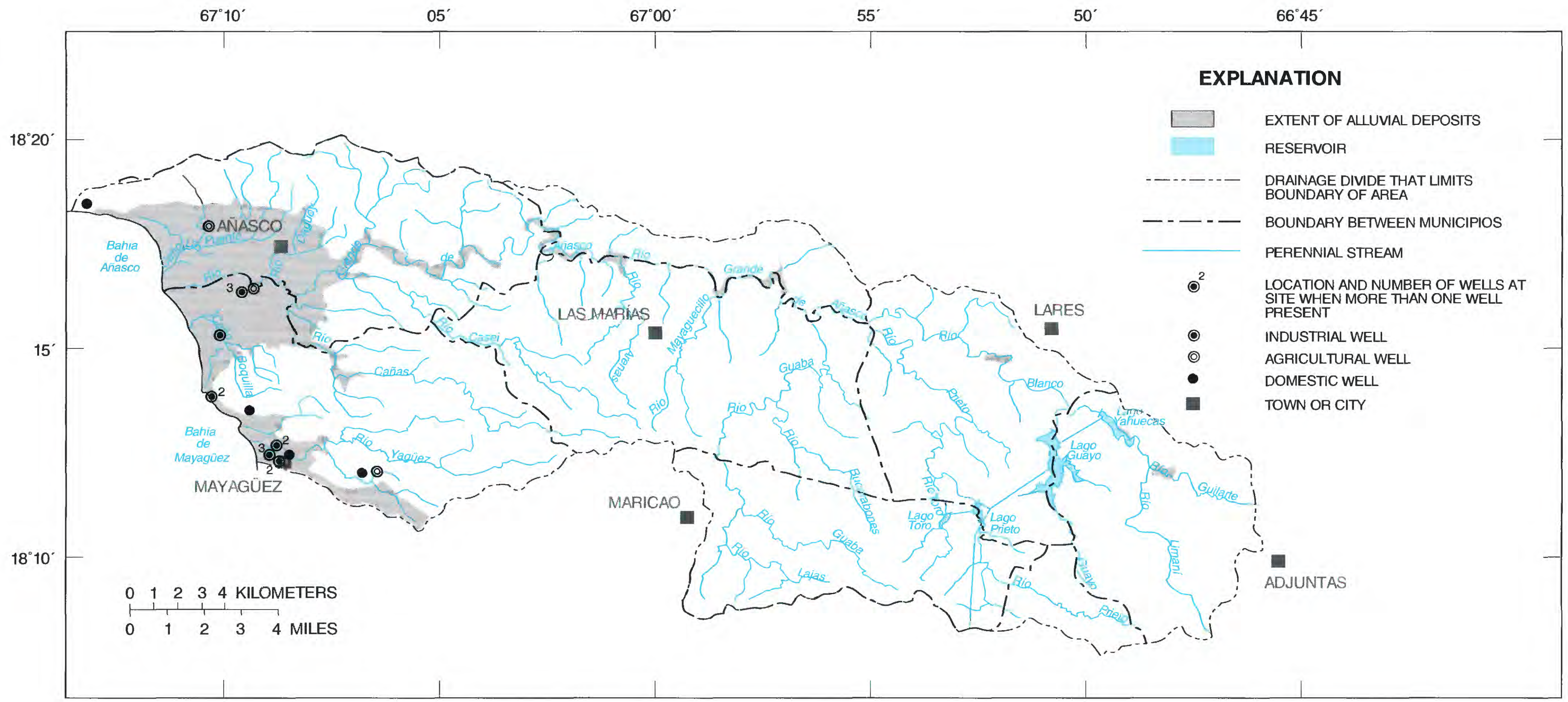
Figure 2.3.1.A-1 Location and major geographic features in the Añasco region, Puerto Rico.

2.3.1.B Population and Estimated Ground-Water Use

The population of the Añasco region totalled 180,480 in 1980 (U.S. Department of Commerce, 1982; table 2.3.1.B-1). It grew by 5 percent from 1980 to 1990, when the total population was 189,583 (U.S. Department of Commerce, 1991). The towns overlying the aquifer areas are Mayagüez and Añasco, which in 1980 had populations of 96,193 and 23,274, respectively. A large portion of Mayagüez lies within the Guanajibo region (section 2.3.2).

Ground-water use within the Añasco region is limited (table 2.3.1.B-2). No public-supply wells were reported for the municipio of Añasco from 1980 to 1982 by Torres-Sierra and Avilés (1986), or in 1983 by Gómez-Gómez and others (1984). Public-supply wells reported by Torres-Sierra and Avilés (1986) and Gómez-Gómez and others (1984) for the municipio of Mayagüez are located outside the Añasco region or inland from the alluvial valley of the Río Yagüez. Public-water supply within the region originated entirely from surface-water sources during 1980 to 1983.

Data from the Ground-Water Site Inventory (U.S. Geological Survey, written communication, 1990) identify several agricultural and industrial wells in the Río Grande de Añasco lower valley (fig. 2.3.1.B-1). In the Río Yagüez valley, there are also several industrial and domestic wells.



From U.S. Geological Survey Ground-Water Site Inventory Database, 1990

Figure 2.3.1.B-1 Approximate well locations in the Añasco region, Puerto Rico.

Table 2.3.1.B-1 Population for the Añasco region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

MUNICIPIO	1980 population TOTAL	URBAN	RURAL	1990 population TOTAL
Adjuntas	18,786	5,239	13,547	19,451
Añasco	23,274	5,646	17,628	25,234
Lares	26,743	5,224	21,519	29,015
Las Marías	8,747	799	7,948	9,306
Maricao	6,737	1,390	5,347	6,206
Mayagüez	96,193	82,968	13,225	100,371
Total	180,480	101,266	79,214	189,583

Table 2.3.1.B-2 Ground-water withdrawals and estimated population served during 1982 for the Añasco region, Puerto Rico (Torres-Sierra and Avilés, 1986)
[Mgal/d, million gallons per day]

[1] Use	Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use		
1. Adjuntas	3,016	0.71
2. Añasco	5,367	1.01
3. Lares	6,296	1.07
4. Las Marías	1,634	0.3
5. Maricao	803	0.16
6. Mayagüez	27,182	6.35
Subtotal	44,218	9.6
II. Commercial Use		
1. Adjuntas	151	0.03
2. Añasco	274	0.07
3. Lares	401	0.08
4. Las Marías	101	0.02
5. Maricao	42	0.01
6. Mayagüez	2,169	0.92
Subtotal	3,138	1.13
III. Industrial Use		
1. Adjuntas	3	0.00
2. Añasco	18	0.05
3. Lares	6	0.00
4. Maricao	6	0.01
5. Mayagüez	86	1.93
Subtotal	119	1.99
Total	47,475	12.72

[1] Municipios not listed under some specific use do not withdraw ground water for the subject use.

2.3.1.C Geologic Setting

Volcanic and volcaniclastic rocks of Cretaceous age, most of which were formed or deposited in a marine environment, are present throughout the Añasco region (fig. 2.3.1.C-1). Small patches of plutonic rocks crop out in the upper reaches of the basin. In the Río Grande de Añasco valley, these volcanic and volcaniclastic rocks are unconformably overlain by alluvial deposits of Quaternary age. The alluvial fill in the valley is composed of clay, silt, and sand with localized gravel deposits. Thin corridors of alluvium have been deposited along the course of the Río Grande de Añasco. Swamp deposits are present over relatively large areas of the valley. Beach deposits are extensive along the coast, extending inland as far as 6 miles.

Seismic surveys were used to locate and describe the subsurface materials in the lower Río Grande de Añasco valley (Díaz and Jordan, 1987). The surface of the volcanic rocks underlying the valley is deeply incised to depths of about 350 feet below present mean sea level, indicating that the Río Grande de Añasco cut deeply into the valley floor during these lower sea levels. A zone of clay, interbedded with limestone, is present in the central part of the valley along the ancient incision. The interbedded clay and limestone layer is about 250 feet thick. Alluvial deposits of Quaternary age, which have a thickness of as much as 100 feet, unconformably overlie the clay and limestone zone and the volcanic and volcaniclastic bedrock.

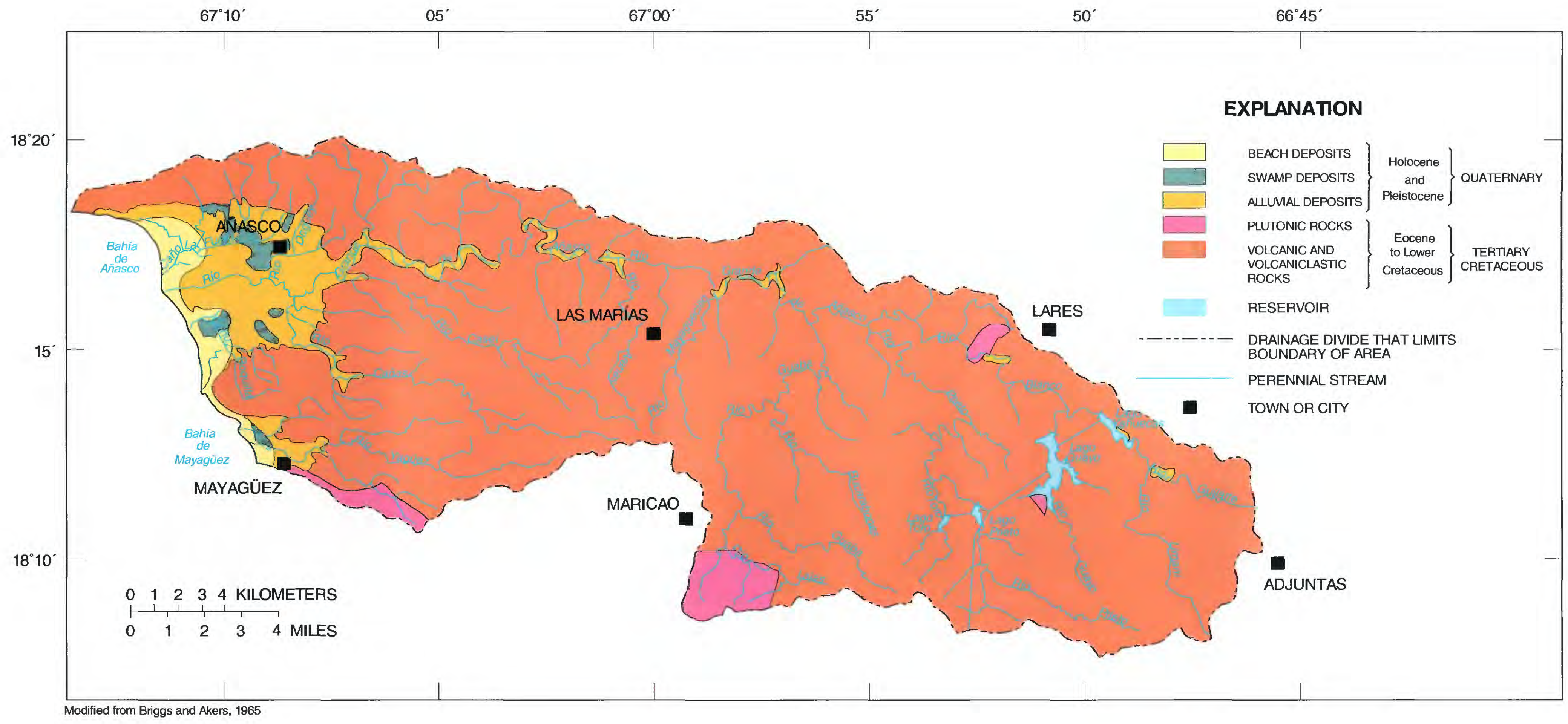


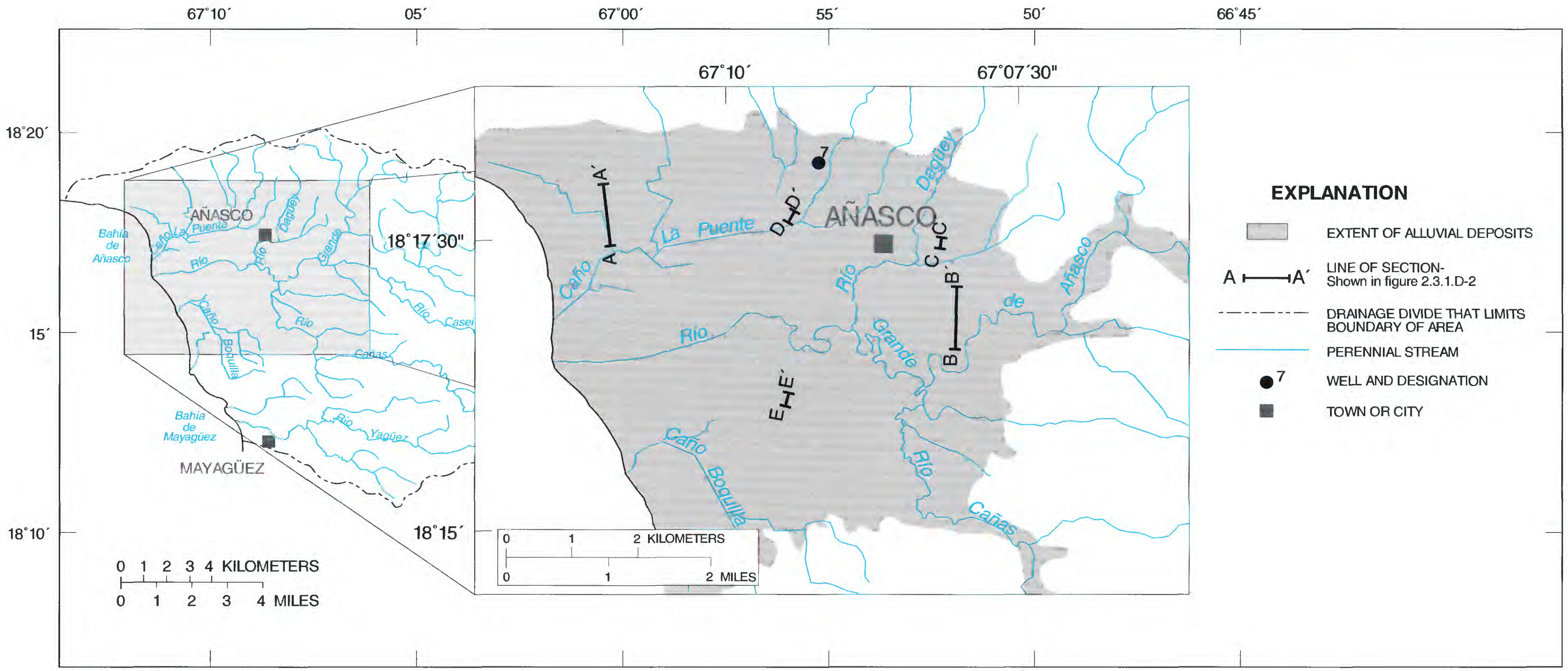
Figure 2.3.1.C-1 Generalized surficial geology in the Añasco region, Puerto Rico.

2.3.1.D Hydrogeology

The principal water-bearing units within the lower Río Grande de Añasco valley are the alluvium and the underlying limestone beds (Díaz and Jordan, 1987). Seismic refraction surveys performed in the lower Río Grande de Añasco valley reveal a saturated zone of alluvium which ranges in thickness from 50 to 100 feet (figs. 2.3.1.D-1 and 2.3.1.D-2; Díaz and Jordan, 1987). The zone between the volcanic and volcaniclastic rocks and the alluvium is composed of hard clay interbedded with soft limestone and is as much as 250 feet thick. The amount of ground water available in the Añasco region is unknown. No ground-water studies have been conducted in the Río Yagüez alluvial valley.

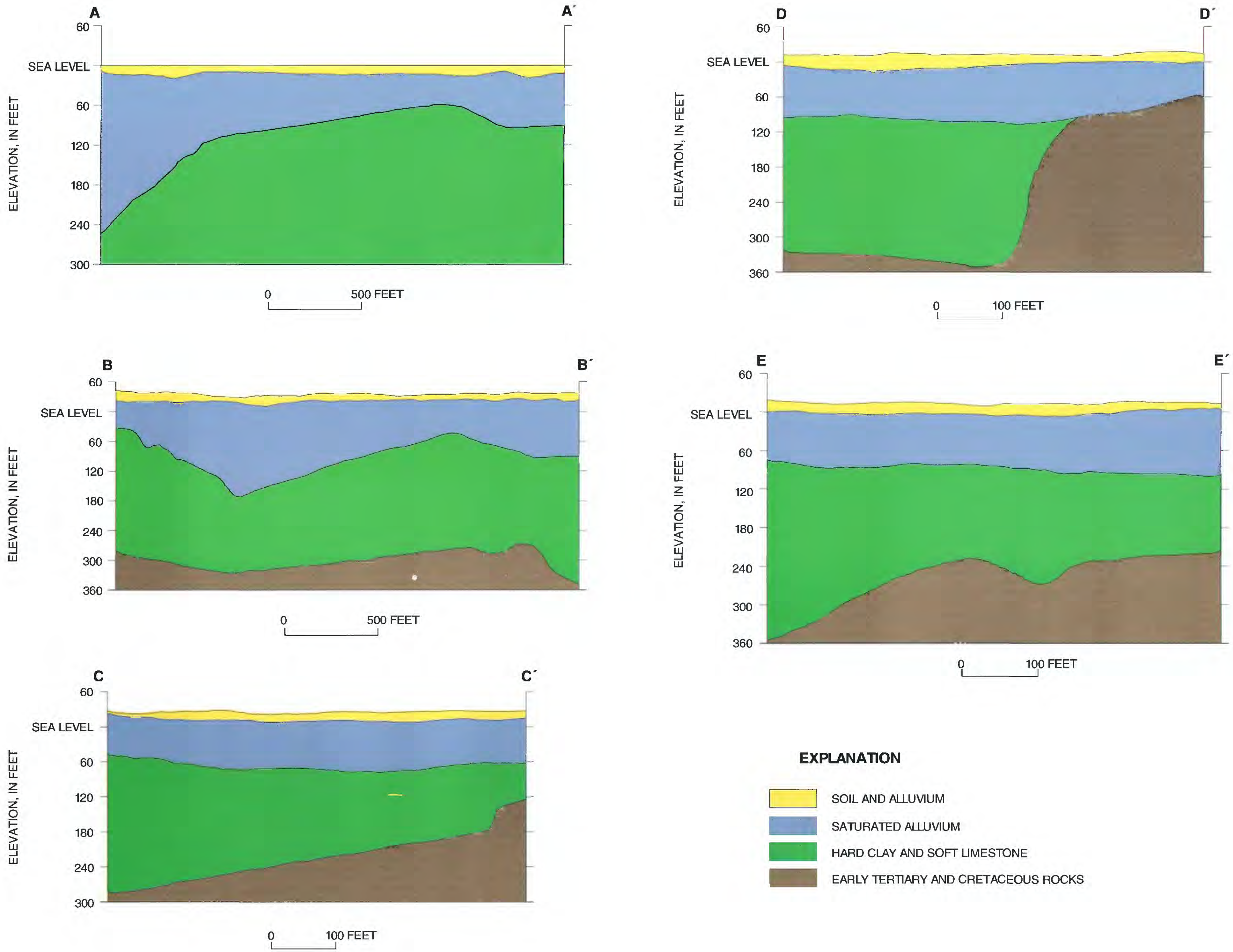
The alluvial deposits have very low permeability, due to the predominance of fine-grained materials in them. Permeability is higher where beds of sand and gravel occur locally within the alluvial deposits. Yields of 100 to 150 gal/min have been documented at wells that tap these sand and gravel beds (Díaz and Jordan, 1987) and are directly proportional to the extent the well penetrates the layer. The more sand or gravel penetrated, the higher the yield.

A shallow aquifer formed by limestone rocks is the principal source of ground water in the Añasco region. Yields of 500 gal/min have been documented from this rock unit (Díaz and Jordan, 1987). The limestone beds have a maximum thickness of 50 feet. The only transmissivity value for the aquifers in the Añasco region was reported from a pumping test performed on well 7 (fig. 2.3.1.D-1), which penetrated 50 feet of limestone. This test gave an estimated transmissivity of 2,150 ft^2/d (Díaz and Jordan, 1987, p. 30). The hydraulic connection between the limestone and the alluvium is poor.



Modified from Díaz and Jordan, 1987

Figure 2.3.1.D-1 Location of seismic-refraction survey cross sections and well in the Añasco region, Puerto Rico (line of section shown in figure 2.3.1.D-2).



Modified from Díaz and Jordan, 1987

Figure 2.3.1.D-2 Aquifer thickness cross section obtained from seismic -refraction velocity profiles surveys and well information in the Añasco region, Puerto Rico (location of section shown in figure 2.3.1.D-1).

2.3.1.E Ground-Water Levels and Movement

The recharge to the alluvium in the lower Río Grande de Añasco valley is almost entirely derived from direct rainfall (Díaz and Jordan, 1987, p. 31). The average annual precipitation at the Mayagüez Airport located at the lower valley areas was 68 inches for the period of 1973-82. Because it lies in a rain shadow, rainfall at the airport may average 10 to 20 inches less than that in the central part of the valley. The sources of recharge to the limestone aquifer are unknown. However, Díaz and Jordan (1987, p. 31) suggest that recharge to this aquifer could originate in the overlying alluvium in places where the clay layer is absent and where in contact with the volcanic rocks.

Ground-water levels in the lower valley range from 0 feet near the coast to about 30 feet above mean sea level in the upper reaches of the valley (fig. 2.3.1.E-1). Ground water flows toward the sea and discharges to the Río Grande de Añasco. Ground water also discharges to the Caño La Puente and Caño Boquilla, where swamp and marsh conditions prevail. Fluctuations in ground-water levels between dry and wet seasons average about 1 foot in most places. Díaz and Jordan (1987, p. 27) state that this small degree of variation indicates a low permeability of the alluvium.

The hydraulic gradient steepens in the vicinity of the Mayagüez Airport (Díaz and Jordan, 1987; fig. 2.3.1.E-1). This rapid change in gradient may be caused by a change in the composition of the alluvium from finer to coarser sediments.

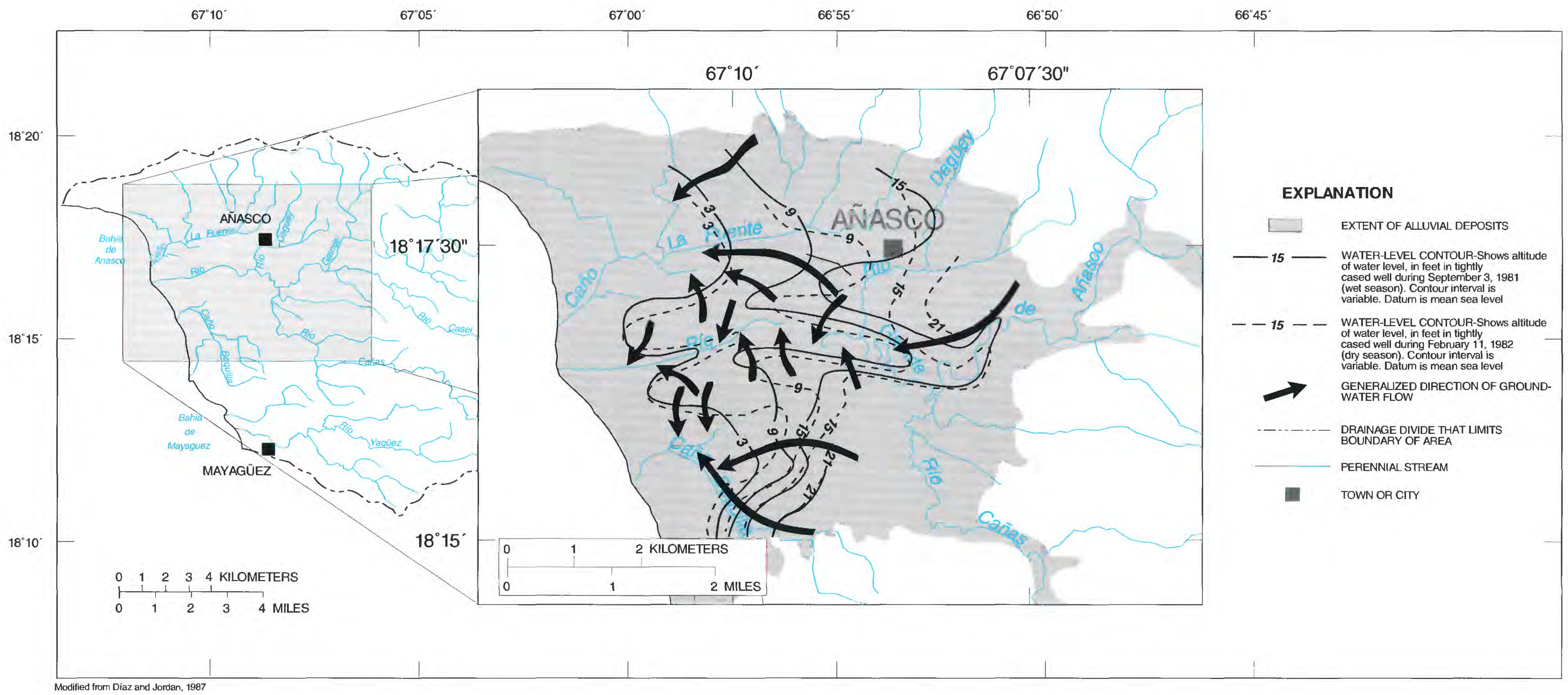


Figure 2.3.1.E-1 Composite altitude of water-level surface for September 1981 and February 1982, and direction of ground-water flow during September 1981 in the Añasco region, Puerto Rico.

2.3.1.F Soil Permeability

The soil associations present over the lower Río Grande de Añasco valley are the Coloso-Toa, and the Consumo-Humatas associations (fig. 2.3.1.F-1). The Coloso-Toa almost entirely covers the valley. The Coloso-Toa association is described by Gierbolini (1975, p. 7) as nearly level, loamy soils that are porous. This association is derived from the underlying limestone and volcanic rocks and has a moderate permeability: values range from 0.60 to 2.00 in/hr. The Consumo-Humatas covers the southern part of the valley near Caño Boquilla. The Consumo-Humatas association is described as strongly leached, sticky, and plastic soils underlain by thick layers of weathered rock. Most of these soils occur on steep side slopes. This association also has moderate permeabilities ranging from 0.60 to 2.00 in/hr. The available water capacity of both associations is very low. The water holding capacity values for the Coloso-Toa association range from 0.11 to 0.14 in/in of soil, and for the Consumo-Humatas association from 0.09 to 0.18. The thickness of both soil associations ranges from near zero to 60 inches.

Other associations that are present in the Añasco region but overlying the volcanic rocks that surround the Río Grande de Añasco valley are the Caguabo-Múcara, the Humatas-Maricao-Los Guineos, and the Nipe-Rosario associations. The characteristics of these associations are shown in table 2.3.1.F-1.

Table 2.3.1.F-1 Thickness, permeability, and available water capacity for the soil associations in the Añasco region, Puerto Rico (Modified from Gierbolini, 1975)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Coloso-Toa	0 to 60	0.60 to 2.00	0.11 to 0.14
Consumo-Humatas	0 to 60	0.60 to 2.00	0.09 to 0.18
Caguabo-Múcara	0 to 22	0.60 to 2.00	0.03 to 0.17
Humatas-Maricao-Los Guineos	0 to 60	0.60 to 2.00	0.09 to 0.18
Nipe-Rosario	0 to 80	2.00 to 6.00	0.11 to 0.13

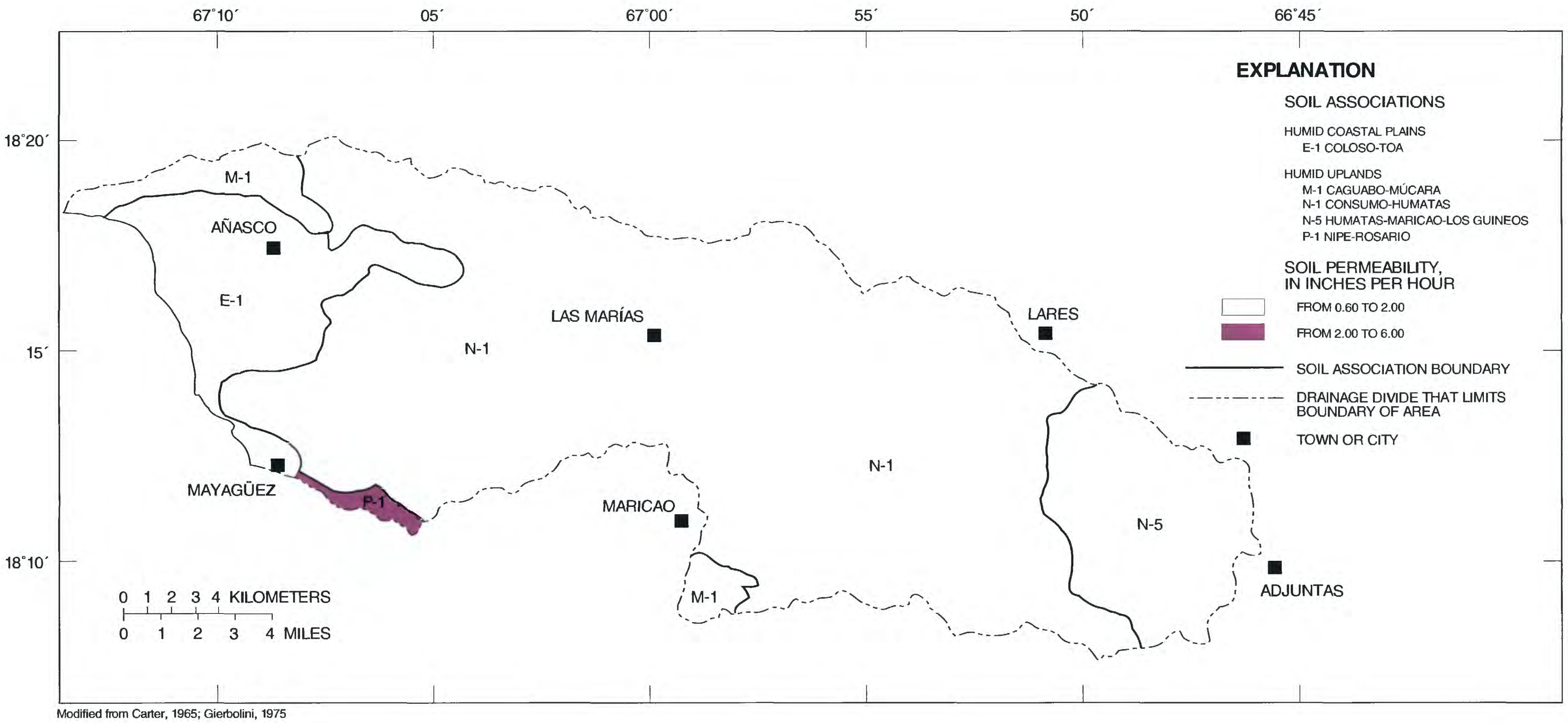


Figure 2.3.1.F-1 Soil associations and permeability in the Añasco region, Puerto Rico.

2.3.2 GUANAJIBO REGION

By Thalia D. Veve

2.3.2.A Location and Major Geographic Features

The Guanajibo region, located on the west coast of Puerto Rico, covers an area of approximately 146 mi^2. The principal population centers in the Guanajibo region are San Germán, Hormigueros, Cabo Rojo, and Mayagüez (fig. 2.3.2.A-1).

The Guanajibo region is characterized by a broad alluvial valley (the Central Guanajibo valley) covering about 29 mi^2. This valley is bounded on all sides by hills, except to the northwest, where it is bounded by the Mona Passage. At the coast, the Guanajibo valley extends northward joining the Río Yagüez valley. A barrier of low-lying hills almost completely separates the Central Guanajibo Valley from the coast. These hills form a ridge called the Cordillera Sabana Alta that reaches its greatest elevation in the east. West of these hills, the shore features a fringe of beach and swampy terrain. A large coastal lagoon, Laguna Joyuda, dominates the west-central coast areas.

The Central Guanajibo valley measures 18 miles in length along its east-west axis, with a width ranging from 6 miles in the east to 12 miles in the west. The Central Guanajibo valley has an area of about 25 mi^2. Elevations within the valley range from mean sea level at the coast to about 200 feet above mean sea level. Hills surrounding the valley reach maximum elevations of 1,968 feet above mean sea level in the Cordillera Central.

The major river in the region is the Río Guanajibo, flowing to the west-northwest. It originates along the western side of the Cordillera Central and flows to the sea on the west coast, south of Mayagüez. The principal tributaries to the Río Guanajibo are the Río Rosario, Río Duey, Río Hoconuco, Río Caín, Río Cupeyes, Río Cruces, and Río Flores, draining to the south-southwest, and the Río Viejo, draining to the west-northwest.

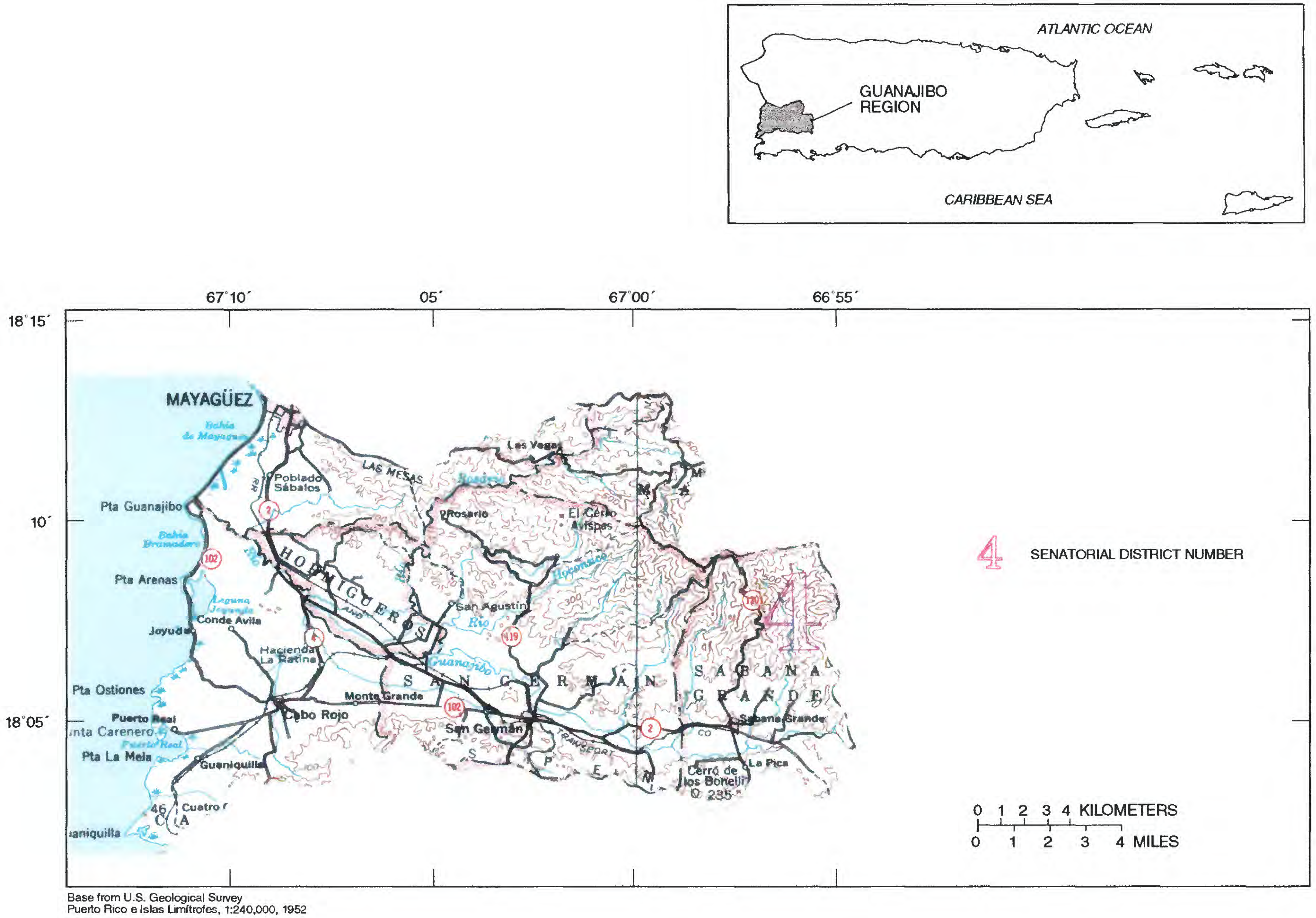


Figure 2.3.2.A-1 Location and major geographic features in the Guanajibo region, Puerto Rico.

2.3.2.B Population and Estimated Ground-Water Use

The total population of the municipios within the Guanajibo region in 1980 was about 204,000 (table 2.3.2.B-1; U.S. Department of Commerce, 1982). Between 1980 and 1990 the population increased by 7 percent to about 218,000 (U.S. Department of Commerce, 1991). However, a large portion of the population in the municipios of Mayagüez and Maricao is outside the Central Guanajibo valley.

Ground-water withdrawals in Cabo Rojo, Hormigueros, Mayagüez, and San Germán totalled less than 5.9 Mgal/d in 1982 (table 2.3.2.B-2; Torres-Sierra and Avilés, 1986). According to Torres-Sierra and Avilés (1986), no ground water was withdrawn in the municipio of Mayagüez from 1980 to 1982. However, Gómez-Gómez and others (1984), reported a withdrawal of 0.45 Mgal/d of ground water for 1981 in that municipio.

During the 1980's, ground water was the only source of water for public supply in Cabo Rojo and Hormigueros. Public-water supply in Mayagüez is from surface-water sources, while in San Germán both surface and ground water contribute in meeting public-water demands.

Public-supply sources provided less than 5.46 Mgal/d for domestic use, while community systems supplied less than 0.43 Mgal/d (table 2.3.2.B-3). Water used for industry, agriculture (livestock), and commerce totalled less than 0.27, 0.25, 0.62 Mgal/d, respectively. Approximate well locations by use are shown in figure 2.3.2.B-1.

Table 2.3.2.B-1 Population for the Guanajibo region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Cabo Rojo	34,045	10,292	23,753	38,521
Hormigueros	14,030	12,031	1,999	15,212
Maricao	6,737	1,390	5,347	6,206
Mayagüez	96,193	82,968	13,225	100,371
Sabana Grande	20,207	7,435	12,772	22,843
San Germán	32,922	13,054	19,868	34,962
Total	204,134	127,170	76,964	218,115

Table 2.3.2.B-2 Ground-water withdrawals for public-water supply by municipio for 1980, 1981, and 1982 in the Guanajibo region, Puerto Rico (Torres-Sierra and Avilés, 1986)
[Mgal/d, million gallons per day]

	Total ground-water withdrawal (Mgal/d)		
MUNICIPIO	1980	1981	1982
Cabo Rojo	3.72	3.28	2.75
Hormigueros	0.98	1.21	1.29
Maricao	0.01	0.00	0.00
Mayagüez	0.00	[1]0.45	0.00
Sabana Grande	0.37	0.44	0.51
San Germán	1.02	1.40	1.54
Total	6.10	6.78	6.09

[1] Value given in Gómez-Gómez and others (1984) for 1981.

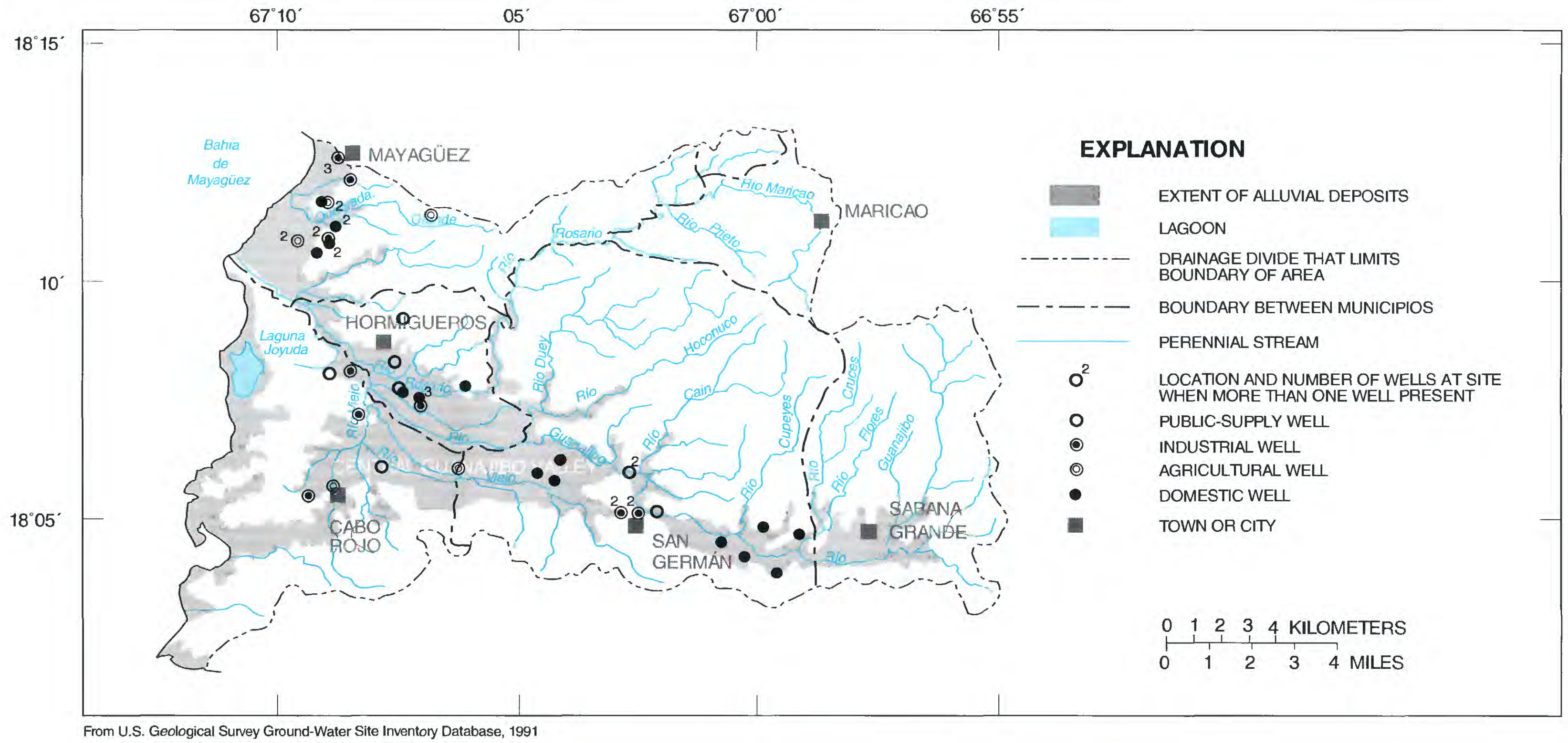


Figure 2.3.2.B-1 Approximate well locations in the Guanajibo region, Puerto Rico.

