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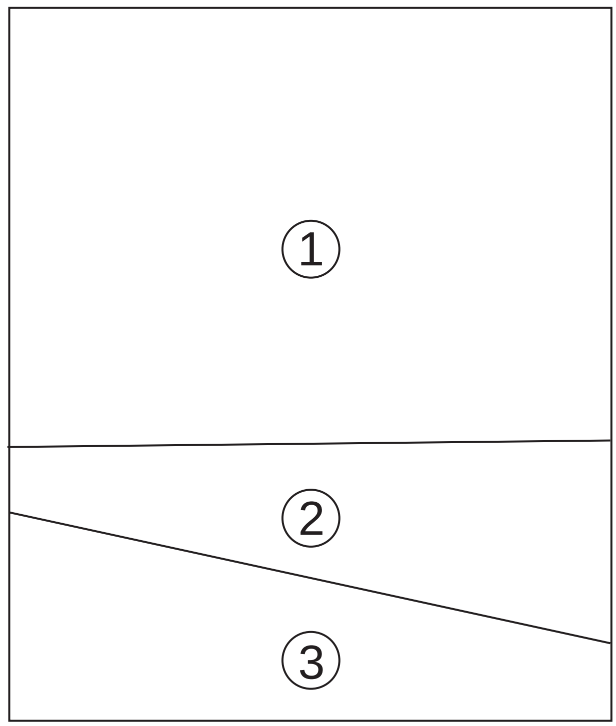
PUERTO RICO DEPARTMENT OF NATURAL AND ENVIRONMENTAL RESOURCES
PUERTO RICO LAND AUTHORITY

Effects of Aquifer Development and Changes in Irrigation Practices on Ground-Water Availability in the Santa Isabel Area, Puerto Rico

WATER-RESOURCES INVESTIGATIONS REPORT 03-4303

USGS



Cover photographs

(1) Modern drip irrigation well at Hacienda Florida, Santa Isabel, Puerto Rico.
(2) Ruins of an early 1900s irrigation canal southeast of Central Cortada, Santa Isabel, Puerto Rico.
(3) Lettuce crop near Central Cortada, Santa Isabel, Puerto Rico.

Photographs taken by José M. Rodríguez, U.S. Geological Survey, February 2003.

Effects of Aquifer Development and Changes in Irrigation Practices on Ground-Water Availability in the Santa Isabel Area, Puerto Rico

By Eve L. Kuniansky, Fernando Gómez-Gómez, and Sigfredo Torres-González

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Conversion Factors Datum

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
Flow rate		
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
gallon per day per square mile [(gal/d)mi^2]	0.001461	cubic meter per day per square kilometer [(m^3/d)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per hour (in/h)	0 .0254	meter per hour (m/h)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Specific capacity		
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s/m]
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)
Transmissivity*		
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [($ft^{3/}$d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

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

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Effects of Aquifer Development and Changes in Irrigation Practices on Ground-Water Availability in the Santa Isabel Area, Puerto Rico

By Eve L. Kuniansky, Fernando Gómez-Gómez, and Sigfredo Torres-González

Abstract

The alluvial aquifer in the area of Santa Isabel is located within the South Coastal Plain aquifer of Puerto Rico. Variations in precipitation, changes in irrigation practices, and increasing public-supply water demand have been the primary factors controlling water-level fluctuations within the aquifer. Until the late 1970s, much of the land in the study area was irrigated using inefficient furrow flooding methods that required large volumes of both surface and ground water. A gradual shift in irrigation practices from furrow systems to more efficient micro-drip irrigation systems occurred between the late 1970s and the late 1980s. Irrigation return flow from the furrow-irrigation systems was a major component of recharge to the aquifer. By the early 1990s, furrow-type systems had been replaced by the micro-drip irrigation systems. Water levels declined about 20 feet in the aquifer from 1985 until present (February 2003).

The main effect of the changes in agricultural practices is the reduction in recharge to the aquifer and total irrigation withdrawals. Increases in ground-water withdrawals for public supply offset the reduction in ground-water withdrawals for irrigation such that the total estimated pumping rate in 2003 was only 8 percent less than in 1987. Micro-drip irrigation resulted in the loss of irrigation return flow to the aquifer. These changes resulted in lowering the water table below sea level over most of the Santa Isabel area. By 2002, lowering of the water table reversed the natural discharge along the coast and resulted in the inland movement of seawater, which may result in increased salinity of the aquifer, as had occurred in other parts of the South Coastal Plain.

Management alternatives for the South Coastal Plain aquifer in the vicinity of Santa Isabel include limiting ground-water withdrawals or implementing artificial recharge measures. Another alternative for the prevention of saltwater intrusion is to inject freshwater or treated sewage effluent into wells along the coast. A digital ground-water flow model was developed to provide information for water managers to evaluate some of these alternatives. After calibration of the ground-water model to historical data, four simulations of ground-water management strategies were performed: ground-water conservation, surface infiltration over existing agricultural fields, or infiltration along streams and canals, or injection wells along the coast.

Simulations of four alternative water management strategies indicate that current condition of water levels below sea level near the coast can be reversed to raise water levels above sea level by either: (1) about a 27 percent reduction in 2003 ground-water withdrawal rates; (2) application of about 1,700 million gallons per year of artificial recharge over more than half of the current agricultural areas; (3) injection of about 3 million gallons per day (1,095 million gallons per year) of freshwater or treated wastewater in wells distributed along the coast; (4) injection of about 3.5 million gallons per day (1,280 million gallons per year) of freshwater or treated wastewater in wells distributed along canals and streams.

Introduction

The alluvial aquifer in the area of Santa Isabel is located within the South Coastal Plain aquifer of Puerto Rico (fig. 1). The South Coastal Plain aquifer is composed of coalescing fan delta deposits that underlie the broad coastal plain that extends from east of the city of Patillas westward to west of the city of Ponce. Ground water in the area has been developed as a source of public and irrigation water supplies since about 1910.

Variations in precipitation, changes in irrigation practices, and increasing public supply demand have been the primary factors controlling water-level fluctuations within the aquifer. Figure 2 illustrates these factors by graphically displaying water levels from 1967 to 2002 at observation well Alomar 1, with annual precipitation and an estimated water budget for the study area (not including ground-water discharge to or from the sea). Until the late 1970s, much of the land in the study area was irrigated using inefficient furrow flooding methods that required large volumes of both surface and ground water (Gómez-Gómez, 1987). A gradual shift in irrigation practices from furrow systems to more efficient micro-drip irrigation systems occurred between the late 1970s and the late 1980s.

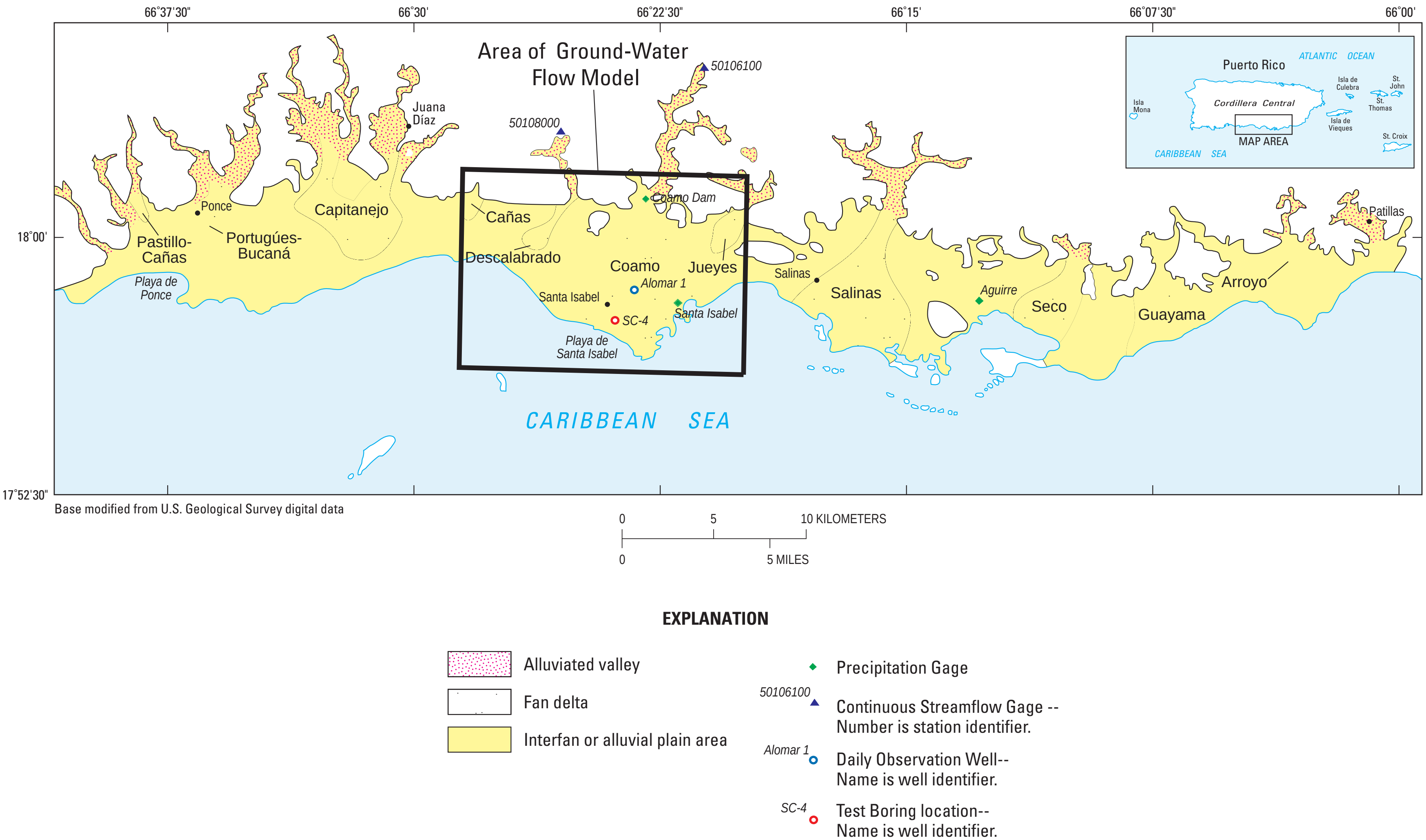


Figure 1. Location of ground-water flow model (study area) and extent of fan deltas of the South Coastal Plain aquifer, Puerto Rico (modified from figure 13, Renken and others, 2002).

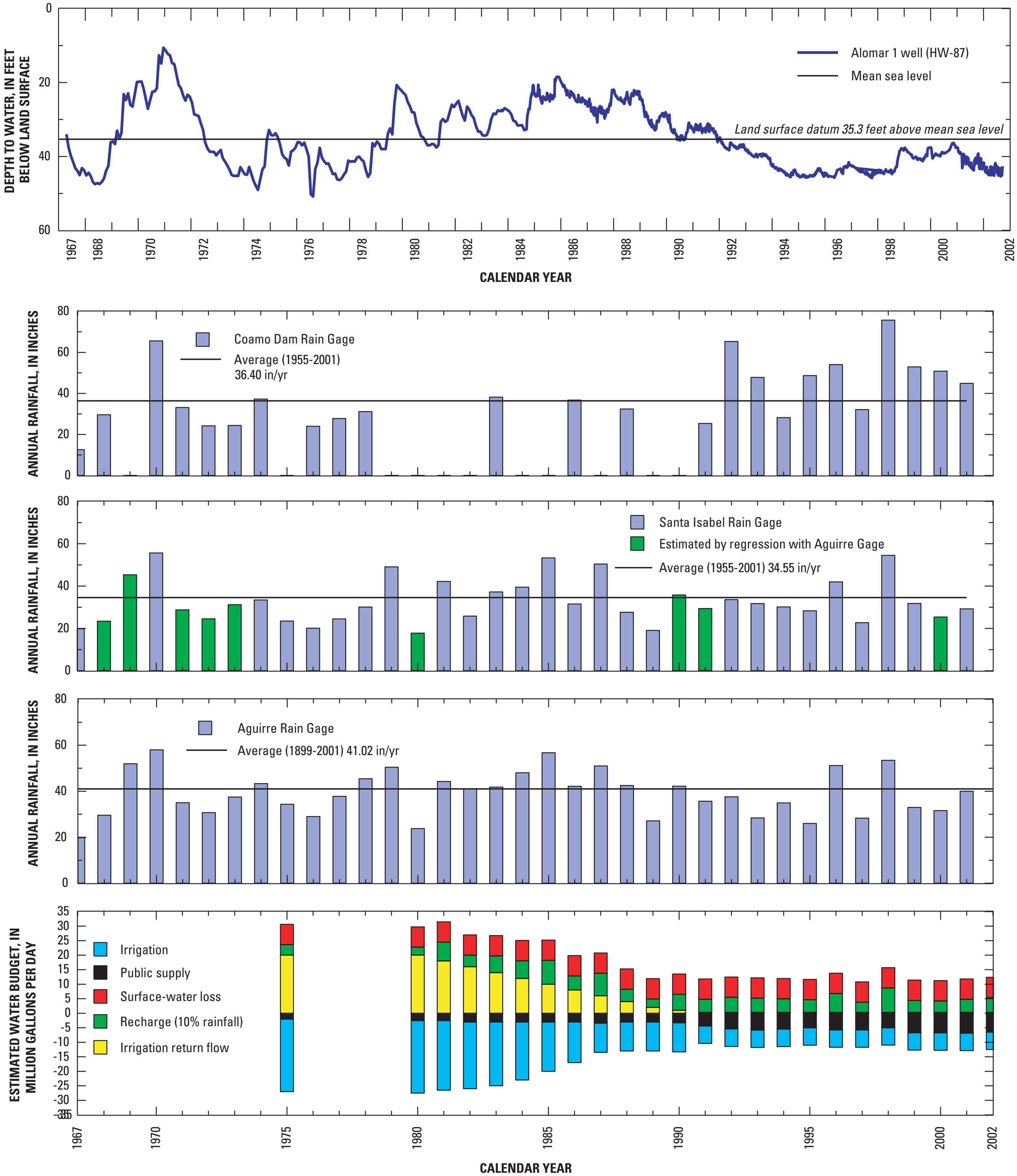


Figure 2. Comparison of ground-water levels, annual rainfall, and estimated ground-water budget, Santa Isabel, Puerto Rico.