Table 2.3.2.B-3 Ground-water withdrawals and estimated population served during 1982 for the Guanajibo region, Puerto Rico (Torres-Sierra and Avilés, 1986)

[Mgal/d, million gallons per day; ---, no data available; <, less than]

[1] Use	Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use		
A. Public Supply		
1. Cabo Rojo	28,419	1.94
2. Hormigueros	13,397	0.84
3. Maricao	---	---
4. Mayagüez	---	---
5. Sabana Grande	19,653	[2] <1.19
6. San Germán	23,634	[2] <1.49
Subtotal	167,455	<5.46
B. Community Systems		
1. Cabo Rojo	5,626	0.22
2. Hormigueros	633	0.03
3. Maricao	4,335	0.18
4. Mayagüez	---	---
5. Sabana Grande	---	---
6. San Germán	9,288	[2] <0.37
Subtotal	36,679	<0.43
II. Commercial Use		
1. Cabo Rojo	---	0.28
2. Hormigueros	---	0.04
3. Maricao	---	---
4. Mayagüez	---	---
5. Sabana Grande	---	[2] <0.07
6. San Germán	---	[2] <0.23
Subtotal	---	<0.62
III. Industrial Use		
1. Cabo Rojo	---	0.03
2. Hormigueros	---	0.01
3. Maricao	---	---
4. Mayagüez	---	---
5. Sabana Grande	---	[2] <0.03
6. San Germán	---	[2] <0.20
Subtotal	---	<0.27
IV. Agricultural Use (livestock)		
1. Cabo Rojo	---	0.13
2. Hormigueros	---	0.01
3. Mayagüez	---	---
4. Sabana Grande	---	[2] <0.04
5. San Germán	---	[2] <0.07
Subtotal	---	<0.25
Total	104,985	<7.03

[1] Municipios not listed under a specific use did not withdraw water for that use.

[2] Includes both surface- and ground-water sources.

2.3.2.C Geologic Setting

There are four major lithologically distinct rock groups present in the Guanajibo region (fig. 2.3.2.C-1). They are: the Bermeja Complex of Jurassic to Early Cretaceous age; a suite of volcanic, volcaniclastic, plutonic, and sedimentary rocks of Late Cretaceous age; limestone formations of Late Cretaceous age; and alluvial deposits of Quaternary age.

The Bermeja Complex of Jurassic to Early Cretaceous age (Montgomery and others, 1994) consists primarily of serpentinite, amphibolite, basalt, and chert. It is highly deformed and metamorphism has destroyed most primary textures, bedding, and lithological relations. It is most extensively exposed in the southwestern part of the Guanajibo region.

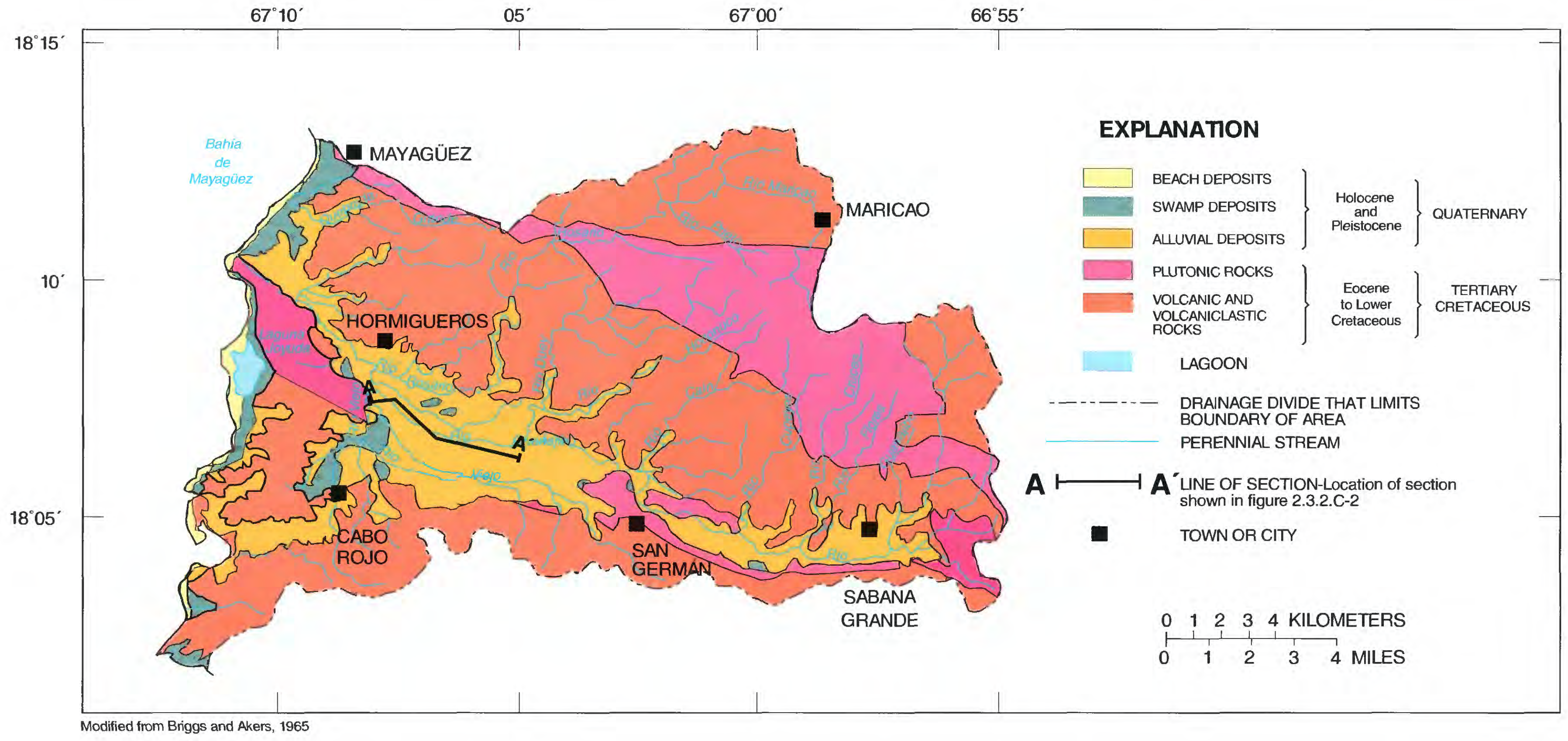


Figure 2.3.2.C-1 Generalized surficial geology in the Guanajibo region, Puerto Rico.

The suite of volcanic, volcaniclastic, plutonic, and sedimentary rocks of Late Cretaceous age predominate in the mountains surrounding the Central Guanajibo valley (fig. 2.3.2.C-2). Subsequent to their formation these rocks were folded and faulted (Colón-Dieppa and Quiñones-Márquez, 1985), and then subjected to extreme weathering and erosion. The Central Guanajibo valley largely lies within an anticline that has been breached by erosion and is bounded in part by faults (Mattson, 1960, p. 321; Colón-Dieppa and Quiñones-Márquez, 1985, p. 10).

The limestone formations of Late Cretaceous age in the Central Guanajibo valley include the Peñones Limestone, Cotui Limestone, Parguera Limestone, and Melones Limestone (Curet, 1986; Volckmann, 1984b and 1984c). While these various formations vary in coloration, they are generally massive to thick-bedded limestones rich in mollusk fossils. These formations overlie the Bermeja Complex and various of the volcanic, volcaniclastic, plutonic, and sedimentary rocks.

Alluvial deposits of Quaternary age overlie volcanic and volcaniclastic rocks in the southwestern Guanajibo region and the Bermeja Complex in the Central Guanajibo valley (Mattson, 1960; Colón-Dieppa and Quiñones-Márquez, 1985, p. 18). Clay predominates in the surface of the alluvium. These surficial clay deposits in the alluvium are generally underlain by sand lenses and, at greater depths, gravel lenses within the clay-rich alluvium.

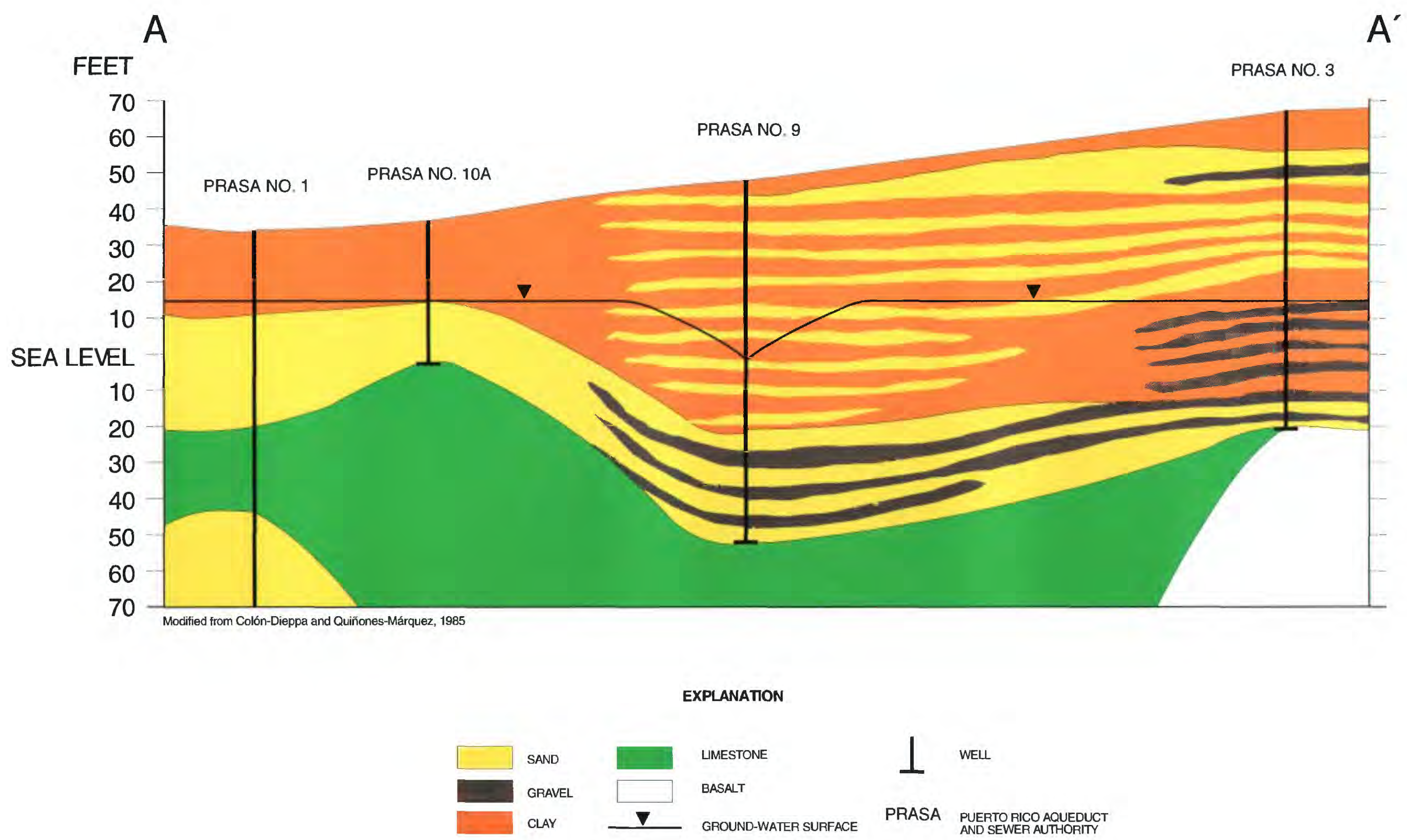


Figure 2.3.2.C-2 Locations of cross section and wells in the Central Guanajibo valley, Puerto Rico (location of cross section shown in figure 2.3.2.C-1).

2.3.2.D Hydrogeology

Ground water within the Central Guanajibo valley occurs in the limestone formations underlying the alluvium and in the sand and gravel lenses within the alluvium. Where volcanic rocks are highly fractured, limited amounts of ground water can be withdrawn. Limestone formations and sand and gravel lenses within the alluvium are concentrated in the western and southwestern parts of the Central Guanajibo valley. Clay, a nearly impermeable material, is more abundant in alluvial deposits in the northern and eastern Guanajibo region than in the Central Guanajibo valley. The alluvium is about 70 feet thick and the limestone is more than 200 feet thick in the Central Guanajibo valley and is thickest near Cabo Rojo, where the bedrock lies at 500 feet below land surface. These deposits become thinner toward the north and west, where they are less than 100 feet thick (fig. 2.3.2.D-1).

Aquifer characteristics in the southwestern Guanajibo region have been estimated from data on driller's logs. Yields to wells average from 280 to 660 gal/min (Colón-Dieppa and Quiñones-Márquez, 1985, p. 48). Maximum yields range from 75 to 1,100 gal/min and specific capacities from 2.4 to 40 gal/min per foot of drawdown (Colón-Dieppa and Quiñones-Márquez, 1985, p. 40). Transmissivities ranging from 670 to 6,000 ft^2/d were estimated from the specific capacities of the Puerto Rico Aqueduct and Sewer Authority wells drilled in the southwestern part of the Central Guanajibo valley (fig. 2.3.2.D-2; Colón-Dieppa and Quiñones-Márquez, 1985, p. 40). The aquifer in the Central Guanajibo valley is composed of limestone with some sand and gravel. Apparent transmissivity estimates for two wells in Cabo Rojo differed by one order of magnitude from 11,000 to 1,600 ft^2/d, in spite of being close together. The water bearing unit here consists primarily of fractured volcanic rock or limestone. The difference in performance between these two wells may be explained by differences in the degree of fracturing of the water bearing unit around them.

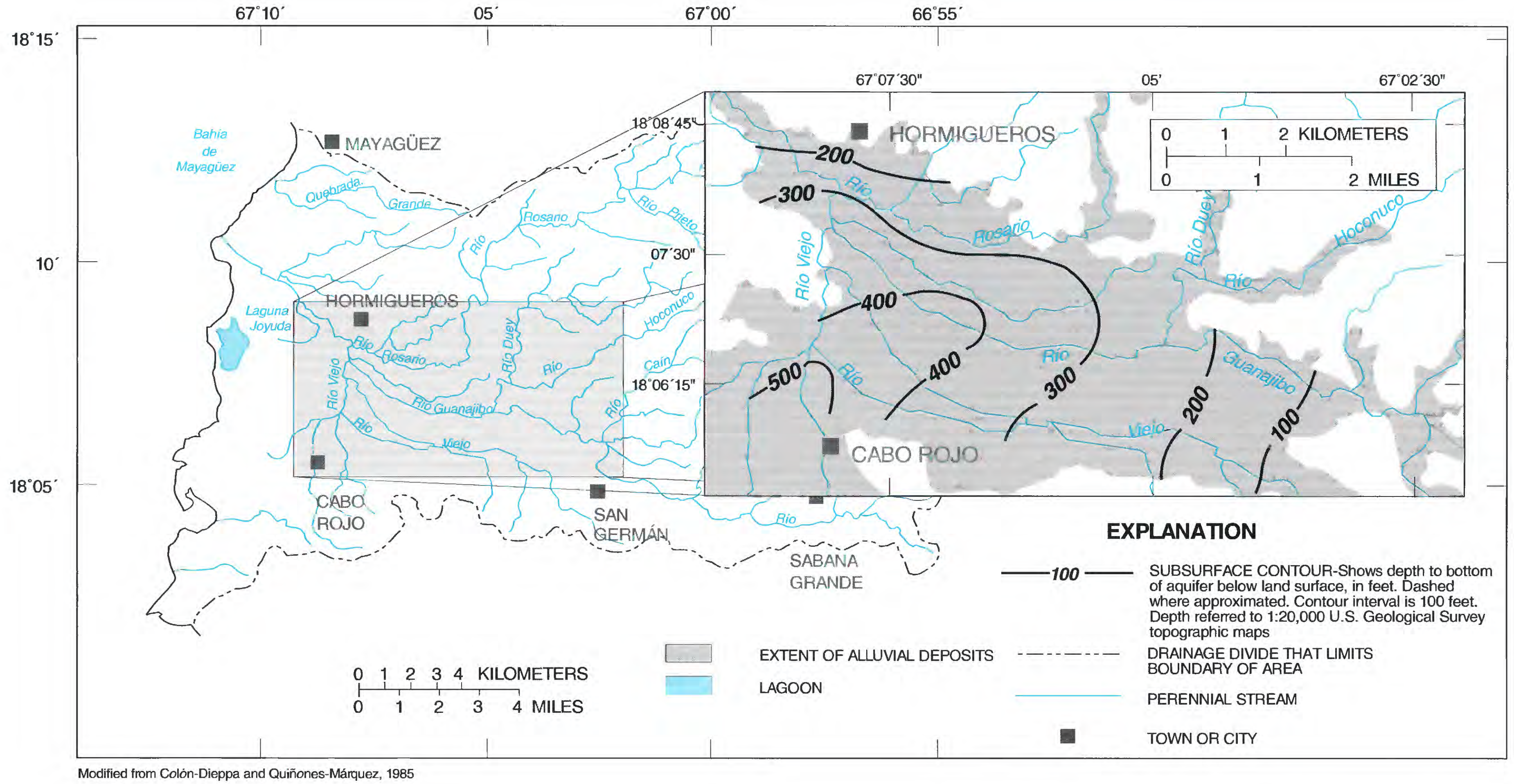


Figure 2.3.2.D-1 Approximate depth to bedrock in the Central Guanajibo valley, Puerto Rico.

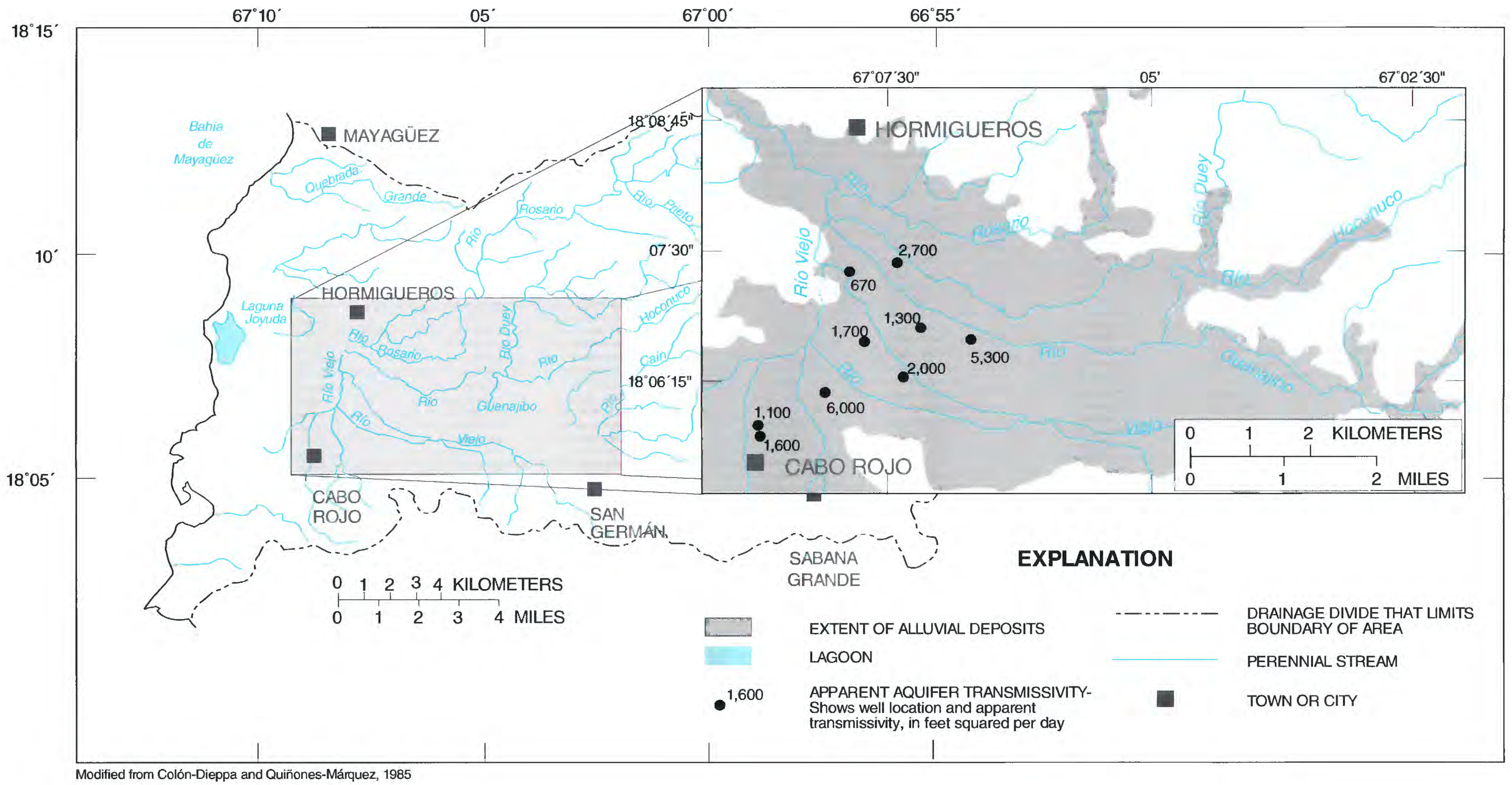
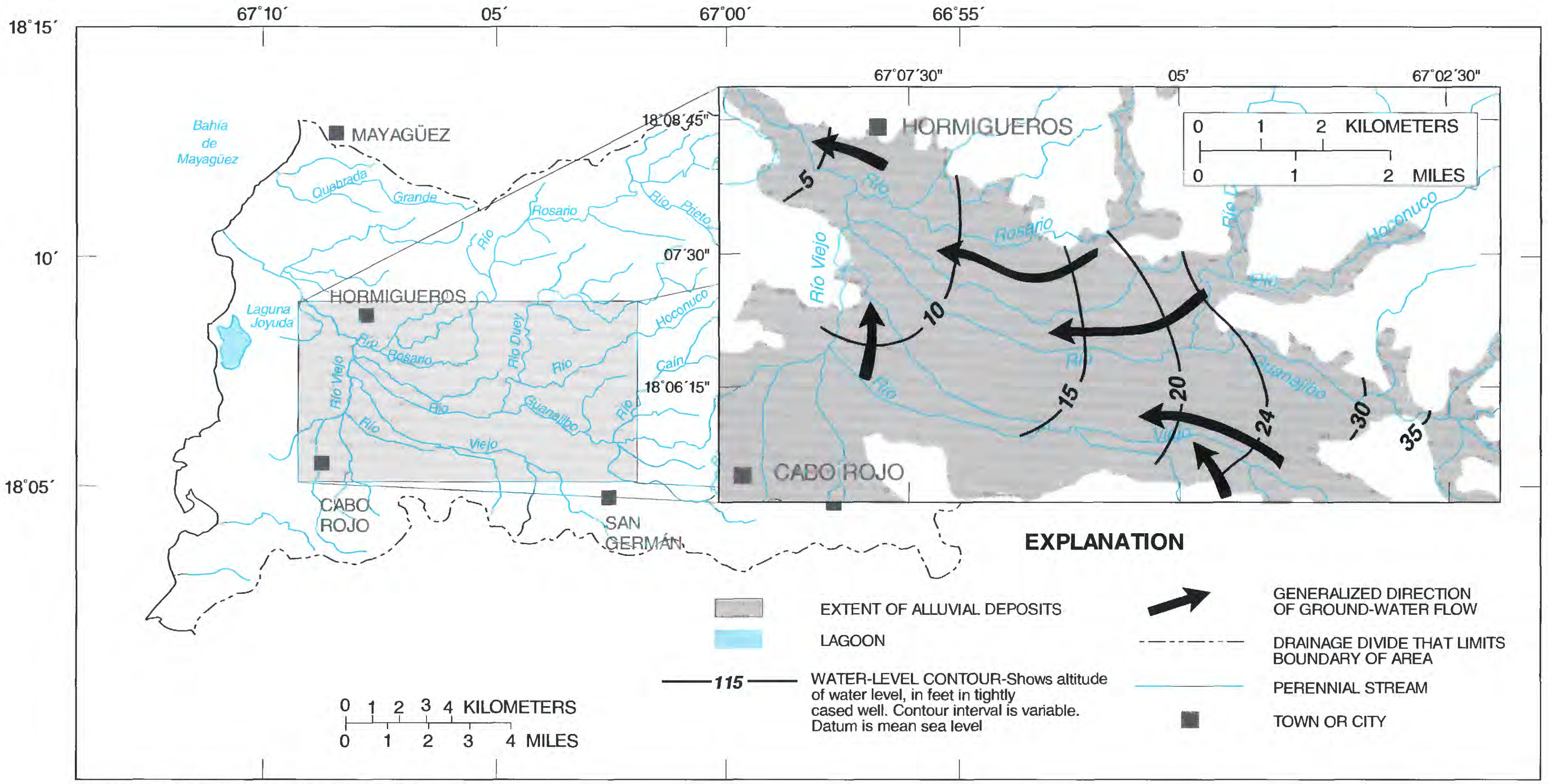


Figure 2.3.2.D-2 Apparent aquifer transmissivity in the Central Guanajibo valley, Puerto Rico.

2.3.2.E Ground-Water Levels and Movement

Aquifer recharge to the Guanajibo region originates principally along the contact between the alluvium and the igneous rocks. Direct recharge from rainfall is not believed to occur throughout the valley since clay covers almost the entire surface. In the few places where more permeable materials (limestone or sand and gravel) reach the surface, rainfall may recharge the aquifer. Annual rainfall in the lower part of the valley averages 56 inches, and in the upper reaches of the basin, annual rainfall ranges from 70 to 100 inches (Colón-Dieppa and Quiñones-Márquez, 1985, p. 6 and 20).

Ground-water levels within the Central Guanajibo valley range from 16 feet above mean sea level west of Hormigueros to 115 feet above mean sea level north of San Germán (fig. 2.3.2.E-1). Ground water moves from the surrounding hills to the center of the valley and then moves towards the coast following the general topography of the region. The water-table gradient generally is about 14 ft/mi (Colón-Dieppa and Quiñones-Márquez, 1985).



Modified from Colón-Dieppa and Quiñones-Márquez, 1985

Figure 2.3.2.E-1 Altitude of water-level surface and direction of ground-water flow during June 1980 in the Central Guanajibo valley, Puerto Rico.

2.3.2.F Soil Permeability

The soil association overlying the Guanajibo region is the Coloso-Toa (fig. 2.3.2.F-1). This association is described by Gierbolini (1975, p. 7) as nearly level, porous soils that are loamy throughout. Scattered ponded areas are present in these soils that are frequently flooded and, subsequently, subject to sediment deposition. These soils were formed in sediments derived from limestone and volcanic rocks. The Coloso-Toa association has moderate permeabilities ranging from 0.60 to 2.00 in/hr (table 2.3.2.F-1). Depth from surface ranges from near zero to 60 inches and available water capacity ranges from 0.11 to 0.14 in/in of soil.

Table 2.3.2.F-1 Thickness, permeability, and available water capacity for the soil associations in the Guanajibo region, Puerto Rico (Modified from Gierbolini, 1975)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Humid Coastal Plains			
Coloso-Toa	0 to 60	0.60 to 2.00	0.11 to 0.14
Voladora-Moca	0 to 64	0.60 to 2.00	0.11 to 0.17
Humid Uplands			
Caguabo-Múcara	0 to 22	0.60 to 2.00	0.03 to 0.17
Consumo-Humatas	0 to 60	0.60 to 2.00	0.09 to 0.18
Nipe-Rosario	0 to 80	2.00 to 6.00	0.11 to 0.13
Semiarid Uplands			
Descalabrado	0 to 20	0.60 to 2.00	0.09 to 0.16
Descalabrado-Jácana-San Germán	0 to 34	0.20 to 0.60	0.03 to 0.16

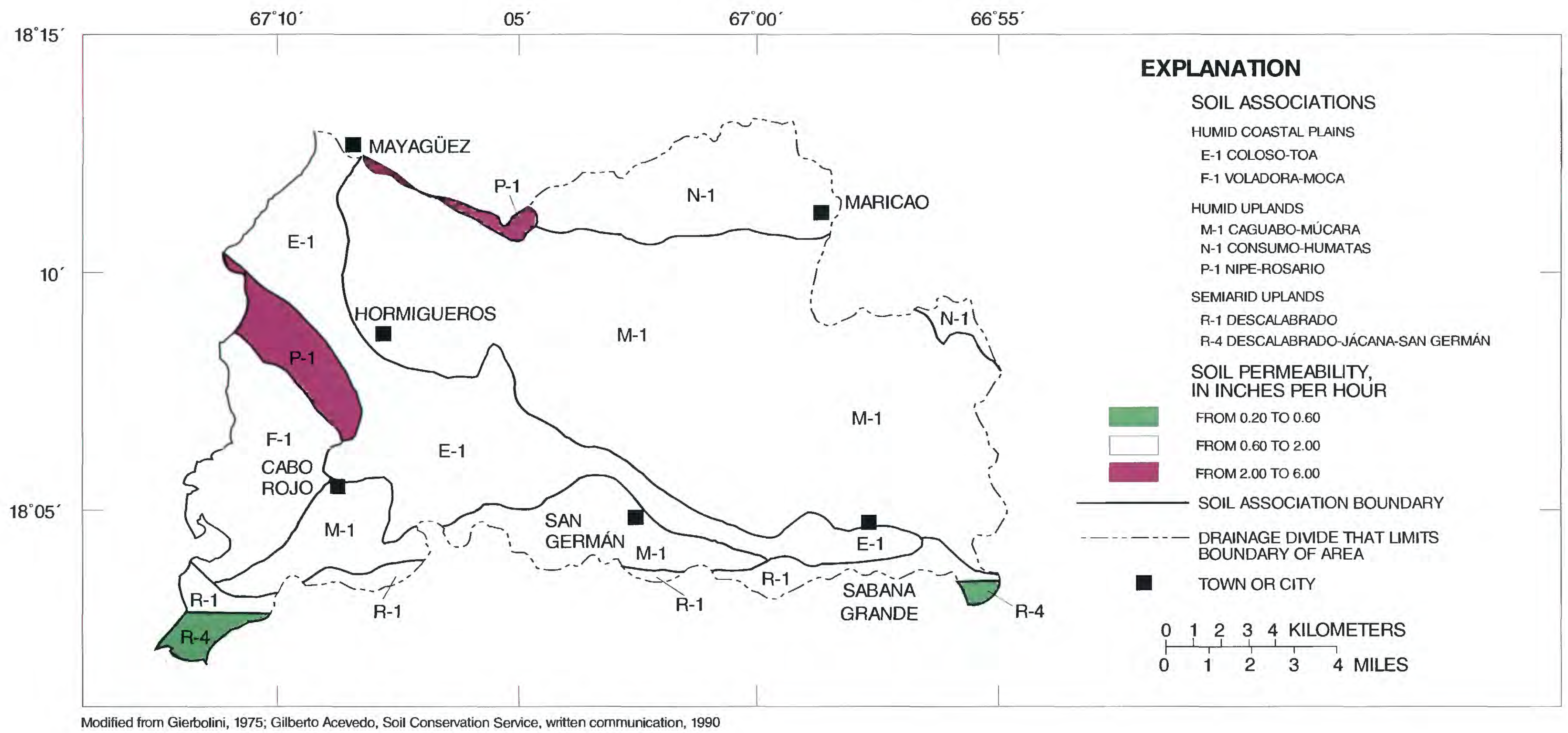


Figure 2.3.2.F-1 Soil associations and permeability in the Guanajibo region, Puerto Rico.

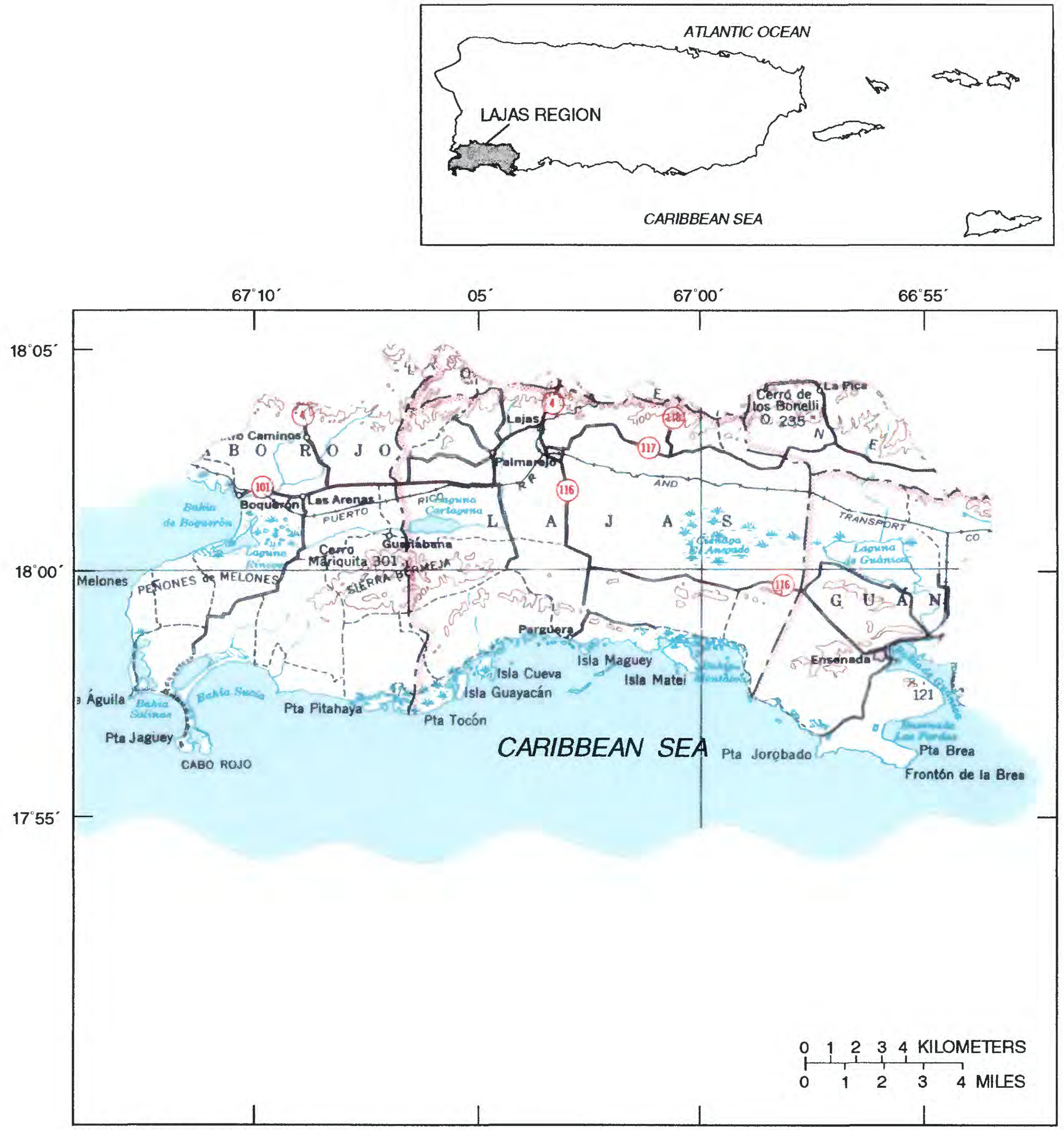
2.3.3 LAJAS REGION

By Robert P. Graves

2.3.3.A Location and Major Geographic Features

The most prominent geographic feature of the 76 mi^2 Lajas region is the Valle de Lajas (fig. 2.3.2.A-1). The valley, oriented along an east-west axis, is approximately 18 miles long and ranges from 1 to 3 miles wide. The valley is open at both ends, draining into the Río Loco and Bahía de Guánica to the east and Bahía de Boquerón to the west. Foothills on the north and south sides of the valley rise to a maximum elevation of 980 and 820 feet above mean sea level, respectively. The elevation of the central valley floor varies from mean sea level to about 43 feet above mean sea level along the east-west drainage divide that is located 6.5 miles east of Bahía de Boquerón. North and south of the central valley floor, the land surface rises to elevations of as much as 164 feet above mean sea level at the base of the bordering foothills.

Surface-water flow in the Valle de Lajas is both natural and man-induced. Natural streams that flow out of the foothills into the Valle de Lajas are small and ephemeral. Man-induced surface-water flow is evident in a gravity-fed irrigation canal that extends westward from Lago Loco to Bahía de Boquerón along the base of the northern foothills. Further, drainage canals have been constructed within the valley. The principal drainage canal extends east-west along the southern edge of the valley and the direction of flow is controlled by the central drainage divide in the valley. Surface-water bodies within the Valle de Lajas include Laguna Cartagena and a mangrove swamp near Bahía de Boquerón.



Base from U.S. Geological Survey
Puerto Rico e Islas Limítrofes, 1:240,000, 1952

Figure 2.3.3.A-1 Location and major geographic features in the Lajas region, Puerto Rico.

2.3.3.B Population and Estimated Ground-Water Use

The total population of the municipios within the Lajas region increased from about 74,000 in 1980 to 84,000 in 1990 (U.S. Department of Commerce, 1982 and 1991), an increase of 13 percent (table 2.3.3.B-1). However, the population within the Lajas region drainage basin was estimated to be approximately 30,000 in 1980; the majority living in the town of Cabo Rojo. In general, ground-water use in the Lajas region is limited. High concentrations of dissolved solids in ground water make it unsuitable for most uses (Graves, 1991). Daily ground-water pumpage in 1986 for municipal, domestic, and agricultural supply was 0.79, 0.16, and 2.00 Mgal/d, respectively (Graves, 1991). The locations of wells supplying water for these uses are shown in figure 2.3.2.B-1. Ground-water withdrawals from public-supply wells are shown by municipio in table 2.3.3.B-2. These totals include water withdrawn from wells that are located in the Lajas region.

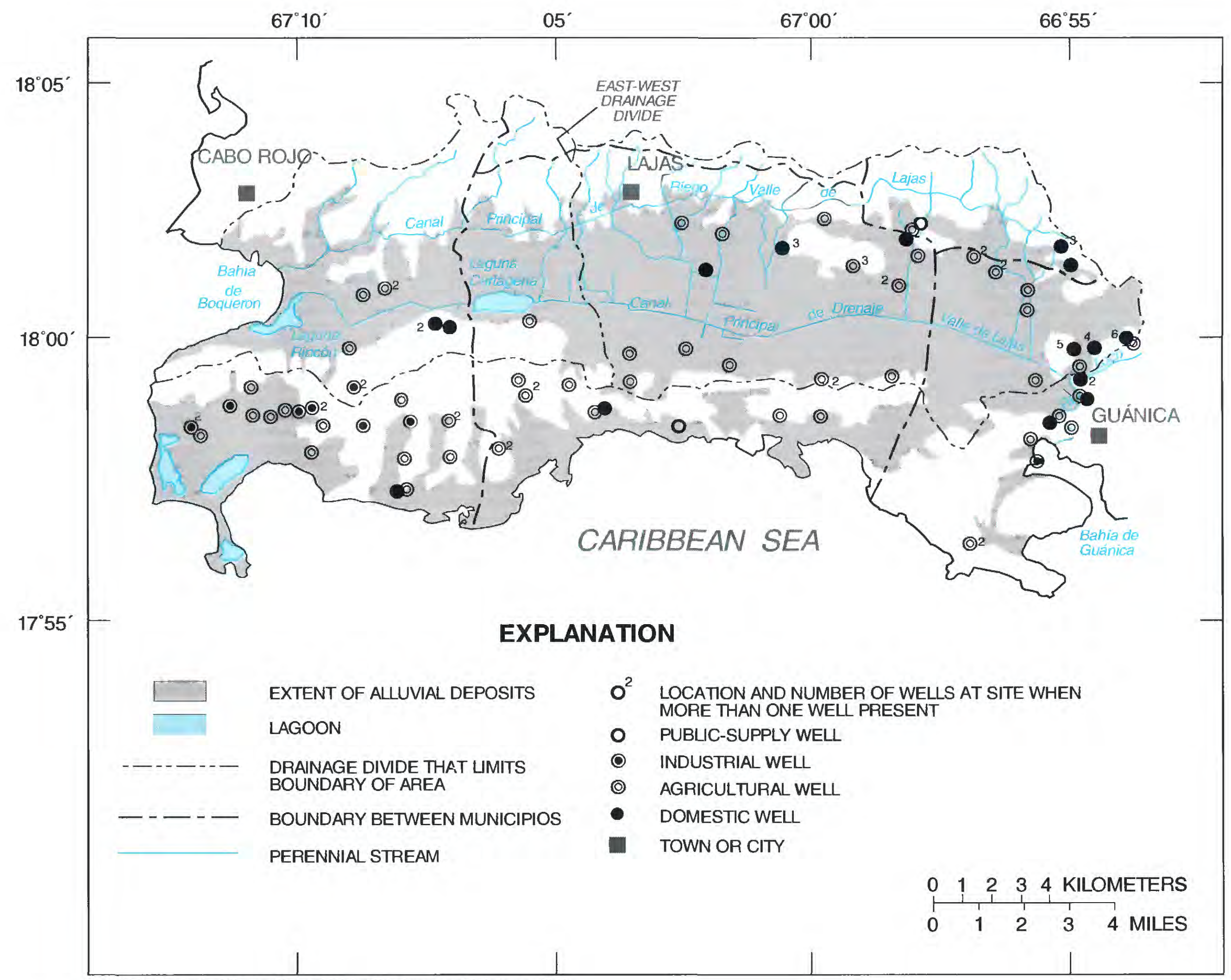
Table 2.3.3.B-2 Ground-water withdrawals for public supply during 1983 in the Lajas region, Puerto Rico
[Mgal/d, million gallons per day]

MUNICIPIO	Average ground-water withdrawals (Mgal/d)
Cabo Rojo	2.84
Lajas	0.79
Guánica	[1]12.3
Total	15.93

[1]Modified from McClymonds (1967) and Graves (1991).