Along with the recharge from precipitation and streamflow losses to the alluvial aquifer, irrigation return flow from the furrow-irrigation systems (30 to 50 percent of the applied water) was a major component of recharge to the aquifer until this method of irrigation was gradually phased out. By the early 1990s, furrow-type systems had been replaced by micro-drip irrigation systems, reducing both irrigation return flow and irrigation ground-water withdrawals. As the irrigation withdrawals decreased, public supply withdrawals gradually increased. Water levels declined about 20 ft in the aquifer since 1988 until present (February 2003) creating the potential for saltwater intrusion because water levels have remained below mean sea level. In order to investigate the effects of aquifer development and the changes in irrigation practices on ground-water availability at Santa Isabel, Puerto Rico, the U.S. Geological Survey (USGS) in cooperation with the Puerto Rico Land Authority and Department of Natural Resources began a water-resources investigation in 2001.

Management alternatives for the alluvial aquifer in the Santa Isabel area include limiting ground-water withdrawals or implementing artificial recharge measures or both. Artificial recharge is defined as any method used to increase recharge to an aquifer by introducing water that would not naturally be present (American Society of Civil Engineers, 2001). Artificial recharge can be accomplished by increasing surface-water infiltration with in-channel or off-channel means. In-channel methods can include in stream dams and weirs or levees to back up water across the flood plain. Off-channel methods involve the development of canals or other structures that route floodwater from the stream to spread over fields. Additionally, artificial recharge may be accomplished with injection wells for pumping freshwater into the aquifer. Another alternative for the prevention of saltwater intrusion is to inject freshwater into wells along the coast. These alternatives can be evaluated quickly and economically with a digital ground-water flow model.

Purpose and Scope

The purposes of the study are to estimate the amount of surface and ground water withdrawn by the various water users in the Santa Isabel area and construct a digital ground-water flow model of the freshwater part of the South Coastal Plain aquifer in the vicinity of Santa Isabel (also referred to as alluvial aquifer in this report), in order to test alternative ground-water management strategies for raising ground-water levels above sea level. The report summarizes the history of water-resources development, changes in irrigation practices, and the construction and calibration of the ground-water flow model of the alluvial aquifer in the Santa Isabel area. Simulations of ground-water management strategies involving ground-water conservation, surface infiltration over existing agricultural fields or along streams and canals, or injection wells along the coast are also presented.

Description of Study Area

In the Santa Isabel area, the alluvial aquifer extends approximately 9 miles (mi) in the east-to-west direction and a maximum of approximately 6 mi in the north-to-south direction, encompassing about 50 square miles (mi^2) (fig. 1). The coalesced fan deltas of the alluvial aquifer are bordered to the north by intensely faulted low hills that progressively rise in altitude from about 160 feet (ft) at the inland boundary of the coastal plain to as much as 2,300 ft above mean sea level at the Cordillera Central mountain chain. The coast along the Santa Isabel area is composed of mangrove swamps and tidal flats.

Sugarcane cultivation was the principal land use in the Santa Isabel area until the 1970s, when gradually replaced by vegetable, fruit, row crops, and seed production crops. Since the late 1980s, the diversification of agricultural activities has made the commercial production of fruits and vegetables a principal economic activity in the area.

Previous Investigations

Reports that describe the geology of Puerto Rico's South Coast ground-water province include Pessagno (1960, 1963), McClymonds and Ward (1966), Moussa and Seigle (1970, 1975), Glover (1971), Monroe (1973, 1980), Krushensky and Monroe (1975, 1978, 1979), Frost and others (1983), and Erikson and others (1990). Bennet (1976) developed an analog ground-water flow model of the South Coast ground-water province. Reports that describe hydrology and hydrogeology of the South Coast ground-water province include McClymonds (1967, 1972), Crooks and others (1968), Díaz (1977a, b; 1979a), Giusti (1966, 1971a, b), Grossman and others (1972), McClymonds and Díaz (1972), Heisel and González (1979), Gómez- Gómez (1987), Quiñones-Aponte (1991), Quiñones-Aponte and Gómez- Gómez (1987), Román-Más and Ramos-Ginés (1987), Rodríguez-del-Río and Gómez-Gómez (1990), Ramos-Ginés (1994), Renken and others (1995), Renken and others (2002). Díaz (1974, 1979b) published information about salinity monitoring and seawater intrusion on the south coast of Puerto Rico. Quiñones-Aponte and others (1997) developed a digital ground-water flow model of the adjacent coastal aquifer to the east of the study area between Salinas and Patillas, Puerto Rico. The geohydrologic framework for this study is described in detail in Renken and others (2002) and the ground-water flow model developed for this study and described in that report is based on this framework. The hydrochemistry of the South Coastal Plain aquifer is described in Gómez-Gómez (1991).

Hydrologic Setting

The orographic effect of the Cordillera Central Mountains creates conditions typical of a semiarid tropical region in the Santa Isabel area. Precipitation is characterized by a relatively wet season from August through November and a relatively dry season from January through April (fig. 3). McClymonds and Díaz (1972) indicated that ground-water levels are more sensitive to dry and wet seasons than ground-water pumpage from the aquifer. However, ground-water withdrawals at the time of the McClymonds and Díaz (1972) study were mainly for sugarcane crops irrigated with furrow irrigation. The effect of the ground-water withdrawals on ground-water levels is probably offset by recharge from irrigation return flow.

Mean-annual rainfall over the South Coastal Plain (fig. 1) is generally about 45 inches, which is 25 inches less than along the North Coastal Plain. The difference in rainfall between the two coastal areas is due to the orographic effect of the Cordillera Central Mountain chain. These mountains partially block the northeast trade winds, producing a partial rain shadow effect over the South Coastal Plain. However, rainfall on the south side of the mountain range averages 78 inches per year (in/yr) (Gómez-Gómez, 1979). Mean-daily temperatures range from 67 to 90 degrees Fahrenheit throughout the year. Local wind direction is usually from east-to-southeast and wind velocities are less than 7 miles per hour (mi/hr) (McClymonds and Díaz, 1972).

Rainfall and Evapotranspiration

The mean-annual rainfall at the Santa Isabel rain gage is 34.55 and 36.40 in/yr at the Coamo Dam rain gage just north of Santa Isabel but south of the Cordillera Central (figs. 1 and 2). Daily rainfall at Santa Isabel (1955-2001), on average, exceeds 0.1 inch 115 days of the year. As can be observed on figure 3, the mean-monthly rainfall at Santa Isabel exceeds 1 inch from April through December and exceeds 2 inches in May and from July through November. At Santa Isabel, the probability that rainfall will exceed 0.1 inch on a given day averages about 13 percent (fig. 3).

Evapotranspiration (ET) from the alluvial aquifer occurs from areas where the water table is very close to land surface, such as in the coastal mangrove swamps. Based on electric analog model results, Bennett (1976) estimated a maximum ET rate of about 65 in/yr when the water table is near land surface, decreasing linearly with depth to 0 in/yr once the water table drops below 6 ft from land surface. However, pan evaporation rates are about 80 in/yr, which translates to an estimated range of 50 to 60 in/yr for ET if using pan coefficients of 0.6 to 0.7, respectively. Throughout much of the aquifer, the depths to water exceed 10 ft below land surface. Thus, significant rates of ET from the alluvial aquifer at Santa Isabel probably occur along a narrow area along the coast where the water table is near land surface. Evapotranspiration data were not collected as part of this study.

Streamflow

The principal streams in the study area from west-to-east are the Río Cañas, Río Descalabrado, Río Coamo, and the Río Jueyes (fig. 4). These streams flow across the alluvial aquifer from the mountains south towards the sea. All except the Río Jueyes are intermittently flowing streams within the coastal plain. The Río Jueyes is an ephemeral stream, flowing only during extreme rainfall events. Base flow, at the edge of the mountains, recharges the alluvial aquifer as these intermittent streams cross the South Coastal Plain. Most streams lose their base flow through downward percolation of water to the alluvial aquifer and do not flow across the entire coastal plain except during storm events. However, there are times when the water table is above the stream channel and there is ground-water discharge to the streams near the coast. The Río Coamo has the largest flows and flows a longer distance over the coastal plain more of the time than the Río Cañas and Río Descalabrado.

Along with natural streams, a series of irrigation canals have been constructed to convey surface water to the agricultural areas. The most important irrigation canal is the Juana Díaz canal, which conveys surface water from Lago Guayabal (fig. 4) west of the study area to the Santa Isabel area.

Infiltration from streams to the alluvial aquifer along the coastal plain was estimated by Giusti (1966) for the Río Cañas and Río Descalabrado. Giusti's (1966) estimates were 0.97 cubic feet per second (ft^3/s) from the Río Cañas and 1.5 ft^3/s from the Río Descalabrado. These estimates include both base flow infiltration and storm flow infiltration.

Based on miscellaneous, instantaneous stream discharge measurements made during this study and in 1987 by Rodríguez-del-Río and Gómez-Gómez (1990), the estimated base flow component of recharge to the alluvial aquifer is greater than 3.0 ft^3/s for the Río Coamo, 0.6 ft^3/s for the Río Cañas, and 0.3 ft^3/s for the Río Descalabrado (table 1, fig. 4). However, streamflow infiltration to the alluvial aquifer during rainfall runoff events after storms may be considerably larger. Thus, these miscellaneous measurements do not reflect the long-term average recharge from these streams or infiltration along unlined segments of irrigation canals.

Table 1. Miscellaneous instantaneous discharge measurements at streams in the vicinity of Santa Isabel, Puerto Rico.

[Coordinates field located from 1:20,000 scale topographic map, Puerto Rico datum, 1940 adjustment; Locations shown on figure 4; Instantaneous streamflow discharge measurements in cubic feet per second, ft^3/s; >, greater than; m/d/yr, month/day/year]

		Río Coamo discharge measurements coordinates		Date (m/d/yr)				
Reference Number	Location Description	Latitude	Longitude	4/2/1987	4/28/1987	6/4/2002	1/29/2003	6/6/2003
1	Above Coamo dam	18º01’36”	66º22’29”	5.53		11.43		
2	Below Coamo dam	18º00’45”	66º23’28”	1.7	3.45	10.17	2.29	5.81
3	At Quarry	18º00’04”	66º23’57”	1.3		6.4	2.17	
4	Below Highway PR-1	17º58’21”	66º25’21”	0	0	5.64	0	2.23
	Total infiltration			4.13	[a]>3.45	[b]5.79	[a]>2.17	[a]>3.58
	Average total infiltration 3.8 ft^3/s							
	[a] Does not include infiltration from Lago Coamo							
	[b] Measurements made shortly after a storm event							

		Río Cañas discharge measurements coordinates		Date (m/d/yr)		
Reference Number	Location Description	Latitude	Longitude	4/3/1987	1/30-31/2003	2/26/2003
5	Above Canal de Juana Díaz	18º02’03”	66º28’00”			estimate 0.2
6	Near powerline	18º01’38”	66º28’00”	1.2	0.41	
7	At bridge below Canal de Juana Díaz	18º01’17”	66º28’05”			estimate 0.2
8	At Hacienda Amelia	18º00’42”	66º02’09”	0.3	0	
9	Below Hacienda Amelia	18º00’35”	66º28’09”	dry	dry	
10	At Highway 535 bridge	18º00’01”	66º28’14”			dry
	Total Infiltration			>1.2	>0.41	0.2
	Average total infiltration about 0.6 ft^3/s					

		Río Descalabrado discharge measurements coordinates		Date (m/d/yr)			
Reference Number	Location Description	Latitude	Longitude	4/3/1987	1/20/2003	1/29/2003	2/26/2003
11	Upstream Canal de Juana Díaz	18º01’08”	66º25’24”	0.6	0.4		
12	Below Canal de Juana Díaz	18º00’52”	66º25’39”				dry
13	At bridge upstream Highway PR-1	18º00’08”	66º26’08”	dry	dry	dry	
14	At Highway PR-1	17º59’33”	66º26’35”				dry
	Total infiltration			0.6	0.4	0	0
	Average total infiltration about 0.25 ft^3/s						
	Río Jueyes						
	Dry stream channel observed at dates of above measurements; flows only during extreme rainfall runoff events						

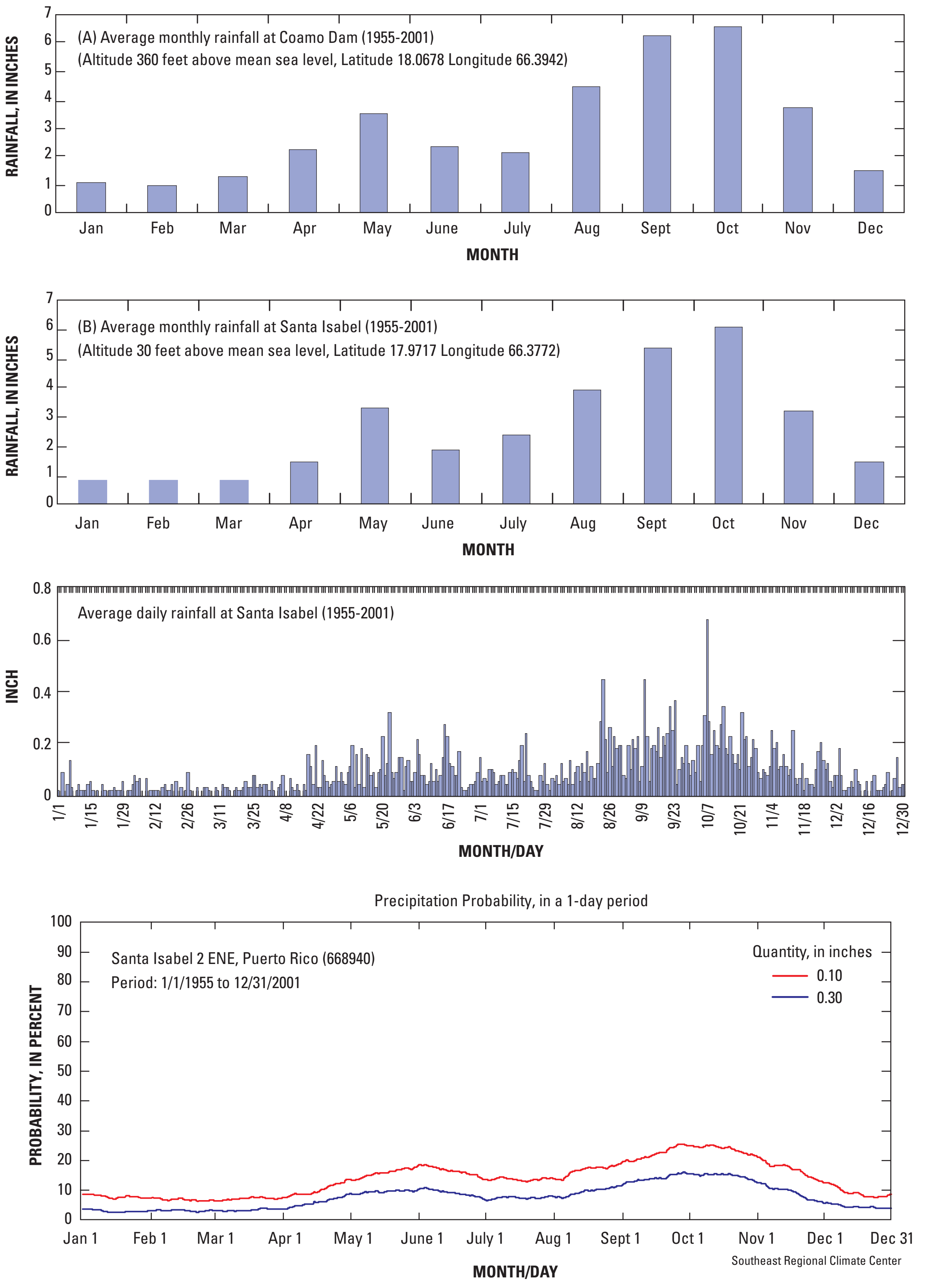


Figure 3. Average monthly rainfall in the study area and average daily precipitation at Santa Isabel (months with missing data excluded, data retrieved on April 2003 from http://www.dnr.state.sc.us/climate/sercc/products/historical/historical.html).