Table 2.3.3.B-1 Population for the Lajas region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Cabo Rojo	34,045	10,292	23,753	38,521
Guánica	18,799	9,628	9,171	19,984
Lajas	21,236	4,275	16,961	23,271
Total	74,080	26,175	49,885	83,766



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.3.3.B-1 Approximate well locations in the Lajas region, Puerto Rico.

2.3.3.C Geologic Setting

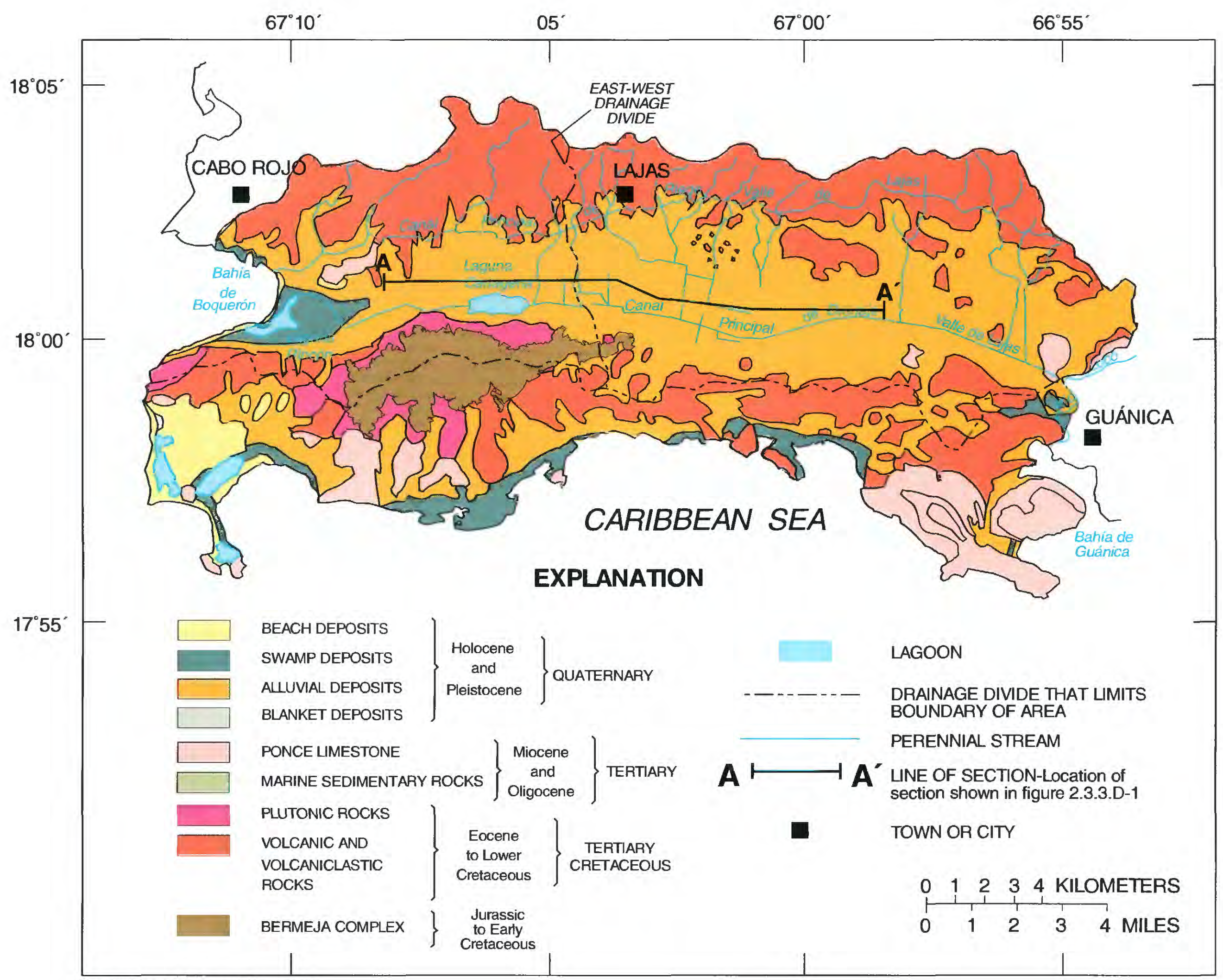
A simplified description of the geology of the Lajas region follows. The four major lithologically distinct rock groups present in the Lajas region are the Bermeja Complex of Jurassic to Early Cretaceous age; a suite of volcanic, volcaniclastic, plutonic, and sedimentary rocks of Late Cretaceous age; limestone formations of Late Cretaceous to Tertiary age; and alluvial deposits of Quaternary age (fig. 2.3.3.C-1).

The Bermeja Complex of Jurassic to Early Cretaceous age (Schellekers and others, 1990) consists primarily of serpentinite, amphibolite, basalt, and chert. It is highly deformed and metamorphism has destroyed most primary textures, bedding, and lithological reactions. It is most extensively exposed in the southern part of the Lajas region in the Sierra Bermeja.

The basement rock under the central Valle de Lajas is igneous rock (quartz diorite or andesite; Graves, 1991). The volcanic, volcaniclastic, plutonic, and sedimentary rocks outcrop on the ridges to the north of the valley (Volckmann,1984a).

Limestone of Tertiary and Cretaceous age and quartz sand deposits of Tertiary age are found locally in the surrounding ridges. The limestone deposits described by Volckmann (1984a) in the Lajas region are the Guanajibo Formation, Ponce Limestone, Sabana Grande Formation, Cotuí Limestone, Melones Limestone, and the Parguera Limestone. The quartz sand deposits consist of extremely angular, moderately sorted, quartz grains and minor amounts of hematite, limonite, or clay.

Alluvial deposits of Holocene and Pleistocene age fill the valley and consist mainly of silt and clay and have fine sand lenses grading into sand and gravel fan deposits on the north and south sides of the valley. Results of test drilling in the Valle de Lajas revealed that the alluvial deposits can exceed 210 feet in thickness (Graves, 1991).



Modified from Briggs and Akers, 1965

Figure 2.3.3.C-1 Generalized surficial geology in the Lajas region, Puerto Rico.

2.3.3.D Hydrogeology

The principal aquifer in the Lajas region is a nonhomogeneous, anisotropic confined aquifer comprised of alluvial deposits. The upper confining unit of the aquifer consists of clay deposits. The alluvial deposits are in hydraulic connection with underlying limestone deposits or quartz-sand deposits; however, it is suspected that because of the difference in rock type, significant differences could exist between the hydraulic characteristics of these geologic units. Because of this, the underlying sedimentary deposits could be considered a distinct aquifer. Geohydrologic data for the sedimentary deposits in the Valle de Lajas are available for only two deep test wells. Therefore, only the alluvial aquifer will be discussed here.

There are few data available delimiting the thickness of the alluvial aquifer or its upper clay confining unit throughout the valley. Test drilling indicates that the top of the alluvial aquifer ranges from 27 to 90 feet below land surface and the base of the aquifer is at depths greater than 210 feet (Graves, 1991; fig. 2.3.3.D-1).

Hydraulic characteristics have been determined only for the alluvial aquifer. Aquifer tests and specific-capacity tests completed by Graves (1991) indicate aquifer transmissivities ranging from 670 to 8,020 ft²/d and a storage coefficient of 9.3 x 10^{-4} (fig. 2.3.3.D-1 and table 2.3.3.D-1).

Table 2.3.3.D-1 Transmissivity of the alluvial aquifer estimated from specific-capacity data (estimates based on method by Meyer, 1963)
[ft²/d, feet squared per day; [(gal/min)/ft], gallons per minute per foot of drawdown]

Well number (fig. 2.3.3.D-2)	Specific capacity [(gal/min)/ft]	Transmissivity (ft²/d)
30	6	1,740
31	20	7,350
36	25	8,020
45	9	2,406
53	5	1,340
71	5	1,340
73	--	7,500
100	7	2,005
102	2	670
103	3	935
105	3	935

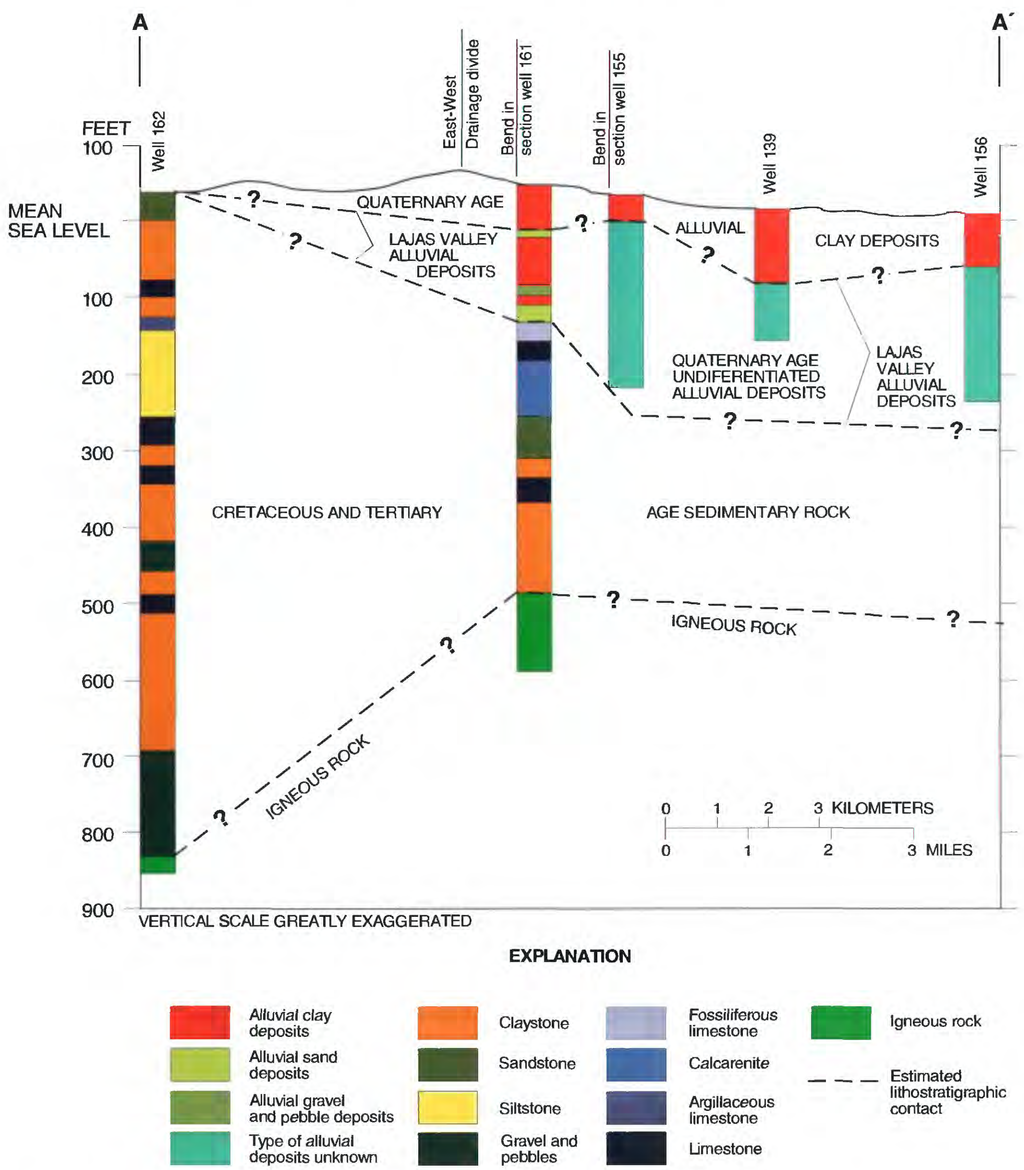


Figure 2.3.3.D-1 Aquifer thickness in the Lajas region, Puerto Rico (line of section shown in figure 2.3.3.C-1).

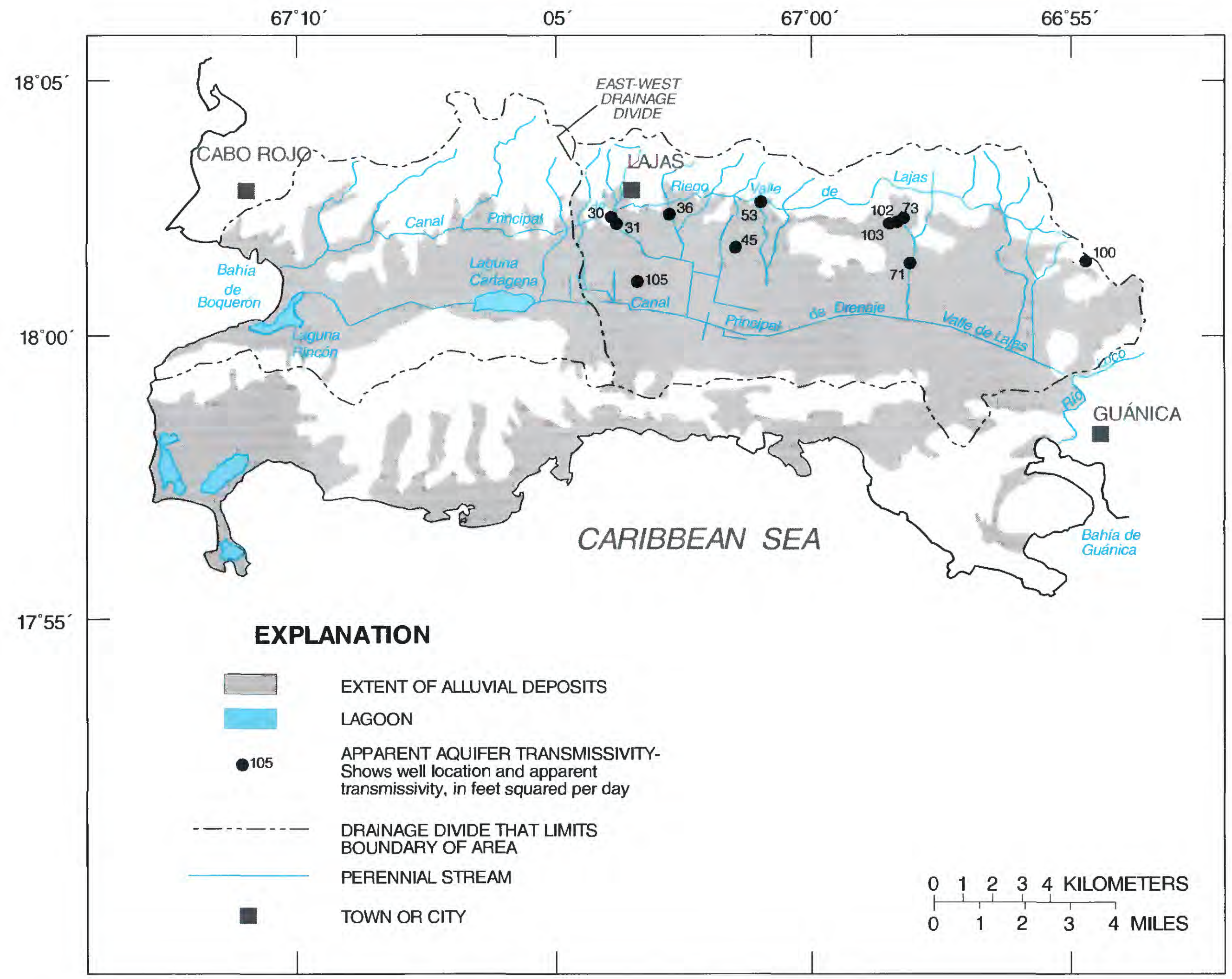


Figure 2.3.3.D-2 Transmissivity in the Valle de Lajas area, Puerto Rico.

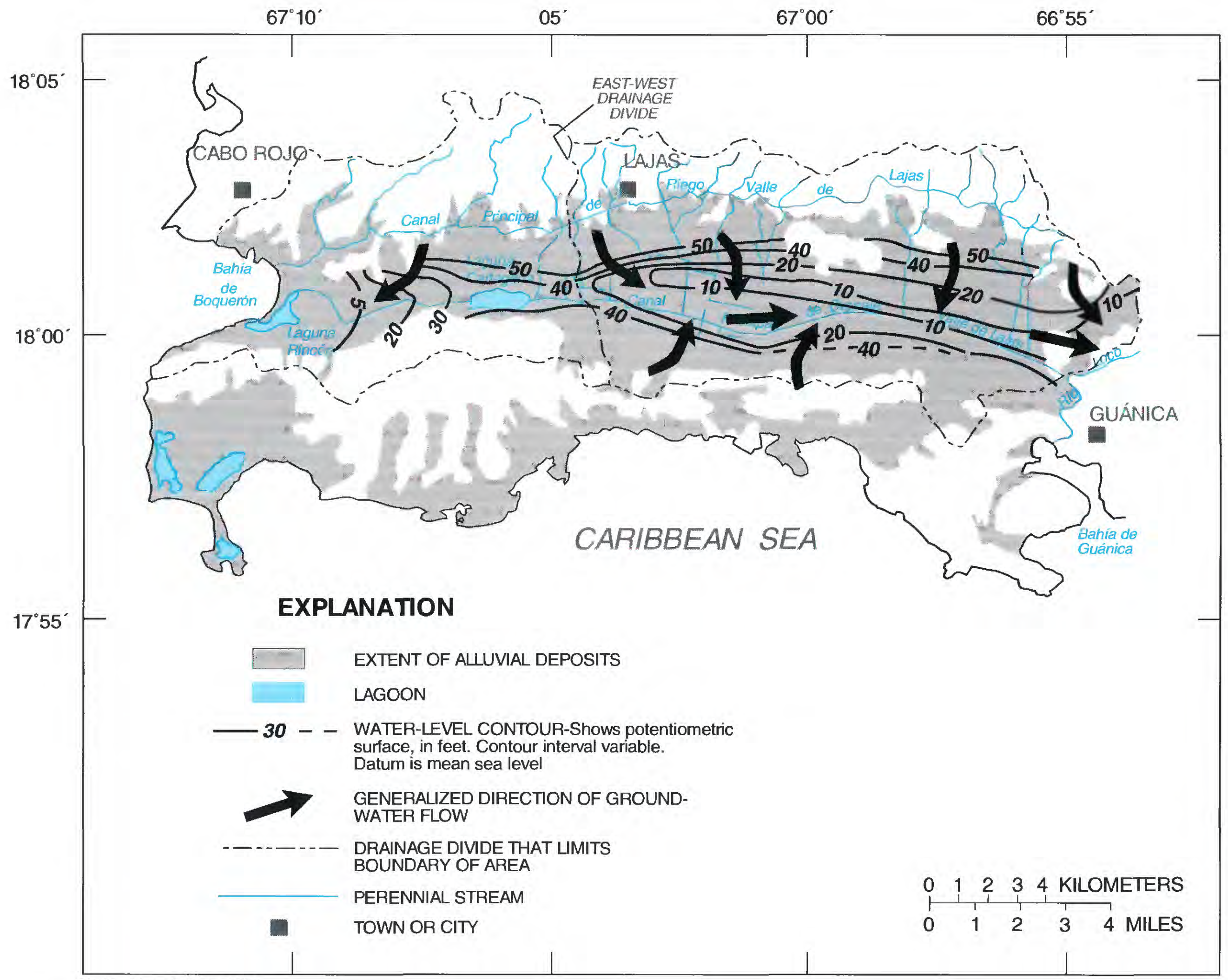
2.3.3.E Ground-Water Levels and Movement

The altitude of the potentiometric surface of the Lajas region alluvial aquifer is more than 50 feet above mean sea level in the northern and southern parts of the valley, about 12 feet above mean sea level in the central part of the valley, and is approximately at mean sea level near Bahía de Boquerón. The main direction of horizontal ground-water flow is from the foothills toward the center of the valley and then, either east to the Bahía de Guánica or west to Bahía de Boquerón (fig. 2.3.3.E-1).

Although long-term fluctuations in the potentiometric surface of the Valle de Lajas alluvial aquifer cannot be evaluated because of the lack of historical data, seasonal fluctuations in the potentiometric surface are evident. Water-level data collected from 1981 to 1986 indicate that heads generally begin to decline in December or January and reach a low in June, July, or August. Recovery of the potentiometric surface usually begins in September.

The Valle de Lajas alluvial aquifer is recharged by streamflow and rainfall. Anderson (1977) estimated the annual recharge to the aquifer to be about 2 inches. Most of this recharge is through the coarse-grained alluvial fan deposits that lie near the edge of the alluvial valley. In the central part of the valley, recharge to the aquifer from rainfall is limited by the less permeable clays near the surface of the alluvial deposits.

Ground-water discharge can occur through pumpage, evapotranspiration, and subsurface seepage. Subsurface seepage occurs at Laguna Cartagena, along the extensive drainage canal system in the Valle de Lajas, and at the mangrove swamp at Boquerón (Anderson, 1977). Subsurface seepage also occurs in the form of base flow to Bahía de Boquerón in the western part of the valley and to the Río Loco and Bahía de Guánica in the eastern part of the valley.



Modified from Graves, 1991

Figure 2.3.3.E-1 Potentiometric surface and direction of ground-water flow during March 1986 in the Lajas region, Puerto Rico.

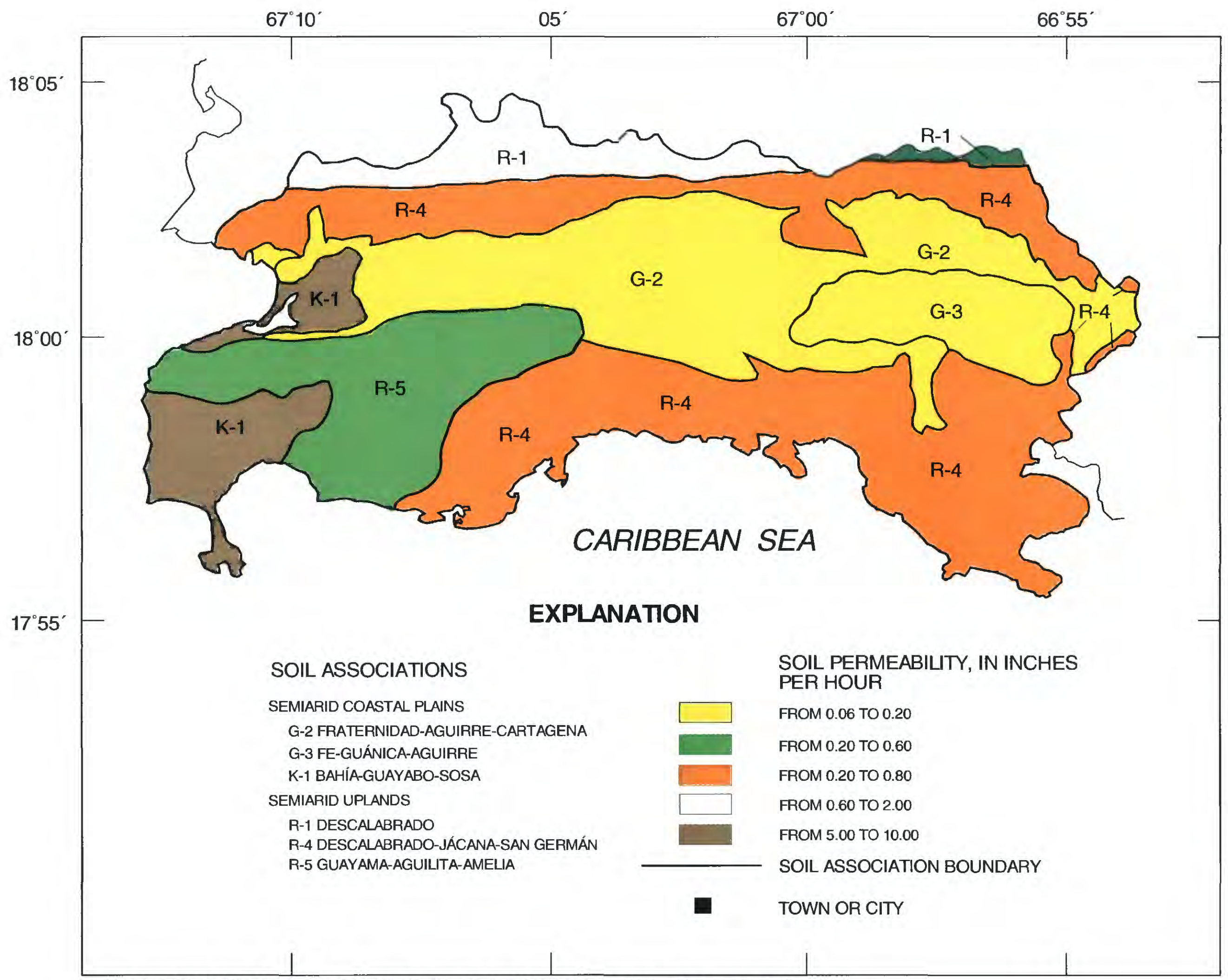
2.3.3.F Soil Permeability

Soils in the Lajas region are of three types. The most prominent soil types in the valley are the Fraternidad-Aguirre-Cartagena and Fe-Guánica-Aguirre soil associations that have a slow soil permeability of 0.06 to 0.20 in/hr (fig. 2.3.3.F-1). The Fraternidad-Aguirre-Cartagena association is described by Carter (1965, p. 5) as moderately well drained to poorly drained, nearly level to sloping, calcareous alluvial soils. The Fe-Guánica-Aguirre association is described as moderately well drained to poorly drained, nearly level, saline-alkali and nonsaline alluvial soils. The third soil type is the Bahía-Guayabo-Sosa soil association which has rapid soil permeabilities ranging from 5.00 to 10.00 in/hr. This association is described as well drained to excessively drained, level to sloping, sandy soils.

Soils in the ridges surrounding the Valle de Lajas are also of three types. The most prominent soil types in the ridges are the Descalabrado-Jácana-San Germán and Guayama-Aguilita-Amelia soil associations which have moderately slow soil permeabilities ranging from 0.20 to 0.60 in/hr. The third soil type is the Descalabrado soil, which has moderate soil permeabilities ranging from 0.60 to 2.00 in/hr. Thickness and available water for each one of the soils in this area are shown in table 2.3.3.F-1.

Table 2.3.3.F-1 Thickness, permeability, and available water capacity for soil associations in the Lajas region, Puerto Rico (Modified from Carter, 1965)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Semiarid Coastal Plains			
Fraternidad-Aguirre-Cartagena	0 to 70	0.06 to 0.20	0.16 to 0.18
Fe-Guánica-Aguirre	0 to 56	0.06 to 0.20	0.12 to 0.18
Bahía-Guayabo-Sosa	0 to 50	5.00 to 10.00	0.00 to 0.13
Semiarid Uplands			
Descalabrado	0 to 12	0.60 to 2.00	0.07 to 0.17
Descalabrado-Jácana-San Germán	0 to 12	0.20 to 0.60	0.07 to 0.17
Guayama-Aguilita-Amelia	0 to 46	0.20 to 0.60	0.08 to 0.17



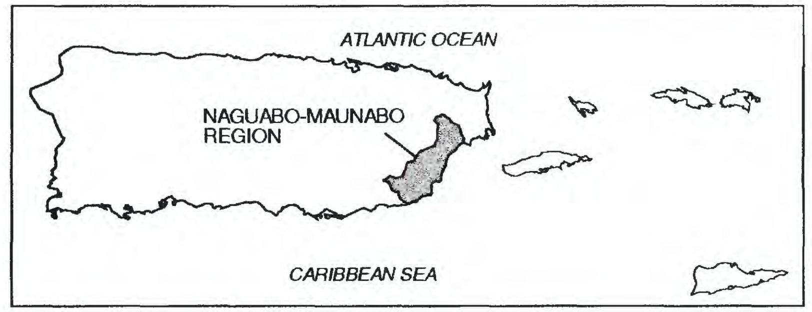
Modified from Carter, 1965; Gierbolini, 1975; Gilberto Acevedo, Soil Conservation Service, written communication, 1990

Figure 2.3.3.F-1 Soil associations and permeability in the Lajas region, Puerto Rico.

2.4 East Coast Area

2.4.1 NAGUABO-MAUNABO REGION

By Angel Román-Más



2.4.1.A Location and Major Geographic Features

Prominent geographic features of the 150 mi^2 Naguabo-Maunabo region are the Sierra de Luquillo and Sierra de Cayey mountain ranges, that form the inland backbone of the province, and three coastal alluvial valley systems in the vicinity of Humacao-Naguabo, Yabucoa, and Maunabo. Within a few miles, steep mountain slopes give way to a series of broad, relatively flat alluvial valleys separated from one another by steep, narrow bedrock ridges. Swamps and lagoons are prominent coastal features in the alluvial valleys, which comprise about one-third of the Naguabo-Maunabo region and contain the principal aquifers, major cities, industrial development, and most of the population and agriculture.

The Humacao-Naguabo basin covers approximately 91 mi^2, of which the alluvial valleys occupy 36 mi^2. There are six distinct drainage basins within these alluvial valleys ranging in elevation from 300 to 500 feet above mean sea level. The Río Humacao and Río Blanco are the major drainage basins, and the Río Candelero, Río Antón Ruiz, Río Santiago, and Quebrada Fronteras are the minor drainage basins. The interconnected alluvium-filled valleys of these six basins range in elevation from mean sea level to 160 feet above mean sea level. A forested wetland and several brackish water lagoons are located near the mouth of the Río Antón Ruiz. Non-forested wetlands are present in coastal depressions (fig. 2.4.1.A-1).

The Yabucoa alluvial valley occupies 7 mi^2 of the 45 mi^2 occupied by the Yabucoa basin. The area is surrounded by hills ranging from 100 to 2,000 feet above mean sea level, except to the east where it is bounded by the Caribbean Sea. There are numerous streams in the area, including the Río Guayanés (the principal stream in the region), Río del Ingenio, and Caño de Santiago (fig. 2.4.1.A-1).

The Maunabo basin covers about 10 mi^2, of which 3.5 mi^2 is the alluvial valley. The area is surrounded by hills ranging from 200 to 1,600 feet above mean sea level, except to the east where it is bounded by the Caribbean Sea. The area is drained by the Río Maunabo, which has its headwaters at Cerro La Torrecilla. Tributaries of the Río Maunabo head in the foothills to the north and south of the alluvial valley.

Base from U.S. Geological Survey
Puerto Rico e Islas Limítrofes, 1:240,000, 1952

Figure 2.4.1.A-1 Location and major geographic features in the Naguabo-Maunabo region, Puerto Rico.

2.4.1.B Population and Estimated Ground-Water Use

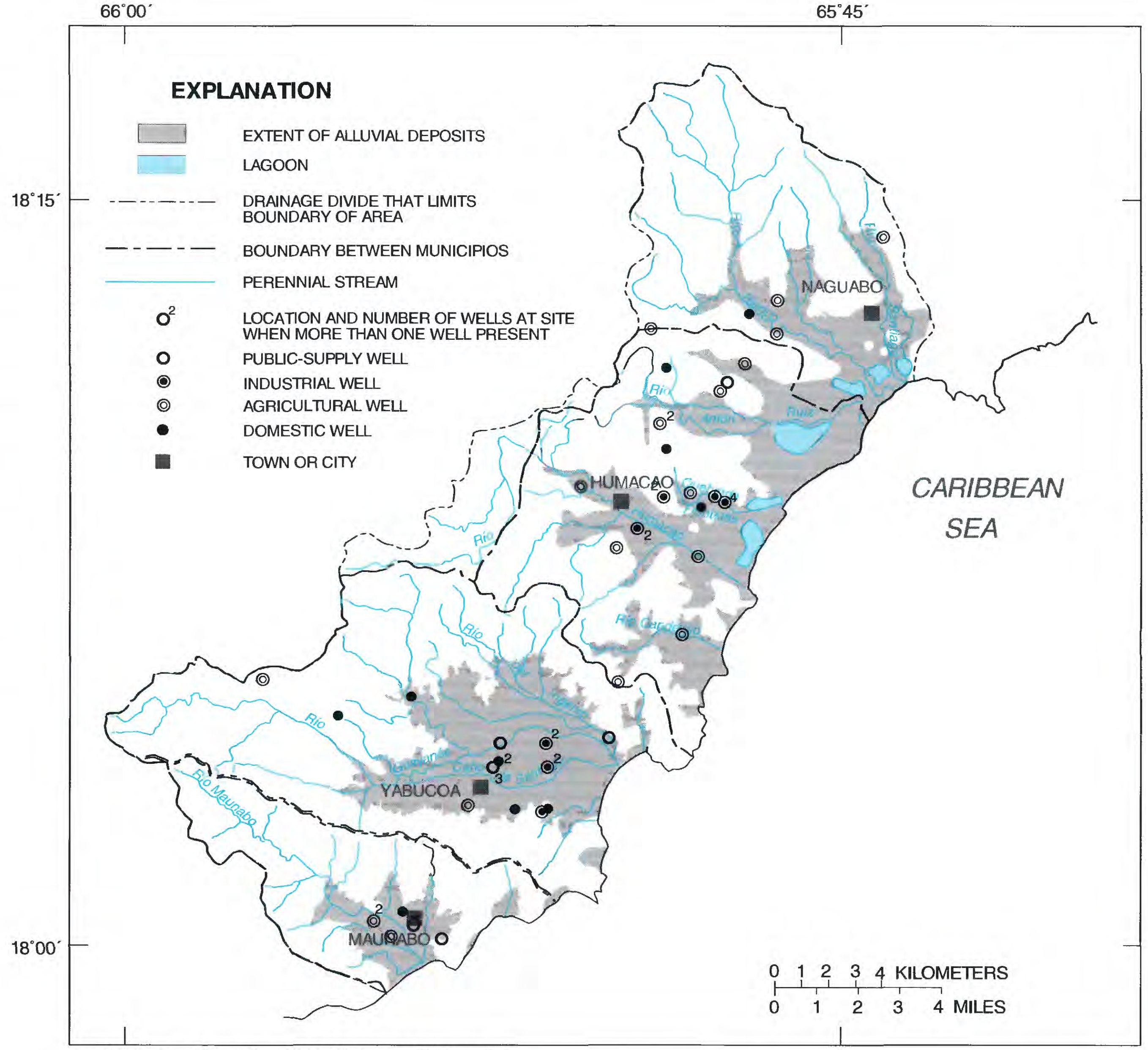
The total population of the Naguabo-Maunabo region increased from about 110,000 in 1980 to about 127,000 in 1990 (table 2.4.1.B-1), an increase of 15 percent. Ground water supplies about 34 percent of the population water-supply needs. Domestic water use was about 56 gallons per person per day. In 1983, approximately 3.8 Mgal/d of ground water was pumped in the region; nearly all from the alluvial aquifers (fig. 2.4.1.B-1 and table 2.4.1.B-2). A minor amount of water for domestic use was obtained from plutonic and volcanic rock aquifers in the mountains. About 55 percent of ground-water withdrawals were for domestic use, 32 percent for industrial use, and 13 percent for agricultural use.

The Humacao-Naguabo basin accounts for 61 percent of the total population within the region. About 35 percent of the population live in urban areas; the remaining 65 percent live in rural areas (table 2.4.1.B-1; U.S. Department of Commerce, 1982, p. 53-4 and 53-6). The population in the Humacao-Naguabo basin increased from about 67,000 in 1980 to about 78,000 in 1990 (U.S. Department of Commerce, 1991), an increase of about 16 percent (table 2.4.1.B-1). In 1983, ground-water withdrawals were approximately 0.90 Mgal/d, of which 0.14 Mgal/d were for domestic use (table 2.4.1.B-2). The aquifers provided water to only 3.9 percent of the population. Industrial use was about 0.62 Mgal/d and was limited to a group of pharmaceutical and light industries located in the vicinity of Humacao. Agricultural uses (livestock and sugarcane) were about 0.14 Mgal/d.

The population by 1980 within the Yabucoa and Maunabo basins was 31,425 and 11,813, respectively (table 2.4.1.B-1). The populations of Yabucoa and Maunabo increased by 16 and 4.5 percent respectively by 1990. Most of the population in Yabucoa (78 percent) and Maunabo (75 percent) live in rural areas. Ground-water withdrawals in the Yabucoa basin were about 2.3 Mgal/d in 1983. Ground water provides about 78 percent of the water demand for domestic use in this area. About 1.4 Mgal/d of the total was withdrawn by the Puerto Rico Aqueduct and Sewer Authority for domestic use (table 2.4.1.B-2). The pharmaceutical, oil refinery, and light industries located in the Yabucoa basin withdraw about 0.6 Mgal/d. In addition, about 0.4 Mgal/d were pumped for agricultural use, mainly sugarcane irrigation. In the Maunabo basin, ground-water withdrawals were 0.61 Mgal/d by 1983 (table 2.4.1.B-2). The Puerto Rico Aqueduct and Sewer Authority accounted for all ground-water withdrawals in the Maunabo basin.

Table 2.4.1.B-1 Population for the Naguabo-Maunabo region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Humacao	46,134	19,147	26,987	55,203
Maunabo	11,813	2,987	8,826	12,347
Naguabo	20,617	4,135	16,482	22,620
Yabucoa	31,425	6,797	16,482	36,483
Total	109,989	33,066	76,923	126,653



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.4.1.B-1 Approximate well locations in the Naguabo-Maunabo region, Puerto Rico.

Table 2.4.1.B-2 Ground-water withdrawals and estimated population served during 1983 for the Naguabo-Maunabo region, Puerto Rico
[Mgal/d, million gallons per day; ---, no data available]

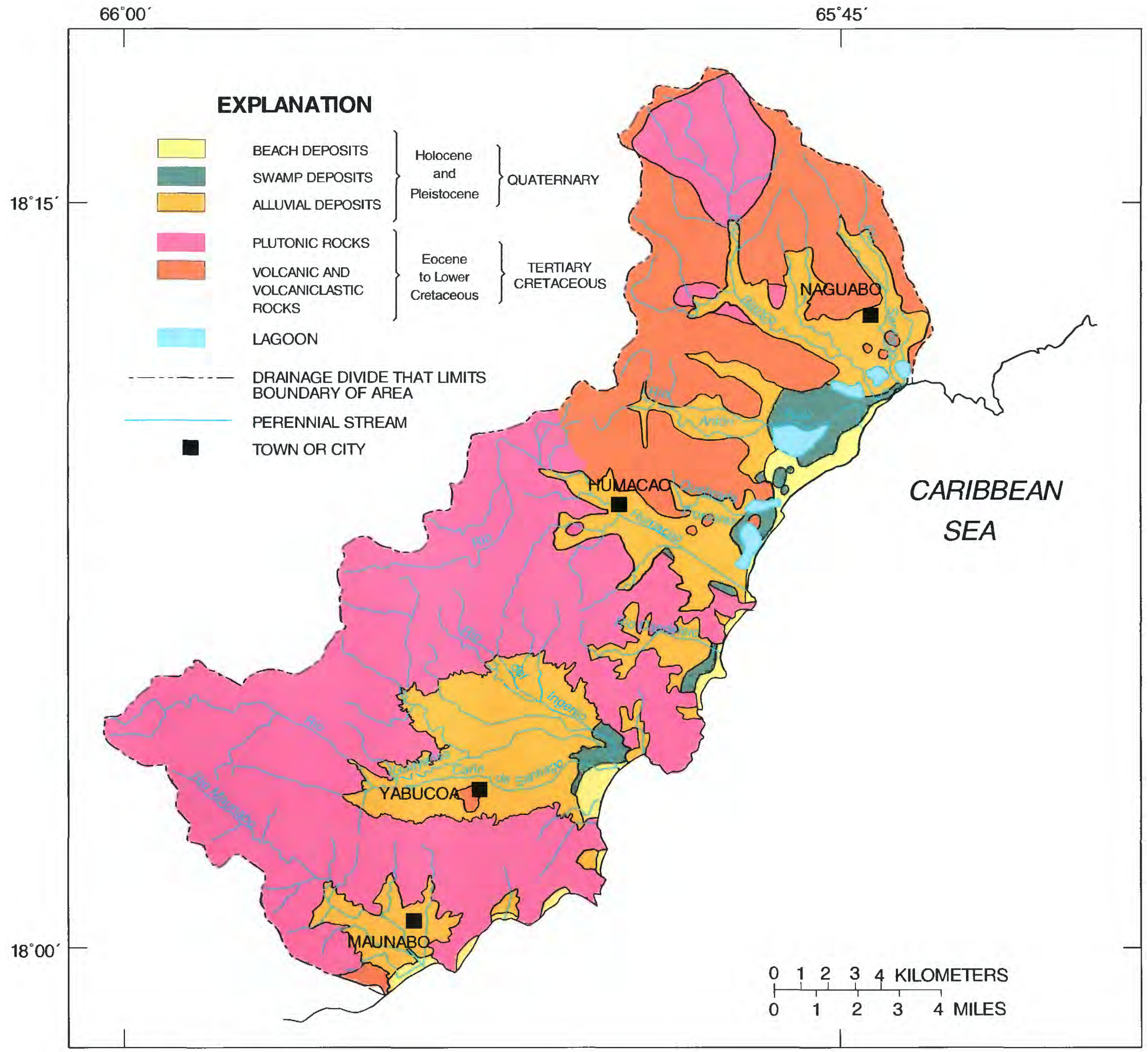
[1] Use and supplier		Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use			
[2] A. Puerto Rico Aqueduct and Sewer Authority			
1. Maunabo		10,872	0.610
2. Yabucoa		24,129	1.370
3. Humacao		1,918	0.100
	Subtotal	36,919	2.080
[3] B. Community Systems			
1. Naguabo		120	0.010
	Subtotal	120	0.010
[3] C. Private Supplies			
1. Humacao		[4] 572	0.036
	Subtotal	572	0.036
[3] II. Industrial Use			
1. Yabucoa		---	0.600
2. Humacao		---	0.619
	Subtotal	---	1.219
[3] III. Agricultural Use			
1. Yabucoa		---	0.360
2. Humacao		---	0.115
3. Naguabo		---	0.020
	Subtotal	---	0.495
	Total	37,611	3.840

[1] Municipios not listed under some specific use do not withdraw ground water for the subject use.
[2] Modified from Gómez-Gómez and others, 1984.
[3] Modified from a written communication of the Puerto Rico Department of Health.
[4] Based on a water consumption of 52 gallons per person per day.

2.4.1.C Geologic Setting

The geology of the Naguabo-Maunabo region is described in terms of two basic lithologic types: the Eocene to lower Cretaceous plutonic and volcanic bedrock outcropping in the mountains and underlying the alluvial deposits in the valleys; and the Holocene and Pleistocene age alluvial deposits filling the valleys (fig. 2.4.1.C-1). Small areas of swamp and beach deposits are associated with coastal alluvial deposits.

The plutonic rocks are mostly granodiorite and quartz diorite of the San Lorenzo Batholith, frequently veined with calcite. The volcanic bedrock is a mixture of medium- to thick-bedded volcaniclastic tuff, breccia, sandstone, and conglomerate, as well as andesitic lava flows. Much of the volcanic rock was deposited in the sea and, during quiescent conditions, was interbedded with limestone (McGonigle, 1978 and 1979; Rogers and others, 1979).



Modified from Briggs and Akers, 1965

Figure 2.4.1.C-1 Generalized surficial geology in the Naguabo-Maunabo region, Puerto Rico.

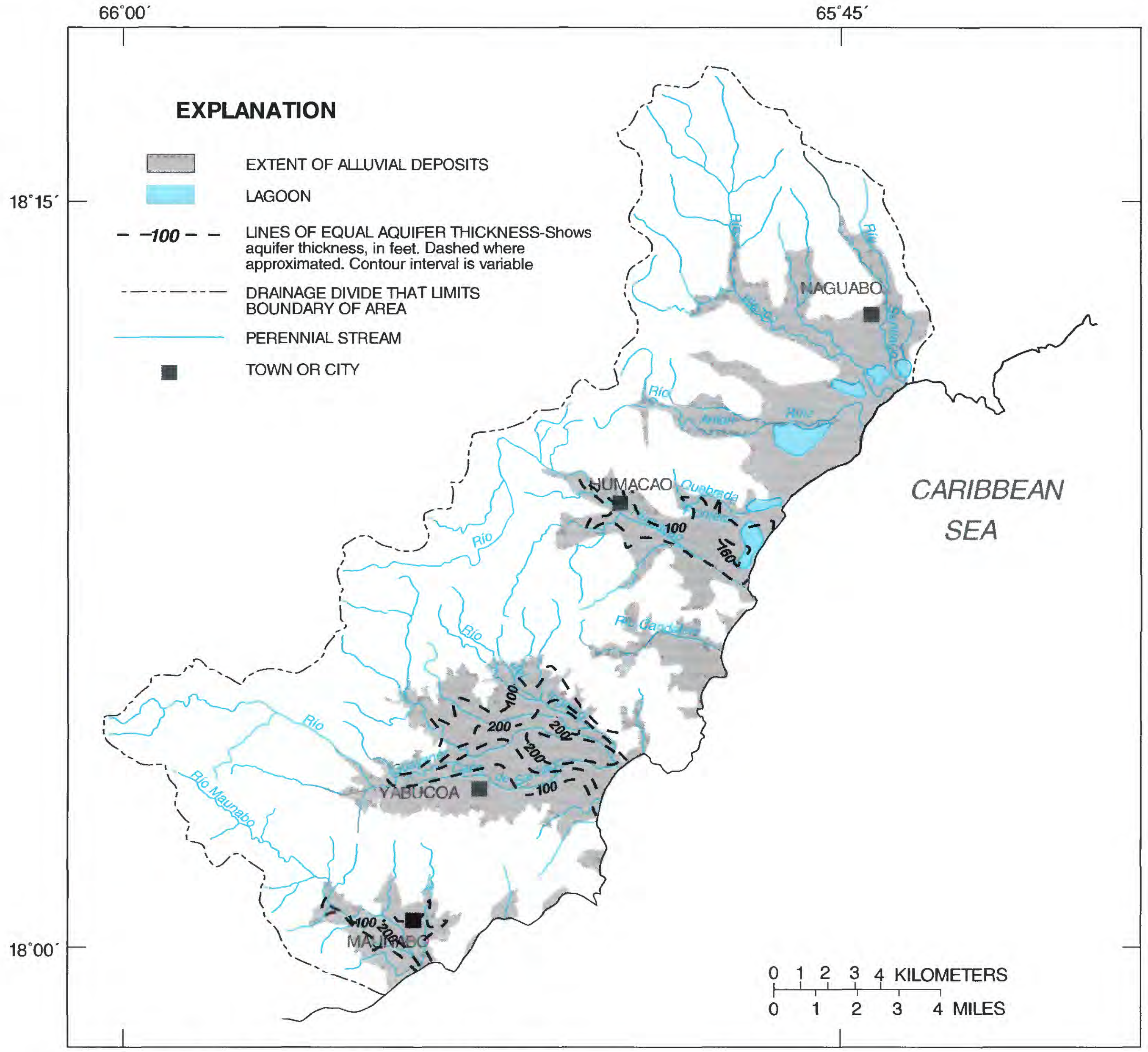
The alluvial deposits are composed of poorly sorted clay, silt, and sand. In the Humacao-Naguabo basin, the alluvial deposits range in thickness from near zero at the bedrock-alluvium contact to more than 160 feet near the coast (Graves, 1989, p. 15). The maximum thickness of the alluvium in the Yabucoa basin is unknown, but probably exceeds 180 feet (Anders, 1971, p. 15). Clean sand beds, as thick as 50 feet, were reported in this area by Anders (1971, p. 15). In the Maunabo basin, the alluvial deposits are estimated to be as much as 200 feet thick (Adolphson and others, 1977, p. 5).

2.4.1.D Hydrogeology

The principal aquifers in the Naguabo-Maunabo region are in the alluvial deposits that fill the valleys. These aquifers are under water-table conditions, but are influenced by the delayed yield of water from clay beds present within them and by anisotropy characterized by a horizontal component of hydraulic conductivity that is several times larger than the vertical component. These aquifers may range in thickness from near zero at the bedrock-alluvium contact to 200 feet near the coast and toward the central part of the valleys (fig. 2.4.1.D-1). The aquifers in the fractured volcanic and plutonic rocks are discussed only briefly in this report because of their very low yields, although locally they may represent an important water source.

Based on data from Anders (1971), Adolphson and others (1977), and Graves (1989), the hydraulic conductivity of the bedrock and the alluvial-bedrock contact area is estimated at about 5 ft/d throughout the region. Average hydraulic conductivity for the alluvial deposits is estimated at about 10 ft/d (fig. 2.4.1.D-2). Observed differences in the hydraulic conductivity for the alluvium result from aerial and vertical variability in sediment particle size. In addition, hydraulic conductivity values along the major rivers are usually high. Within the Humacao-Naguabo basin a minor increase in hydraulic conductivity to 20 ft/d is observed along the Río Humacao, Río Blanco, Río Santiago, and the lower part of the Río Antón Ruiz. In the Yabucoa basin, hydraulic conductivity is also about 20 ft/d along the major streams (Río Guayanés and Río del Ingenio). Along the Maunabo basin, hydraulic conductivity averages 100 ft/day (Adolphson and others, 1977). Along the major tributaries to the Río Maunabo and other streams in the Maunabo basin, hydraulic conductivity ranges from 50 to 75 ft/d (fig. 2.4.1.D-2).

Apparent transmissivity values within the Humacao-Naguabo basin range from about 600 to 2,000 ft^2/d (Graves, 1989). In the Yabucoa basin, apparent transmissivity can be as high as 7,000 ft^2/d. Transmissivity values as high as 20,000 ft^2/d were calculated for areas adjacent to the Río Maunabo, due to large values of hydraulic conductivity.



Modified from Graves, 1989; Robison and Anders, 1973; Adolphson and others, 1977

Figure 2.4.1.D-1 Aquifer thickness in the Naguabo-Maunabo region, Puerto Rico.

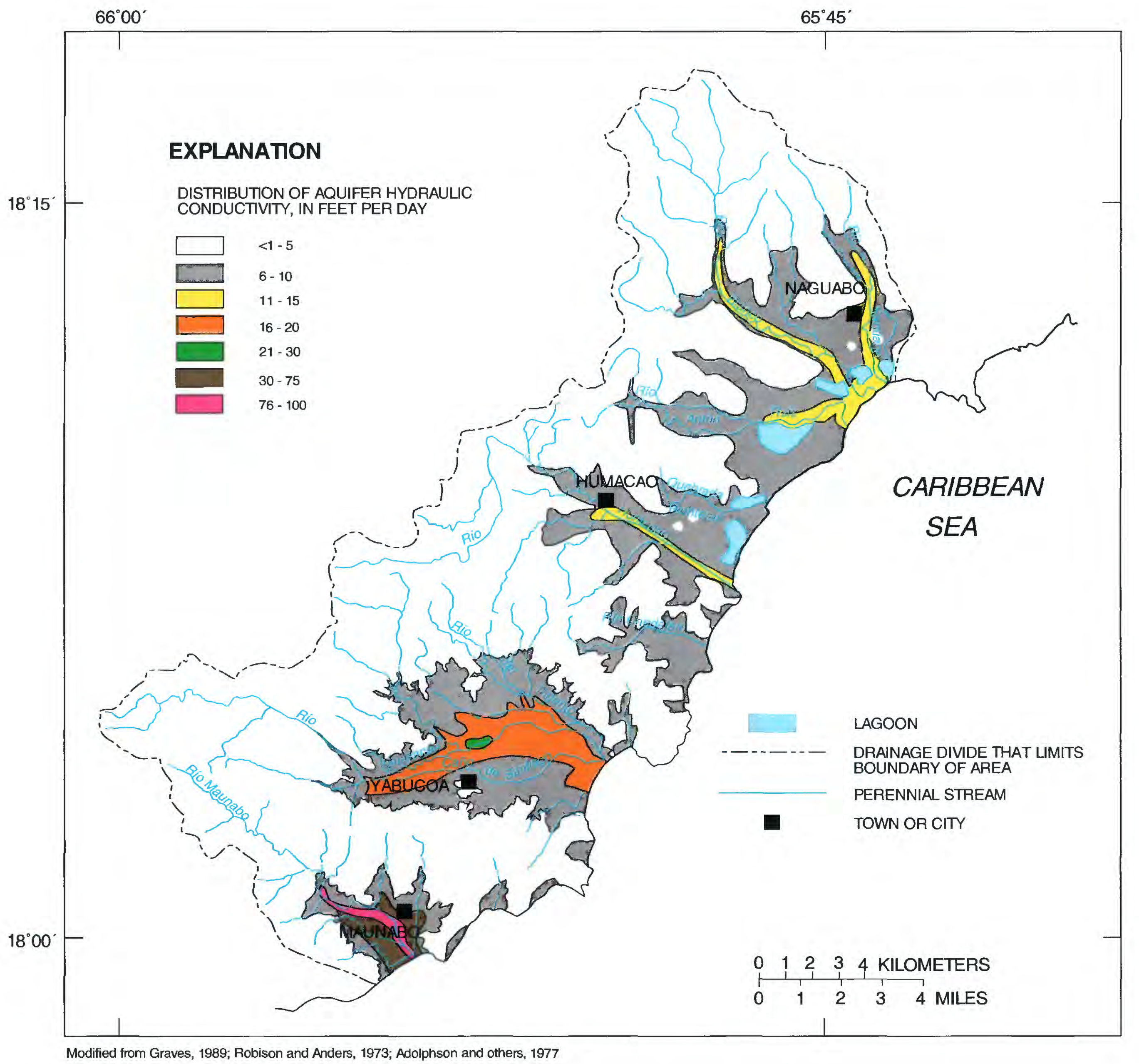


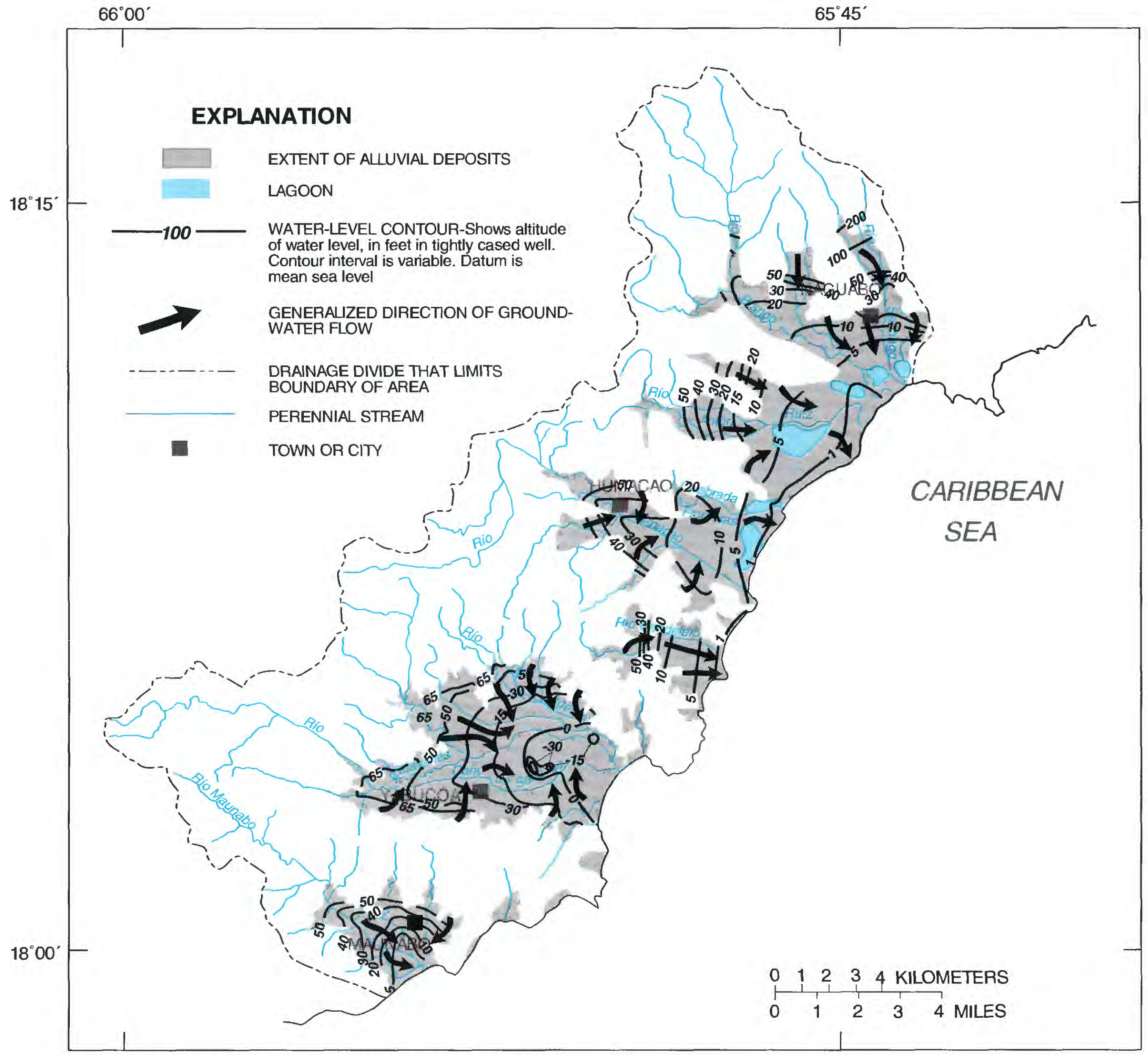
Figure 2.4.1.D-2 Regional distribution of hydraulic conductivity in the Naguabo-Maunabo region, Puerto Rico.

2.4.1.E Ground-Water Levels and Movement

Ground-water levels in the plutonic and volcanic rocks in the mountains and uplands follow the topography. The water-table surface lies within 50 to 100 feet below land surface in the ridges and at or near land surface in the valleys. Ground-water discharge from the plutonic and volcanic rocks maintains stream base flow in the mountain and upland areas. The contribution to ground water from the volcanic and plutonic rocks to the alluvial aquifers is relatively small compared to the total quantity of ground water in the valleys.

Water levels within the alluvial aquifers of the Naguabo-Maunabo region vary from 100 feet above mean sea level near the bedrock-alluvium contact to near mean sea level in coastal areas (fig. 2.4.1.E-1). Although the water table fluctuates seasonally due to rainfall, pumpage has caused major overall declines in the Yabucoa and Maunabo basins. The water table is generally at its lowest elevation during the dry months of March and April and at its highest elevation in September.

Ground water in the alluvial aquifers flows east in the Humacao-Naguabo and Yabucoa basins, and southeast in the Maunabo basin, towards the coast. Ground water may flow toward or away from streams, depending on the hydraulic gradient between the stream and the adjacent aquifer. Within the Humacao-Naguabo basin, a considerable amount of ground water discharges to the rivers in the upper reaches of the alluvial valleys; whereas in the lower reaches, the alluvial aquifer is recharged by streamflow losses (Graves, 1989, p. 20). In the lower-most reaches, swampy areas and lagoons serve as aquifer discharge zones (Graves, 1989, p. 48). In contrast, rivers in the Yabucoa and Maunabo alluvial valleys drain the alluvial aquifer. According to the water budget presented by Anders (1971, p. 38) and Adolphson and others (1977, p. 17), discharge from the alluvial aquifers into the streams represents 27 and 50 percent of the annual river flow in Yabucoa and Maunabo basins, respectively.



Modified from Graves, 1989; Collar and others, 1990; Adolphson and others, 1977

Figure 2.4.1.E-1 Altitude of water-table surface and direction of ground-water flow in the Naguabo-Maunabo region, Puerto Rico (data for the Naguabo to Humacao alluvial valleys are from March 1984, for the Yabucoa valley from April 1990, and for the Maunabo valley from June 1974).

2.4.1.F Soil Permeability

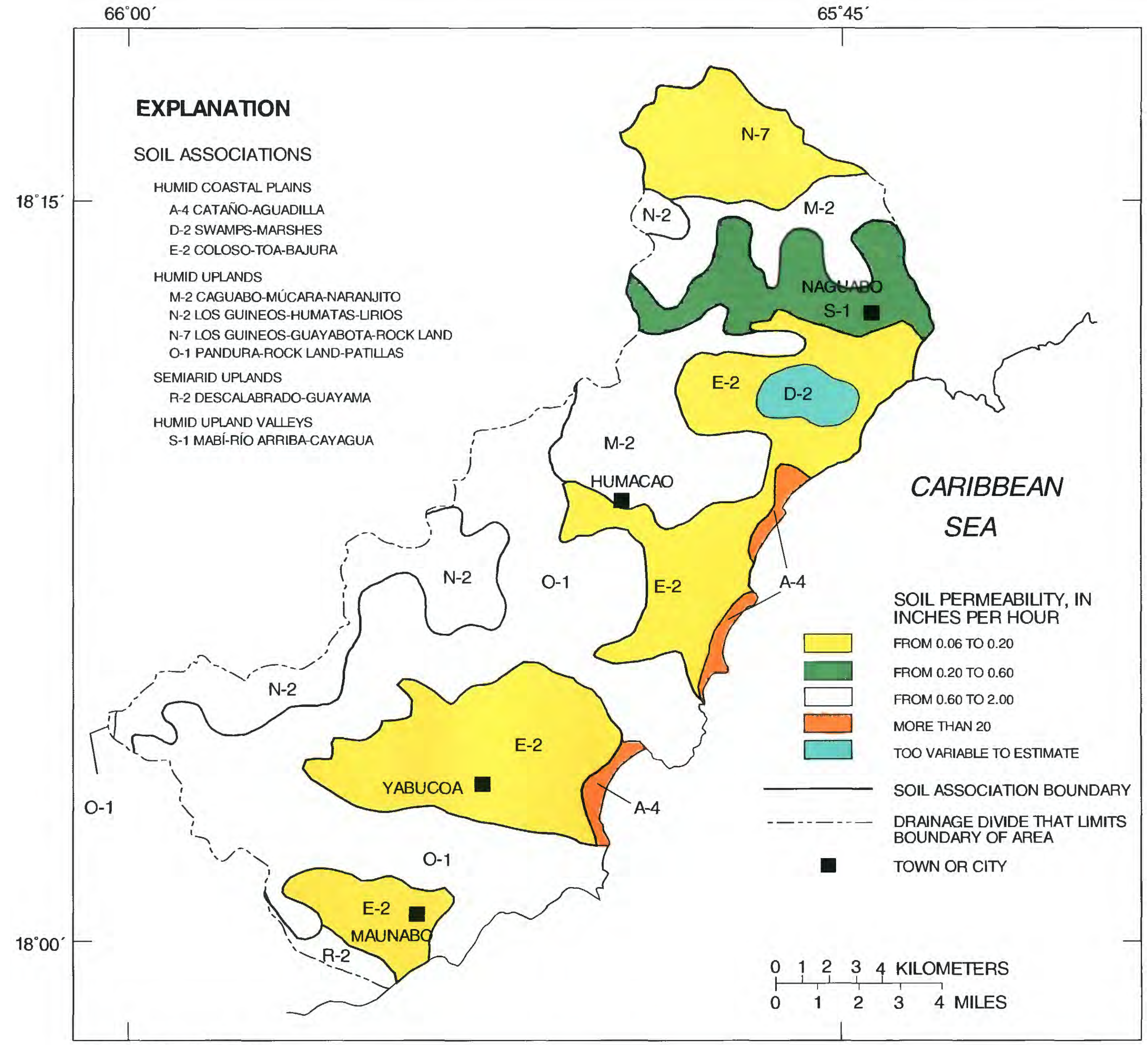
Soils in the mountain and upland areas associated with plutonic rocks, the Pandura-Rock Land-Patillas and the Los Guineos-Humatas-Lirios soil associations, some of the soils associated with volcanic rocks, such as the Caguabo-Múcara-Naranjito, have permeabilities of 0.6 to 2.0 in/hr. Other soils in the mountain and upland areas (Los Guineos-Guayabota-Rock Land soil association) have permeabilities (0.06 to 0.2 in/hr) similar to the soils in the valleys (fig. 2.4.1.F-1 and table 2.4.1.F-1).

Soils in the alluvial valleys are generally less permeable than those in the mountains and upland areas. Soils of high permeability occur along the edges of the alluvial valleys in the San Lorenzo Batholith. Finer grained and less permeable soils predominate in the centers of the valleys and throughout the valleys where surrounded by volcanic rocks.

North of the Río Humacao, in the Humacao and Naguabo basin, the Caguabo-Múcara-Naranjito soil association overlies the alluvial aquifer. Permeability for these clayey soils ranges from 0.60 to 2.0 in/hr. South of the Río Humacao and in the northern part of the Yabucoa basin, the Pandura-Rock Land-Patillas soil association overlies the aquifer. Permeability of soils in this association ranges from 0.6 to 2.00 in/hr. The Cataño-Aguadilla soil association overlies the alluvial aquifer near the coast in the Humacao-Naguabo and Yabucoa basins. Permeability of these sandy soils, ranges from 6 to more than 20 in/hr. A Swamp-Marshes soil association has developed at the mouth of the Río Antón Ruiz. Permeability of this soil association is too variable to be estimated. Within the Humacao-Naguabo basin, the Coloso-Toa-Bajura association overlies most of the valley area. However, south of the Río Maunabo, the Descalabrado-Guayama association overlies the valley. Permeability for this soil association ranges from 0.6 to 2.0 in/hr.

Table 2.4.1.F-1 Thickness, permeability, and available water capacity for the soil associations in the Naguabo-Maunabo region, Puerto Rico (Modified from Boccheciamp, 1977; Gilberto Acevedo, Soil Conservation Service, written communication, 1990)
[<, less than]

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Humid Coastal Plains			
Cataño-Aguadilla	0 to 72	< 20.00	< 0.03
Swamps-Marshes		Too variable to be estimated	
Coloso-Toa-Bajura	0 to 72	0.06 to 0.20	0.10 to 0.20
Humid Uplands			
Caguabo-Múcara-Naranjito	0 to 72	0.60 to 2.00	0.10 to 0.18
Los Guineos-Humatas-Lirios	0 to 72	0.60 to 2.00	0.08 to 0.20
Los Guineos-Guayabota-Rock Land	0 to 60	0.06 to 0.20	0.15 to 0.20
Pandura-Rock Land-Patillas	0 to 72	0.60 to 2.00	0.05 to 0.14
Semiarid Uplands			
Descalabrado-Guayama	0 to 26	0.60 to 2.00	0.10 to 0.15
Humid Upland Valleys			
Mabí-Río Arriba-Cayagua	0 to 60	0.20 to 0.60	0.15 to 0.20



Modified from Boccheciamp, 1977

Figure 2.4.1.F-1 Soil associations and permeability in the Naguabo-Maunabo region, Puerto Rico.

2.5 East Central Area

2.5.1 AGUAS BUENAS-JUNCOS REGION

By Juan C. Puig

2.5.1.A Location and Major Geographic Features

The East Central area (the Aguas Buenas-Juncos region) coincides with the upper Río Grande de Loíza basin, an area of about 210 mi^2 (fig. 2.5.1.A-1) This drainage basin encloses the Caguas and the Gurabo-Juncos valleys, which contain the only significant aquifer in the area. These valleys, which have a surface area of approximately 35 mi^2, is surrounded by high mountains reaching elevations of as much as 1,074 feet above mean sea level in the northeast and 903 feet above mean sea level in the southeast.

The two major valleys in the Aguas Buenas-Juncos region are: (1) the nearly circular-shaped Caguas valley to the west, covering an area of about 16.6 mi^2; and (2) the elongate Gurabo-Juncos valley to the east, covering an area of about 18.5 mi^2 (fig. 2.5.1.A-1). These valleys are connected along a 3,500 feet reach of the Río Grande de Loíza just upstream of Lago Loíza. The Caguas valley has an average diameter of about 4 miles. The Caguas valley floor is steep and irregular and has a maximum elevation of about 490 feet above mean sea level south of Caguas and a minimum elevation of about 145 feet above mean sea level near Lago Loíza. In contrast, the Gurabo-Juncos valley floor is a flat, narrow plain about 12 miles long and from 0.5 to 1.5 miles wide. The Gurabo-Juncos valley has a maximum elevation of about 360 feet above mean sea level at the eastern boundary and a minimum elevation of about 145 feet above mean sea level near Lago Loíza.

The principal streams in the Caguas valley are the Río Grande de Loíza, flowing from south to north along the central parts; the Río Turabo, flowing from west to east in the southwest part of the valley; the Río Cagüitas, flowing from west to east in the northern part of the valley; and the Río Bairoa, flowing from west to east along the northwest part of the valley. Two main streams flow through the Gurabo-Juncos valley: the Río Gurabo flows from east to west along the center of the valley, and the lower reach of the Río Valenciano which flows from south to north near Juncos. All streams and creeks eventually discharge into Lago Loíza, which is located in the lowest point in the basin at the northern boundary.

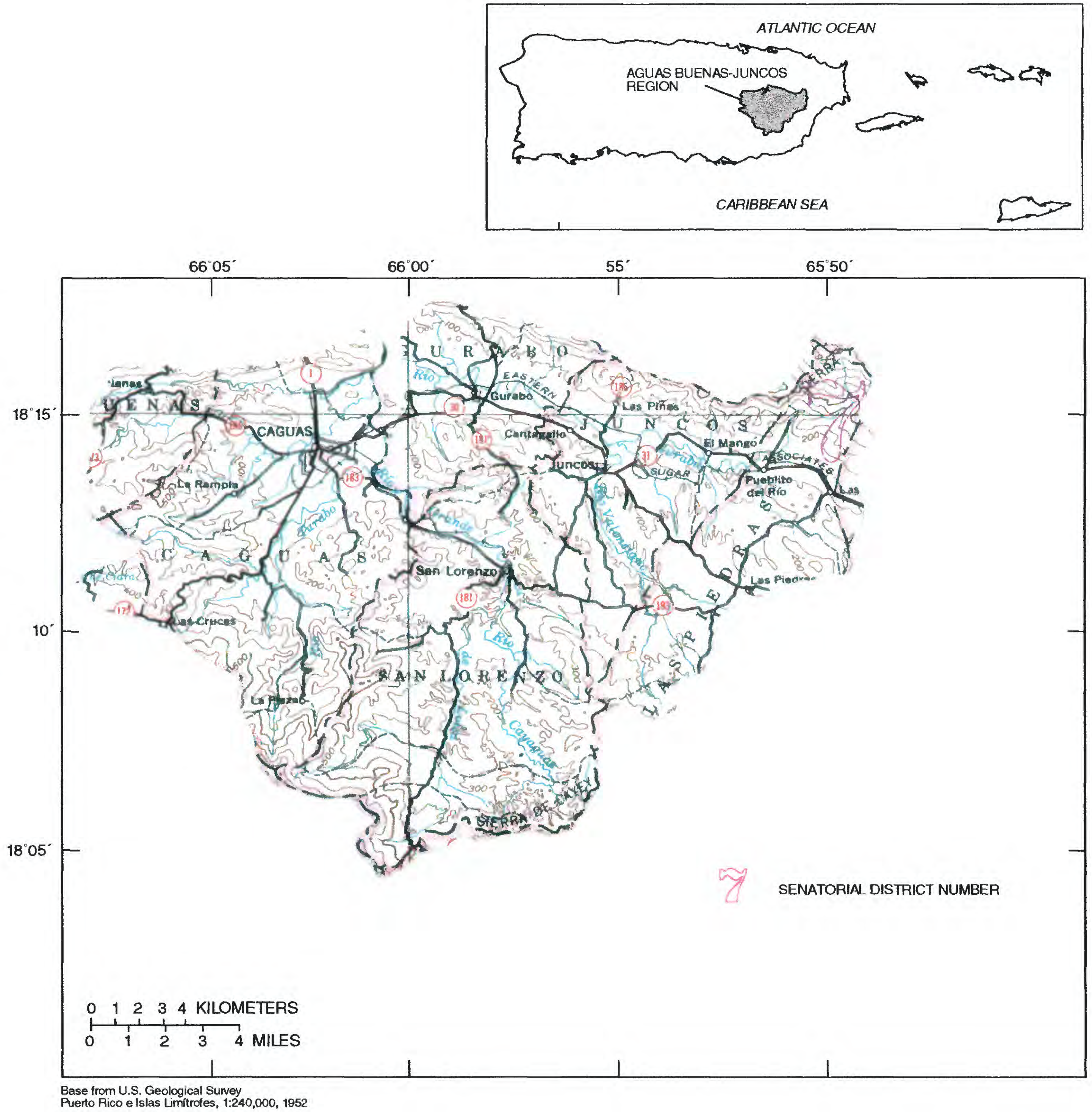


Figure 2.5.1.A-1 Location and major geographic features in the Aguas Buenas-Juncos region, Puerto Rico.

2.5.1.B Population and Estimated Ground-Water Use

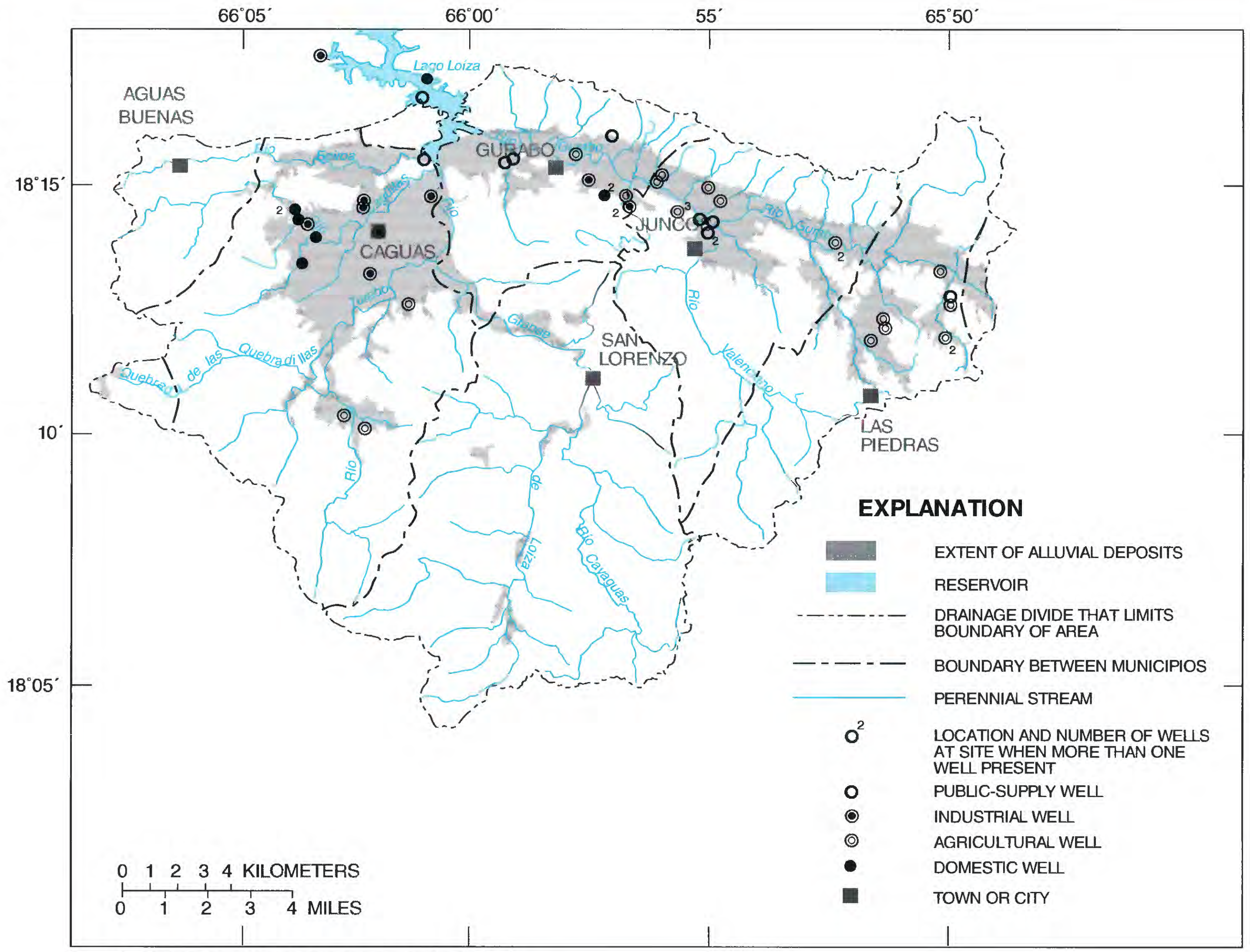
Population of the Aguas Buenas-Juncos region is concentrated principally in the municipios of Aguas Buenas, Caguas, Gurabo, Juncos, Las Piedras, and San Lorenzo. The population totaled about 244,000 in 1980 (U.S. Department of Commerce, 1982). A 16 percent increase in population was recorded from 1980 to 1990 (U.S. Department of Commerce, 1991), when the population for the region totaled about 282,000 (table 2.5.1.B-1). The municipio of Caguas accounts for nearly 50 percent of the total population within the region. About 49 percent of the total population of the Aguas Buenas-Juncos region live in urban areas, the remaining 51 percent live in rural areas (table 2.5.1.B-1).

Most wells in the Caguas-Juncos valley are screened in the alluvial deposits (fig. 2.5.1.B-1). These deposits constitute the main aquifer in the region. Yields to wells in the Caguas-Juncos valley are variable, but pumping rates of up to 310 gal/min have been observed. Ground-water withdrawal for public supply has been reduced from 3.71 Mgal/d in 1986 to about 2.6 Mgal/d in 1988, because the Puerto Rico Aqueduct and Sewer Authority inactivated eight of their public-supply wells in this region (table 2.5.1.B-2). The estimated total ground-water withdrawal at 22 active wells on dairy farms averaged about 0.27 Mgal/d from 1986 to 1988. Withdrawal from eight industrial wells averaged about 0.13 Mgal/d. Withdrawals from domestic and commercial wells were low, averaging about 0.07 Mgal/d. The total ground-water withdrawal for all water uses was about 4 Mgal/d in 1986 and 1987, but decreased to 3 Mgal/d in 1988 (Puig and Rodríguez, 1992).

Public-water supply during 1986 in the Aguas Buenas-Juncos region was distributed as follow: local surface water, 10.6 Mgal/d; local ground water, 3.7 Mgal/d; and basin transfers, 4.5 Mgal/d from Guaynabo and 2.8 Mgal/d from Humacao; for a total of 21.6 Mgal/d. However, about 80 Mgal/d are transferred from the Lago Loíza to the San Juan metropolitan area for public-water supply.

Table 2.5.1.B-1 Population for the Aguas Buenas-Juncos region, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

	1980 population			1990 population
MUNICIPIO	TOTAL	URBAN	RURAL	TOTAL
Aguas Buenas	22,429	3,766	18,66	25,424
Caguas	117,959	87,214	30,745	133,447
Gurabo	23,574	7,645	15,929	28,737
Juncos	25,397	7,851	17,546	30,612
Las Piedras	22,412	4,857	17,555	27,896
San Lorenzo	32,428	8,880	23,548	35,163
Total	244,199	120,213	123,986	281,279



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.5.1.B-1 Approximate well locations in the Aguas Buenas-Juncos region, Puerto Rico.

Table 2.5.1.B-2 Ground-water withdrawals and estimated population served during 1986 for the Aguas Buenas-Juncos region, Puerto Rico
[Mgal/d, million gallons per day; ---, no data available]

Use[1]		Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Public Use			
1. Caguas		3,650	0.26
2. Juncos		15,360	2.34
3. Gurabo		17,320	0.83
4. Aguas Buenas		460	0.05
5. Las Piedras		1,630	0.23
	Subtotal	38,420	3.71
II. Domestic Use			
1. Caguas		---	0.04
2. Gurabo		---	0.03
	Subtotal	---	0.07
III. Industrial Use			
1. Caguas		---	0.08
2. Gurabo		---	0.05
	Subtotal	---	0.13
IV. Agricultural Use			
1. Caguas		---	0.08
2. Gurabo		---	0.04
3. Juncos		---	0.08
4. Las Piedras		---	0.07
	Subtotal	---	0.27
	Total	38,420	4.18

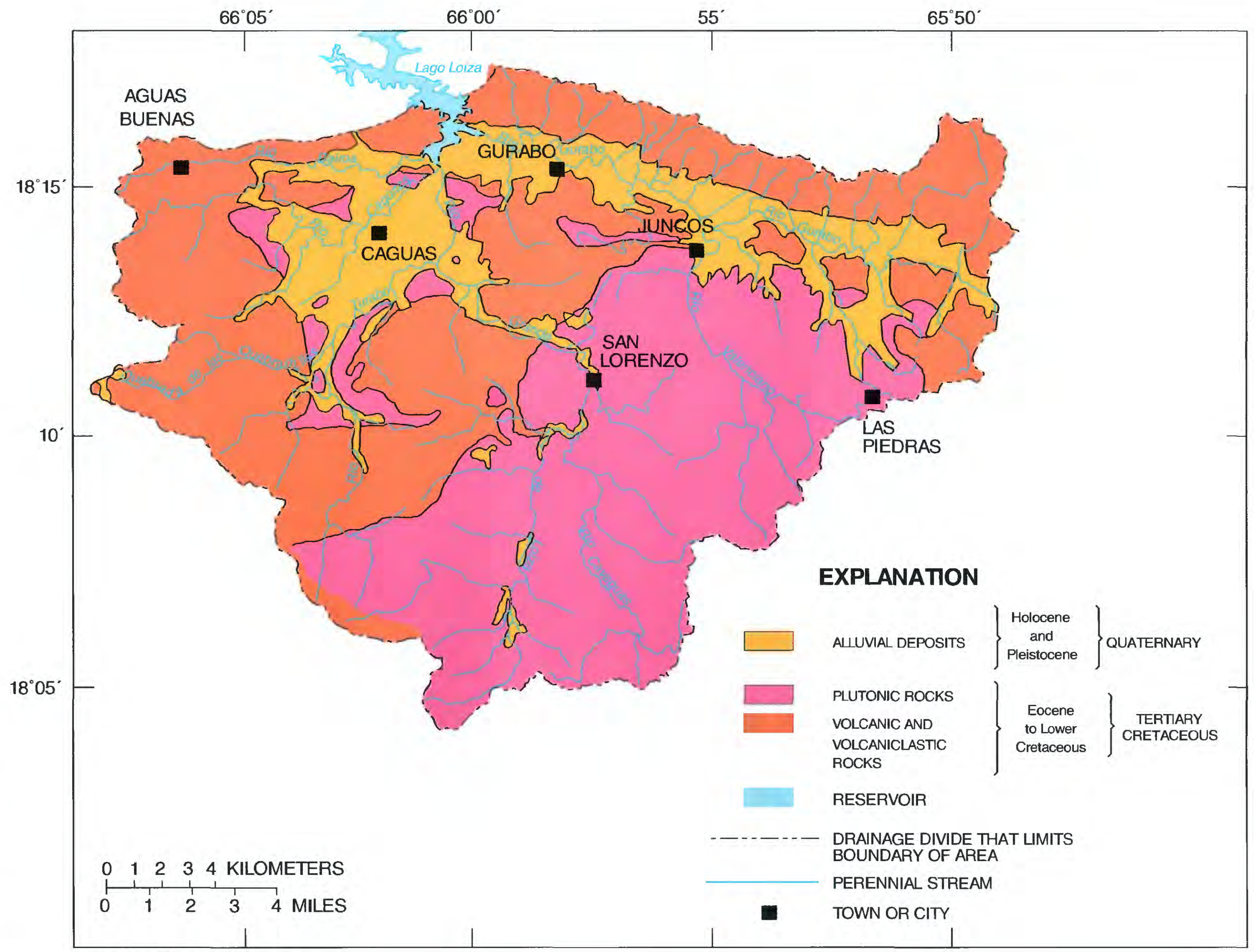
[1] Municipios not listed under some specific use do not withdraw ground water for the subject use or data is not available.