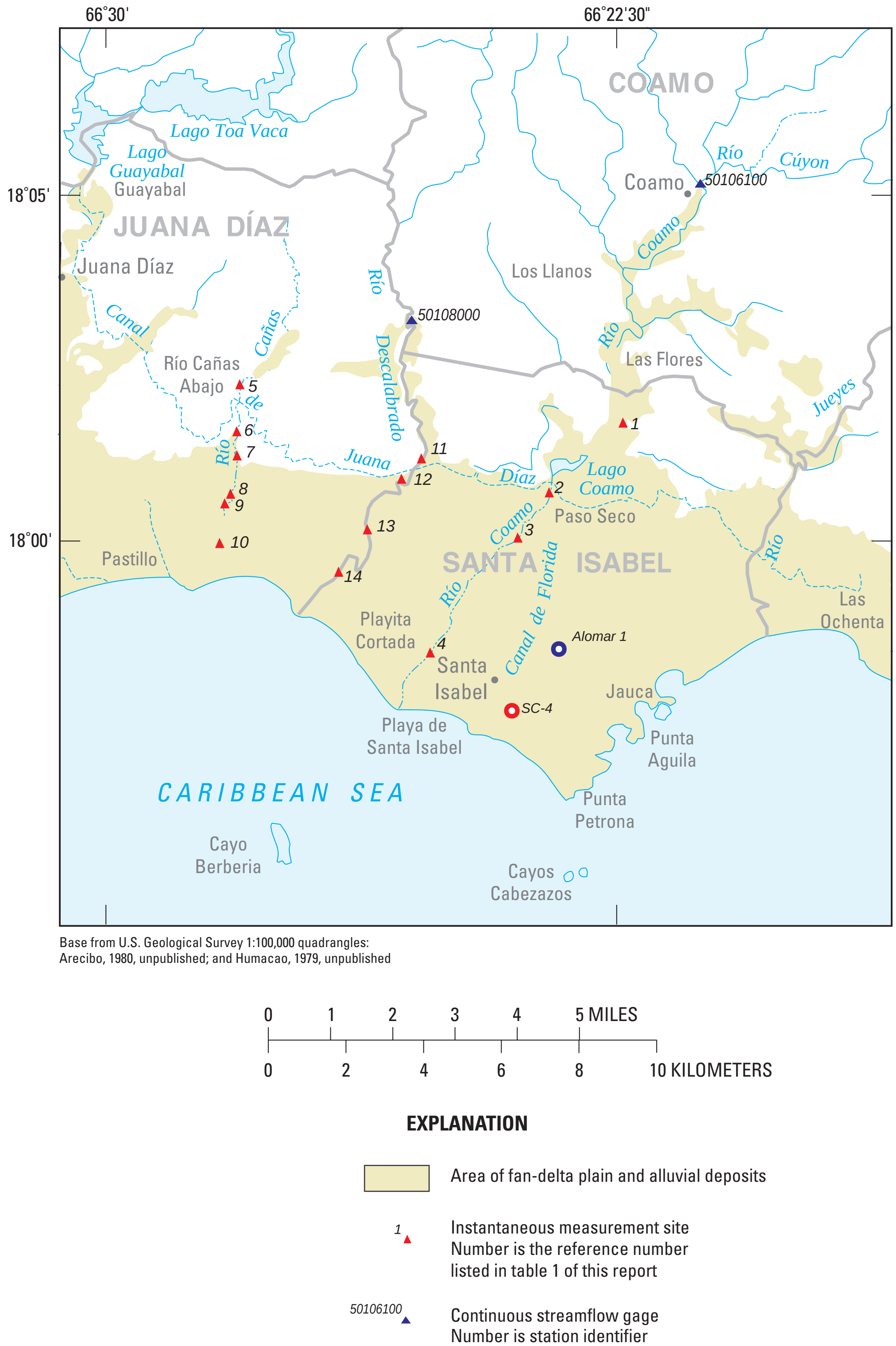


Figure 4. Location of miscellaneous instantaneous stream discharge measurements (refer to table 1 for more details).

The only streams with long-term continuous streamflow data are the Río Coamo at Highway 14, Coamo, Puerto Rico (fig. 1, station number 50106100, drainage area 43.5 mi^2) and the Río Descalabrado near Los Llanos, Puerto Rico (fig. 1, station number 50108000, drainage area 12.9 mi^2). Both stations are near the foothills of the Cordillera Central north of the coastal plain, where the streams are perennial. Hydrograph separation was performed using the computer program PART (Rutledge, 1993). The estimated base flow for 1988-1999 at Río Coamo (50106100) and Río Descalabrado (5010800) is 12 and 4 ft^3/s, respectively. However, much of this base flow is lost to channel evaporation before reaching the northern edge of the coastal plain, which is why the estimated base flow infiltration to the alluvial aquifer is less than the base flow at the gages. The long-term record was examined in order to determine the frequency that the estimated base flow infiltration to the alluvial aquifer is exceeded. At Río Coamo, 32 percent of the days the daily flow is greater than the estimated long-term average base flow with the highest daily discharge was 4,350 ft^3/s. At Río Descalabrado, 31 percent of the days, the daily flow is greater than the estimated long-term average base flow with the highest discharge was 10,000 ft^3/s (during a hurricane). Because the period of continuous record examined is only 11 years, the percent of time daily streamflow equaled or exceeded the daily base flow estimate was also compared. Daily streamflow equaled or exceeded base flow 72 and 61 percent of the days for Río Coamo and Río Descalabrado, respectively. Thus, about 50 percent of the time the infiltration into the alluvial aquifer from the streams would more than likely exceed the estimated base-flow infiltration rates.

Miscellaneous measurements on the Río Coamo, June 4, 2002, after a storm, indicate about 4.5 ft^3/s infiltrated the aquifer along the Río Coamo below the Lago Coamo dam (fig. 4, table 1). The long-term continuous data in combination with miscellaneous discharge measurements made along the Río Coamo near Santa Isabel in 1987, 2002 and 2003 indicate that: (a) during base flow periods, 2 to 4 ft^3/s infiltrates into the aquifer downstream of the Coamo dam; (b) 1 to 4 ft^3/s infiltrates the aquifer from Lago Coamo, and (c) 50 percent of the time significantly greater amounts, perhaps in excess of 4.5 ft^3/s, may infiltrate to the aquifer along the Río Coamo between the Lago Coamo dam and the coast. Thus, the estimated long-term recharge from base flow and storm flow to the aquifer from Lago Coamo and Río Coamo may exceed 6 ft^3/s.

Estimated streamflow infiltration rates for the study area have a large degree of uncertainty in that there are not long-term continuous discharge measurement sites along streams at the northern edge of the alluvial aquifer or along the Juana Díaz canal. Average infiltration from Río Cañas could be about 1 ft^3/s, Río Descalabrado about 2 ft^3/s, Río Coamo and Lago Coamo could exceed 6 ft^3/s, and unknown for the Río Jueyes, Juana Díaz canal, and unlined irrigation canals.

History of Water Resources Development and Changes in Agricultural Practices

Prior to 1930, virtually all of the water for agricultural purposes was supplied by surface water from lakes, ponds, and canals and percolation of rainfall to the water table. Ground-water withdrawals for agriculture peaked in the late 1960s, when most of the land that could be cultivated in sugarcane was under cultivation. Estimates of agricultural areas in the Santa Isabel area are shown on figures 5, 6, and 7 for years 1977, 1987, and 1991-92, respectively. Table 2 summarizes the estimates of agricultural areas from these different sources.

Beginning in the 1970s, there was a gradual conversion from sugarcane cultivation with furrow irrigation to vegetable and other row crops cultivated with more water efficient micro-drip irrigation. Micro-drip irrigation is designed to provide a 0.3 inch of water to the soil zone on days when the soil moisture requires water delivery. Furrow irrigation is very inefficient and requires the flooding of furrows along rows of crops. About 30 to 50 percent of the water used for furrow irrigation percolates into the aquifer system as irrigation return flow (McClymonds and Díaz, 1972). Based on deuterium and oxygen-18 isotope data from 1986-1889, Gómez-Gómez (1991) determined that 45 to 70 percent of the ground water in the first 160 ft of the aquifer was from surface water (either direct streamflow loss from infiltration to the alluvial aquifer or surface-water supplied irrigation return flow). Irrigation return flow from micro-drip irrigation is negligible. Thus, irrigation return flow could have been as great as 26 Mgal/d in 1977 (half of the required water in table 2), dropping to 0 after all fields have converted to micro-drip irrigation practice (see estimated water budget in fig. 2).

Based on the 1987 field survey (fig. 6), the conversion from furrow irrigation to micro-drip irrigation was not complete at Santa Isabel. However, by the 1991-92 survey (fig. 7), almost all of the irrigated crops were various vegetable and fruits or other row crops, and micro-drip irrigation was used for all of the irrigated areas. The crop classification from the landsat thematic mapper data for 1991-92, was not thoroughly checked in the field; however the irrigated areas appear to be reasonable, based on the February 2003 field observations made during collection of ground-water levels and conductance. Another change is in the total irrigated area, which decreased between 1977 and 1991 from about 16,000 to 11,000 acres. Some of the water required by the crops comes from rainfall and surface water; thus, the amounts listed in table 2 do not reflect the average ground-water withdrawals, but do indicate that the ground-water withdrawals for irrigation have decreased significantly as a result of the decrease in irrigated areas and converting to micro-drip irrigation practice.

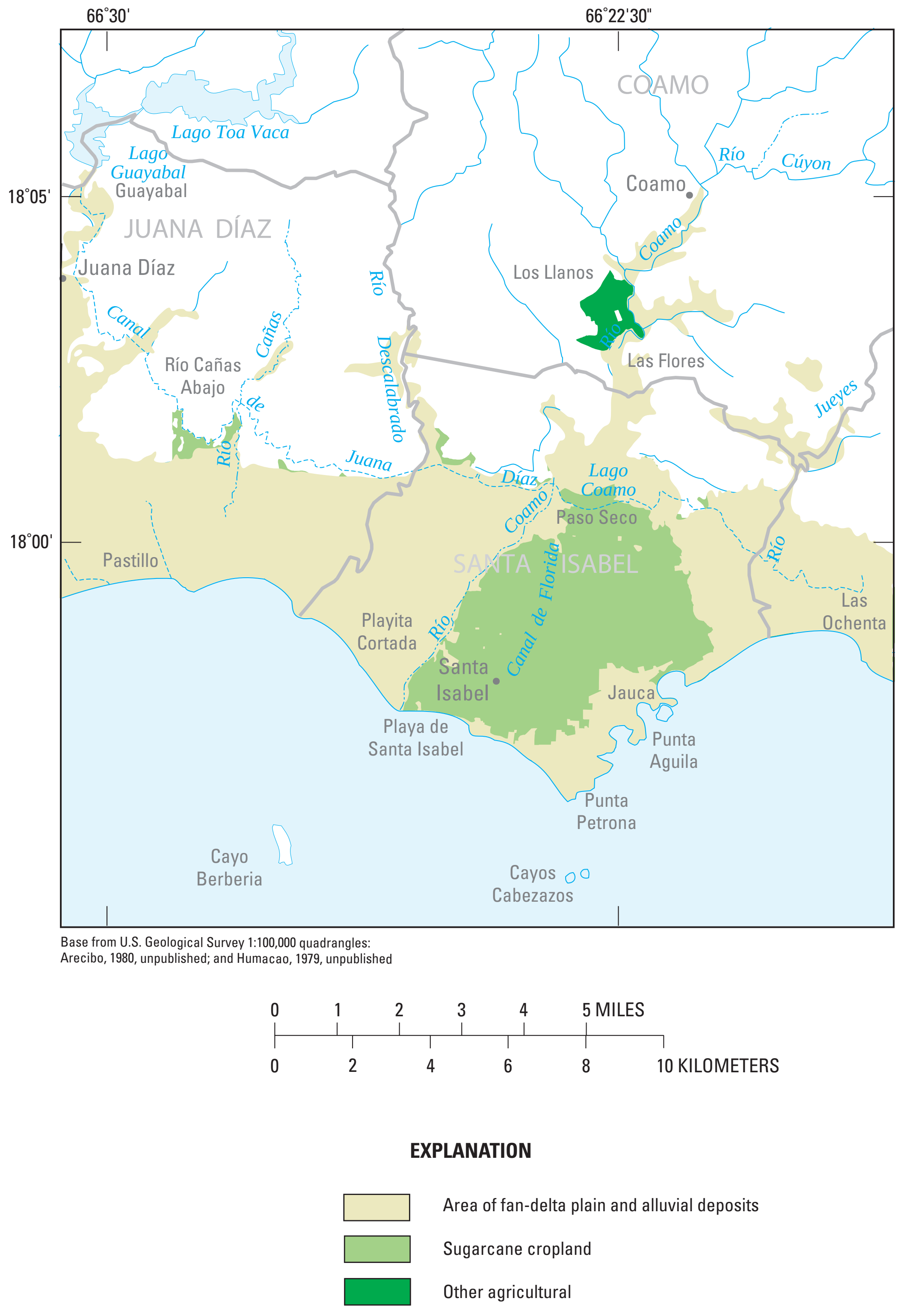


Figure 5. Field survey of agricultural areas defined from aerial photography, 1977.