2.5.1.C Geologic Setting

The group of rocks constituting the basement and flanks of the Aguas Buenas-Juncos region is made up largely of volcaniclastics, lavas, intrusives, minor amounts of metamorphic rock of Late Cretaceous to early Tertiary age and locally minor amounts of limestone of early Tertiary age (Puig and Rodríguez, 1993). This rock complex is overlain by Holocene surface deposits, mainly of alluvial origin (fig. 2.5.1.C-1).

The volcanic rocks are the most abundant rocks in the study area. The Late Cretaceous and rocks of early Tertiary age are highly faulted, and locally folded. The volcaniclastic and other consolidated rock groups are of little hydrologic importance, because they do not have the necessary permeability to serve as water-bearing units. Water in fractures within the volcanic rocks is the source for water discharge in perennial and ephemeral low-flow springs.

The surface deposits are predominantly alluvial in origin and consist of varying lithologies, which reflect both the changing nature of the source material and the dynamics of the fluvial history of the rivers that drain the enclosing basin. The alluvial sediments are composed of poorly sorted clay, silt, and sand. In the vicinity of Caguas, the alluvial sediments range in thickness from near zero at the bedrock-alluvium contact, to more than 150 feet in the center of the valley, and are mostly composed of silt, clay, and fine-grained sand, with subordinate amounts of gravel and coarse-grained sand. Alluvial sediments in Gurabo and Juncos thin toward the western and eastern ends of the valley and toward the northern and southern edges of the valley, and have a maximum thickness of about 160 feet. The amount of gravel and coarse sand in the alluvium is greater in the Gurabo-Juncos valley than in the Caguas valley. The principal aquifer in the Aguas Buenas-Juncos region is in the alluvial deposits that fill these valleys.



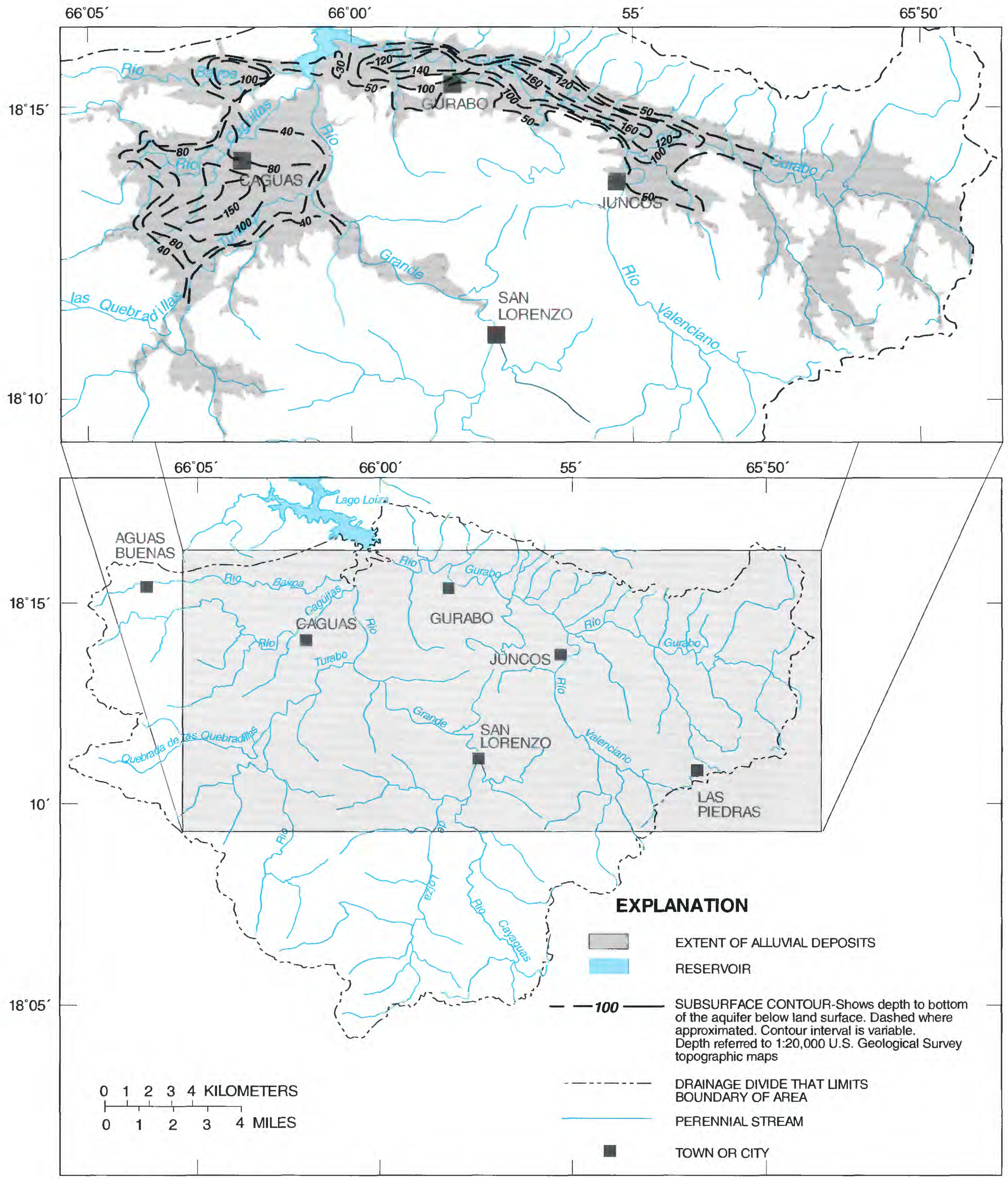
Modified from Briggs and Akers, 1965

Figure 2.5.1.C-1 Generalized surficial geology in the Aguas Buenas-Juncos region, Puerto Rico.

2.5.1.D Hydrogeology

The Caguas and the Gurabo-Juncos alluvial valleys aquifer of the Aguas Buenas-Juncos region is under water-table conditions, but is influenced by the delayed yield of water from clay beds and by anisotropy characterized by a horizontal component of hydraulic conductivity that is several times higher than the vertical component. This aquifer may range in thickness from near zero at the bedrock-alluvium contact to about 130 feet toward the central part of the Caguas valley and to about 140 feet along the Río Gurabo flood plain (fig. 2.5.1.D-1). The aquifers in the fractured volcanic and plutonic rocks have very low yields, although locally they may represent a viable water source.

The transmissivity of the alluvial aquifer can range from less than 66 ft^2/d to a maximum of 4,770 ft^2/d (Puig and Rodríguez, 1993; fig. 2.5.1.D-2). Along the main stream channels, transmissivity values are usually higher. The area along the Río Bairoa appears to have the highest transmissivities in the Caguas valley. Within the Gurabo-Juncos valley, higher transmissivity values occur along the Río Gurabo.



Modified from Puig and Rodríguez, 1992

Figure 2.5.1.D-1 Depth to bedrock in the Aguas Buenas-Juncos region, Puerto Rico.

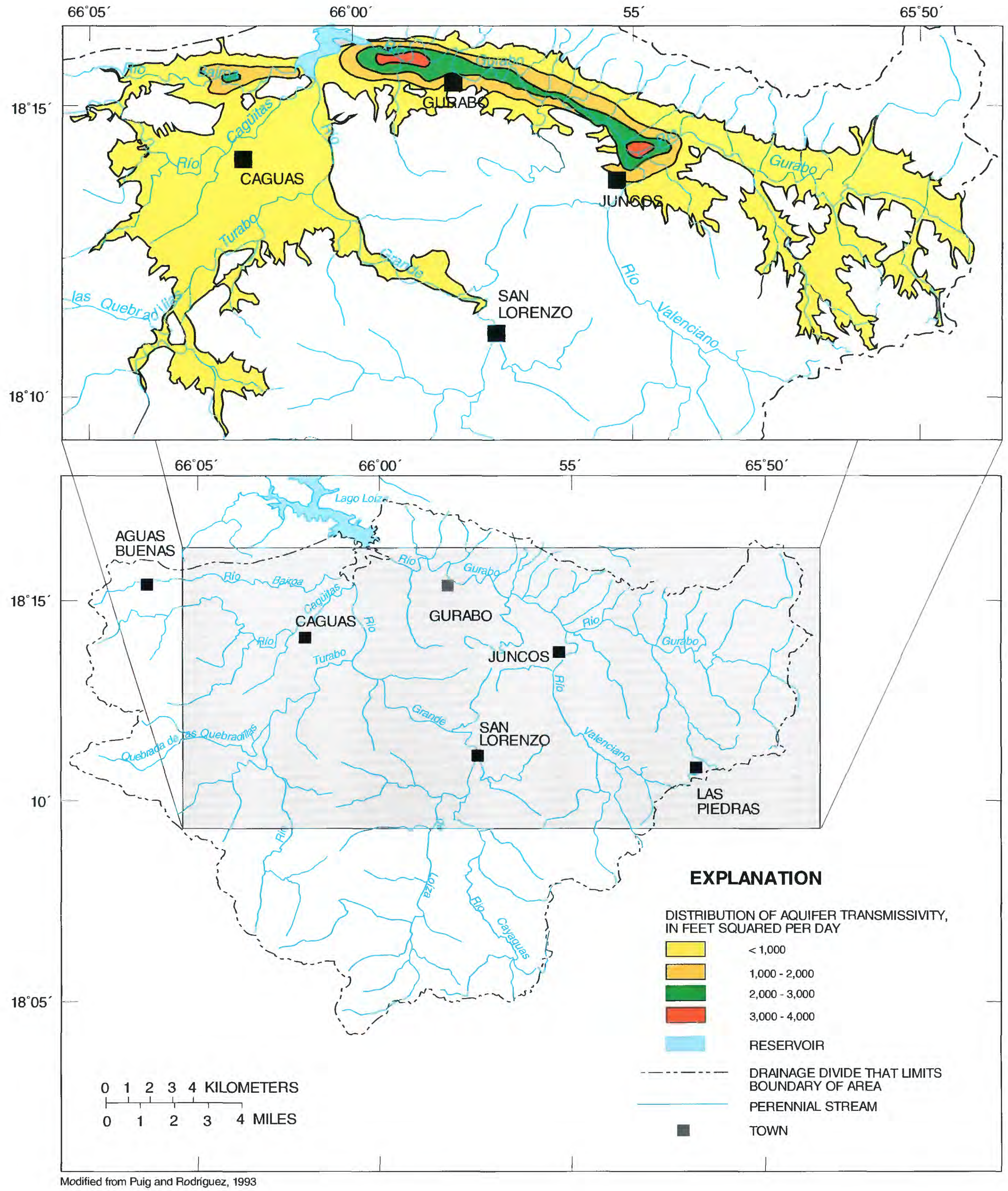


Figure 2.5.1.D-2 Regionalized apparent transmissivity values in the Aguas Buenas-Juncos region, Puerto Rico.

2.5.1.E Ground-Water Levels and Movement

Regional ground-water movement in the Caguas valley differs from that of the Gurabo-Juncos valley. In the Caguas valley, ground water moves from southwest to northeast in the southern part and from west to east in the northern part. In the Gurabo-Juncos valley, the regional ground-water movement is along flow paths from the northern and southern boundaries of the aquifer toward the Río Gurabo (fig. 2.5.1.E-1). Low ground-water levels for the year are usually in April and normally correspond to the end of a period of low rainfall. High ground-water levels are usually during November and December, at the end of the wet season.

In the Aguas Buenas-Juncos region, streams and aquifers are generally hydraulically well connected, and flow through valleys where the water-table may be lower than the stream stage, promoting recharge of the aquifer from the streams. Nevertheless, seepage studies in the Caguas-Juncos valley indicate that water flowing out of the streams to the aquifer eventually discharges back to the stream, causing a net stream gain (Puig and others, 1989; Puig and Rodríguez, 1990).

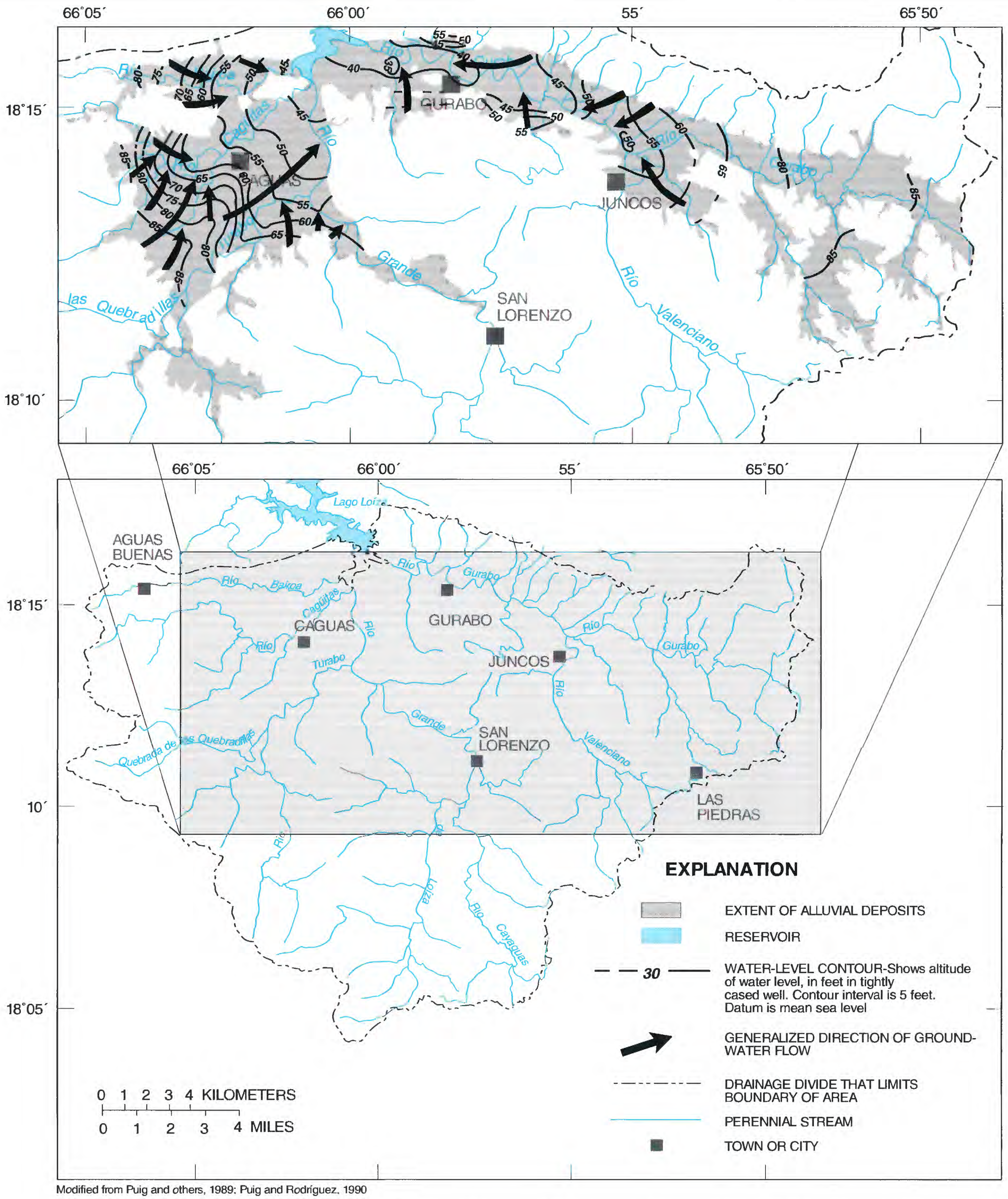


Figure 2.5.1.E-1 Altitude of water-level surface and direction of ground-water flow during March 1988 in the Aguas Buenas-Juncos region, Puerto Rico.

2.5.1.F Soil Permeability

Soils in the mountains and upland areas that are associated with volcanic and volcaniclastic rocks are moderately permeable ranging from 0.6 to 2.0 in/hr (fig. 2.5.1.F-1). These soil associations include the Caguabo-Múcara, Caguabo-Múcara-Naranjito, Los Guineos-Humatas-Lirios, and Humatas-Naranjito-Consumo. The soils associated with plutonic rocks, the Pandura-Rock Land-Patillas and the Pandura-Lirios, also have moderate permeabilities, ranging from 0.6 to 2.0 in/hr.

Soils in the alluvial valley are generally less permeable than those in upland areas and in the mountains. Within the valley, soils with high permeability are in the southern part of Caguas and along the southern edge of the Gurabo-Juncos valley. In most of the Caguas and Gurabo area, the Mabí-Río Arriba soil association overlies the alluvial aquifer (fig. 2.5.1.F-1). The permeability of these clayey soils ranges from 0.06 to 0.2 in/hr. Between Gurabo and Juncos, and along the upstream section of the Río Gurabo, the Coloso-Toa-Bajura soil association overlies most of the aquifer (fig. 2.5.1.F-1). The permeability of soils in this association also ranges from 0.06 to 0.2 in/hr (table 2.5.1.F-1). In the remaining part of the valley, along the southeast and northeast end, the Mabí-Río Arriba-Cayagua soil association dominates. The permeability of this soil association ranges from 0.2 to 0.6 in/hr (fig. 2.5.1.F-1). A wedge of the Caguabo-Múcara-Naranjito soil association along the eastern boundary of the valley has higher permeabilities that vary from 0.6 to 2.0 in/hr (fig. 2.5.1.F-1).

Table 2.5.1.F-1 Thickness, permeability, and available water capacity for the soil associations in the Aguas Buenas-Juncos region, Puerto Rico (Modified from Boccheciamp, 1977)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch/inch)
Humid Coastal Plains			
Coloso-Toa-Bajura	0 to 0.60	0.06 to 0.20	0.10 to 0.20
Humid Upland Valleys			
Mabí-Río Arriba-Cayagua	0 to 0.10	0.20 to 0.60	0.03 to 0.20
Mabí-Río Arriba	0 to 0.99	0.06 to 0.20	0.15 to 0.20
Humid Uplands			
Múcara-Caguabo	0 to 0.32	0.63 to 2.00	0.10 to 0.17
Caguabo-Múcara-Naranjito	0 to 0.38	0.60 to 2.00	0.08 to 0.20
Los Guineos-Humata-Lirios	0 to 0.60	0.60 to 2.00	0.08 to 0.20
Humatas-Naranjito-Consumo	0 to 0.60	0.60 to 2.00	0.10 to 0.20
Maricao-Los Guineos	0 to 0.60	0.60 to 2.00	0.10 to 0.20
Pandura-Rock Land-Patillas	0 to 0.48	0.60 to 2.00	0.05 to 0.14
Pandura-Lirios	0 to 0.50	0.60 to 2.00	0.05 to 0.15

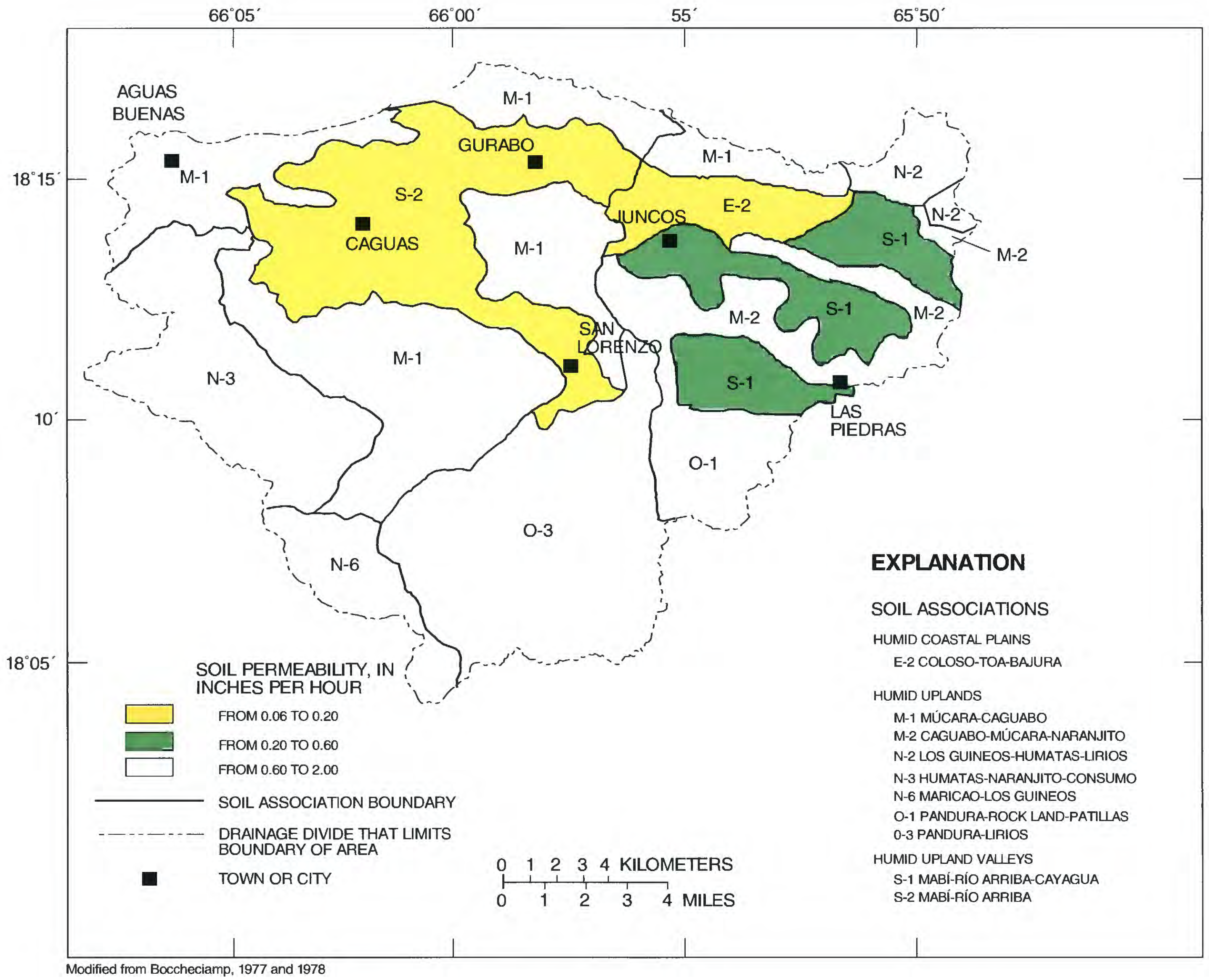


Figure 2.5.1.F-1 Soil associations and permeability in the Aguas Buenas-Juncos region, Puerto Rico.

2.6 Puerto Rico Offshore Islands

2.6.1 ISLA DE CULEBRA AND ISLA DE VIEQUES, PUERTO RICO

By Thalia D. Veve and Angel Román-Más

2.6.1.A Location and Major Geographic Features

The islands of Isla de Culebra and Isla de Vieques lie a few miles off the eastern coast of Puerto Rico (fig. 2.6.1.A-1). Isla de Culebra, the smaller of the two islands with an area of about 10 mi^2, is 7 miles long and 5 miles wide. The island of Isla de Vieques covers an area of about 20 mi^2 and is approximately 18 miles long and 3 miles wide. There are no perennial streams on either island.

Isla de Culebra contains an east-west trending ridge with an average elevation of about 300 feet above mean sea level in the northern part of the island. The highest peak along this ridge and on the island is the 640 feet high Monte Resaca. The land slopes steeply from the crest of the ridge northward to the coast. To the south, the slope is steep near the peaks becoming less steep below an elevation of 200 feet above mean sea level, where southward trending valleys separated by low ridges continue to the coast. The larger of these valleys contain alluvium in small embayments where they reach the coast. Intermittent stream channels drain the valleys on the south side of the ridge. An interior valley located in east central Isla de Culebra contains a relatively extensive area of alluvium in its upper reaches. A northwest to southeast trending ridge, ranging from 300 to 440 feet above mean sea level, forms the western part of Isla de Culebra. The ridge is separated from the remainder of the island by a low saddle between Ensenada Honda and Bahía Flamenco. The principal population center on Isla de Culebra is the town of Culebra, located west of Ensenada Honda.

Isla de Vieques is dominated by a 250 to 500 feet high east-west trending ridge stretching the length of the island. Monte Pirata, at the west end of Isla de Vieques, is the highest point on the island with an elevation of 988 feet above mean sea level. With the exception of Monte Pirata, the topography is gentle, consisting of relatively broad valleys separated by rounded hills trending seaward from the central ridge. The Resolución valley, which cuts completely across Isla de Vieques, isolates Monte Pirata topographically from the rest of the island. In the south central part of the island, east of Esperanza, several valleys coalesce to form an alluvial coastal plain about 0.5 miles wide and 5 miles long. Several of the larger drainage basins in south-central Isla de Vieques have streams with intermittent flow. The most important of these streams are the Quebradas Mina, Pilón, and Urbano. These intermittent streams discharge into the south coastal plain during rain events. The principal population centers on Isla de Vieques are Isabel Segunda on the north coast and Esperanza on the south coast. About three-fourths of the island's territory is used by the Atlantic Fleet Weapons Training Facility, under the jurisdiction of the U.S. Department of Defense.

2.6.1.B Population and Estimated Ground-Water Use

Isla de Culebra had a permanent population of 1,265 in 1980 (U.S. Department of Commerce, 1982; table 2.6.1.B-1). In 1990, the total population was 1,542 (U.S. Department of Commerce, 1991), which represents an increase of 22 percent. In recent years, the island has become a popular tourist area and location for vacation homes. The transient population may equal that of the permanent population, especially during the winter months.

Public-water supply on Isla de Culebra comes from a desalination plant that yields more than 0.1 Mgal/d (Turner, 1991, p. 1, 21). At present, this plant meets the water needs of Isla de Culebra. In 1982 total of 0.05 Mgal/d were withdrawn from ground-water sources (Torres-González, 1989), supplementing the desalination plant yields. In 1982, ground water supplied about 0.03 Mgal/d of water for domestic purposes and 0.01 Mgal/d for commercial uses (table 2.6.1.B-2). Based on the 1980 census, an estimated 742 persons were served by public supply. About 523 persons used self-supplied water that probably came from community operated purification plants not owned by the Puerto Rico Aqueduct and Sewer Authority or from private wells. There are a few shallow private wells on the island (fig. 2.6.1.B-1) dug in the coastal areas that yield brackish water used for watering cattle.

In 1980, the population of Isla de Vieques consists of a civilian population of 7,662 (table 2.6.1.B-1), a permanent staff population at the U.S. Marine facilities at Camp García of a few hundred, and a transient population at Camp García that may swell to several thousand during training exercises. From 1980 to 1990, the civilian population of Isla de Vieques increased by 12 percent to 8,602.

Until 1977, ground water supplied both the civilian and military population as well as minor industrial, commercial, and agricultural demands (Torres-González, 1989). Water for civilian use was obtained from four well batteries in the alluvial coastal plain near Esperanza on the south coast. Water for military use was withdrawn from three wells tapped in the Resolución valley in western Isla de Vieques. Small industries either used private wells or used the public supply. Agriculture (mainly cattle) relied primarily on dug wells.

Ground-water withdrawals have been stopped in the Resolución valley, and operation of the well field in the Esperanza valley was discontinued in 1978 as a result of increasing salinity and maintenance problems (Torres-González, 1989). In 1977, a pipeline was laid from eastern Puerto Rico to Isla de Vieques. Since that time, the water needs of both the civilian and military population are being supplied by the pipeline, which obtains its water from the Río Blanco filtration plant in eastern Puerto Rico. In 1989, about 500,000 gal/d of potable water were pumped through the pipeline to Isla de Vieques (Torres-González, 1989).

Table 2.6.1.B-1 Population for Isla de Culebra and Isla de Vieques, Puerto Rico (U.S. Department of Commerce, 1982, table 1; U.S. Department of Commerce, 1991, table 1)

MUNICIPIO	1980 population			1990 population
	TOTAL	URBAN	RURAL	TOTAL
Isla de Culebra	1,265	938	327	1,542
Isla de Vieques	7,662	2,330	5,332	8,602
Total	8,927	3,268	5,659	10,144

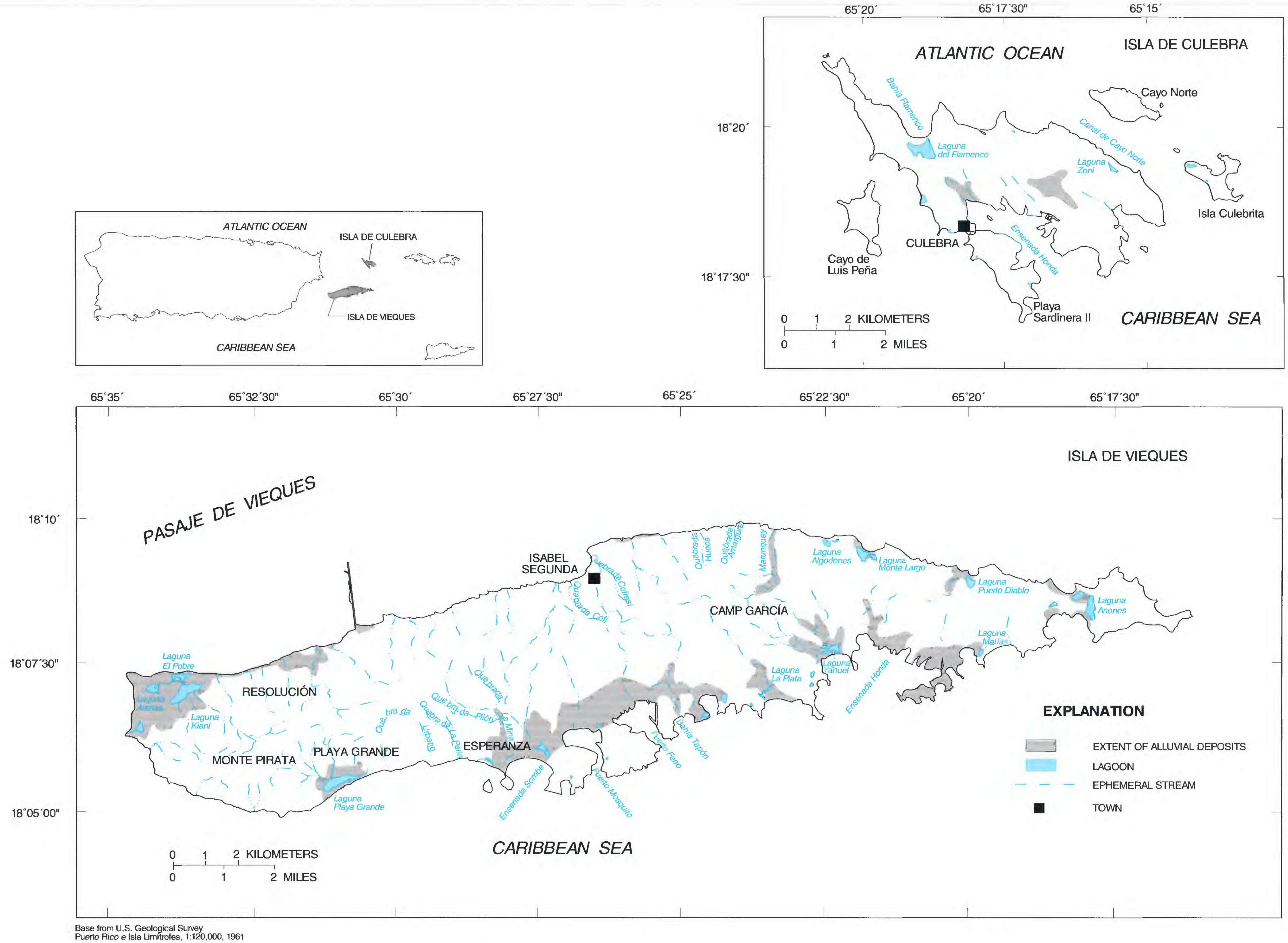
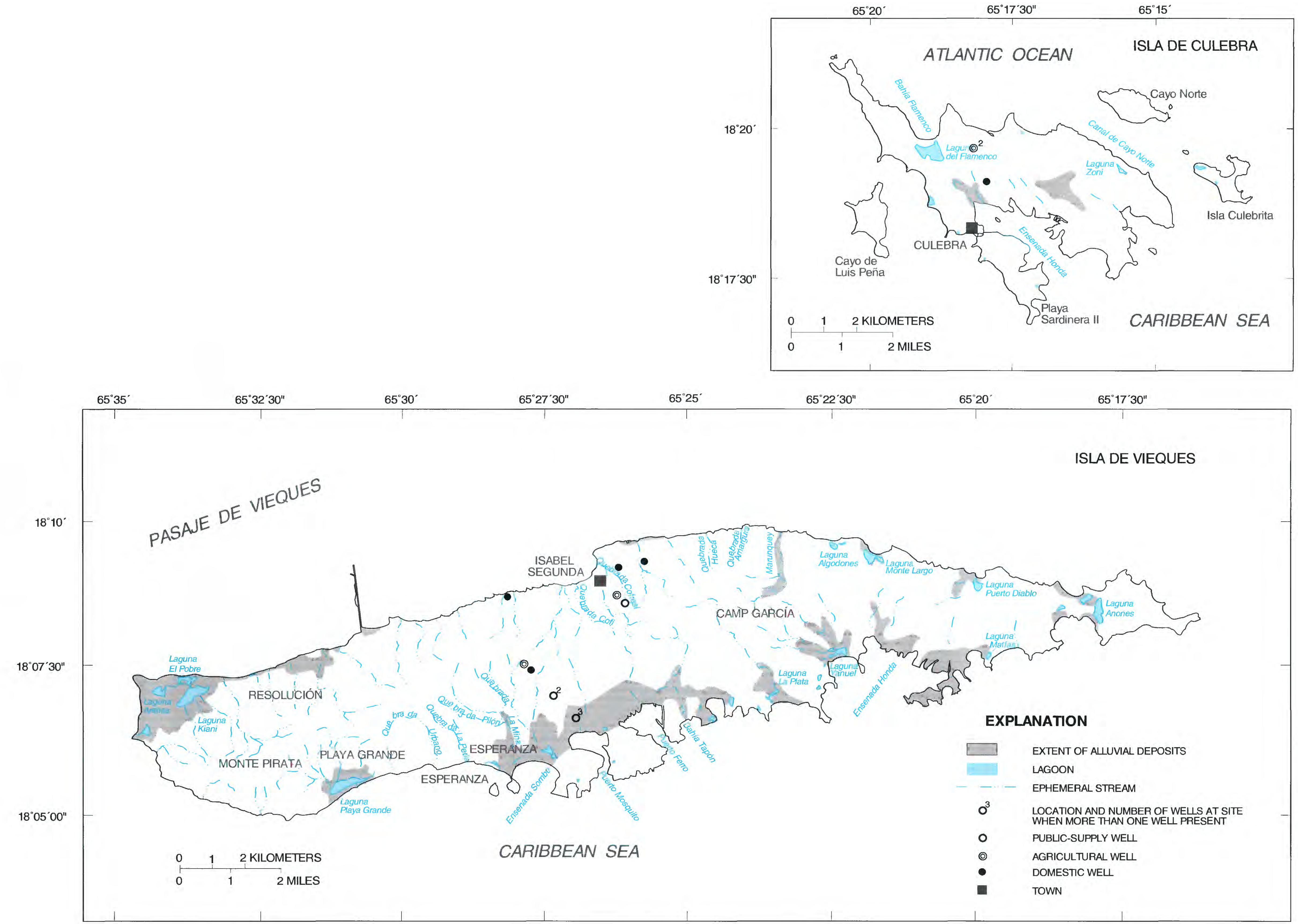


Figure 2.6.1.A-1 Locations and major geographic features in Isla de Culebra and Isla de Vieques, Puerto Rico.



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

Figure 2.6.1.B-1 Approximate well locations in Isla de Culebra and Isla de Vieques, Puerto Rico.

Table 2.6.1.B-2 Ground-water withdrawals and estimated population served during 1982 for Isla de Culebra and Isla de Vieques, Puerto Rico (Modified from Torres-Sierra and Avilés, 1986; Gómez-Gómez and others, 1984)
[Mgal/d, million gallons per day; ---, no data available, <, less than]

[1] Use and supplier		Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use			
A. Puerto Rico Aqueduct and Sewer Authority			
1. Isla de Culebra		742	0.03
2. Isla de Vieques		7,114	[2]<0.01
	Subtotal	7,856	0.03
[1] B. Community Systems			
1. Isla de Culebra		523	0.02
2. Isla de Vieques		548	0.02
	Subtotal	1,071	0.04
II. Agriculturall Use (livestock)			
1. Isla de Culebra		---	0.02
2. Isla de Vieques		---	<0.01
	Subtotal	---	<0.03
III. Commercial Use			
1. Isla de Culebra		---	0.01
2. Isla de Vieques		---	0.05
	Subtotal	---	0.06
	Total	8,927	0.16

[1] Includes water from desalination plants.

[2] Sigfredo Torres-González, U.S. Geological Survey, written communication, 1989.

2.6.1.C Geologic Setting

Isla de Culebra and Isla de Vieques are geologically associated with Puerto Rico. They were separated from the main island by fairly recent drowning of a more extensive Puerto Rico land mass during the melting of the late Pleistocene ice sheets of North America and Europe in the Holocene (Monroe, 1980a, p. 30).

The rocks of Isla de Culebra are primarily volcanic and plutonic rocks of Late Cretaceous age (fig. 2.6.1.C-1). Andesite lava, lava breccia, and tuffs are the dominant volcanic rocks. These rocks were intruded by diorite and diorite porphyry. These plutonic type rocks crop out in the north-central part of the island. Earth movements have fractured these rocks and formed in a joint pattern. Some faulting is also present, with major faulting aligned in a northwest-southeast direction. Alluvium, predominately composed of silt and clay with minor quantities of sand and gravel, was subsequently deposited in the few existing river valleys near the coast. On the coast, alluvium interfingers with coral, beach, and mangrove deposits. Alluvium is also found in the high valley of east-central Isla de Culebra.

The rocks comprising Isla de Vieques are predominately plutonic (fig. 2.6.1.C-1). Quartz-diorite and granodiorite underlie most of the western half of the island. These plutonic rocks are part of the San Lorenzo-Humacao Batholith that crops out in southeastern Puerto Rico. Volcanic rocks predominate in the eastern part with small patches of plutonic rocks cropping out in the east-central area. The rocks of volcanic origin are sandstones, breccias, and tuffs, most of which were deposited in a marine environment. Minor beds of marine limestone are locally interbedded with these rocks. Small areas of soft clayey Tertiary limestone are present in the easternmost part of Isla de Vieques and on the headlands in the vicinity of Puerto Mosquito on the south coast. The only major alluvial deposits underlie the coastal plain east of Esperanza. Small alluvial deposits are present at the north and south ends of the Resolución valley and in the larger valleys of both the north and south coasts. The alluvium of the southern coastal plain east of Esperanza is composed primarily of sand and occasional lenses of fine gravel interbedded with beds of clay and occasional beds of limestone. These deposits range in thickness from near zero to 90 feet (Torres-González, 1989; fig. 2.6.1.C-2). Alluvium in the Resolución valley and the larger valleys that head in the plutonic rocks is composed of beds of sand with some clay. The alluvium in the valleys that head in the volcanic rocks is primarily a mixture of clay and angular rock fragments with occasional lenses of sand and angular gravel. Beach and dune sand is present in the coastal embayments, covering an area of more than 0.5 mi^2 in the west (Torres-González, 1989).