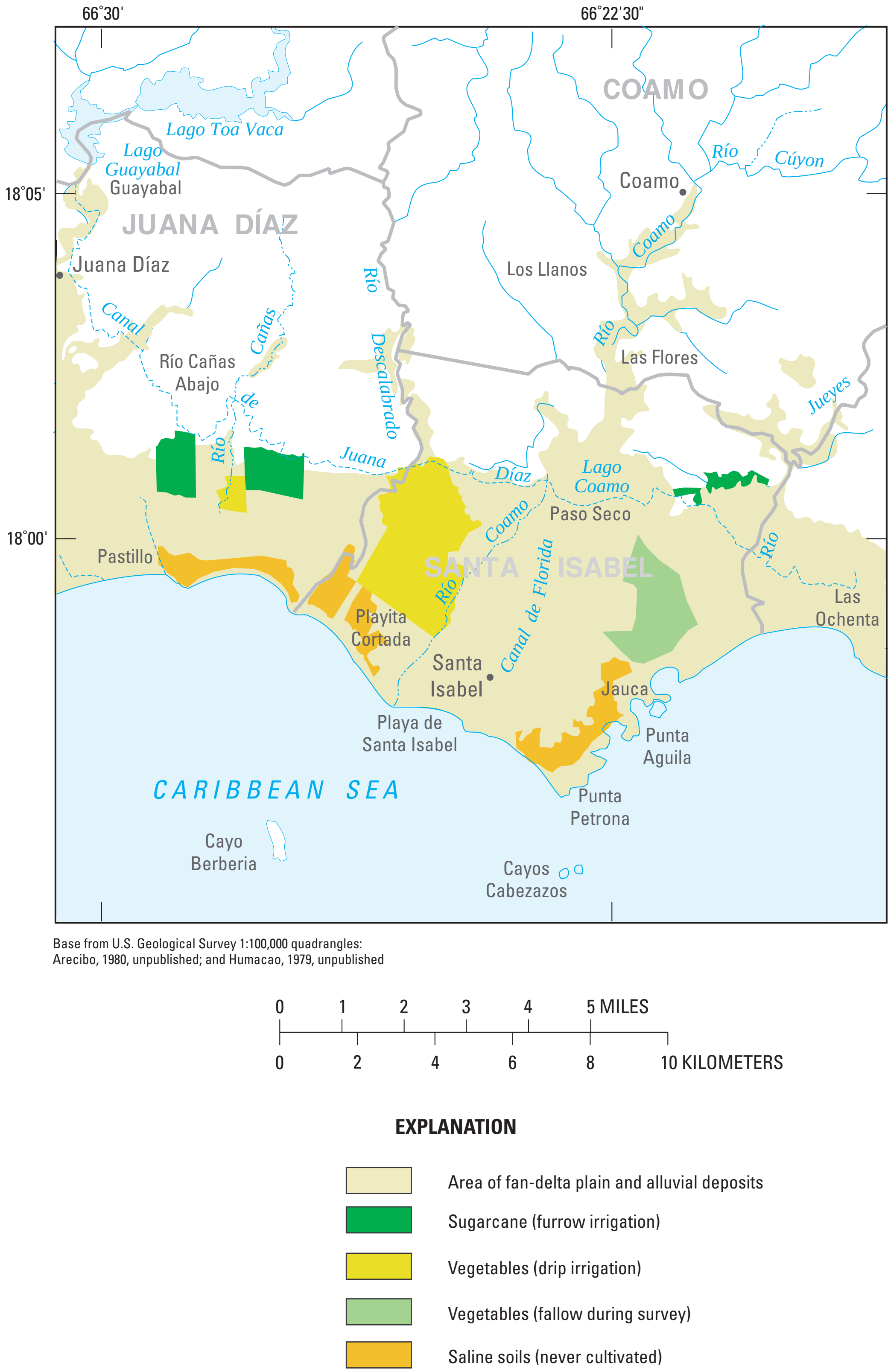


Figure 6. Field survey of agricultural areas, 1987 (from Rodríguez-del-Río and Gómez-Gómez, 1990).

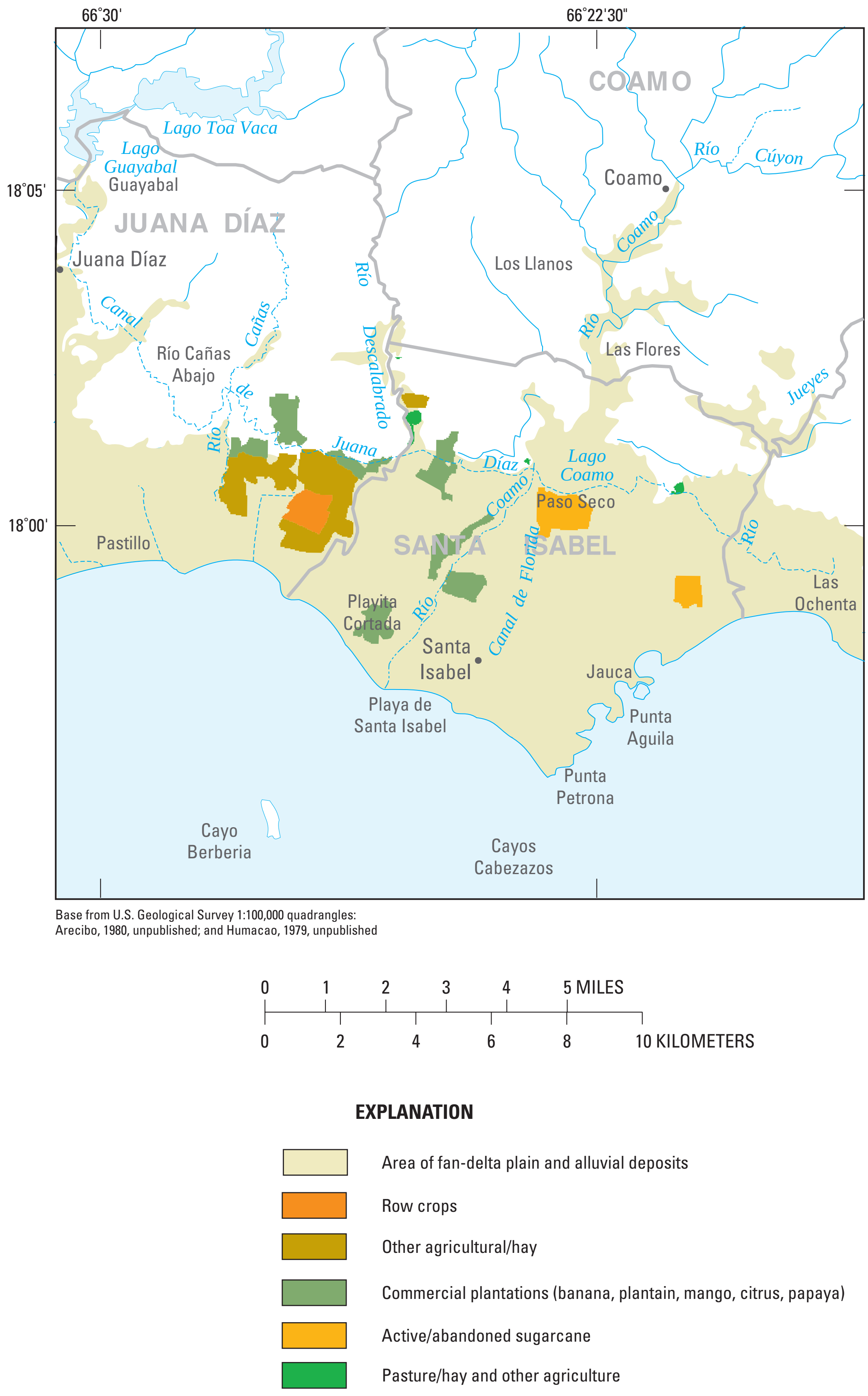


Figure 7. Agricultural classification by U.S. Forest Service from 1991 Landsat data (modified from Helmer and others, 2002; O.M. Ramos, U.S. Forest Service, written commun., 2003).

Table 2. Estimates of agricultural areas and water use requirements from 1977, 1987, and 1991-92, in the vicinity of Santa Isabel, Puerto Rico.

(A) Estimates of 1977 crop classification (from aerial photography, compiled by the Puerto Rico Department of Natural Resources Scientific Inventory Division and digitized by USGS Caribbean District, M. Santiago, U.S. Geological Survey, written. commun., 2003, (*) assumed at one harvest per year)

Description	Total acres cultivated	Total in square miles	Percent total area of alluvium	Crop water application rate		
				in feet per year	in million gallons per year	in acre-feet per year
Sugarcane	14,632	22.9	68.5	4	52.2	58,528
Other agricultural	1,069	1.7	5.0	2 (*)	1.9	2,138
Total irrigated area and water required by crop	15,701	24.5	73.5		54.2	60,666

(B) Estimates of 1987 crop classification from field survey (from Rodríguez-del-Río and Gómez-Gómez, 1990)

Description	Total acres cultivated	Total in square miles	Percent total area of alluvium	Crop water application rate		
				in feet per year	in million gallons per year	in acre-feet per year
Sugarcane field (furrow irrigation)	4,198	6.6	19.6	4	15.0	16,791
Vegetables/fruits (drip irrigation)	4,090	6.4	19.1	2 (*)	7.3	8,180
Vegetables (fallow during survey)	865	1.4	4.0	2 (*)	1.5	1,730
Total irrigated area and water required by crop	9,153	14.3	42.7		23.8	26,701

(C) Estimates from 1991-92 Landsat Thematic Mapper (Helmer and others, 2002; reclassification of Landsat Thematic Mapper imagery by O.M. Ramos, U.S. Forest Service, written commun., 2003)

Description	Total acres cultivated	Total in square miles	Percent total area of alluvium	in feet per year	in million gallons per year	in acre-feet per year
Active/abandoned sugarcane plantations	489	0.8	2.3	4	1.7	1,957
Commercial plantations-banana, plantain, mango, citrus, papaya	926	1.4	4.3	2	1.7	1,853
Other agricultural/hay	5,268	8.2	24.6	1	4.7	5,268
Pasture/hay and other agriculture	481	0.8	2.2	1	0.4	1,926
Row crops	3,711	5.8	17.3	2 (*)	6.6	3,711
Total irrigated area or water required by crop	10,876	17.0	50.8		15.2	14,714

In 1967, about 8 Mgal/d of surface water supplied for irrigation was from the Juana Díaz canal and Lago Coamo (Giusti, 1966, 1971b). During a 1987 field survey of hydrologic conditions, irrigation delivery of surface water to the Santa Isabel area from the Juana Díaz canal was about the same as in 1967 (Rodríguez-del-Río and Gómez-Gómez, 1990). The majority of the surface water supplied from the Juana Díaz canal comes from Lago Guayabal (fig. 4), west of the study area.

The irrigated areas have remained fairly constant since 1990. However, farming has changed from a sugarcane monoculture in the 1970s to miscellaneous row crops of fruits, vegetables, ornamental plants, and genetically engineered seed production (figs 5, 6, and 7). In tandem with this change, improvements have been made in making the drip irrigation even more efficient in order to conserve water and electricity.

Although ground-water withdrawals for irrigation decreased since the 1970s, public supply ground-water withdrawals have steadily increased from about 2 Mgal/d in 1975 to about 7 Mgal/d in 2003 (figs. 2 and 8). The reported values from Puerto Rico Aqueducts and Sewer Authority were less than those from field surveys of the public-supply wells conducted by the USGS in 1987, 2002, and 2003 (W. Molina, U.S. Geological Survey, written commun., 2003). The solid lines on figure 8 reflect rates estimated by the USGS and are considered closer to actual total amounts of ground-water withdrawals from the public-supply wells.

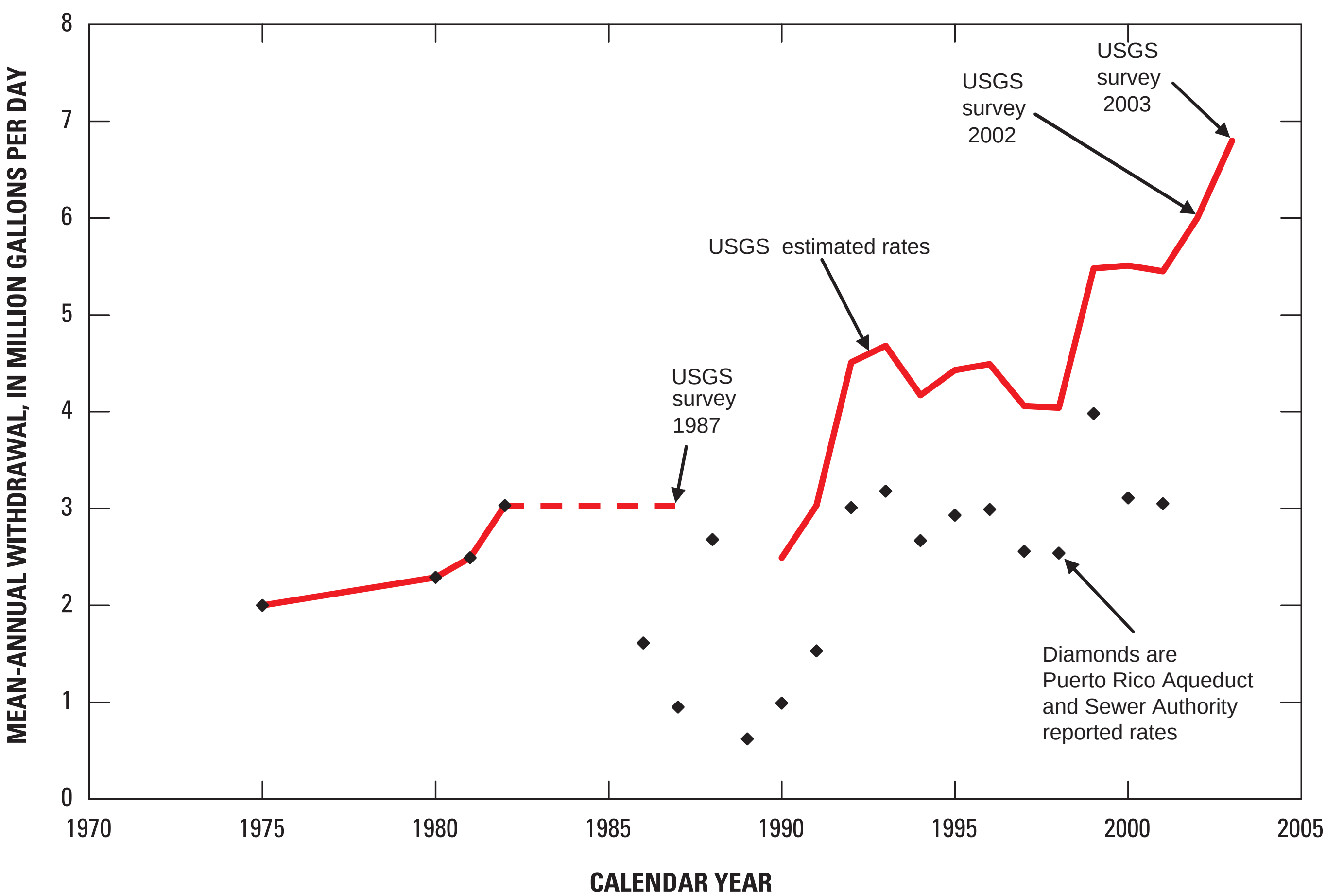


Figure 8. Public supply ground-water withdrawals at Santa Isabel.

Geohydrology

The study area is within a low-lying narrow fan-delta plain underlain by gravel, sand, and silt of Quaternary age (fig. 9). Steep gradient intermittent streams with relatively small drainage basins formed the coalesced fan deltas during periods of flooding, when large amounts of sediment were transported. The largest of the fan deltas in the study area is the Río Coamo alluvial fan (Coamo fan, fig. 1). Smaller fan deltas associated with the Río Cañas, Río Descalabrado, and Río Jueyes coalesce with the Coamo fan encompassing about 20 mi^2 of the coastal plain between Río Cañas and Río Jueyes (fig. 1).

Fan-delta and alluvial deposits that constitute the alluvial aquifer in the Santa Isabel area can exceed 1,000 ft in thickness in the southern area along the coast; these deposits thin to approximately 60 ft in the northern area near the alluvial fan apex (fig. 10). There are numerous en echelon faults paralleling the coast along with perpendicular faulting that create horst and graben structures (fig. 9). The thickness of the most permeable sediments that form the principal flow zone of the alluvial aquifer is highly variable and is mainly controlled by the position of horst and graben structures and major rivers that fed the fan-delta during depositional periods.

In the northern part of the area, the alluvial aquifer is underlain by volcanic, sedimentary, and igneous rocks of Cretaceous and early Tertiary age (fig. 10). These bedrock units are highly fractured as a result of the en echelon faulting.

A geologic section constructed along the axis of the Coamo fan (figs. 11a and b) indicates that the younger unconsolidated clastic sediments, of Pleistocene and Holocene age, are fairly thin above the volcanic bedrock, but thicken to more than 200 ft on the coastal side of the fault. The lithologic data presented in figure 11b indicate that the unconsolidated sediments vary in grain size. The older sediments are poorly consolidated. The permeability may decrease with depth because these deeper, older sediments are more consolidated. Most wells are drilled to depths of less than 200 ft, because of a decrease in permeability. Additionally, water-quality data indicate that there is a slight change in chemistry of the natural waters with depth (Gómez-Gómez, 1991). The principal flow zone (more permeable sediments) of the aquifer occurs near land surface to 200 ft below land surface.

The grain sizes of the sediments underlying the Santa Isabel area vary considerably both vertically and horizontally (Renken and others, 2002). The sand and gravel percentage maps of the deposits (fig. 12) indicate higher percentages of sand and gravel along the lobes of the fan deltas and a decrease in sand and gravel percentage in the interlobe areas. Additionally, there appears to be finer grained sediments along the coast. The appendix provides the lithologic description from a 532 ft deep test hole, SC-4 (location shown in fig. 11a), near the coast at Santa Isabel. These finer grained clayey sediments near land surface along the coast may confine the aquifer near the coast.

Hydraulic Properties of the Alluvial Aquifer

The hydraulic conductivity of the alluvial aquifer is greatest where thick alluvial deposits fill graben structures and along the lobes of the fan deltas and is smallest between the lobes of the fan deltas. The estimated hydraulic conductivity of the deposits within 160 ft of land surface is shown in figure 13 and may range from 1 to 250 feet per day (ft/d) (Bennett, 1976; Renken and others, 2002). The higher values occur in the thickest part of the Río Coamo alluvial fan delta. In general, the estimated distribution of hydraulic conductivity compares well with the map showing percentage of sand and gravel distribution (fig. 12) and the depositional environment more fully described in Renken and others (2002). The only exception is that there probably should be higher hydraulic conductivity values along the Cañas, Descalabrado, and Jueyes fan deltas, where the sand and gravel percentage is greater than the interlobe areas (fig. 12).

Quiñones-Aponte (1989) estimated a storage coefficient of 0.0003 from an aquifer test conducted in the southeastern section of the Salinas fan east of the Santa Isabel area. This storage coefficient value represents semi-confined to confined leaky beds, conditions that occur in the lower fan areas along the coast. Specific yield in the range of 0.1 to 0.2, representative of unconfined conditions, is assumed for the upper fan-delta areas where the semi-confined leaky bed units are nonexistent.

Because of the fluvial depositional environment of these unconsolidated deposits, it is proper to assume that there is some natural vertical anisotropy in which the horizontal hydraulic conductivity would be greater than the vertical hydraulic conductivity. Bennett and Giusti (1971) developed an electrical analog model and initially assumed a vertical to horizontal anisotropy ratio of 1:100 for the Ponce area coastal plain deposits, but achieved better results using a ratio of 1:1,000. However, the 1:1,000 ratio seems extreme, because ratios for unconsolidated sediments typically are 1:10 (Bouwer, 1978; Fetter, 1994).

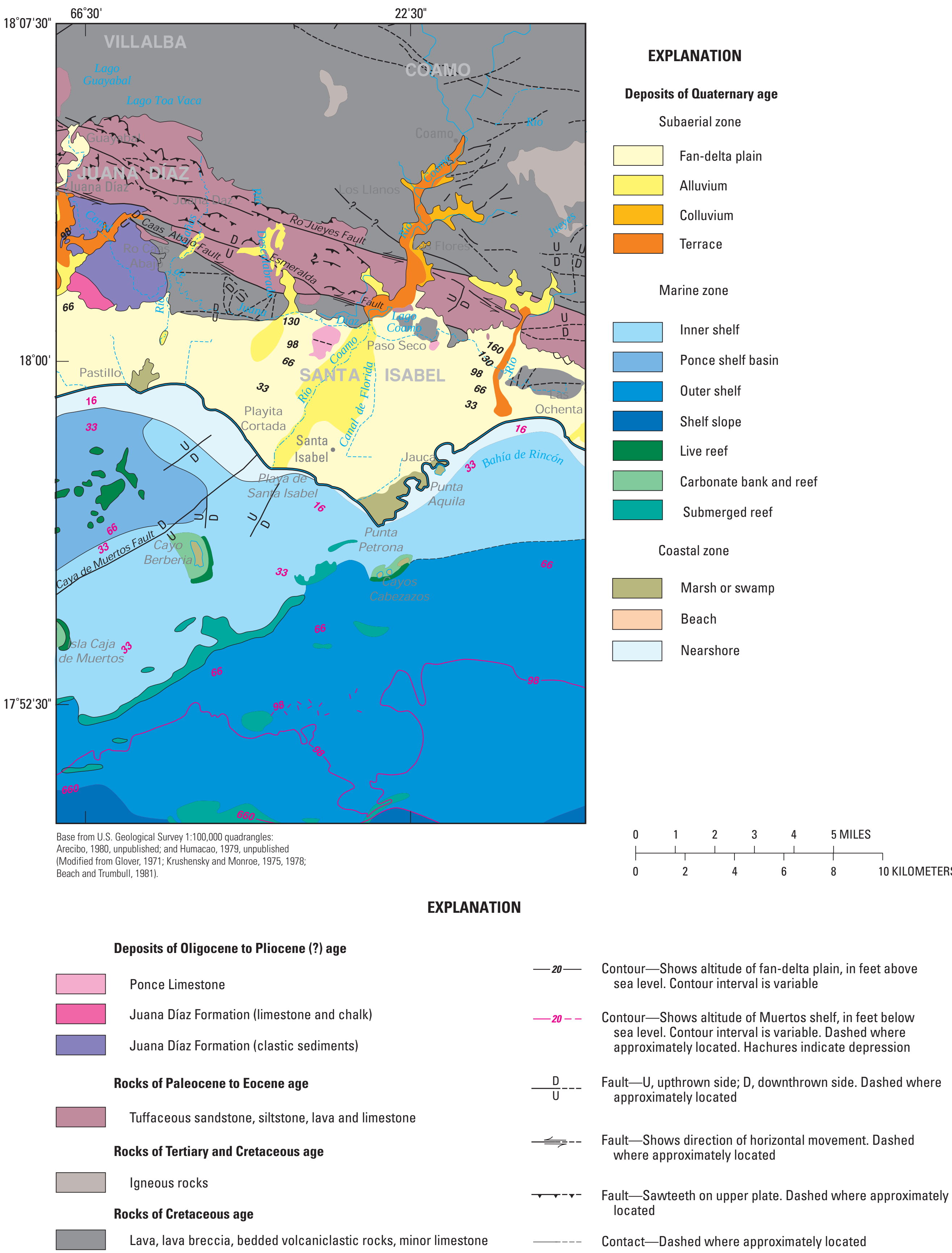
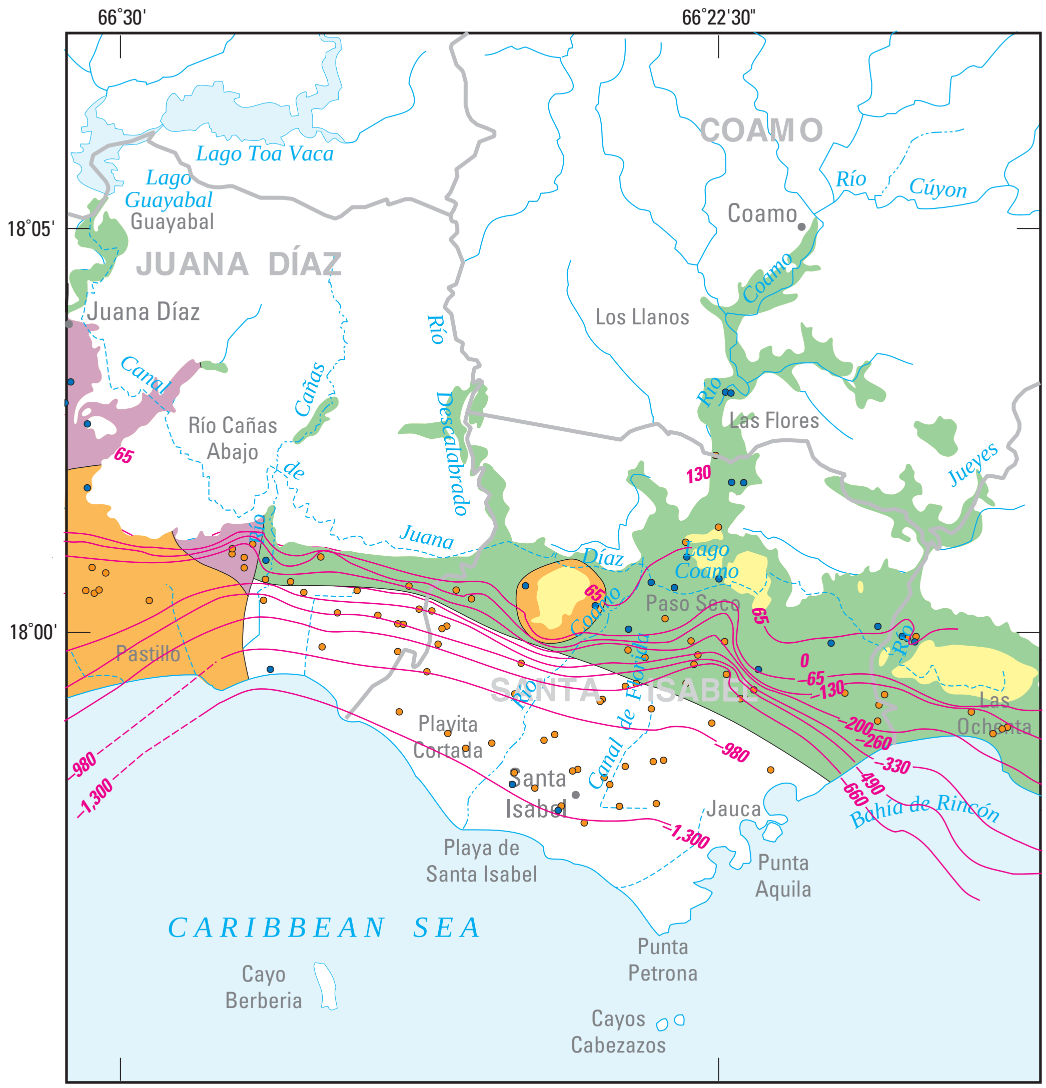


Figure 9. Geology of the south coast ground-water province in the vicinity of Santa Isabel, Puerto Rico (modified from plate 1, Renken and others, 2002).