2.6.1.D Hydrogeology

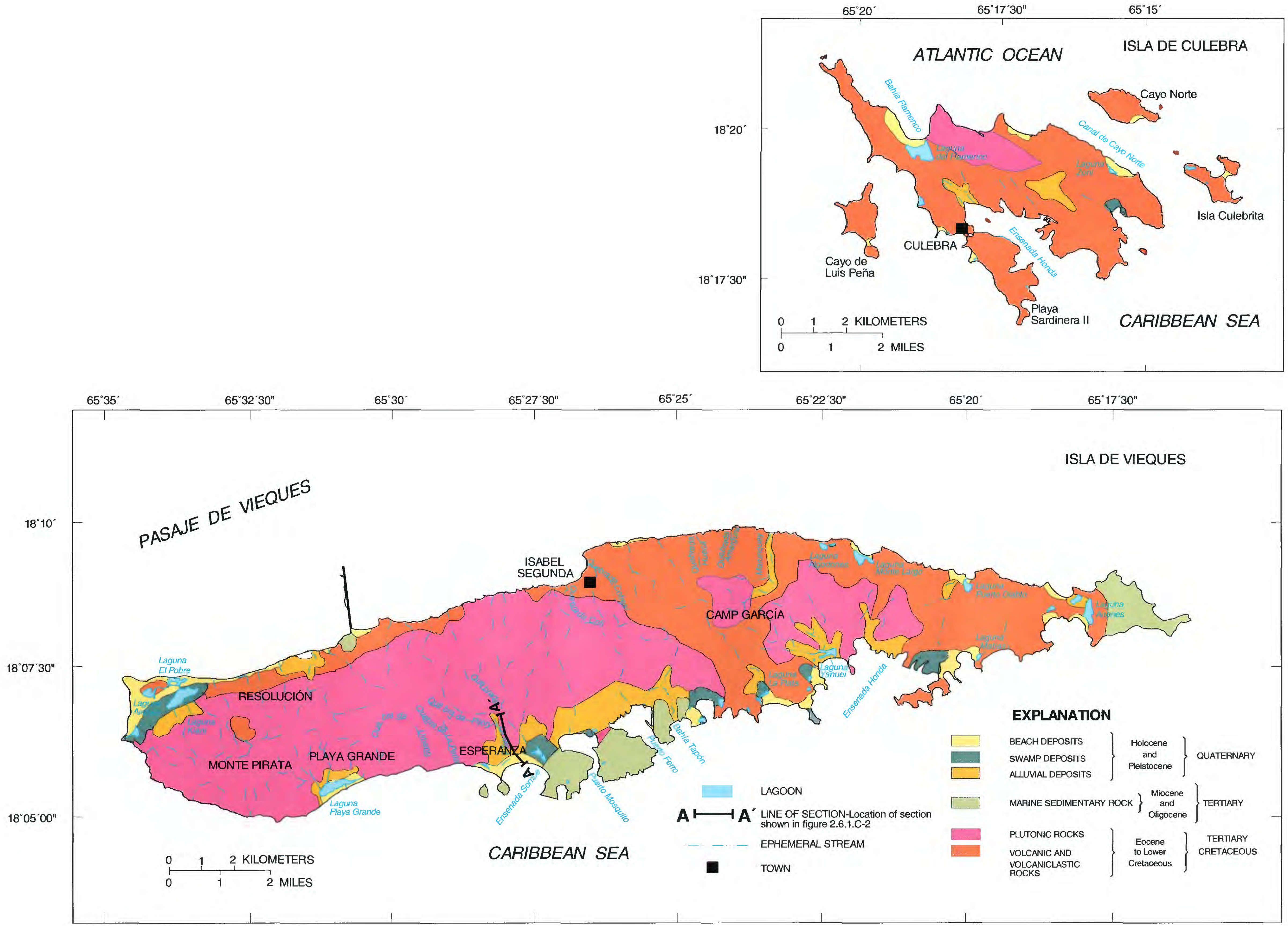
Although scarce, ground water in Isla de Culebra is known to occur in alluvial deposits and in the volcanic and plutonic rocks. Alluvial deposits are located along major stream valleys that reach the coast. The alluvium is mostly composed of silt and clay with limited quantities of sand and gravel. Fractures and joints within the volcanic and plutonic rock formations store water in small quantities. Most of these fractures and joints diminish in number and size with depth and pinch out at about 300 feet below land surface. Water-table conditions prevail in the bedrock aquifer. By comparing changes in water levels with records of pumpage and estimates of recharge, the specific yield for the bedrock aquifer was estimated as less than one percent (Jordan and Gilbert, 1976, p. 16).

The most important aquifers in Isla de Vieques are alluvial deposits in the Esperanza and Resolución valleys. Another, less important, source of ground water is found in the Playa Grande area. Of these aquifers, only the Esperanza valley aquifer has been studied in detail (Torres-González, 1989).

The Esperanza valley covers about 10 mi^2 and extends from Ensenada Sombé near the town of Esperanza towards the east to Bahía Tapón. The alluvium in this valley consists of a mixture of sand, silt, and clay, with increasing clay content at depth; overlies volcanic bedrock and marine sedimentary deposits; and contains a clay layer 5 feet thick at about 25 feet below land surface (Torres-González, 1989). Inland, the entire aquifer behaves as a water-table aquifer. However, as the clay layer becomes more clearly defined near the coast, the alluvial deposits above the clay layer behave as a strongly anisotropic water-table aquifer, while those below the clay layer behave as an artesian aquifer (Torres-González, 1989). Hydraulic-conductivity values range from 1 ft/d inland to 40 ft/d near the coast, where sand content is greater (fig. 2.6.1.D-1). Aquifer thickness increases towards the sea reaching a depth of about 70 feet below land surface at the coast (fig. 2.6.1.D-2). Depth to bedrock also increases towards the sea reaching a maximum of about 90 feet below sea level (fig. 2.6.1.D-2). Transmissivity increases from east to west and ranges from 200 ft^2/d at the eastern limit of the aquifer to 2,000 ft^2/d in the western limit (Torres-González, 1989).

The Resolución valley covers an area of 8 mi^2 and extends from the northwest corner of Isla de Vieques to east of the Isla de Vieques Airport. Geophysical surveys revealed that the Resolución valley is similar to the Esperanza valley in that alluvium thickness averages 30 feet, with a clay unit located 20 to 30 feet below land surface. An estimated 200,000 gal/d may be pumped from this aquifer (Torres-González, 1989).

The Playa Grande area covers about 5 mi^2 and is located on the south coast, to the west of Esperanza valley. Water-table conditions prevail in this aquifer. The aquifer yielded 50,000 gal/d of water up to 1965 (Henry Anderson, U.S. Geological Survey, written communication, 1972; Torres-González, 1989).



Modified from Briggs and Akers, 1965; Torres-González, 1989

Figure 2.6.1.C-1 Generalized surficial geology in Isla de Culebra and Isla de Vieques, Puerto Rico.

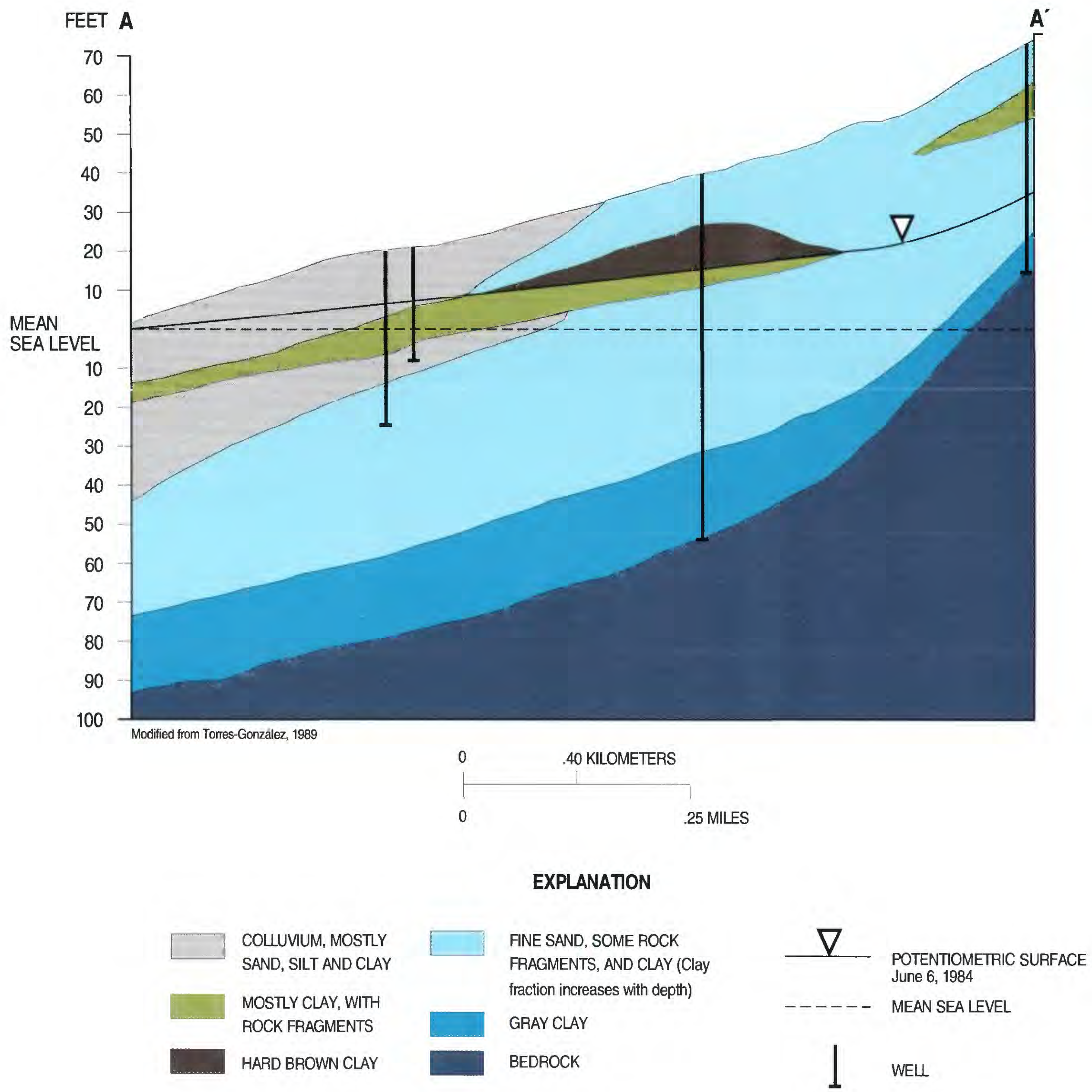


Figure 2.6.1.C-2 Hydrogeologic section of the aquifer in the Esperanza valley, Isla de Vieques, Puerto Rico (line of section shown in figure 2.6.1.C-1).

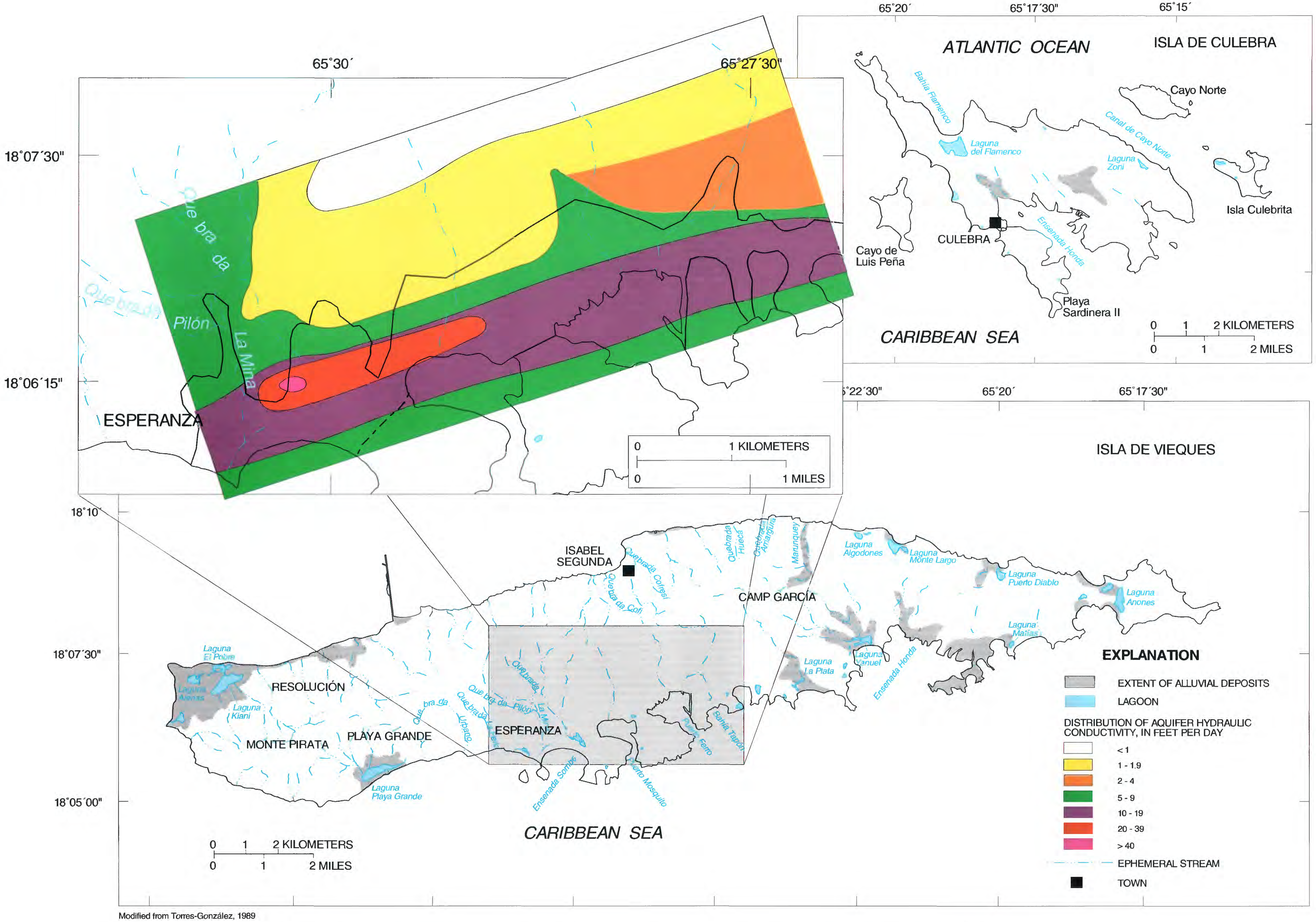
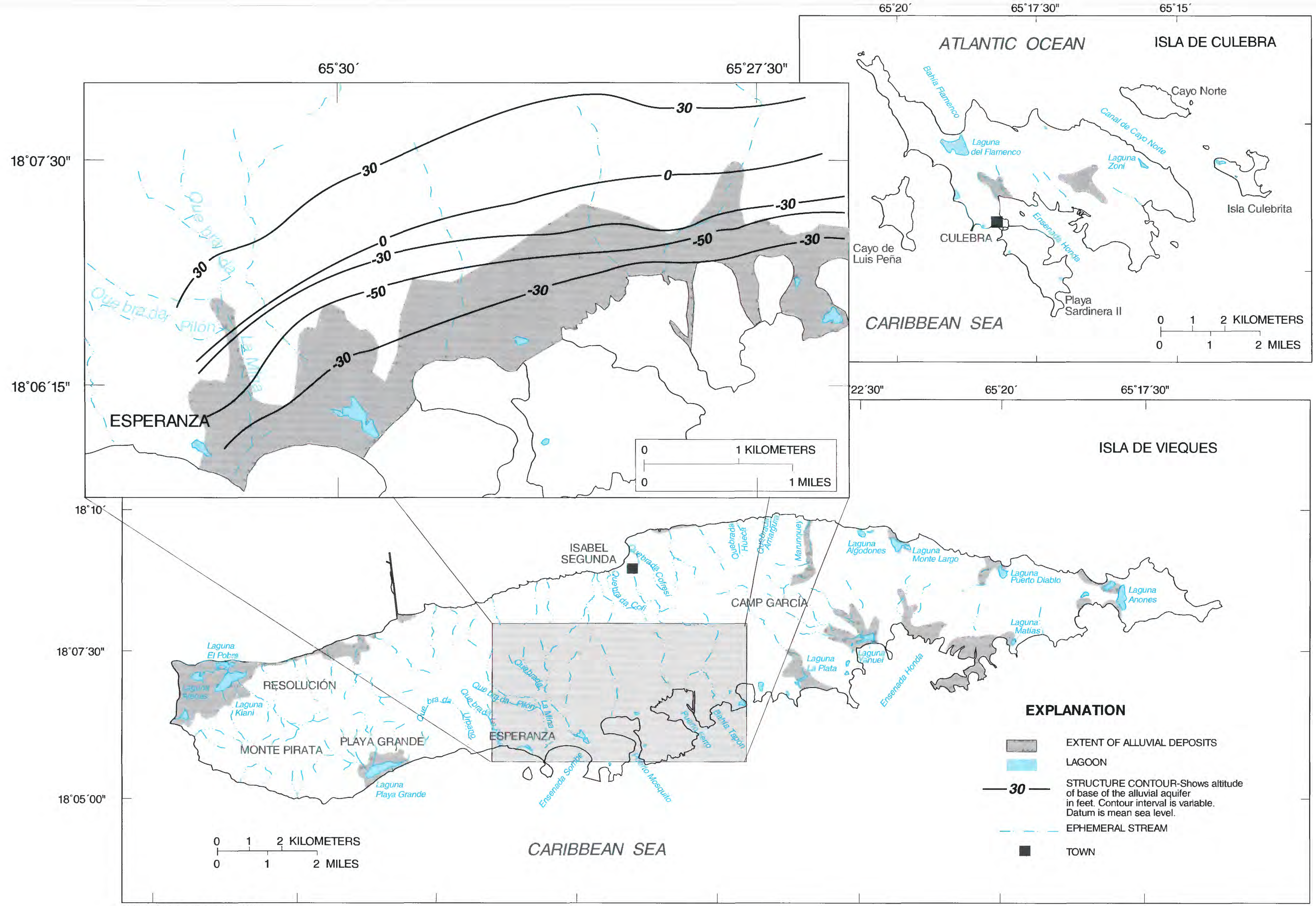


Figure 2.6.1.D-1 Distribution of aquifer hydraulic conductivity values in the Esperanza valley, Isla de Vieques, Puerto Rico.



Modified from Torres-González, 1989

Figure 2.6.1.D-2 Altitude of base of the Esperanza valley alluvial aquifer, Isla de Vieques, Puerto Rico.

2.6.1.E Ground-Water Levels and Movement

The only source of recharge for the aquifers of Isla de Culebra is direct rainfall. Annual rainfall on Isla de Culebra averaged approximately 32 inches from 1961 to 1970 (Jordan and Gilbert, 1976). However, recharge from rainfall only occurs during storms that last two to four days. Such storms take place only two to three times a year. About one percent of the rainfall infiltrates to the aquifer during these events. Annual recharge ranges from 0 to 6.8 percent of annual rainfall (Jordan and Gilbert, 1976). A relation between water levels and rainfall events exists; after rainstorms, water levels rise for several months (fig. 2.6.1.E-1). This is caused by a thick layer of soil or fine grained alluvium that acts as a reservoir and that releases water at a slow rate. This reservoir system occurs in the alluvium and underlying saprolite of the high valley that lies at the eastern end of the dioritic rocks in north-central Isla de Culebra. The yield of bedrock wells in the valley is due to the reservoir system. Water-table conditions prevail in the bedrock aquifer. Each stream drainage basin constitutes a separate aquifer with a ground-water divide impeding movement between basins. The depth to the water table beneath the hills may be 100 feet or more, but in the lower part of the valleys may be less than 10 feet. The water flows towards the sea, but little water is discharged to the sea because it mostly evaporates from the water table. In coastal embayments, the water table usually is 1 to 2 feet above mean sea level. Because of the low heads and the proximity to the sea, salt water encroachment is common.

On Isla de Vieques, the long-term annual rainfall average is 45 inches (Torres-González, 1989). The western part of the island receives about twice as much precipitation as the eastern part. Recharge rates have been estimated to range from three to five percent of annual rainfall. Sources of recharge to the Esperanza valley aquifer are direct rainfall and infiltration from ephemeral streams during storms through the alluvial fans in the vicinity of the bedrock-alluvium contact. The clay layer found at a depth of 25 feet limits the amount of water that can recharge the lower part of the aquifer, especially near the coast. The water-table elevation ranges from 100 feet above mean sea level near the inland part of the coastal plain to about 5 feet near the coast (fig. 2.6.1.E-1). The hydraulic gradient is steep near Camp García and becomes less steep towards Esperanza.

In the Resolución valley, the water table ranges from about 30 feet below land surface in the inland part of the alluvial deposit to about 10 feet below land surface near the coast. Recharge is from rainfall on the sandy soil and by infiltration from streams during wet weather. Ground-water movement on Isla de Vieques is generally towards the sea.

2.6.1.F Soil permeability

On Isla de Culebra, the soil cover is homogeneous and only one soil association, the Descalabrado-Guayama, is present. This association is described by Boccheciamp (1977) as composed of shallow, well drained, strongly sloping to very steeply sloping soils derived from the underlying volcanic rocks. Its permeability is moderate and ranges from 0.6 to 2.0 in/hr. The Descalabrado-Guayama association is also present on Isla de Vieques and covers the eastern half of the island.

The Esperanza and Resolución valleys on Isla de Vieques are overlain principally by the Swamps-Marshes and the Coamo-Guamaní-Vives associations (fig. 2.6.1.F-1). The Swamps-Marshes association is present near the coast in the Esperanza valley and in the northwestern corner of the Resolución valley. It also covers most of the Playa Grande area. The soils in this association are generally deep, poorly drained, sandy or clayey, and contain organic material derived from decaying mangrove trees. Characteristics of the Swamps-Marshes association are too variable to be estimated. The Coamo-Guamaní-Vives association covers the northernmost reaches of the Esperanza valley and the central and eastern parts of the Resolución valley. These soils are described as deep, well drained, nearly level to strongly sloping soils on terraces and alluvial fans (Boccheciamp, 1977). These soils were formed from sediment derived from limestone and volcanic rocks, and their permeability ranges from 0.6 to 2.0 in/hr increasing with depth to more than 20 in/hr in the Guamaní series. Small areas of these valleys are overlain by the Pandura-Rock Land-Patillas association. This association is composed of shallow, well drained, steep and very steep soils derived from the underlying plutonic rocks; permeability is moderate (0.6 to 2.0 in/hr) but increases to rapid (6.00 to 20.00 in/hr) with depth in both the Pandura and Patillas series.

Available water capacity values and depth from the surface for each of the associations in Isla de Culebra and Isla de Vieques are given in table 2.6.1.F-1. The available water capacity of these soils is very low, less than 3 in/in in all the associations. The deepest associations are the Pandura-Rock Land-Patillas and the Coamo-Guamaní-Vives. These associations reach a depth of 50 feet below surface. The Descalabrado-Guayama association is the shallowest of the four associations, with a maximum depth of 19 feet below land surface.

Table 2.6.1.F-1 Thickness, permeability, and available water capacity for the soil associations in Isla de Culebra and Isla de Vieques, Puerto Rico (Modified from Boccheciamp, 1977)

[<, less than]

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Humid Coastal Plains			
Swamps-Marshes	too variable to be estimated		
Semiarid Coastal Plains			
Coamo-Guamaní-Vives	0 to 50	0.60 to 2.00	<0.05 to 0.16
Humid Uplands			
Pandura-Rock Land-Patillas	0 to 48	0.60 to 2.00	0.05 to 0.14
Semiarid Uplands			
Descalabrado-Guayama	0 to 19	0.60 to 2.00	0.10 to 0.15

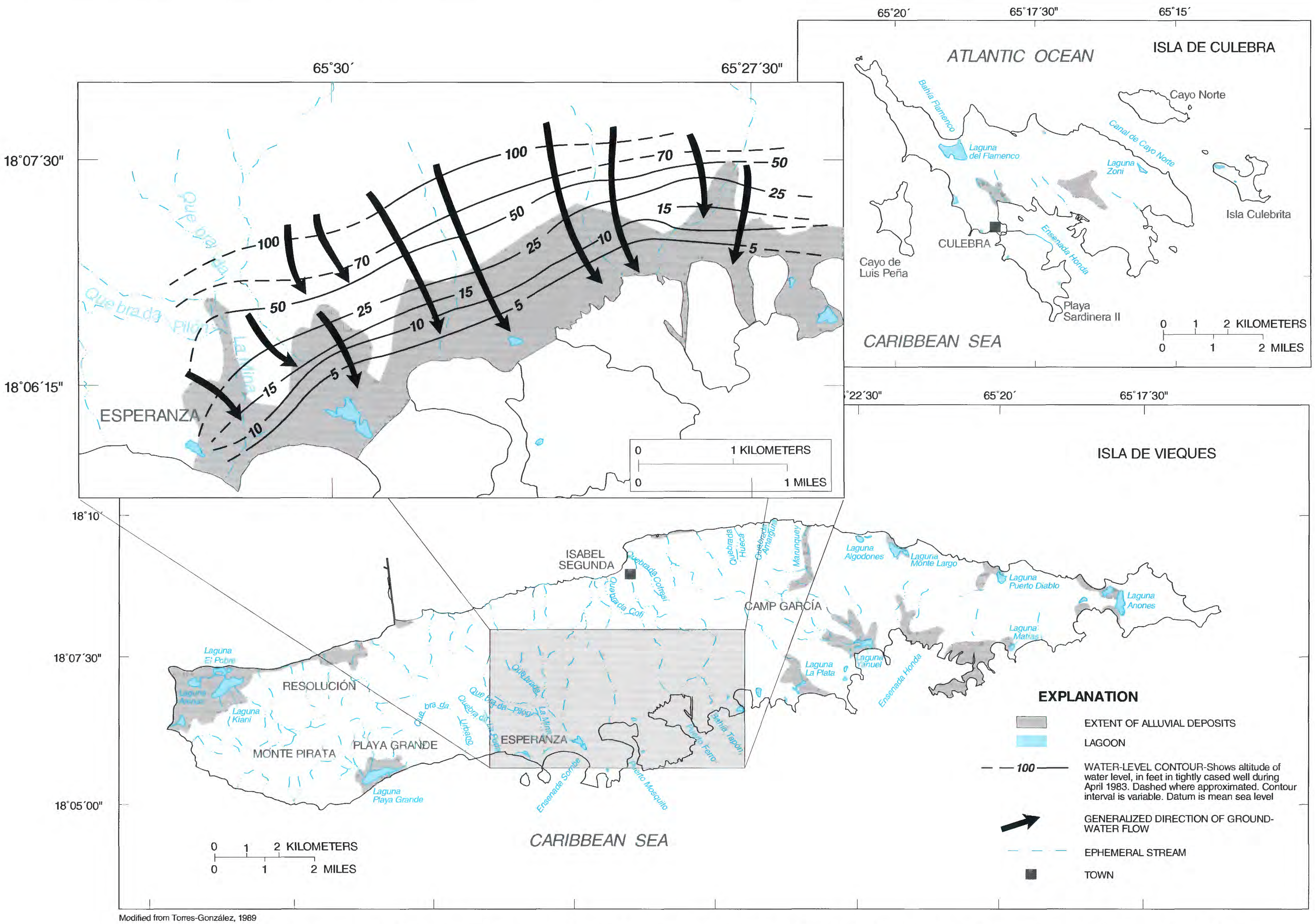
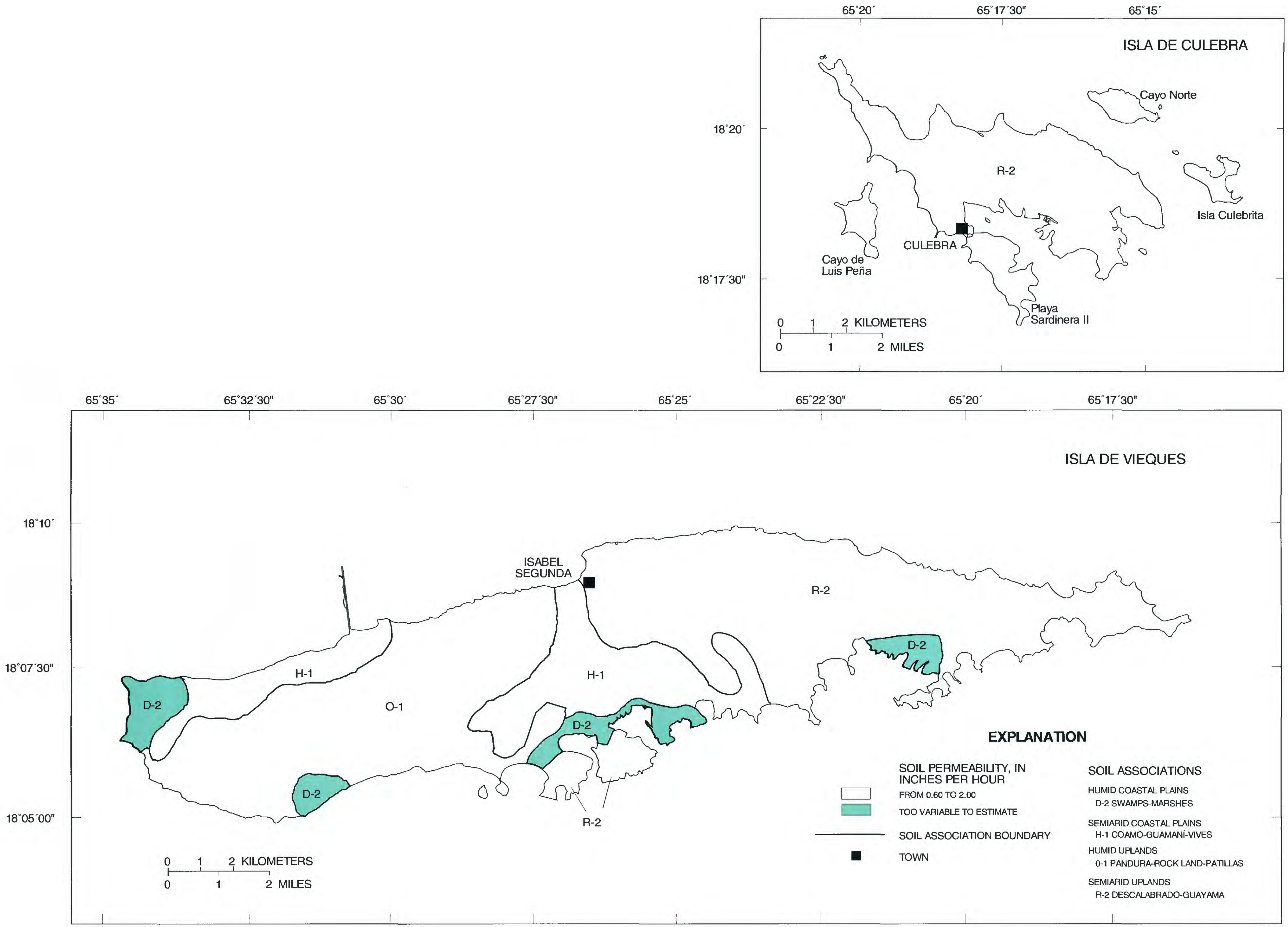


Figure 2.6.1.E-1 Altitude of water-level surface and direction of ground-water flow during April 1983 in the Esperanza valley aquifer, Isla de Vieques, Puerto Rico.



Modified from Boccheciamp, 1977

Figure 2.6.1.F-1 Soil associations and permeability in Isla de Culebra and Isla de Vieques, Puerto Rico.

3.0 GROUND-WATER RESOURCES AREAS IN THE U.S. VIRGIN ISLANDS

3.1 U.S. VIRGIN ISLANDS

3.1.1 ST. THOMAS AND ST. JOHN, U.S. VIRGIN ISLANDS

By Robert P. Graves

3.1.1.A Location and Major Geographic Features

St. Thomas, the second largest of the three principal islands of the U.S. Virgin Islands, is approximately 14 miles long and 2 to 3 miles wide, and has an area of 32 mi^2 (fig. 3.1.1.A-1). Charlotte Amalie is the only city on the island, however, St. Thomas is so densely populated that the whole island could be considered urban.

The land surface of St. Thomas is almost entirely sloping and extends seaward from a central ridge, that is 800 to 1,200 feet above mean sea level and runs the length of the island (Jordan and Cosner, 1973). The slopes, which commonly exceed 35 degrees, are dissected by numerous stream channels of steep gradient. The general appearance of St. Thomas is a panorama of steep interstream spurs and rounded peaks (Jordan and Cosner, 1973). Flat land in St. Thomas is confined to the Charlotte Amalie area and a few small alluvial-filled embayments. The only variation in the general topography is in the upper valley of Turpentine Run in eastern St. Thomas. This valley has rolling hills in a basin surrounded by steep slopes and sharp ridges. Streamflow on St. Thomas is generally intermittent, however, Bonnes Resolution Gut, on the north side of the island and Turpentine Run Gut, on the southeast, have perennial reaches. Turpentine Run Gut base flow consists predominantly of sewage effluent (Santiago-Rivera and Colón-Dieppa, 1986).

St. John, the smallest of the three principal islands of the U.S. Virgin Islands, is about 6 miles long and 3 miles wide, and has an area of 19 mi^2, of which approximately two-thirds is the Virgin Islands National Park (fig. 3.1.1.A-1). St. John is composed of a main eastward trending ridge with steep slopes that descend to the sea to the north (Cosner, 1972). In contrast, the south side of the ridge has several prominent spur ridges that extend southward. The highest point on the island is 1,277 feet above mean sea level (Cosner, 1972). Flat land on St. John is confined to small, isolated coastal embayments. The largest drainage basins on St. John are Reef Bay Gut and Fish Bay Gut, which together drain 1.77 mi^2 (Cosner, 1972). Other basins are Coral Bay Gut and Guinea Gut with 1.69 and 0.72 mi^2 of drainage, respectively. Guinea Gut is the only stream considered to be perennial on St. John.

St. John has two small population centers and these are Cruz Bay (the largest) on the west end and Coral Bay near the east end. Because a large portion of the island is part of the Virgin Islands National Park, residences are confined to the two population centers. St. John does not have an airport and is accessed only by ferry service from St. Thomas.

3.1.1.B Population and Estimated Ground-Water Use

The total population of St. Thomas in 1990 was 48,166. About 43 percent of the population is concentrated in the Charlotte Amalie subdistrict and 19 percent in the Tutu subdistrict. The remaining 38 percent is divided among the Northside, Eastend, Southside, Westend, and Water Island subdistricts. However, the entire island can be considered a single urban complex.

The demand for freshwater on St. Thomas exceeds the available supply. Ground water is an important resource in the U.S. Virgin Islands (fig. 3.1.1.B-1), and provides about 18 percent of the total freshwater supply in all the islands. However, on St. Thomas, ground water supplies only about one percent or 0.35 Mgal/d of the estimated 3.5 Mgal/d of freshwater used (table 3.1.1.B-1; Torres-Sierra and Dacosta, 1987). The remainder of the freshwater supplies in St. Thomas come from desalinated seawater, estimated at 2.5 Mgal/d; and rainfall runoff to cisterns estimated at 0.65 Mgal/d. However, ground-water production is increasing on St. Thomas; during 1991, the U.S. Virgin Islands Water and Power Authority completed a new well field in the Charlotte Amalie area that has an estimated yield of 0.136 Mgal/d.

The total population of St. John in 1990 was 3,504. As on St. Thomas, St. John has been divided into subdistricts. The largest subdistrict is Cruz Bay which has 70 percent of the population; the smallest districts are Central, Coral Bay, and Eastend which had 18, 10, and 2 percent of the population, respectively.

Ground-water use on St. John is minimal; ground-water discharge is equal to only 0.30 Mgal/d (table 3.1.1.B-1). Freshwater is predominantly supplied by rainwater collected from rooftop catchment systems. Ground-water use in the Cruz Bay area consists of 0.10 Mgal/d from the nearby Susannaberg well field (fig. 3.1.1.B-1). The ground-water supplies from the Susannaberg well field are stored in a water tank to serve as backup supplies for the public-water supply system. The remaining 0.10 Mgal/d of ground water used on St. John is from wells located in the Virgin Islands National Park and from private well owners located throughout the island.

Table 3.1.1.B-1 Ground-water withdrawals and estimated population served during 1983-84 for St. Thomas and St. John, U.S. Virgin Islands
[Mgal/d, million gallons per day; ---, no data available]

[1] Use and supplier	[1] Estimated population served	Average ground-water withdrawals (Mgal/d)
St. Thomas		
I. Domestic Use	2,884	0.15
II. Commercial Use	---	0.20
Subtotal	2,884	0.35
St. John		
I. Domestic Use	---	
A. U.S. Virgin Islands Water and Power Authority	2,395	0.20
B. Private Supplies	---	0.10
Subtotal	2,395	0.30
Total	5,279	0.65

[1] Based on a water consumption of 52 gallons per person per day.
[2] Modified from Torres-Sierra and Dacosta, 1987.

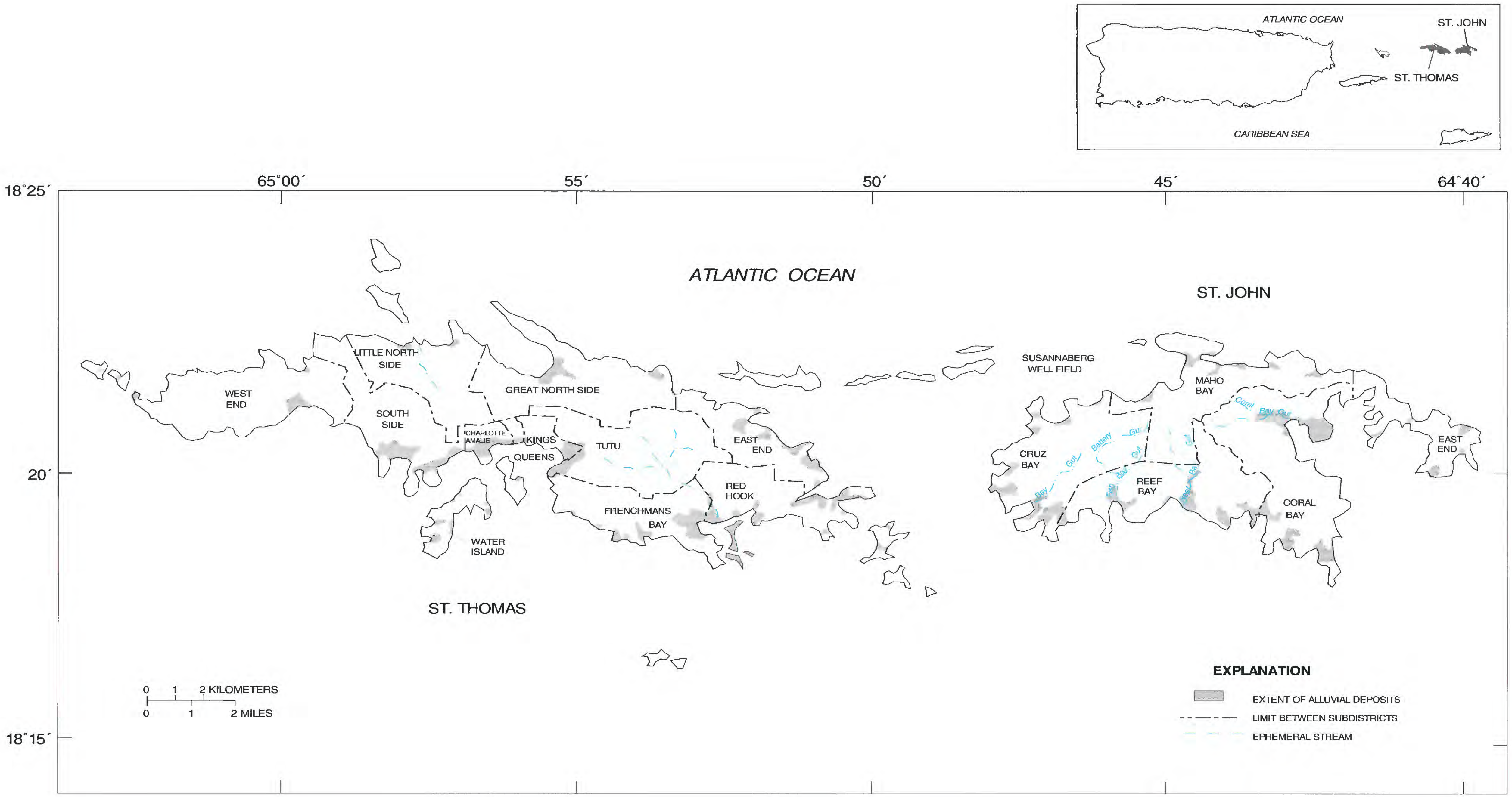


Figure 3.1.1.A-1 Locations and major geographic features in St. Thomas and St. John, U.S. Virgin Islands.

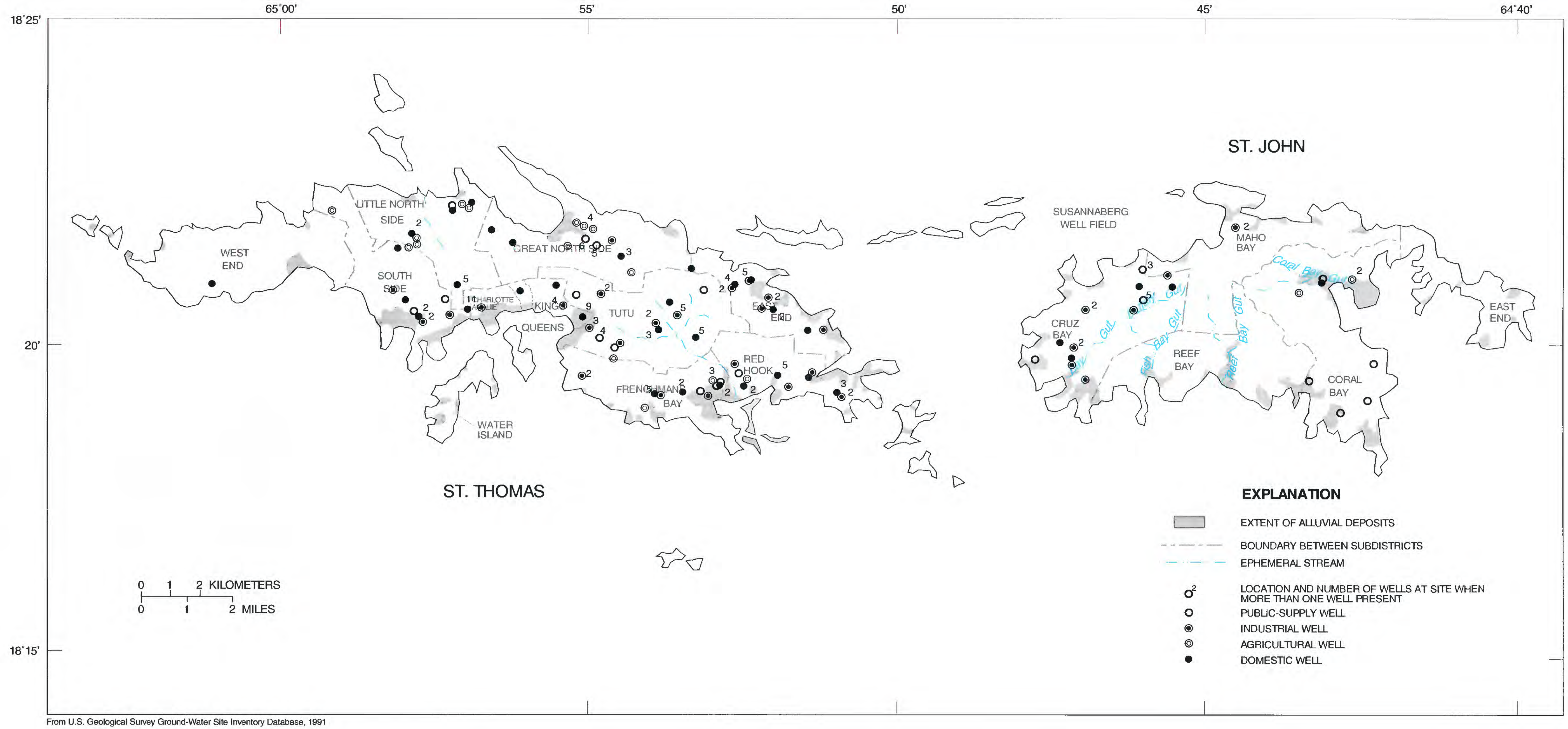


Figure 3.1.1.B-1 Approximate well locations in St. Thomas and St. John, U.S. Virgin Islands.