Base from U.S. Geological Survey 1:100,000 quadrangles:
Arecibo, 1980, unpublished; and Humacao, 1979, unpublished

0 1 2 3 4 5 MILES

0 2 4 6 8 10 KILOMETERS

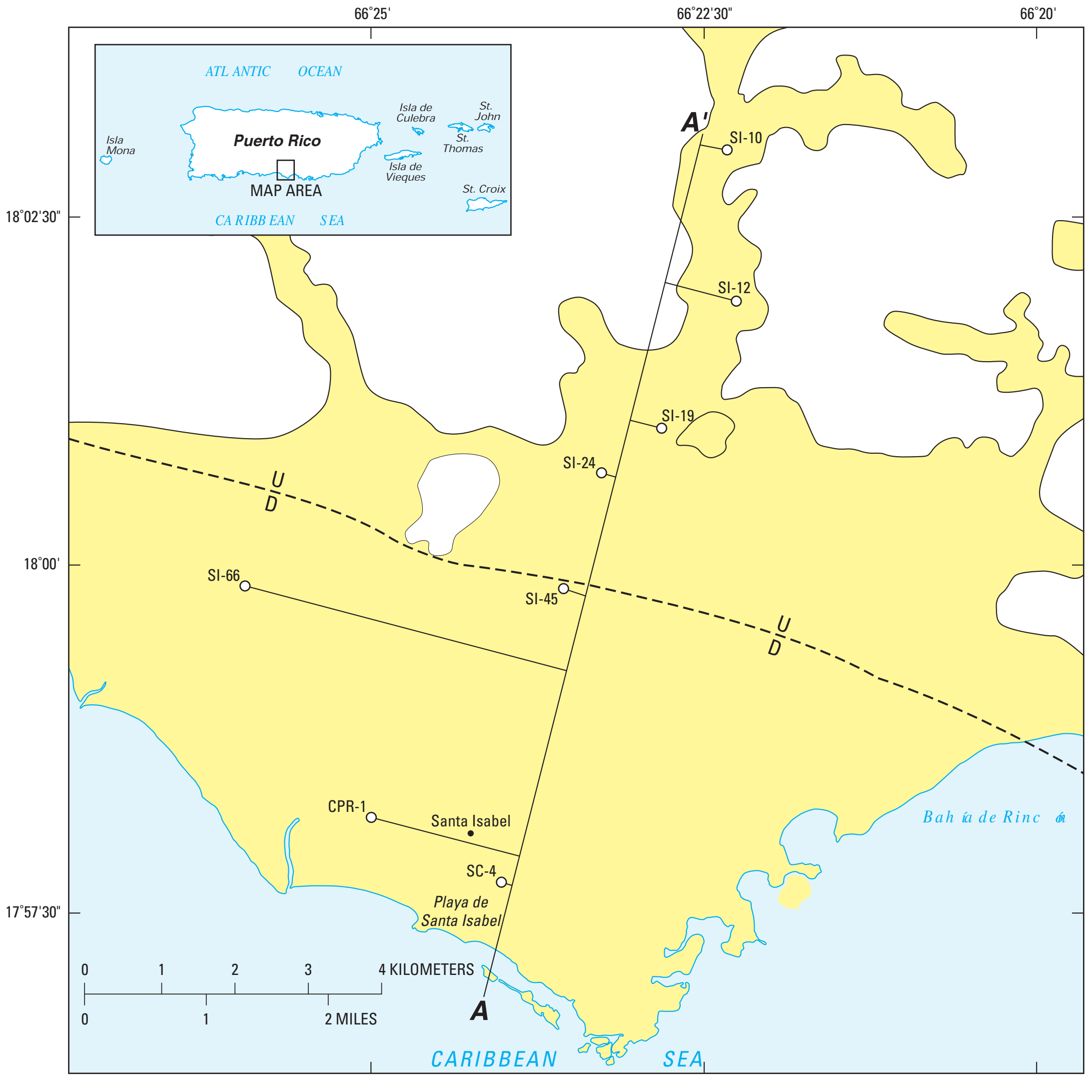
EXPLANATION

- Area underlain by clastic sediment equivalent to the Ponce Limestone
- Area underlain by carbonate rocks of the Ponce Limestone and/or the Juana Díaz Formation
- Area underlain by clastic sediments of the Juana Díaz Formation
- Area underlain by volcanic, sedimentary, and igneous rocks of Cretaceous and early Tertiary age
- –65 Bedrock contour—Shows altitude of base of fan-delta deposits of Quaternary age. Contour interval, in feet, is variable. Dashed where uncertain. Datum is mean sea level

Well—Control point

- Well completed in bedrock of pre-Quaternary age
- Well completed in sediment deposits of Quaternary age

Figure 10. Configuration of bedrock surface underlying fan-delta and alluvial deposits of Quarternary age in the vicinity of Santa Isabel, Puerto Rico (modified from plate 1, Renken and others, 2002).



Base modified from U.S. Geological Survey digital data

EXPLANATION

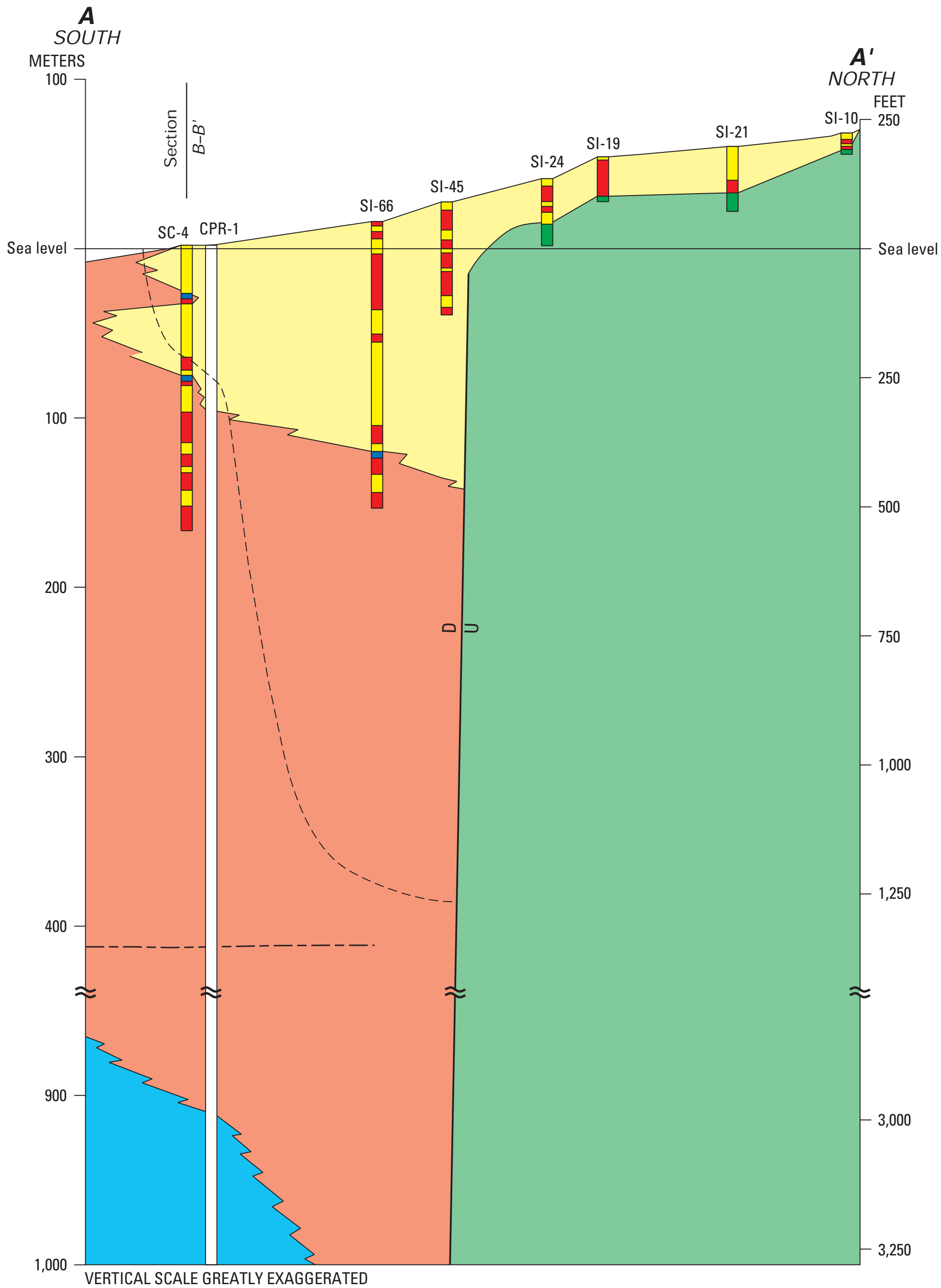
Unconsolidated clastic sediments—Boulder- to silt- or clay-size clastic detritus deposited under subaerial conditions, mostly during Pleistocene to Holocene time

U / D Fault—U, upthrown side; D, downthrown side. Dashed where infered

A A' Line of section

SC-4 Control point—Well name abbreviations on figure 10

Figure 11a. Section A-A' down the axis of the Coamo fan delta, south-central Puerto Rico (fig. 12 from Renken and others, 2002).



EXPLANATION

Rocks of Miocene to Quaternary age

Unconsolidated clastic sediments—Boulder- to silt- or clay-size clastic detritus deposited under subaerial conditions, mostly during Pleistocene to Holocene time

Unconsolidated to poorly consolidated sediments—Boulder- to silt- or clay-size detritus, minor limestone and marl deposited under subaerial, nearshore, and shallow marine conditions. Deeply buried sediments may be as old as Miocene age and are equivalent to the Ponce Limestone. Uppermost deposits are Pleistocene and/or Holocene in age

Limestone—Consists of limestone with brackish- to shallow-marine fauna. Considered equivalent to Ponce Limestone

Rocks of Cretaceous to early Tertiary age

Bedrock—Consists of bedded, lithified sequence of conglomeratic sandstone, siltstone, volcanic and igneous rocks, and minor limestone

Well lithology
- Sand-size or larger
- Silt-size or smaller
- Limestone, limey clay, or marl
- Bedrock

Line showing approximate position of freshwater-saline water interface

Line showing top of Amphistegina Angulata-Elphidium lens fauna—Considered to be a Miocene stratigraphic datum (Todd and Low, 1976)

U / D Fault—U, upthrown side; D, downthrown side. Dashed where inferred

Figure 11b. Section A-A' down the axis of the Coamo fan delta, south-central Puerto Rico.—Continued

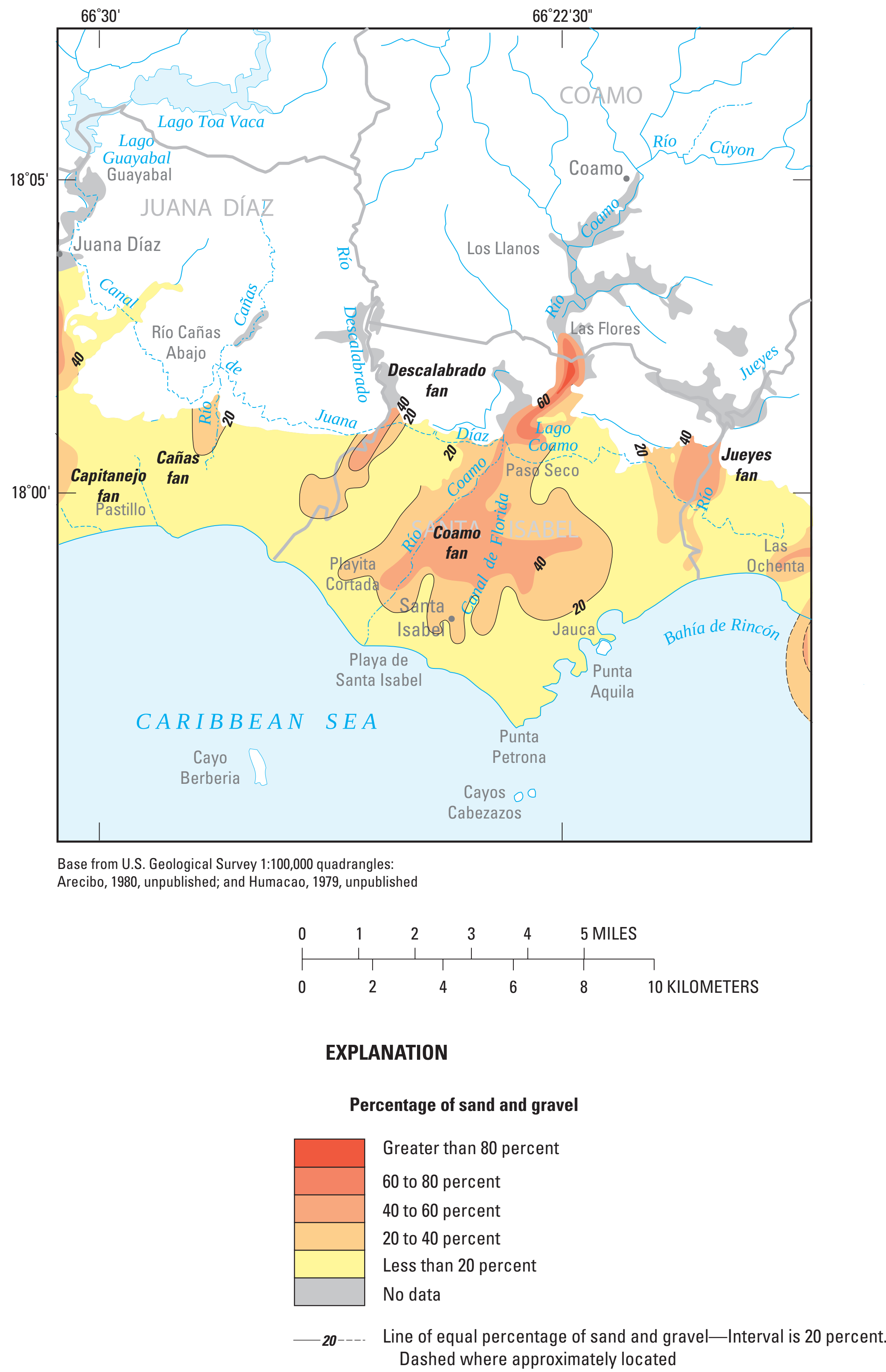


Figure 12. Percentage of sand and gravel in fan-delta plain and alluvial deposits in the vicinity of Santa Isabel, Puerto Rico (modified from plate 1, Renken and others, 2002).

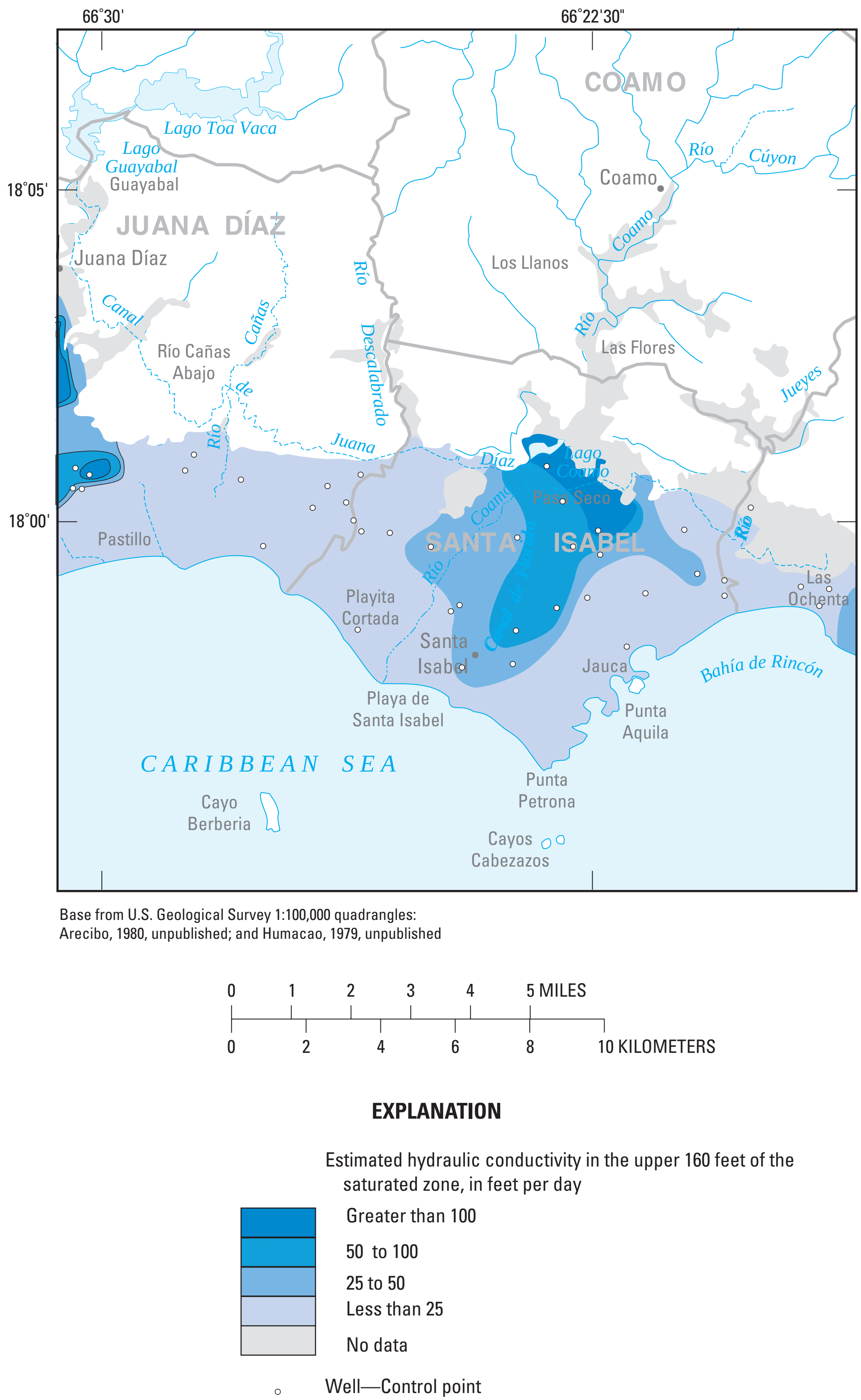


Figure 13. Distribution of hydraulic conductivity within the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico (modified from plate 1, Renken and others, 2002).

Ground-Water Flow Patterns and Specific Conductance

According to the configuration of the predevelopment potentiometric surface (Ramos-Ginés, 1994), predevelopment ground-water flow in the Santa Isabel area closely followed the topographic patterns. Figure 14 (Renken and others, 2002) shows the cones of depression that formed in the area by 1968 as a result of an extended drought which began in 1964, during which ground-water withdrawals were nearly the sole source of water for public supply and irrigation in the Santa Isabel area. In 1968, these cones of depression were as much as 10 ft below mean sea level. Reductions in ground-water withdrawals combined with above-average precipitation conditions in the mid 1980s resulted in a recovered water-table surface in 1986 following the topography similar to predevelopment with ground-water flow towards the coast (fig. 15; Renken and others, 2002). However, the increased ground-water withdrawals and slightly less than average rainfall, combined with less irrigation return flow resulted in lowering the water table at Santa Isabel as documented by the synoptic survey of water levels conducted for this study in February 2003 (fig. 16).

Recharge to the alluvial aquifer is from streamflow infiltration near the fan apex, rainfall infiltration, irrigation canal seepage, and irrigation return flow. Stream infiltration to the alluvial aquifer is greatest where modern-day streams are in hydraulic connection with buried, high-energy stream channel and fan-delta deposits. According to McClymonds and Díaz (1972), almost all of the streams along the South Coastal Plain cease to flow in the upper parts of the valley because the water infiltrates into the aquifer system, due to the high permeability of the alluvial material and streambed deposits.

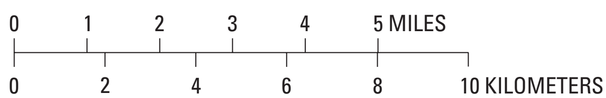
Giusti (1971b) assumed 10 percent of rainfall reaches the water table as recharge in the Coamo fan area. However, McClymonds (1972) speculated that during wet rainfall years, greater than 10 percent of the rainfall could reach the water table; and that during dry years, the recharge from rainfall could be less than 10 percent of the rainfall. Thus, long-term average recharge from rainfall at Santa Isabel could range from 2 to 5 in/yr, which is approximately 5 to 15 percent of the mean-annual rainfall, respectively. The data plotted on the water budget in figure 2 were produced by multiplying 10 percent of the annual precipitation by the alluvial area (20,724 acres) to calculate the annual recharge rate from rainfall.

Ground-water discharge occurs principally to wells, to springs, as diffuse upward leakage to swamp areas along the coast, to lower river reaches, and to the seabed. The water budget shown in figure 2 shows estimated components of the water budget excluding the discharge to the coast and swamps. As can be seen in figure 2, the largest changes in the water budget over time are the reduction in irrigation return flow after 1987 and the reduction in ground-water withdrawals for irrigation. Prior to 1990, there were greater inflows to the aquifer (recharge, irrigation return flow, and surface-water losses) than outflows from the aquifer (public supply and irrigation pumpage). After 1992, based on the estimated water budget (fig. 2), the outflows exceed inflows in 8 of the 10 years.

Seawater lies underneath the majority of the alluvial aquifer, but the estimated thickness of the freshwater lens in 1986-87 ranged from 65 to over 660 ft over most of the area and is less than 65 ft thick beneath the eastern part of the coast (fig. 17). If the current (February 2003) potentiometric surface conditions persist, seawater intrusion and upconing of poorer quality of water may become a problem in the Santa Isabel area as in other parts of the coastal aquifer (Díaz, 1974; Gómez-Gómez,1991).

Specific conductance data collected during 2003 are shown on figure 18. Specific conductance, in microsiemens per centimeter at 25ºC (µS/cm), is related to the total dissolved solids in milligrams per liter (mg/L), and thus, the salinity of the water. There generally is a linear relation between the two values in the form of the equation, KA=S; where, K is the specific conductance in µS/cm, S is total-dissolved-solids concentration in mg/L, and A is the slope of the linear relation (Hem, 1985). The slope constant, A, varies for different ranges of total-dissolved-solids and different water chemistry. Based on specific conductance and total-dissolved-solids data collected in parts of the South Coastal Plain aquifer by Díaz (1974, 1979b), conductance less than 850 µS/cm is preferred for public supply. The preferred limit of conductance for irrigation use is about 2,500 µS/cm; however, conductance as great as 5,000 µS/cm may be the upper limit for irrigation use, and generally is considered the lower limit for saline ground water. Additionally, the constant A determined from the graph published by Díaz (1979b) is about 0.6 for the range in conductance data shown in figure 18. Conductance at Santa Isabel during 2003 ranged from about 600 to 2,000 µS/cm (approximately 350 to 1200 mg/L). The pattern of the conductance shown in figure 18 is fairly complex. However, the conductance data suggest lower dissolved solids in the center of the Coamo fan delta, where freshwater enters the aquifer from streamflow losses along the Río Coamo and along Río Cañas, Río Descalabrado, and Río Jueyes as was noted previously by the dissolved-solids map published by Gómez- Gómez (1991) for data collected in 1987. The current (2003) data indicate that there may be a slight increase in conductance at the coast just north of Punta Petrona. There is a large increase in conductance at the two wells with the highest conductance water (1843 and 1963 µS/cm conductance), where the previous dissolved-solids concentration was 520 mg/L (approximately 870 µS/cm). There also appears to be increased salinity in the area between the Río Coamo and Río Jueyes from 1987 to 2003. The slight increase near the coast may be a result of lateral seawater intrusion. The other areas of increased salinity may be a result of upconing of poorer quality water from depth Gómez- Gómez (1991).

Base from U.S. Geological Survey 1:100,000 quadrangles:
Arecibo, 1980, unpublished; and Humacao, 1979, unpublished



EXPLANATION

Area of fan-delta plain and alluvial deposits

— 5 — Potentiometric contour—Shows altitude at which water would have stood in tightly cased wells open to the South Coastal Plain aquifer in February 1968. Dashed where approximately located. Hachures indicate depression. Contour interval, in feet, is variable. Datum is mean sea level

Figure 14. Estimated potentiometric surface of the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico, February 1968 (modified from plate 1, Renken and others, 2002).

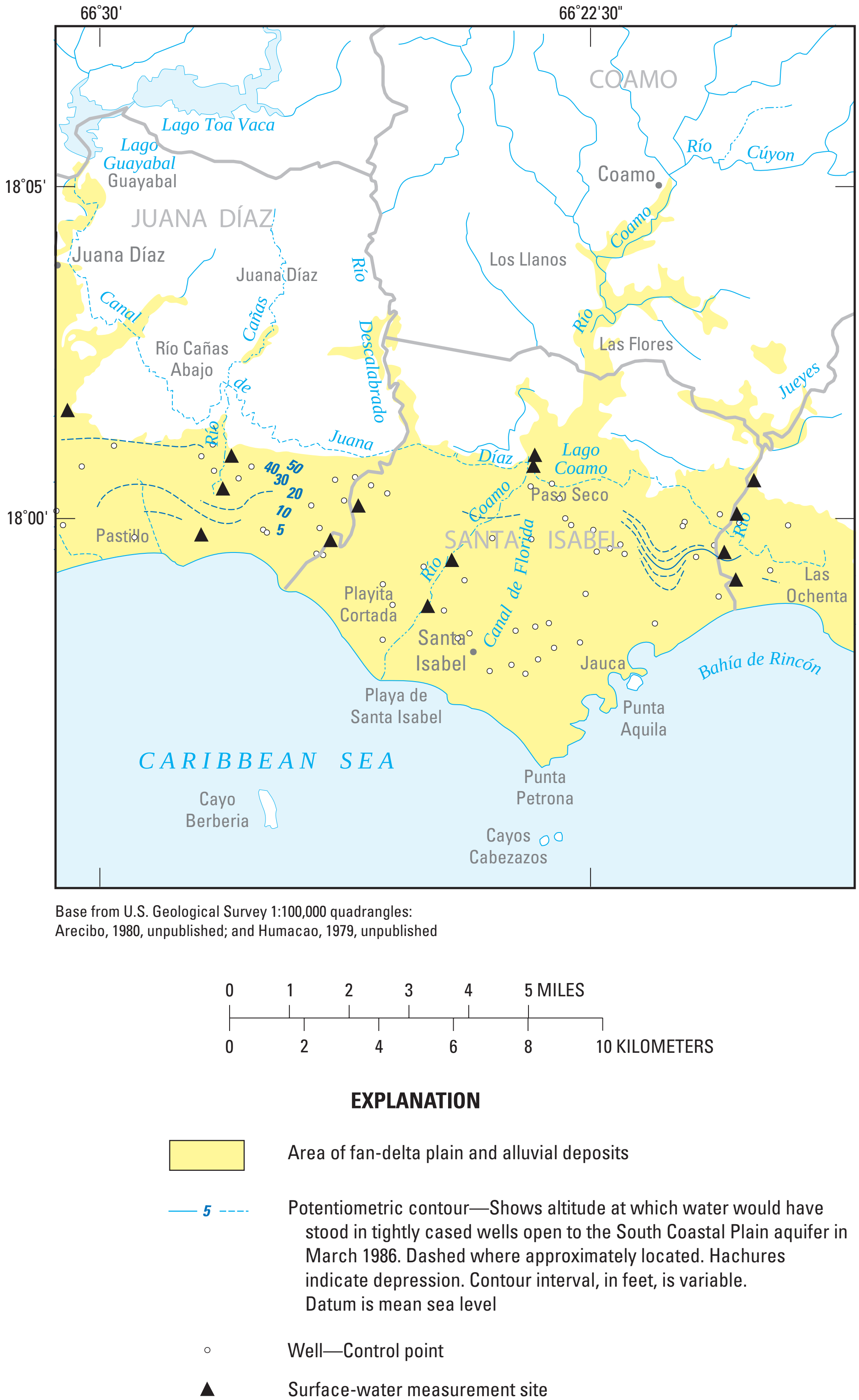
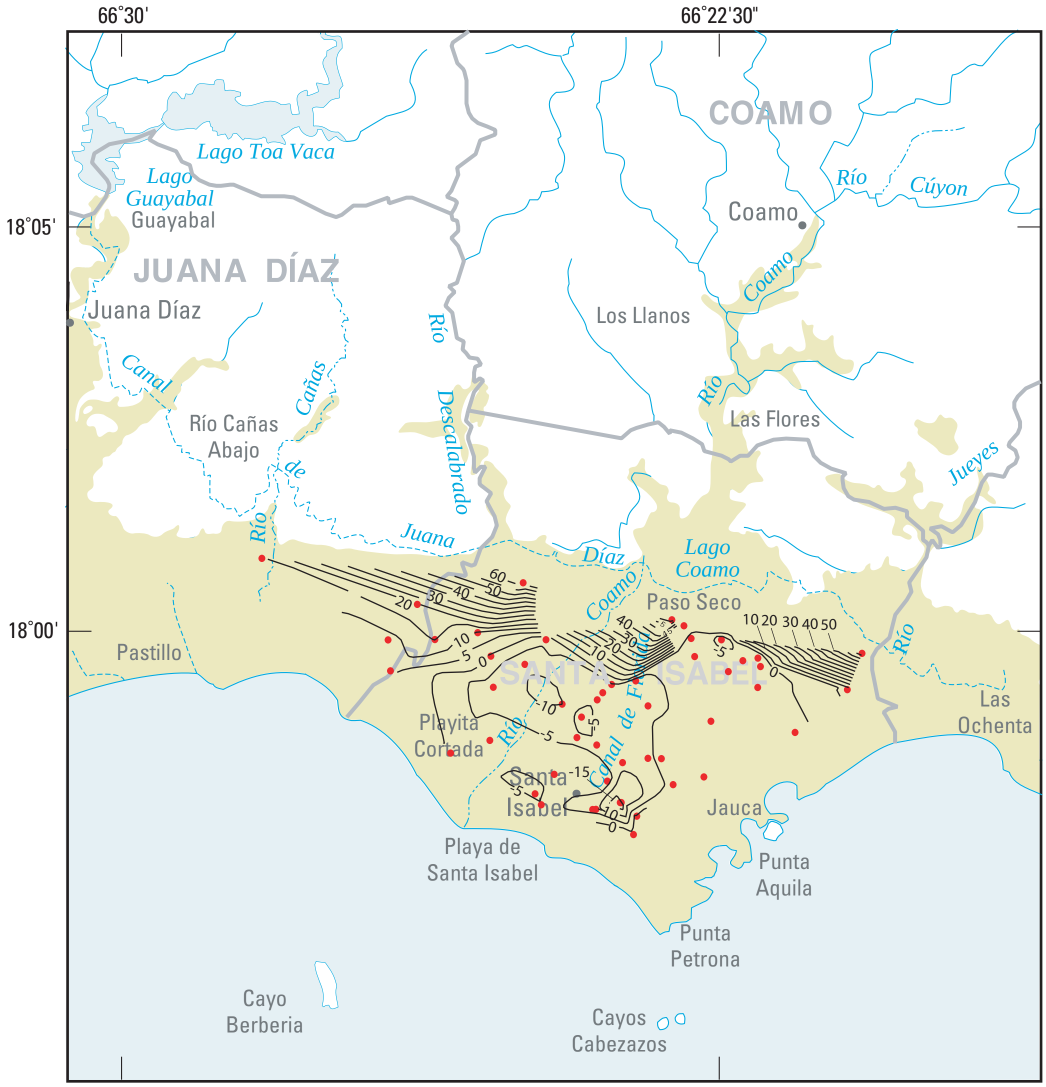


Figure 15. Estimated potentiometric surface of the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico, March 1986 (modified from plate 1, Renken and others, 2002).