3.1.1.C Geologic Setting

The geology of St. Thomas and St. John is similar (fig. 3.1.1.C-1). The islands are underlain by mildly deformed Cretaceous volcanic rock and limestone that were intruded and contact metamorphosed by dioritic plutons during Late Cretaceous or early Tertiary time (Donnelly, 1959). Volcanic rock is the predominant rock type on St. Thomas and St. John. The oldest volcanic rock is the Water Island Formation, which consists predominantly of lava flows and flow breccias. Overlying the Water Island Formation is the Louisenhoj Formation, which was extruded from a volcanic center and is a combination of very coarse reworked cone debris and fine-grained tuff. Near the base of the Louisenhoj Formation is a conglomerate composed chiefly of rock from the Water Island Formation. Overlying the Louisenhoj Formation is the Outer Brass Limestone which consists of 200 to 600 feet of thin-bedded graphitic silicified radiolarian limestone. The youngest rock exposed on St. Thomas and St. John is the Tutu Formation, which is composed of angular debris derived from the Louisenhoj Formation and minor limestone debris. Locally, small alluvial deposits, which range from Pleistocene to Holocene age, lie in the valley of Turpentine Run and the larger coastal embayments.

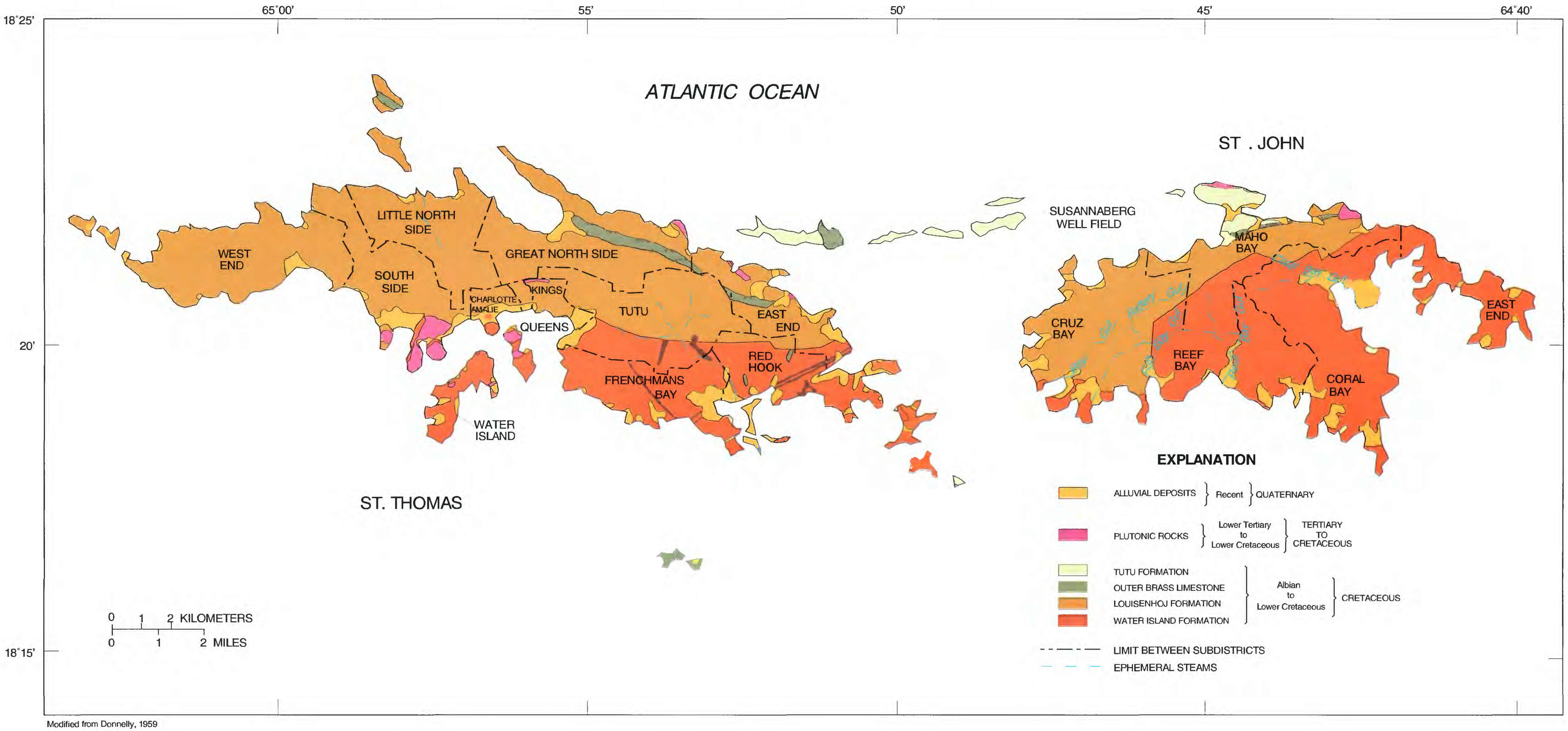


Figure 3.1.1.C-1 Generalized surficial geology in St. Thomas and St. John, U.S. Virgin Islands.

3.1.1.D Hydrogeology

Ground water in St. Thomas and St. John is under water-table conditions in the volcanic rock, limestone, and alluvial deposits. The availability of ground water from the limestone and alluvial aquifers is limited because of their small areal extent. Consequently, the fractured volcanic rock aquifers are the principal source of ground water (fig. 3.1.1.D-1).

The volcanic rock consists of regolith, transition zone, and bedrock. The regolith is a highly weathered volcanic material that occurs as saprolite or very friable and highly weathered volcanic rock. The transition consists of shattered to highly fractured volcanic rock underlying the regolith, and contains areas of highly weathered volcanics that grade upward to saprolite. The volcanic bedrock is a dense, indurated and locally contains horizontal and vertical fractures.

In the volcanic rock aquifers, ground water is principally in the fractured and highly shattered transition zone. The regolith overlying the transition zone has an overall low permeability that limits yields. However, when the regolith is saturated, it acts as an excellent storage reservoir and contributes considerable water to the underlying transition zone (Jordan and Cosner, 1973). Ground water is found in fractures within the underlying bedrock; however, yields are negligible. Deep wells, completed into the transition zone and the underlying bedrock, have never had higher yields than wells completed only in the transition zone.

Well yields from the transition zone are dependent on saturated thickness, abundance of fractures, and the density of the highly shattered zones. Aquifer yields in the transition zone may range from 21,000 to 72,000 gal/d.

Wells completed into the aerially limited limestone aquifers are capable of short term yields of 150,000 gal/d and sustained yields of 50,000 gal/d (Jordan and Cosner, 1973). Where the alluvial deposits are found to be saturated, aquifer yields to wells as high as 43,000 gal/d can occur.

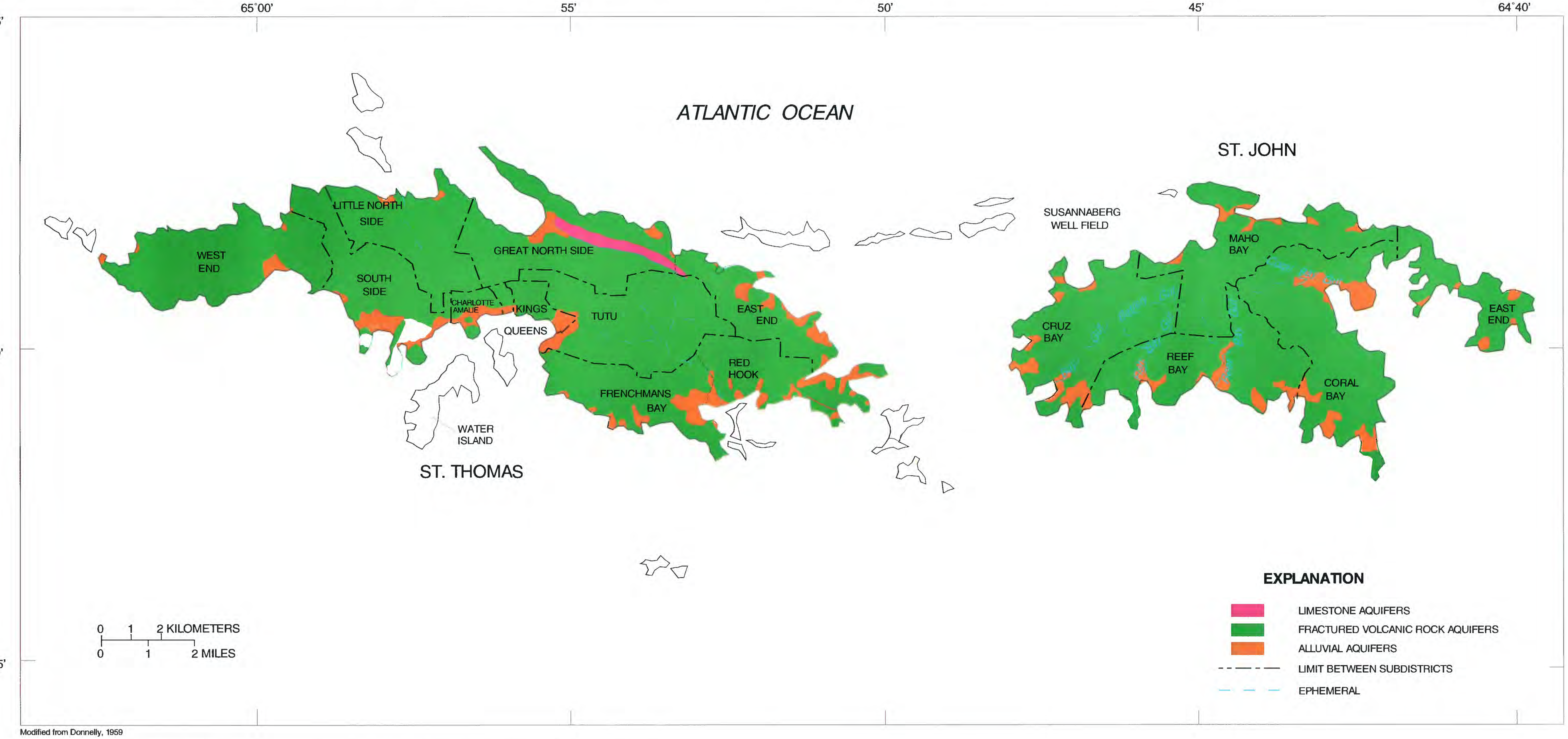


Figure 3.1.1.D-1 Principal aquifers in St. Thomas and St. John, U.S. Virgin Islands.

3.1.1.E Ground-Water Levels and Movement

Because of the complexity of the fractured volcanic rock, limestone, and alluvial aquifers, an islandwide potentiometric map of either St. Thomas or St. John has not been completed. Potentiometric maps covering small areas have been completed by Jordan and Cosner (1973) and Graves and González (1988). In general the water-table surface on St. Thomas and St. John parallels the topography. Ground-water movement is down gradient and perpendicular to the topographic contours towards the sea (fig. 3.1.1.E-1). Depending on the location, the water table can range from within a few feet of land surface to as deep as 120 feet below land surface (Jordan and Cosner, 1973).

3.1.1.F Soil Permeability

Soils on St. Thomas and St. John are of two types, the Cramer-Isaac and Dorothea-Victory-Magens associations (fig. 3.1.1.F-1, table 3.1.1.F-1), each of which have a soil permeability of 0.63 to 2.0 in/hr (Rivera and others, 1979). The Cramer-Isaac association is the predominant soil association that covers all of St. John and approximately 80 percent of St. Thomas. These soil associations, when dry, are coarsely granular, because clay and silt particles have a tendency to clump (Jordan and Cosner, 1973). Prolonged saturation is necessary before the granules break down and weld together. As a result, the soil has a high permeability until well saturated, but once saturated, the soil becomes poorly permeable and retains water in the pore spaces between particles. Any excess water is shed.

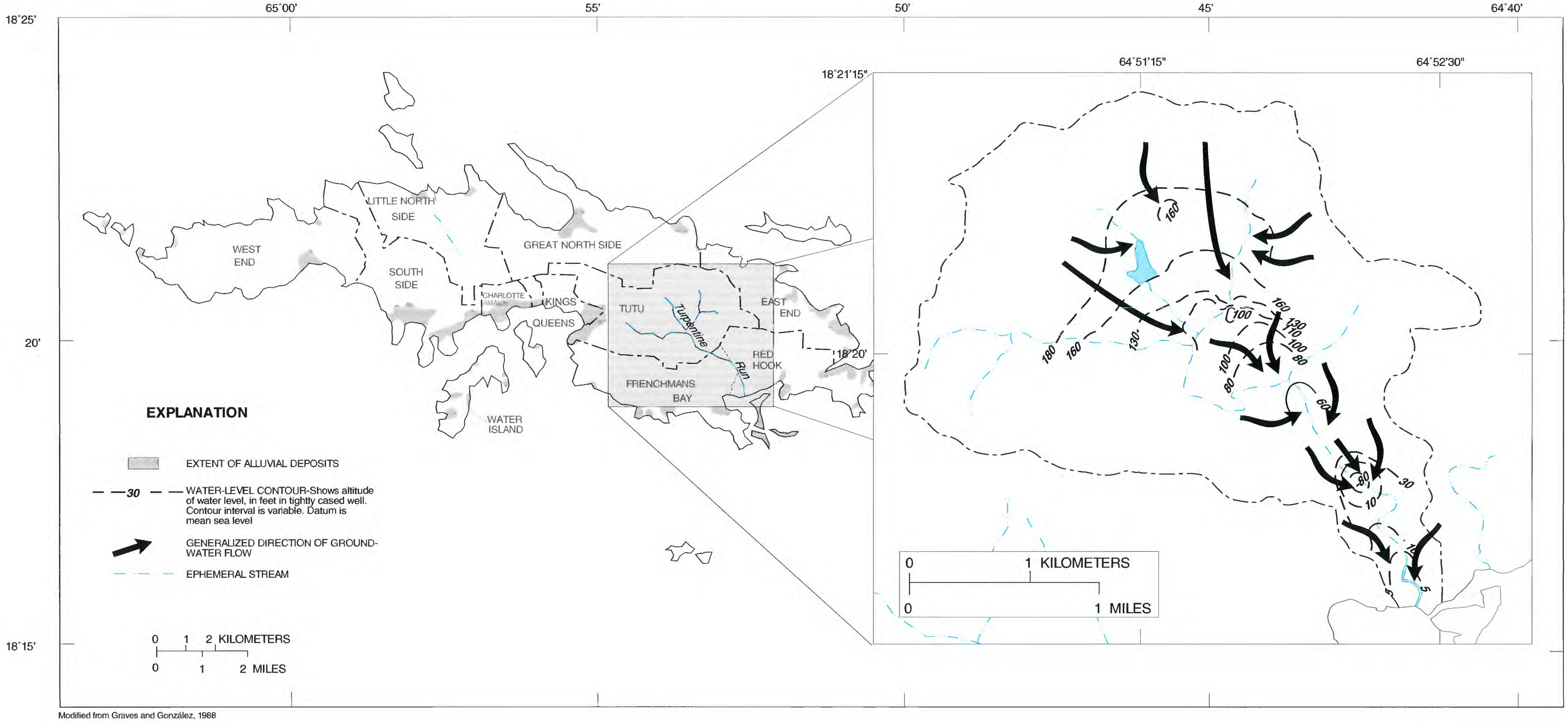


Figure 3.1.1.E-1 Altitude of water-level surface and direction of ground-water flow during September 11, 1987, in St. Thomas and St. John, U.S. Virgin Islands.

The typical soil zone will absorb about 2 inches of water before some water is shed or moves to the underlying bedrock (Jordan and Cosner, 1973). Fully saturated, the soil will probably retain 3 inches of water per foot of depth.

The capacity of the soil to hold large volumes of water, the infrequency of major rainstorms, and a high evapotranspiration rate, reduce ground-water recharge and storm runoff. Thickness, permeability, and available water capacity values for both soil associations are shown on table 3.1.1.F-1.

Table 3.1.1.F-1. Thickness, permeability, and available water capacity for the soil associations in the St. Thomas and St. John, U.S. Virgin Islands (Modified from Rivera and others, 1979)

Area and soil association	Thickness (inches)	Permeability (inch per hour)	Available water capacity (inch per inch)
Cramer-Isaac	0 to 36	0.63 to 2.00	0.15 to 0.20
Dorothea-Victory-Magens	0 to 84	0.63 to 2.00	0.10 to 0.20

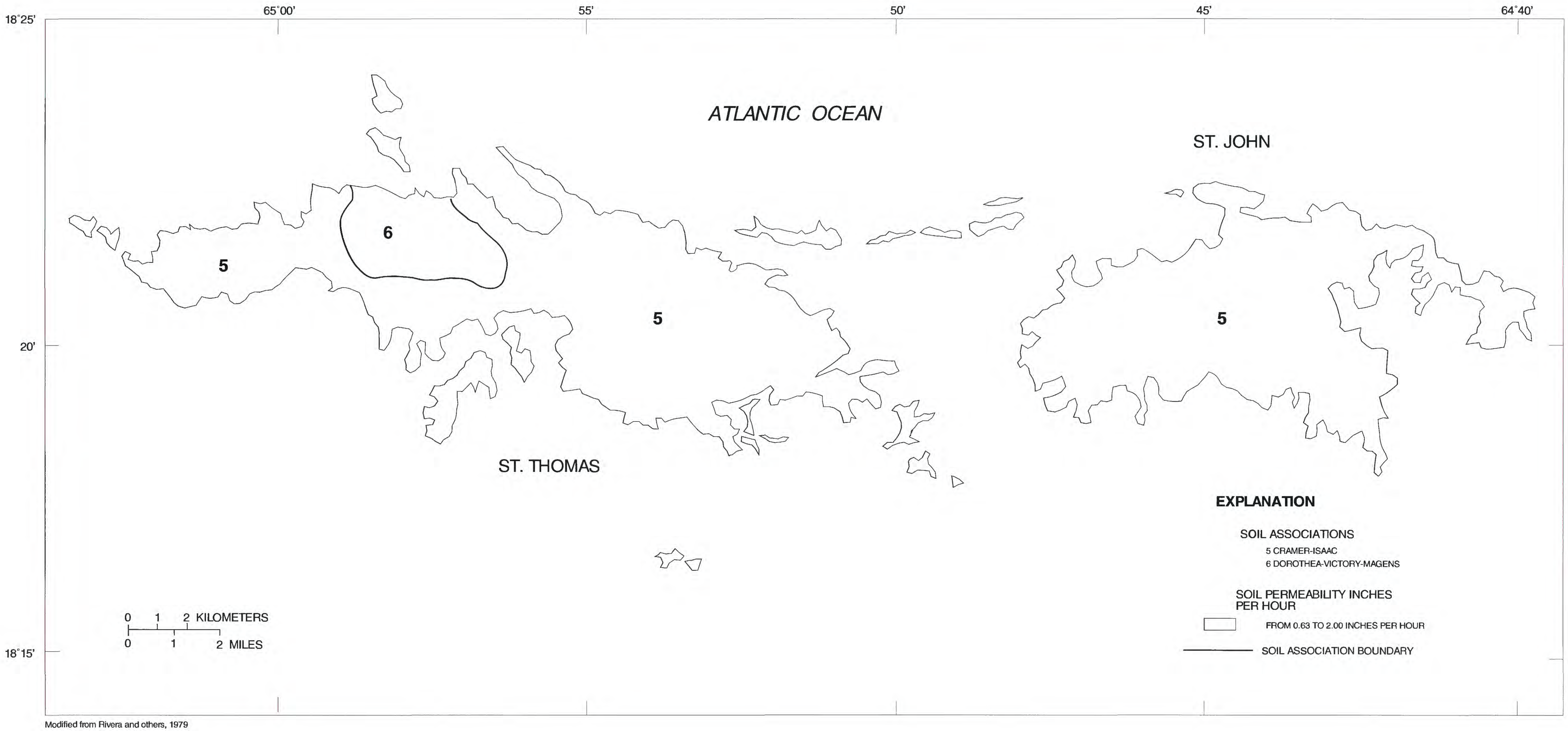
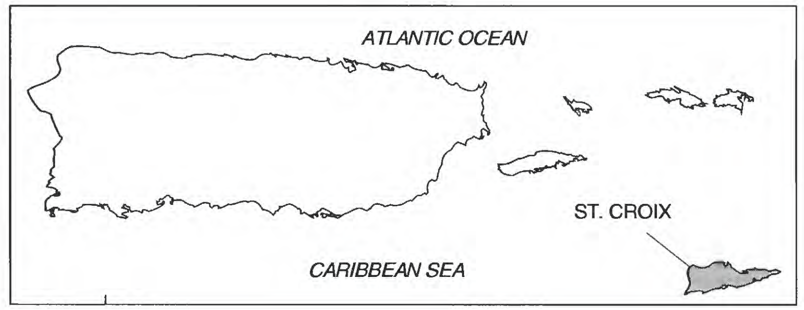


Figure 3.1.1.F-1 Soil associations and permeability in St. Thomas and St. John, U.S. Virgin Islands.

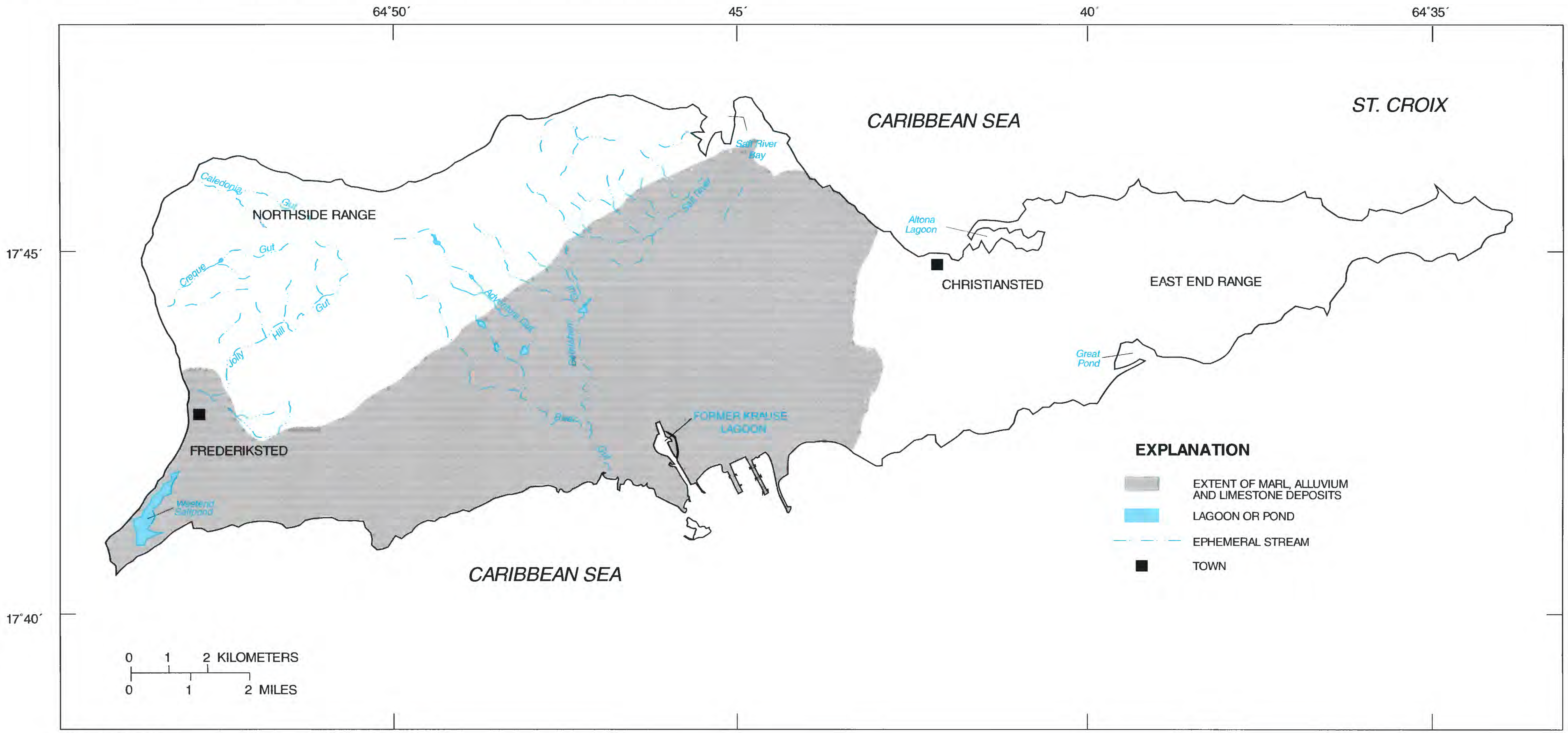
3.1.2 ST. CROIX, U.S. VIRGIN ISLANDS

By Zelda Chapman Bailey



3.1.2.A Location and Major Geographic Features

St. Croix, the largest of the U.S. Virgin Islands, is about 20 miles long and 5 miles wide at its widest point (fig. 3.1.2.A-1). Total land area is about 82 mi^2. St. Croix lies about 40 miles south of St. Thomas and St. John, and about 60 miles east-southeast of Puerto Rico. Christiansted and Fredricksted are the principal population centers, but a number of villages are scattered throughout the island.



Modified from Gill, 1991

Figure 3.1.2.A-1 Location and major geographic features in the Kingshill aquifer, St. Croix, U.S. Virgin Islands.

The northwestern part of St. Croix is a rugged mountainous area called the Northside Range, which runs from the west end of the island to Salt River Bay. Elevations generally range from 600 to 800 feet above mean sea level, although two peaks are higher than 1,000 feet. Steep, deeply entrenched valleys extend from the central ridge. To the north and west, the mountains slope directly to the sea. The mountains are bounded by a gently rolling plain to the south. Eastward, the plain broadens and is marked by rounded limestone hills and broad valleys. East of Christiansted, the mountainous East End Range has peaks that reach 800 feet in elevation above mean sea level and are more rounded.

Headwaters of the major streams of the island (fig. 3.1.2.A-1) originate in the Northside Range (Jordan, 1975, p. 10). These streams were once perennial, but now flow only when recharged by rainfall. The River Gut system, which includes Adventure and Bethlehem Guts, drains about 11 mi^2. Jolly Hill and Salt River Guts drain about 4 and 4.5 mi^2, respectively. Creque and Caledonia Guts each drain about 1 square mile.

3.1.2.B Population and Estimated Ground-Water Use

The population of St. Croix in 1985 was about 54,000, more than triple the population in 1960. The population is concentrated in the two cities, Fredricksted (population 4,350) and Christiansted (population 3,700), and in a number of villages and housing developments located primarily on the central lowland. About 60 percent of the population is served by public-water supply, which derives water primarily from desalination plants. Ground water furnishes about 10 percent of the freshwater for public supply throughout the island. The remaining population is self supplied, either from rainfall collected from rooftops or from ground water. Total ground-water pumpage in 1985 (table 3.1.2.B-1) was about 1.3 Mgal/d (Torres-Sierra, 1987). About 59 percent of ground-water withdrawals were for public supply (0.22 Mgal/d) and domestic self-supplied (0.55 Mgal/d). Commercial ground-water usage was about 26 percent (0.34 Mgal/d) of the total, and industrial usage was almost 15 percent (0.19 Mgal/d).

A pipeline between the two principal cities on St. Croix is connected to saltwater desalination plants at Christiansted and to well fields at Adventure, Barren Spot, Concordia, Fairplain, Golden Grove, Negro Bay, La Grange, and Mahogany Road (fig. 3.1.2.B-1). Other wells supply individual villages. A large number of privately owned wells are used for domestic and commercial supplies.

Pumping from municipal and commercial well fields in 1967 was about 0.9 Mgal/d (Jordan, 1975, p. 42). Prior to 1967, pumping had been as much as 1.28 Mgal/d, but the Golden Grove and Manning well fields were taken out of production due to the closing of a sugar factory. Pumping from the Mahogany Road well field was reduced by 30 percent because of saltwater encroachment, and pumping from the Adventure well field was reduced by 90 percent because of low ground-water levels. Demand for water increased the pumping at the other well fields, and in 1990, ground-water withdrawals from the municipal well fields totalled 1.13 Mgal/d, an increase from the 0.22 Mgal/d pumped in 1985 (table 3.1.2.B-2).

Table 3.1.2.B-1 Ground-water withdrawals and estimated population served during 1985 for St. Croix, U.S. Virgin Islands (Modified from Torres-Sierra, 1987)
[Mgal/d, million gallons per day; ---, no data available]

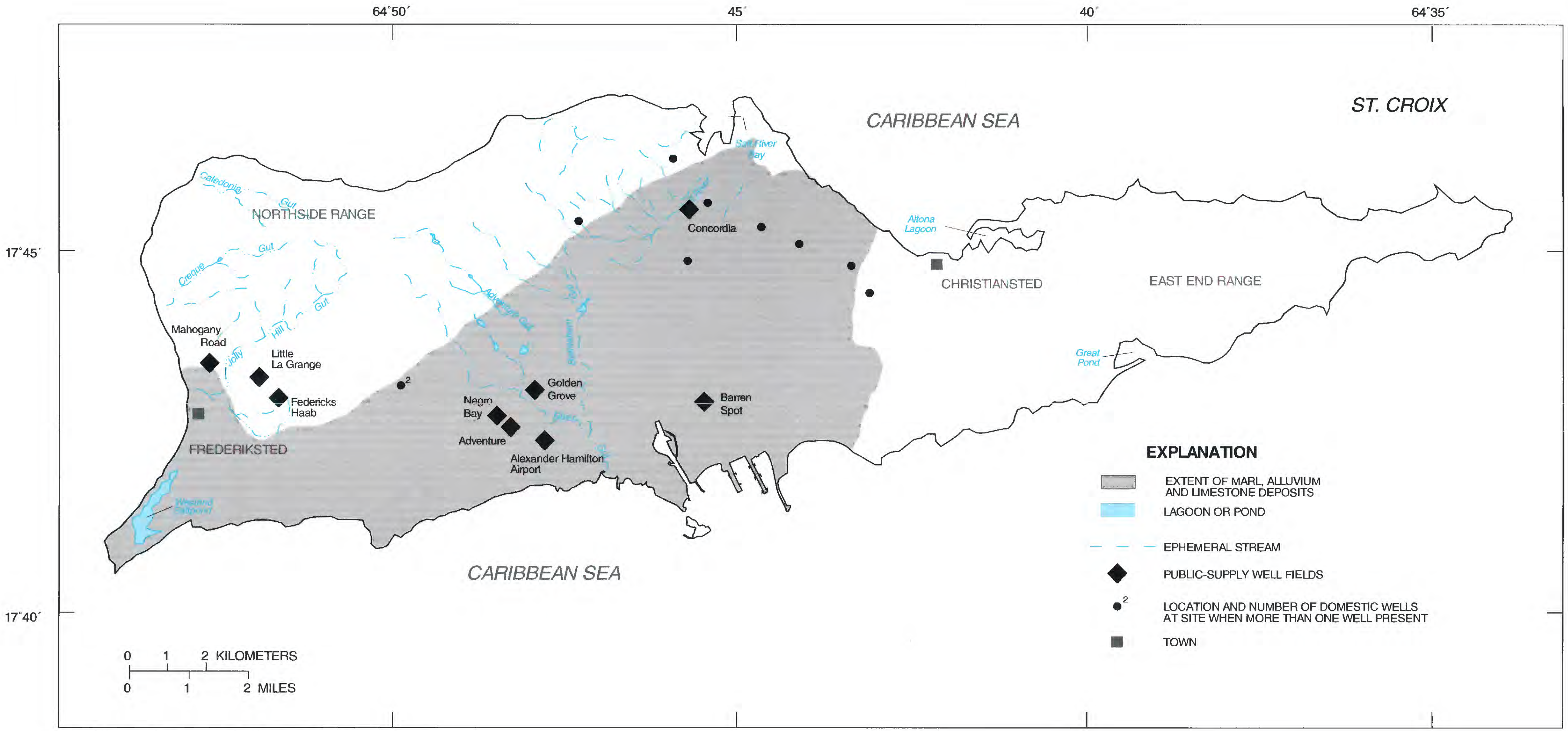
Use and supplier	Estimated population served	Average ground-water withdrawals (Mgal/d)
I. Domestic Use		
[1] A. Virgin Islands Water and Power Authority	30,000	0.22
B. Private Supplies (wells or purchased)	[2] 24,000	0.55
Subtotal	54,000	0.77
II. Industrial Use	---	0.19
III. Commercial Use	---	0.34
Total	54,000	1.30

[1] Supply supplemented with 1.9 Mgal/d of desalinated sea water.

[2] Population supplied supplements ground water with rain water.

Table 3.1.2.B-2 Average daily ground-water withdrawals from municipal well fields during September to November 1990, St. Croix, U.S. Virgin Islands (Data from daily operational sheets of the Virgin Islands Water and Power Authority)

Well Field	Pumpage (gallons per day)
Barren Spot	291,900
Concordia	261,700
Fairplain	
Adventure, Golden Grove, Negro Bay, and areas north of Alexander Hamilton Airport	417,200
Prosperity,	
Little La Grange, Fredericks Haab, and Mahogany Road	158,600
Total	1,129,400



From U.S. Geological Survey Ground-Water Site Inventory Database, 1991

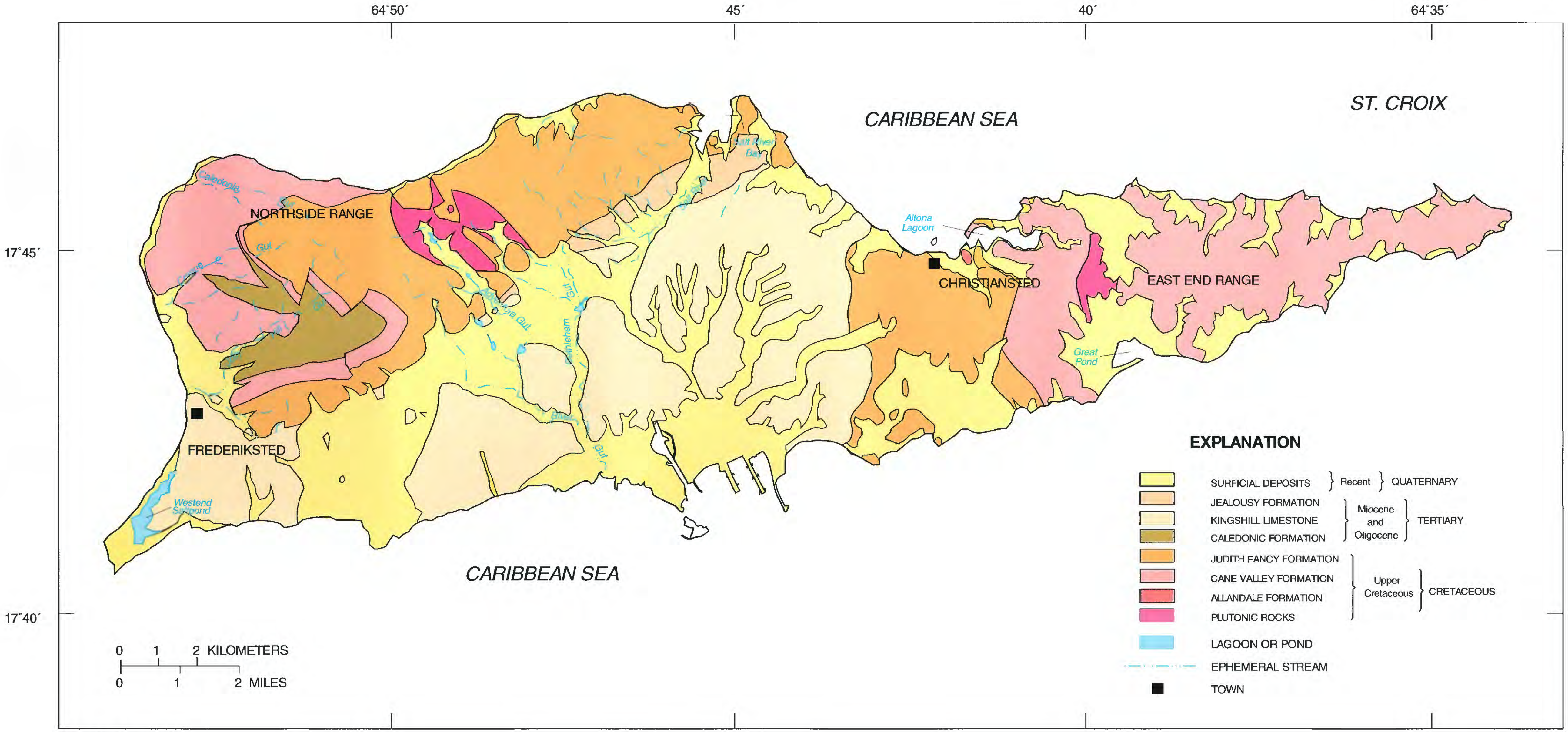
Figure 3.1.2.B-1 Clusters of well fields and location in St. Croix, U.S. Virgin Islands.

3.1.2.C Geologic Setting

The mountainous areas of the northwestern and eastern ends of St. Croix are composed largely of fractured and deformed rocks of volcanic origin or of sedimentary rocks derived by the erosion of older volcanic rocks. The volcanic rocks are the Caledonic, Judith Fancy, Cane Valley, and Allandale Formations of Cretaceous age (fig. 3.1.2.C-1). These formations are primarily metamorphosed tuffs (Cederstrom, 1950, p. 16). Two areas have small intrusions of plutonic rocks; gabbro in the northwest and diorite in the east. Stream valleys cut into the volcanic rocks are filled with alluvium in the coastal areas. The alluvium is composed mostly of clay and silt, and contains some thin beds or lenses of sand and gravel. Alluvium in the valleys draining the gabbro intrusion is composed largely of sand.

During Oligocene and Miocene time, a volcanic ash was deposited between the mountain masses in what was probably a graben in a larger St. Croix island mass. Coarse- and fine-grained alluvial material from the northwestern mountains was also carried into the graben and interfingered with the volcanic ash (Cederstrom, 1950). This material, consisting of alluvial-deposited, calcareous conglomerate in outcrop and blue clay in the subsurface, are together called the Jealousy Formation, and exceeds 1,400 feet in thickness. The Jealousy Formation is overlain by the calcareous mud and reef deposits of the Kingshill Limestone, which has a maximum thickness of about 450 feet.

Fine-grained Quaternary alluvium mantles the coastal lowland. Alluvium in the River Gut drainage, containing considerable deposits of sand and gravel, cuts across the Kingshill Marl. In other valleys, the alluvium generally is composed of silt and clay and contains occasional lenses of sand and gravel.



Modified from Whetten, 1966

Figure 3.1.2.C-1 Generalized surficial geology in St. Croix, U.S. Virgin Islands.

3.1.2.D Hydrogeology

Recharge to the ground-water system in St. Croix is small because of the low storage capacity of the aquifers (Jordan, 1975, p. 9). Only about one to six percent of annual rainfall may reach the water table and recharge the aquifers (Jordan, 1975, p. 43). The eastern third of the island usually receives less than 30 inches of rain annually. This low rainfall, coupled with high evapotranspiration, results in infrequent recharge to the aquifers and often there is no recharge over periods of a year or more. Flow is rare in the ephemeral streams of the area. Ground-water quality is generally poor because mineral salts are concentrated by evapotranspiration. In contrast, the northwestern quarter of the island receives as much as 50 or more inches of rain annually. Aquifers in this area are recharged several times a year, and the recharge is reflected in ground-water discharge that maintains flow in perennial reaches of several streams in the Northside Range.

Fractured volcanic rock aquifers underlie eastern and northwestern St. Croix. Permeability is low in these aquifers, consisting of openings along joints and fractures. The greatest permeability occurs where these openings have been enlarged by weathering and dissolution. Ground water from the fractured rock aquifer has the lowest mineral salts content of any ground water on the island.

The principal aquifer on St. Croix is in the Kingshill Limestone (fig. 3.1.2.C-1). The quality of water in this aquifer is poor. Transmissivity is variable in the Kingshill aquifer, ranging from between 50 and 4,000 ft^2/d (fig. 3.1.2.D-1). The saturated thickness of the aquifer in 1968 was as much as 200 feet (Robison, 1972). Water is obtained from solutioned and fractured limestone lenses and reef deposits in the Kingshill Limestone. Sand- and gravel-filled stream channels in the eastern part of the Kingshill Marl are the important water-bearing units. Buried alluvial fans that are water bearing in the Kingshill Marl are located where several present-day streams flow from the Northside Range onto the central lowlands. The quality of ground water in the Kingshill aquifer is affected by residual water trapped in the lagoonal muds originally deposited. Dissolved-solids concentrations range from about 500 mg/L to more than 1,000 mg/L. Mineral salts carried into the aquifer by recharge and concentrated in the soil zone by evapotranspiration also contribute to the poor quality of the water in the aquifer.

Alluvium is deposited in the valleys of several streams that originate in the Northside Range and cross south-central St. Croix. In general, these alluvial deposits are too thin or clayey to be significant aquifers, but act as reservoirs that recharge the underlying Kingshill Marl. Only along the lower reaches of River Gut (fig. 3.1.2.A-1) are the alluvial deposits of sufficient extent and thickness to be of importance as an aquifer. The water from the alluvium of the central lowlands resembles a mixture of water from the Kingshill aquifer and from the fractured rock aquifer of the Northside Range in quality. In the upper reaches of River Gut, thick water-bearing alluvial deposits are associated with dioritic rocks that were intruded into the volcanic rocks. Elsewhere, the alluvial deposits generally fill coastal embayments at the mouths of streams. These alluvial deposits act as a recharge reservoir for the underlying fractured rock aquifer.

Well yields from the volcanic aquifers are generally inadequate for public supply, but may provide water for domestic use. The Kingshill aquifer is capable of yielding several hundred gal/min if wells were drilled through the entire saturated thickness, but the quality of water would be poor (Robison, 1972, p. 3). Wells in joints, isolated beds of limestone or sand and gravel within the marl yield 5 to 10 gal/min. Wells in the reef-associated limestone may yield between 10 and 300 gal/min (Jordan, 1975, p. 21). The Kingshill Marl is the principal aquifer supplying the Barren Spot and Concordia well fields. The alluvium, although too thin to provide much water in most areas, is the principal aquifer supplying the Adventure and Fairplain well fields. Well yield from the more productive areas of alluvium are between 10 and 50 gal/min (Jordan, 1975, p. 21).

3.1.2.E Ground-Water Levels and Movement

The ground-water surface in the fractured rock water-table aquifers of the East End and Northside Ranges is about 200 feet below land surface and generally follows the topography of the land surface. At the base of the mountains and in the mountain valleys, the water surface is about 50 feet below land surface. Ground-water levels were as much as 160 above mean sea level in 1962 (Jordan, 1975, p. 23).

The Kingshill aquifer is under water-table conditions. Water levels ranged from mean sea level to 100 feet above mean sea level in July 1987 (fig. 3.1.2.E-1). In general, ground-water levels and movement are controlled by the major valleys and movement is toward and down the valleys to the sea.

Water levels declined 20 feet or more in the mountains between 1940 and 1967, which probably explains a concurrent reduction in streamflow during the same period (Jordan, 1975, p. 24). Water levels have continued to decline and were about 5 feet lower in 1987 than in 1967 (Torres-González, 1991).

3.1.2.F Soil Permeability

Soil associations (fig. 3.1.2.F-1) developed on steep or strongly sloping areas include Descalabrado-Jácana and Cramer-Isaac, formed on volcanic rock; Aguilita-Fredensborg-Sion, formed on marly limestone; and Southgate-Parasol, formed on weathered granitic rock and alluvial fans (U.S. Department of Agriculture, 1970, p. 3-5). These soils are well drained but thin, and the areas covered are useful primarily for pasture or woodland. Permeability of these soil associations ranges from 0.2 to 2.0 in/hr (table 3.1.2.F-1).

Nearly level to gently sloping areas are covered by the Fraternidad-Aguirre-Glynn and Cornhill-Coamo-San Antón associations. These associations form on alluvial fans and flood plains, and range from well- to poorly-drained. Cornhill-Coamo-San Antón soils are suited only for pasture or woodland. The Fraternidad-Aguirre-Glynn soils are the only soils suited to agriculture, but are limited to certain crops. Permeability of these soil associations ranges from 0.06 to 0.60 in/hr.

Table 3.1.2.F-1 Thickness, permeability, and available water capacity for the soil associations in St. Croix, U.S. Virgin Islands (Modified from U.S. Department of Agriculture, 1970)

Area and soil association	Thickness (inches)	Permeability (inches per hour)	Available water capacity (inches per inches)
Descalabrado-Jácana	0 to 36	0.20 to 0.60	0.10 to 0.20
Aguilita-Fredensborg-Sion	0 to 20	0.60 to 2.00	0.10 to 0.20
Fraternidad-Aguirre-Glynn	0 to 60	0.06 to 0.20	0.10 to 0.20
Southgate-Parasol	0 to 60	0.20 to 0.60	0.10 to 0.20
Cramer-Isaac	0 to 72	0.60 to 2.00	0.15 to 0.20
Cornhill-Coamo-San Antón	0 to 60	0.20 to 0.60	0.10 to 0.20

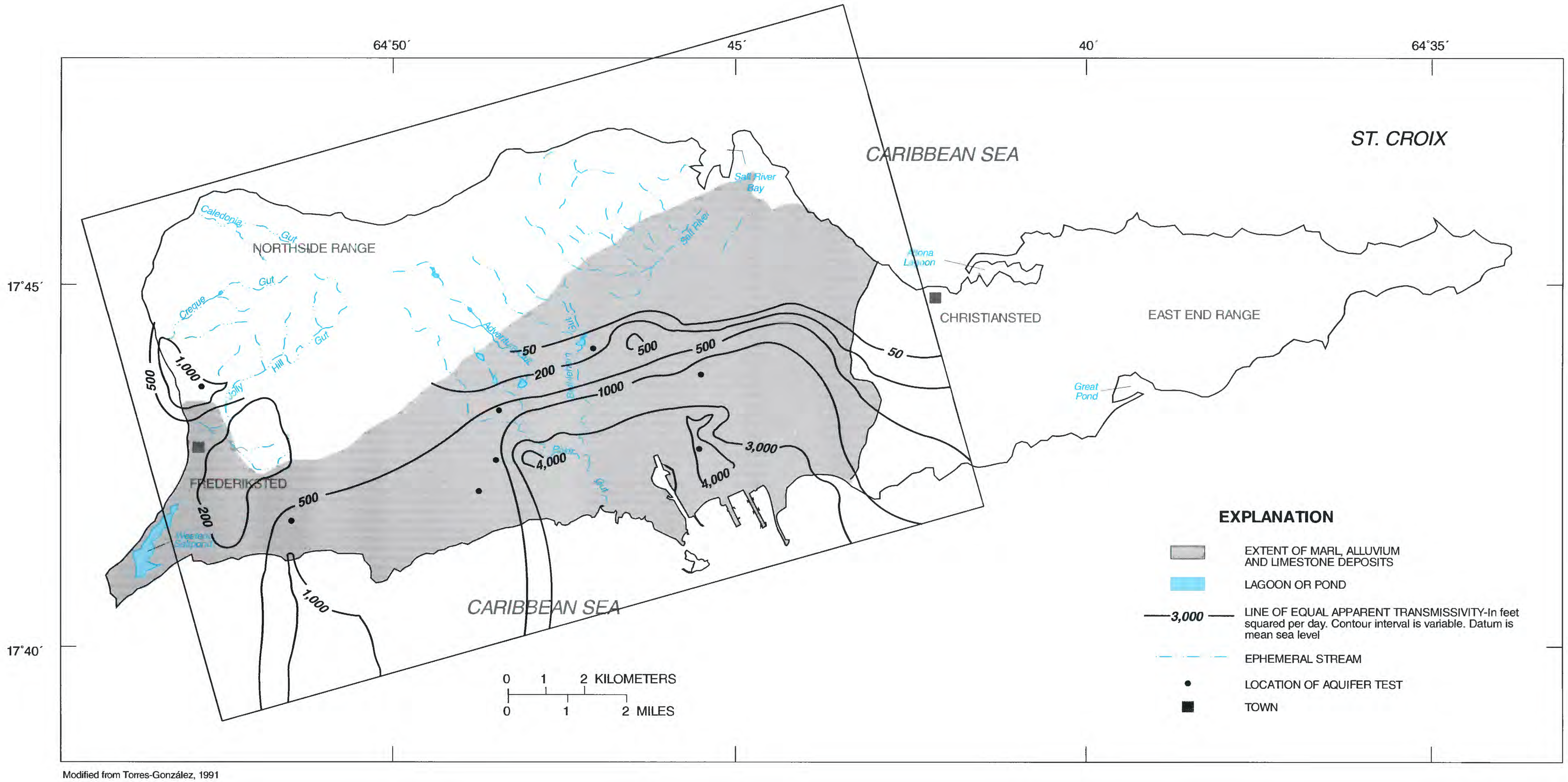
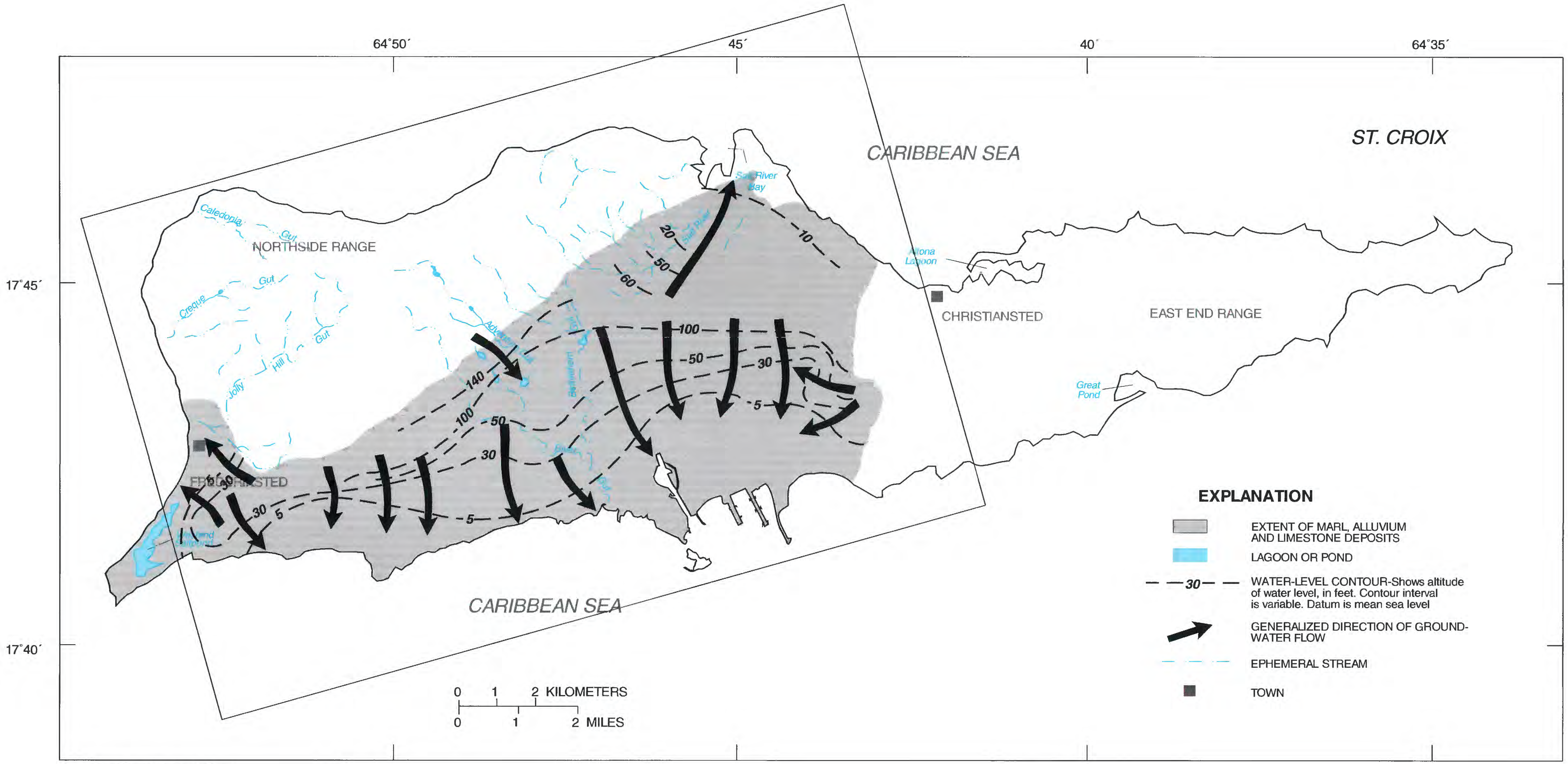
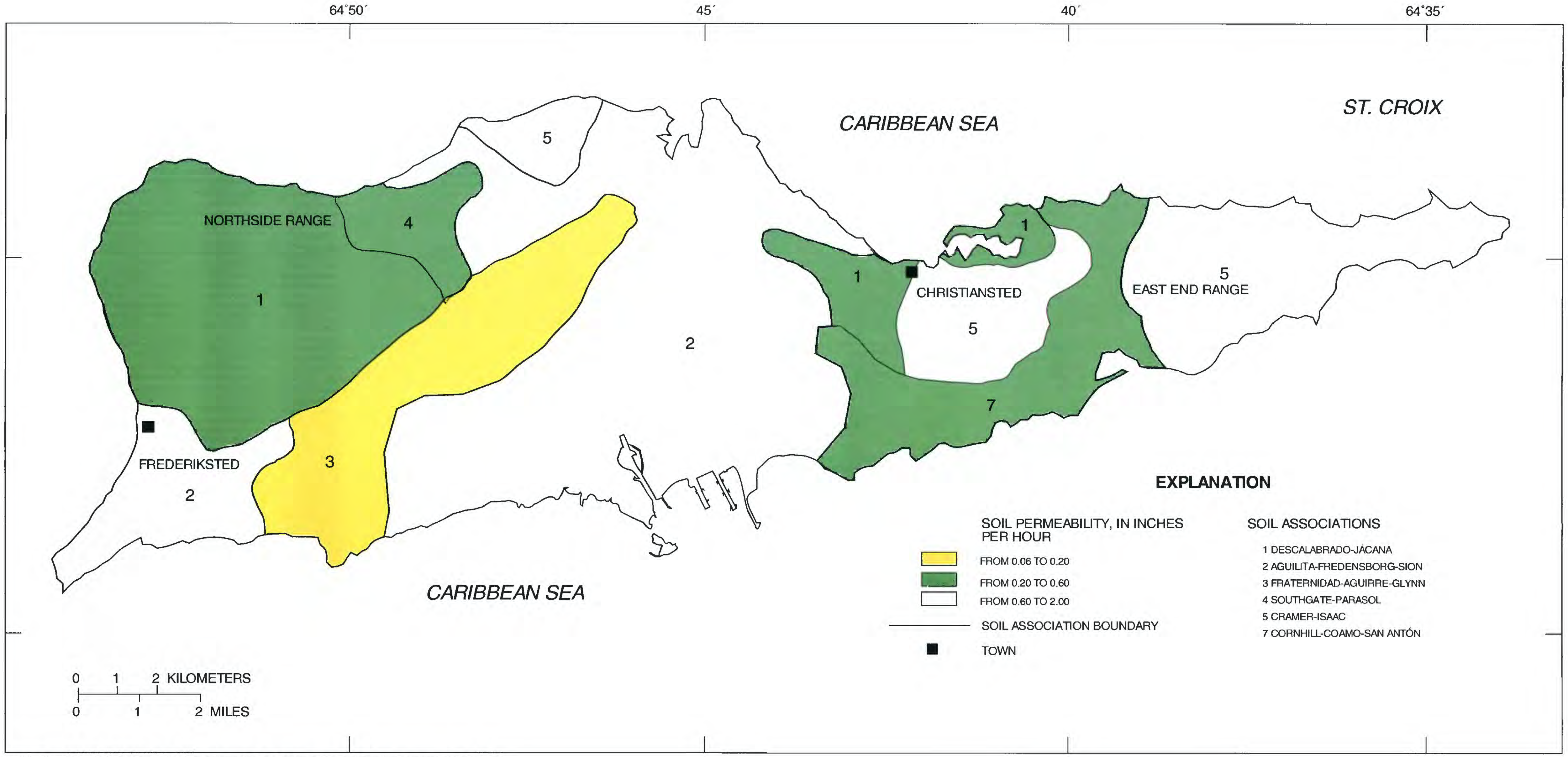


Figure 3.1.2.D-1 Transmissivity estimates at selected wells in the regionalized transmissivity distribution as obtained through model calibration in St. Croix, U.S. Virgin Islands.



Modified from Torres-González, 1991

Figure 3.1.2.E-1 Altitude of water-level surface and direction of ground-water flow during July 1987 in St. Croix, U.S. Virgin Islands.



Modified from Rivera and others, 1975; Gilberto Acevedo, Soil Conservation Service, written communication, 1990

Figure 3.1.2.F-1 Soil associations and permeability in St. Croix, U.S. Virgin Islands.

4.0 PRESENT AND POTENTIAL GROUND-WATER PROBLEMS IN PUERTO RICO AND THE U.S. VIRGIN ISLANDS

4.0 PRESENT AND POTENTIAL GROUND-WATER PROBLEMS IN PUERTO RICO AND THE U.S. VIRGIN ISLANDS

In this concluding section, present or potential problems related to ground water are discussed. Common problems include ground-water demand versus potential for development, possible contamination sources, sea-water encroachment, natural concentration of minerals in ground water, and consequences of ground-water development.

4.1 NORTH COAST AREA

4.1.1 Aguadilla-Hatillo Region

The Aguadilla-Hatillo region contains some of the most highly developed karst features on Puerto Rico. The presence of abundant sinkholes and solution cavities provide for rapid infiltration of any contaminants and very little, if any, attenuation of contaminants. Five active municipal landfills were reported for the Aguadilla-Hatillo region in 1977, and all of these landfills were developed in or adjacent to sinkholes, which would provide a direct pathway for leachate to enter the ground-water system (Torres-González and Gómez-Gómez, 1982). Karst features also provide potential pathways for contaminants, such as agricultural chemicals and petroleum products from leaking underground storage tanks (for example from gasoline station tanks), to enter the ground-water system.

Existing demand for water in the Aguadilla-Hatillo region is met primarily by water from Lago Guajataca. Additional urban and tourist-industry growth will result in additional demands for water, some of which could be supplied by ground water. However, because of the relatively thin aquifer, the potential for additional ground-water development is limited. Drilling of water-supply wells is expensive because of the great depth to the water table over much of the region. Also, yields to wells may be low unless a particularly productive zone is penetrated. Additional pumping near coastal areas, where the freshwater lens is thin, could induce inland movement of saline water and subsequent contamination of wells.

An additional problem in the Aguadilla-Hatillo region is the generally limited knowledge of the hydrogeologic system. Knowledge of such factors as aquifer hydraulic properties, depth to the water table, water quality, stream-aquifer relations, and areas of existing or potential contamination is essential in assessing the potential for additional ground-water development and contamination.

4.1.2 Arecibo-Manatí Region

Ground water from the upper unconfined and lower artesian is suitable for drinking and most other uses throughout the Arecibo-Manatí region; and development of the ground-water resources in the region has increased dramatically since the early 1970's. Pumpage from both aquifers increased from less than 8 Mgal/d in 1970 to more than 18 Mgal/d in 1982, of which the lower aquifer supplied about 5 Mgal/d. Yields of the upper aquifer are rapidly approaching a rate beyond which extensive sea-water encroachment could occur. Competition for ground water among industries, municipios, and agriculture is intense in the region and is expected to increase in the future.

The saltwater encroachment of sea water as the result of lowered water levels in the upper aquifer has affected public-supply wells completed in the limestone near the edge of the flood plain of the Río Grande de Manatí (Gómez-Gómez, 1984). Similar saltwater encroachment problems have been reported in wells at Central Cambalache in the flood plain of the Río Grande de Arecibo.

There are two known cases of ground-water contamination affecting the upper aquifer in the region. Both are related to organic compounds from the industrial area along Highway 2 near Cruce Dávila. In one case, a public water-supply well was contaminated by backflow of organic wastes from a nearby injection well (Angel Class-Cacho, U.S. Geological Survey, written communication, 1982). In the other case, water in a small area of the upper aquifer at Barceloneta was contaminated as a result of an accidental spill of carbon-tetrachloride (Zack and others, 1987a, p. 441). In the latter case, organic compounds were detected in a shallow injection well injecting organic compounds into the saline parts of the Aymamón Limestone.

Two industrial injection wells were drilled into the Lares Limestone in the late 1960's. Both wells are located near Cruce Dávila in the Highway 2 industrial area. One of the wells was used to inject acid waste and the other, mentioned previously, was used to inject organic wastes. Neither well is currently being used for injection. The high potentiometric surface overlying freshwater in the Lares Limestone, about 400 feet above mean sea level, could result in contamination of the upper or lower aquifers if the casings in these wells are ever breached by corrosion.

Drainage in karst areas is mostly underground and the abundance of sinkholes provides easy access for contaminants to reach the aquifers. Sinkholes, which are numerous in the Arecibo-Manatí region, have been used in the past for disposal of liquid and solid wastes by individuals and industries. In addition, at least three municipal landfills in the region were located in sinkholes. Sources of contaminants to the upper aquifer in the region include effluent from septic tanks and, in the more densely populated rural areas, effluent from sewage treatment plants.

4.1.3 Vega Baja-Toa Baja Region

Through the end of 1992, the only problem that has affected use of ground water in the Vega Baja-Toa Baja region was the discovery in 1983 of organic solvents at a public water-supply well in the vicinity of an industrial park at Vega Alta (Guzmán-Ríos and Quiñones-Márquez, 1984). The principal solvents detected were trichloroethylene (TCE) and tetrachloroethylene (PCE) in concentrations as high as 480 and 776 µg/L, respectively. Since 1983, five public water-supply wells have been closed, resulting in a yield loss of about 2 Mgal/d. This loss has been offset by increasing withdrawals in other wells and the construction of new wells in unaffected areas. The extent of aquifer contamination by volatile organics having a total concentration of 10 µg/L or more was determined to be about 2 mi^2 in 1985 (Bechtel Environmental, Inc., 1990).

The slow increase in dissolved-solids concentration that may result from saltwater encroachment along the coastal part of the aquifer could also become a major problem in the near future (Gómez-Gómez and Torres-Sierra, 1988). In general, all wells located northward of the karst tableland and within the coastal plain yield ground water that has dissolved-solids concentrations greater than 350 mg/L, and several major production wells have been abandoned as a result of increased salinity.

Although an assessment on the effect of septic tank infiltration to the aquifer has not been made, rapid population growth since 1980 and the relatively low percentage of housing units served by public sewers indicates that septic tank effects could become a problem in the foreseeable future. The soils that overlie the karst tableland, consisting principally of residuum deposits derived from weathering of the limestone rocks, have poor permeability. As a result, most septic tanks at areas underlain by blanket sands deposits are sited within near-surface exposures of carbonate rocks. The 1980 census estimated that there were approximately 9,860 housing units within Vega Alta and Dorado which were not connected to public sewage treatment facilities. Total nitrogen generated from this number of housing units could be about 240 tons per year based on an average of 3.6 persons per housing unit and 17 grams of nitrogen produced per person per day (17 grams of nitrogen represents the average protein consumption per person in United States).

4.1.4 Bayamón-Loíza Region

Urban and industrial development are reducing the recharge areas of the aquifers in the Bayamón-Loíza region due to the construction of buildings and paving of the open land. This decrease in recharge area affects the ground-water supply and could result in additional salt-water intrusion to the aquifers. The channelization of rivers may also reduce the recharge to the aquifers and affect local ground-water levels.

The water-use demand in the Bayamón-Loíza region is met principally with surface water from Lago Loíza and Lago La Plata. Due to the finite saturated thickness and low transmissivity of the aquifers in the Bayamón-Loíza region the development potential of aquifers to meet additional water demand is limited.

Leaky underground tanks and sewer lines are a potential source of ground-water contamination, especially in highly urbanized and industrial areas such as the San Juan metropolitan area. Contamination of the aquifers from industrial and domestic waste disposal practices is a potential problem in the region. Three landfills are located within the region, including the largest one on the island, which is located near Bahía de San Juan. In the southern part of the region where farmland dominates, livestock waste disposal may represent a potential ground-water contamination problem.

4.2 SOUTH COAST AREA

4.2.1 Santa Isabel-Patillas Region

The quality of ground water in the Santa Isabel-Patillas region makes it suitable for most uses. Dissolved solids concentration range from 130 to 2,500 mg/L, increasing toward the coast where seawater encroachment occurs. Seawater intrusion and use of fertilizers and pesticides in agriculture represent potential ground-water quality problems in the region. Although seawater intrusion has not been detected in the Santa Isabel-Patillas region, the potential exists for coastal areas in the vicinity of Bahía Jobos and between Río Descalabrado and Río Jueyes (Díaz, 1974, p. 23-24; Giusti, 1971, p. 24). Application of large quantities of fertilizers and pesticides represents a potential source of ground-water contamination. However, samples collected by the U.S. Geological Survey have shown no contamination in the aquifer with either fertilizers or pesticides. A reconnaissance sampling for organic compounds conducted in 1983 indicated no contamination with organics in the alluvial aquifer (Guzmán-Ríos and Quiñones-Márquez, 1985a and 1985b).

Simulations of ground-water flow have shown that east of the Río Jueyes, ground-water levels may decline if aquifer recharge from irrigation canal systems is diminished and actual ground-water pumpage is maintained (Sigfredo Torres-González, U.S. Geological Survey, written communication, 1987). Seawater intrusion may result from ground-water level declines. West of the Río Jueyes, the drip-irrigation system could diminish net recharge to the aquifer. Changes from furrow to drip irrigation are expected to reduce aquifer recharge by as much as 30 percent. Drip-irrigation implies a reduction in the ground-water demand in relation to furrow irrigation. However, according to a recent survey, ground-water pumpage in the region remains about the same (Orlando Ramos-Ginés and Angel Román-Más, U.S. Geological Survey, written communication, 1987).

Streamflow represents the major source of ground-water recharge in the area west of the Río Jueyes (Ramos-Ginés, 1993). Use of streamflow as a water source results in reduction of ground-water recharge, which in turn could cause an abrupt decline of the ground-water levels and possible seawater intrusion.

4.2.2 Juana Díaz-Ponce Region

The alluvial aquifer in the Juana Díaz-Ponce region generally has good-quality water, but its suitability for particular uses may be affected by water from underlying formations. Ground-water samples collected in the region show that the dissolved-solids concentration from the upper part of the alluvial aquifer may have increased as a result of mixing with water from either the Ponce Limestone or the Juana Díaz Formation. Consequently, ground-water development in the upper valley areas is limited, although the thickness of the alluvium and permeability are adequate. Additional development of ground water may be possible closer to the coast line. Although seawater intrusion has not been detected in the Juana Díaz-Ponce region in recent years, inadequate management of ground-water withdrawals could result in overpumping the aquifer and subsequent seawater intrusion. Stream water development may need to be limited in the Juana Díaz-Ponce region because streamflow is a major source of ground-water recharge. Reduction of ground-water recharge from streamflow may result in an abrupt decline of the ground-water levels and subsequent seawater intrusion.

The large quantities of fertilizers and pesticides used in agricultural areas represent another potential source of ground-water contamination. However, samples collected by the U.S. Geological Survey have shown no contamination in the aquifer by fertilizers or pesticides. A reconnaissance sampling for organic compounds conducted in 1983 indicate the presence of methylene chloride extractable and tetrachloroethylene in two of four wells sampled in the region (Guzmán-Ríos and Quiñones-Márquez, 1985a and 1985b).

4.2.3 Peñuelas-Guánica Region

Although available ground-water resources in the Peñuelas-Guánica region seem to be adequate to supply the present water needs, the aquifer is sensitive to changes in recharge patterns. Results of simulations made with electric analog and digital ground-water flow models indicate that diminished ground-water availability and seawater intrusion problems may occur if recharge into the aquifer decreases markedly (Bennett, 1976, p. 70-71; Quiñones-Aponte, 1986b, p. 31). These studies indicate that aquifer recharge is very sensitive to streamflow conditions and seepage from irrigation channels. As streamflow increases by releasing more water from headwater reservoirs, aquifer recharge also increases. Furrow irrigation is another major source of aquifer recharge, and any decrease in this recharge source could result in future lower water levels if ground-water withdrawals remain the same.

Ground water in the Peñuelas-Guánica region is suitable for most uses. Dissolved-solids concentrations in water within the alluvial aquifer range from 160 to 260 mg/L in the Tallaboa Valley (Grossman and others, 1972, p. 81), from 200 to 450 mg/L in the Guayanilla-Yauco Valleys and coastal plain (Crooks and others, 1968, p. 51), and from 130 to 800 mg/L in the Río Loco Valley (McClymonds, 1967, p. 40). In general, dissolved-solids concentrations increase toward the coast. Near the limestone hills, ground water is slightly higher in dissolved-solid concentrations (Grossman and others, 1972, p. 82). Seawater encroachment in lower valley areas and coastal plains may affect the suitability of ground water as total dissolved solids increase from 250 mg/L to seawater concentrations. Wells in coastal areas may yield water that ranges from fresh (shallow wells) to brackish (seawater upconing due to heavy pumpage) to salty (deep wells). For instance, any attempt to use and divert most of the river water within the valley could produce an inland advance of the salt-water wedge, because streamflow seepage into the aquifer is the major source of aquifer recharge (Grossman and others, 1972, p. 101). Seawater also may intrude into the aquifer through streambeds if lower streams reaches are channelized in order to provide better local drainage and to accelerate flood runoff

(Grossman and others, 1972, p. 98). Waste-water discharges to streams also could affect ground-water quality through stream seepage. A reconnaissance sampling for organic compounds conducted in 1983 found no detectable contamination with organics at public water-supply wells in the alluvial aquifer (Guzmán-Ríos, and Quiñones-Márquez, 1985a and 1985b).

4.3 WEST COAST AREA

4.3.1 Añasco Region

Díaz and Jordan (1987) documented evidence of inland movement of saltwater in 1981 and 1982. Saltwater was reaching the alluvium through Caño La Puente and Caño Boquilla. High concentrations of chloride were detected in water samples from swamp and marsh areas near these two streams, probably due to high evapotranspiration rates that characterize these areas. Chloride concentrations of 100 mg/L were detected in water samples as far as 1.5 miles inland in the Caño La Puente area during June 1981, and as far as 1.8 miles inland in February 1982 (Díaz and Jordan, 1987, p. 41).

Another potential ground-water problem is contamination from septic-tank effluents where residential areas overlie the aquifers. In the Añasco region, where about 43 percent of all residential units use a septic tank or cesspool (U.S. Department of Commerce,1982), major residential areas are located over the lower valley aquifer.

Although ground-water use in this region is limited, ground-water quality is generally suitable for most uses, and is within the U.S. Environmental Protection Agency limits for drinking water (U.S. Environmental Protection Agency, 1976; Díaz and Jordan, 1987, p. 42).

4.3.2 Guanajibo Region

According to Colón-Dieppa and Quiñones-Márquez (1985, p. 42), ground-water in the central Guanajibo Valley is generally suitable for most uses, including irrigation. High concentrations of sulfate and nitrates were detected in samples from two wells in the valley. In 1967, a sample obtained from a well had sulfate concentrations that exceeded the secondary maximum contaminant levels (U.S. Environmental Protection Agency, 1976). Another well, showed similar results, exceeding the recommended U.S. Environmental Protection Agency drinking standards for sulfate concentrations in 1980. Both of these wells are located downstream from urban areas, which suggests that they were affected by domestic contamination (Colón-Dieppa and Quiñones-Márquez, 1985, p. 42).

The San Germán municipal landfill cover material is very permeable and leached substances from the landfill have contaminated an adjacent creek that drains to the Río Guanajibo (Torres-González and Gómez-Gómez, 1982, p. 115). This represents a potential source of contamination for the ground-water resources of the region.

4.3.3 Lajas Region

The development of ground-water supplies in the Lajas region could be limited due to the high mineral content of the ground water. Samples were collected from 20 wells in the Lajas Valley and analyzed for principal cations and anions, iron, manganese, barium, and aluminum. Water samples from 19 of these wells had dissolved-solids or chloride concentrations that exceeded the secondary maximum contaminant levels for drinking water standards of 500 and 250 mg/L, respectively (U.S. Environmental Protection Agency, 1973). Samples from 13 of the 20 wells had concentrations of dissolved iron or manganese that exceeded the secondary maximum contaminant level for drinking water standards of 0.3 and 0.05 mg/L, respectively (U.S. Environmental Protection Agency, 1986).

The high concentration of dissolved solids found in most of the samples was due primarily to high concentrations of sodium and chloride ions. An analysis of 75 ground-water samples collected from wells located throughout the valley had chloride concentrations ranging from 20 to 6,760 µg/L.

4.4 EAST COAST AREA

4.4.1 Naguabo-Maunabo Region

The development of surface-water supplies in the Naguabo-Maunabo region are limited because topography precludes the construction of reservoirs in the upper stream reaches, and sewage contamination inhibits development in the lower reaches. Future development will probably rely on ground water for industrial, agricultural, and domestic supply. Large-scale ground-water development will be limited to the alluvial aquifers that are presently the most developed.

Ground-water development in the upland areas will be small because yields to wells generally range from 5 to 50 gal/min. The development of agriculture in the upland areas represents a potential non-point source of pollution to these aquifers from fertilizers, herbicides, and insecticides and point-source pollution by waste from dairy-cattle farms. The location of municipal landfills in the upland areas represents additional point sources of pollution to the aquifer. Pollution of the aquifer from this latter source is generally limited in areal extent.

The low transmissivity of the alluvial aquifer within the Humacao-Naguabo area limits its potential for development. This contrasts with the fact that large industrial and urban development is planned for the region. In addition, the effects of any future ground-water development on lagoons and wetlands in the region should be evaluated. These lagoons and wetlands, which depend on ground water as their major water source, have been recognized by the PRDNER as areas of great ecological importance. Other aspects of ground-water resources that need to be considered in the Humacao-Naguabo area are: (1) potential contamination from the Humacao municipal landfill (Torres-González, and Gómez-Gómez, 1982, p. 71); (2) seawater encroachment, particularly in the area between the Río Antón Ruiz and Río Santiago; (3) high concentrations of iron and manganese in the ground water; (4) potential contamination of the aquifer by industrial spills; and (5) potential contamination from river seepage (Torres-González and Gómez-Gómez, 1982).

The potential for additional development of the alluvial aquifer in the Yabucoa valley seems to be promising in terms of water availability. Nevertheless, any industrial spill from the oil refinery could impair the potential for future development. Saltwater intrusion into the aquifer probably occurs along the ship channel and port facilities at the refinery and near the mouths of the Río Guayanés and Caño de Santiago. Both streams are contaminated by sewage effluent. Additional ground-water development could cause a reversal in the ground-water gradient along the streams, thus inducing infiltration of seawater or contaminated water from the streams. Excessive pumping could draw seawater into the aquifer in the coastal area. The presence of high concentrations of iron and manganese in the ground water locally affects the suitability of the water for some uses.

The alluvial aquifer of the Maunabo valley has potential for additional development. Potential and existing problems are similar to those of the Yabucoa Valley: potential contamination by infiltration of sewage effluent from the Río Maunabo or seawater near the river mouth; seawater encroachment as the result of excessive pumpage; and local water-quality problems due to naturally occurring iron and manganese.

4.5 EAST CENTRAL AREA

4.5.1 Aguas Buenas-Juncos Region

Analyses of ground water from the area indicate localized water-quality problems, including high concentrations of iron and manganese and selected volatile organic compounds. The use of underground tanks that store fuel or other substances within the Caguas and Gurabo-Juncos valleys is a threat to ground-water quality. Livestock waste is commonly disposed of on the land surface and, in some instances, into ponds excavated in the unsaturated zone directly above the water-table aquifer. These wastes may leach into the aquifer. The use of agricultural chemicals in the area also is a potential source of ground-water contamination.

Municipal landfills constitute a potential source of ground-water contamination in the Aguas Buenas-Juncos region, particularly landfills that are located near or within the alluvial valley boundaries. There are five landfills in the region, of which three have been closed. One of the closed landfills is the old Juncos landfill, which has been included in the U.S. Environmental Protection Agency "National Priority List" of contaminated sites for clean-up purposes.

The public wastewater disposal and treatment systems may also be a source of contamination. For example, in the city of Caguas, urban sewer pipes and the wastewater treatment plants lie directly above the aquifer and any leakage could introduce wastewater into the aquifer. Many communities that are not connected to the public sewer system use septic tanks or sewer trenches or discharge untreated wastewater directly into nearby creeks or streams. Production wells located near areas of contaminated or poor-quality water may not produce water suitable for public supply unless the water undergoes extensive treatment.

Much of the available surface water of the Aguas Buenas-Juncos region flows into Lago Loíza and is exported to San Juan (about 80 Mgal/d). If a ground-water supply is developed near streams, the hydraulic gradient from the river into the aquifer will increase, which would induce seepage from the river. This would improve well yield and decrease streamflow. However, a minimum river flow is necessary to sustain the required inflow into Lago Loíza reservoir. It might be difficult to maintain the required inflow during droughts if the amount of induced seepage from the river to the aquifer is large.

4.6 PUERTO RICO OFFSHORE ISLANDS

4.6.1 Isla de Culebra and Isla de Vieques

The fractured rock aquifer of Isla de Culebra is considered a set of independent aquifers: the aquifer in each drainage basin is separated from the aquifer in adjacent basins by a ground-water divide. Although ground-water resource is scarce, existing or potential pollution of an aquifer, therefore, will usually affect a single basin. The ground water on Isla de Culebra is rich in mineral concentrations, which, in most cases, exceed EPA standards for drinking water. Dissolved-solids concentration range from 500 to 1,000 mg/L. This condition is a result of airborne particulates that fall in the land surface and infiltrate the aquifer during periods of recharge, evapotranspiration in the soil zone, and the limited amount of recharge. The most serious potential threat to ground water on Isla de Culebra are effluents from septic tanks. The effluents can quickly infiltrate through the thin soil and saprolite zone and enter the fractured bedrock aquifer in a nearly unfiltered, unaltered state. The greater the concentration of septic tanks in an area, the greater the potential threat to the aquifer.

On Isla de Vieques, although ground water is more abundant and alluvial deposits are more extensive than on Isla de Culebra, evapotranspiration affects ground-water quality. High sodium concentrations in the ground water due to overpumpage may limit its use for agricultural purposes (Torres-González, 1989). Septic tank effluents pose the same potential threat to the fractured rock aquifers on Isla de Vieques as on Isla de Culebra. On that part of Isla de Vieques underlain by plutonic rocks, the soil and saprolite zone is thicker than in the area underlain by volcanic rocks. However, because the soil is more permeable in areas of saprolite than in areas that have the Pandura-Rock Land-Patillas association, the rate of movement of septic-tank effluents would still pose a threat to the aquifer.

Some sea water encroachment has occurred in the Puerto Rico Aqueduct and Sewer Authority well field in the alluvial aquifer at Esperanza on the south coast of Isla de Vieques because of over pumping. The alluvial aquifer at the north end of the Resolución valley also is susceptible to sea water encroachment. Withdrawals in excess of 0.40 Mgal/d could induce saline water intrusion and, during a drought, saline water intrusion could occur at pumpages as low as 0.20 Mgal/d (Torres-González, 1989, p. 35).

4.7 U.S. VIRGIN ISLANDS

4.7.1 St. Thomas and St. Johns

Ground water has been polluted by sewage effluent on St. Thomas. High concentrations of fecal coliform and fecal streptococci bacteria have been found in water from wells on both islands (Zack and others, 1987b). An estimated 20,000 to 25,000 people use septic tanks. The thin soil zone, usually less than 2 feet thick, is not capable of filtering the effluent wastes. The effluent either escapes to the surface or enters the open joints and fractures of the bedrock and, subsequently, the ground-water reservoir.

Residents on St. John also rely upon septic tanks for sanitary waste disposal. As the same hydrogeologic conditions prevail on St. John as on St. Thomas, effluents from septic tanks can pose the same hazard to the ground water on St. John.

4.7.2 St. Croix

The major issues of concern for ground-water supplies are (1) the growing population and tourism that increase the demand for water, (2) contamination by hazardous wastes, septic tanks, and leaky sewage lines and infiltration of sewage treatment plant discharges, and (3) saltwater intrusion (Troester, 1988).

The Kingshill Marl provides most of the ground water for St. Croix, but the overall quality is poor. The water exceeds the EPA secondary drinking water standards for dissolved solids and chloride; median concentrations are 1,440 mg/L and 560 mg/L, respectively (Zack and others, 1987b, p. 489). Reverse osmosis has been used as a means of improving the quality of water from this aquifer. Excessive ground-water pumping from the Kingshill aquifer, particularly near the coast, has caused saltwater upconing and encroachment (Zack and others, 1987b, p. 489), which further degrades the water quality.

Contamination by fecal coliform and fecal streptococci bacteria are common in the aquifers (Zack and others, 1987b, p. 491). Septic-tank effluent is a problem in the Kingshill aquifer where residential housing is concentrated. The effluent is often inadequately filtered by the thin soil, and contamination can become widespread in areas of fractured rock aquifers. Breakdowns or overloads in the sewage-treatment plants generally result in a discharge of effluent to dry streambeds, which are major ground-water recharge areas. This practice increases the potential for effluent to contaminate the aquifers (Zack, and others, 1987b, p. 492).

Solid waste has been deposited for many years in the vicinity of Krause Lagoon, but the effect on the underlying Kingshill aquifer is minor because water in the aquifer is brackish, and the ground-water gradient causes mixing of better quality water from inland.

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