Base from U.S. Geological Survey 1:100,000 quadrangles:
Arecibo, 1980, unpublished; and Humacao, 1979, unpublished

0 1 2 3 4 5 MILES

0 2 4 6 8 10 KILOMETERS

EXPLANATION

Area of fan-delta plain and alluvial deposits

Potentiometric contour—Shows altitude at which water would have stood in tightly cased wells open to the South Coast Aquifer in February 2003. Dashed where approximately located. Hachures indicate depression. Contour interval, 5 feet. Datum is mean sea level

Well—Control point

Figure 16. Estimated potentiometric surface of the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico, February 2003.

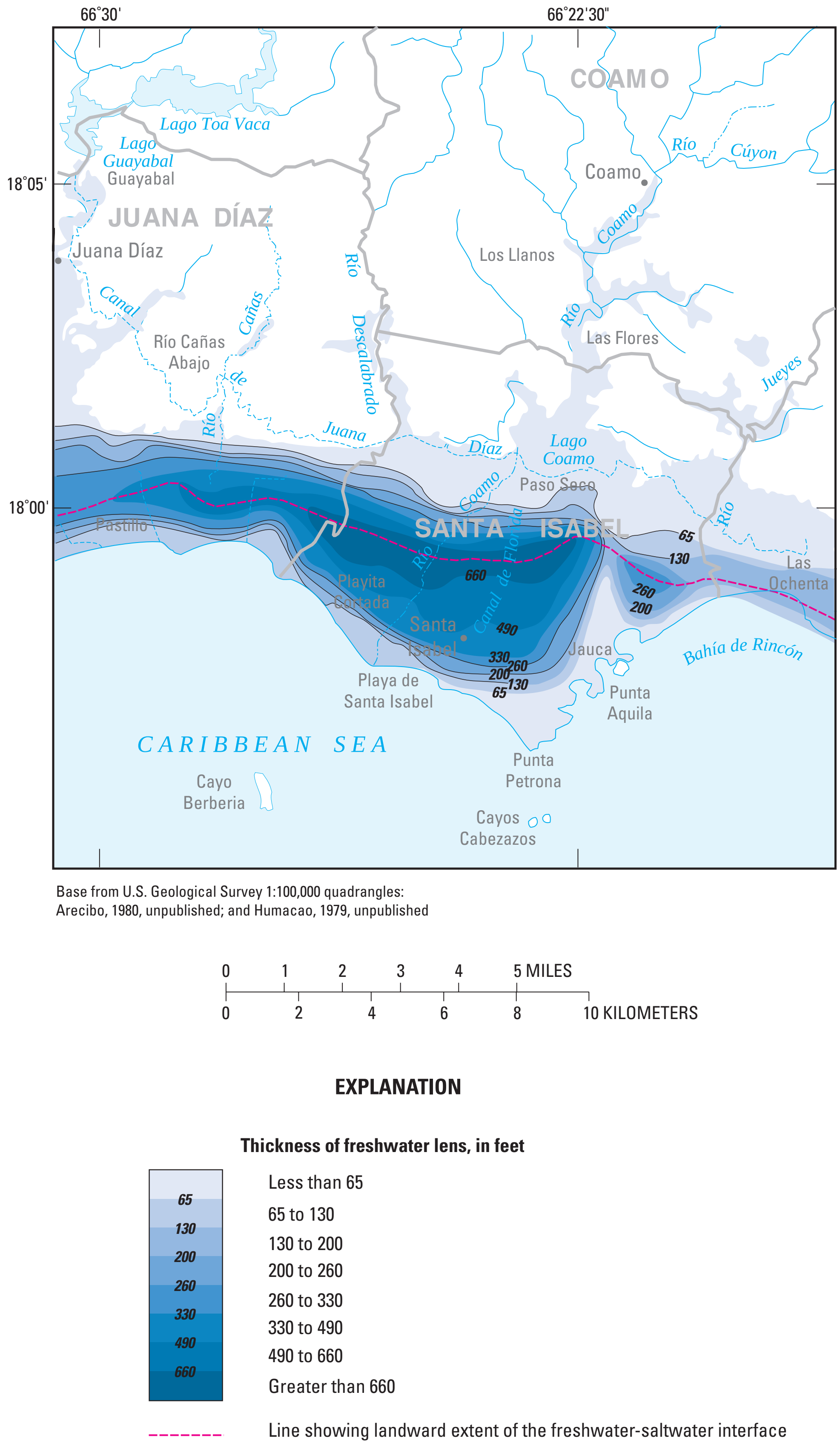
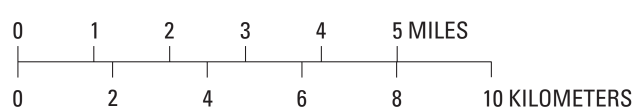


Figure 17. Estimated thickness of the freshwater lens contained in the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico, 1986-87 (modified from plate 1, Renken and others, 2002).

Base from U.S. Geological Survey 1:100,000 quadrangles:
Arecibo, 1980, unpublished; and Humacao, 1979, unpublished



EXPLANATION

Area of fan-delta plain and alluvial deposits

576/350 Observation well--Top number indicates specific conductance in microsiemens per centimeter at 25 degrees Celsius. Bottom number is estimated total-dissolved-solids concentration in milligrams per liter calculated by multiplying 0.6 times the conductance value.

Figure 18. Specific conductance of ground water at observation wells in the South Coastal Plain aquifer in the vicinity of Santa Isabel in 2003.

Simulation of Ground-Water Flow

The ground-water flow system in part of the South Coastal Plain Aquifer in the vicinity of Santa Isabel area was numerically simulated with a constant-density digital ground-water flow model to evaluate how changing irrigation practices have affected water levels and how future ground-water withdrawals may affect the alluvial aquifer. Specifically, the numerical simulations were used to determine: (1) how the change from furrow to drip irrigation systems have affected ground-water flow; (2) how future changes in ground-water withdrawals may affect ground-water levels in the study area; and (3) the potential for future saltwater encroachment. Simulated output, such as water levels in aquifers and streamflow losses, were compared to measured or estimated values to verify the validity of the numerical approximations.

The ground-water flow system at Santa Isabel was simulated using MODFLOW88/96 and MODFLOW-2000, widely used modular 3-dimensional finite-difference computer programs for simulating ground-water flow of uniform density (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh and others, 2000; and Hill and others, 2000). The modeled area is centered on the Coamo fan (fig. 1). The alluvial aquifer model was initially constructed in MODFLOW88/96, using the geohydrologic framework presented in previous sections, and then classical sensitivity analysis was performed. The model data files were then converted to MODFLOW-2000, for use of parameter estimation and calibrated in steady-state mode to 1987 water levels and average 1987 pumpage and recharge estimates. Transient (time-varying) simulations of the1987-2003 period were constructed with public supply and irrigation ground-water withdrawal estimates previously discussed. Miscellaneous instantaneous streamflow measurements (table 1, fig. 4) were used to estimate the streamflow losses to the aquifer. Hydraulic conductivity parameters and zones were adjusted based on parameter estimation until satisfactory matches to estimated ranges were achieved and were in general agreement with the geohydrologic framework. Ranges in percent precipitation for estimating net areal recharge and irrigation return flow to the aquifer were tested in both the steady state and transient simulations and were examined with the aid of parameter estimation and sensitivity analysis.

Hypothetical water-resource management-alternative simulations involving ground-water conservation, surface infiltration over existing agricultural fields, along streams and canals, and injection wells along the coast were developed in order to determine alternatives that would raise water levels above sea level. The amounts of ground-water withdrawal reduction or water required for artificial recharge from the different alternatives are compared.

Model Conceptualization and Construction

Three layers are used in the conceptual model to represent freshwater flow in the geohydrologic units that constitute the alluvial aquifer in the Santa Isabel area (fig. 19). The upper layer represents the shallow coastal water-table aquifer that occurs between land surface to 200 ft below land surface. This layer represents the most permeable principal flow zone and consists of fan-delta and alluvial deposits, and is the most important geohydrologic unit in the aquifer. The principal flow zone has a large variation in hydraulic conductivity that is associated with the areal distribution of sand and gravel. This distribution is controlled by the dynamics of fan-delta deposition and fluvial geomorphological processes.

The second layer represents the freshwater part of fan-delta and alluvial deposits from 200 to 250 ft below land surface. Less information is available for this part of the alluvial aquifer. However, it is assumed that this layer is relatively lower in permeability than the top layer based on water-quality changes and lithologic information described in drillers' logs and results from a test well drilled near Santa Isabel (Gómez-Gómez, 1991).

The third layer represents the freshwater part of the system in the lower part of the alluvial and fan-delta deposits and older unconsolidated to poorly consolidated sediments 250 ft below land surface to approximately 700 ft below land surface. These sediments are believed to be of lower permeability, but there are no data on hydraulic conductivity for this layer.

An equal-spaced finite-difference grid with sides of 1,000 ft was used for the simulations (fig. 20a). The northern boundary of the active area of the top layer is based on the areal extent of the alluvial deposits and the Juana Díaz irrigation canal (Renken and others, 2002). The Juana Díaz irrigation canal was simulated with a general head boundary condition. The southern boundary follows the coastline and was simulated with a general head boundary allowing exchange of water between the aquifer and the sea. The eastern and western boundaries are near the Río Jueyes and Río Cañas, respectively, and were simulated as no flow.

The lower two layers represent the freshwater part of the alluvial aquifer and have no-flow boundaries along the lateral sides, with the lowest layer also having a no-flow boundary along the bottom (figs. 20b and c). The no-flow boundary along the coast of these two layers represents the freshwater/saltwater interface as defined by Renken and others (2002). Because the freshwater is much less dense than the seawater, it tends to flow above the seawater and the interface is commonly treated as a no-flow boundary in constant-density models in coastal aquifers (Reilly, 2001). The northern no-flow boundary is generally along the bedrock/alluvial contact.

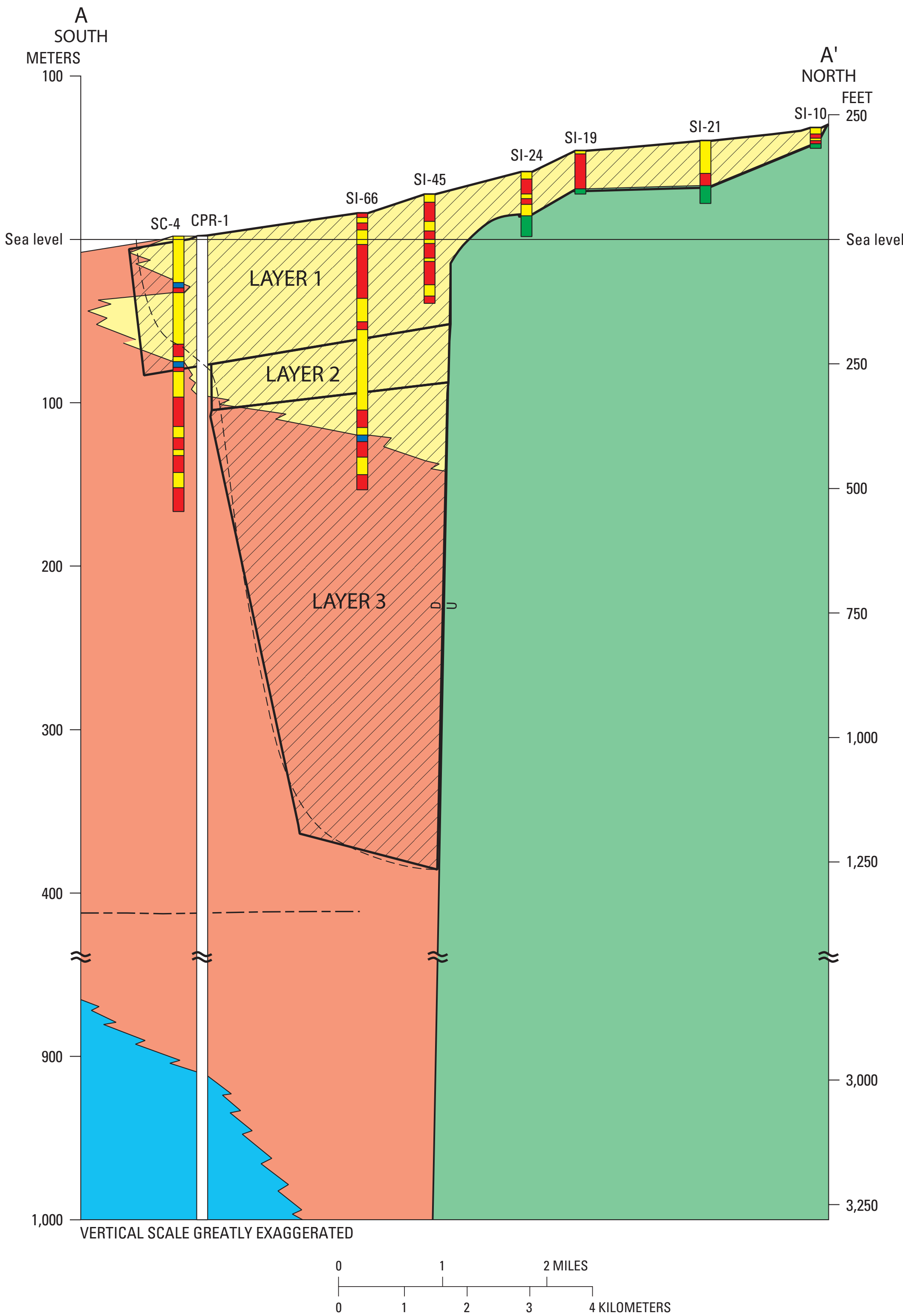


Figure 19. Section A-A' down the axis of the Coamo fan delta, south-central Puerto Rico showing model layers (section location and explanation in figs. 11a, b).

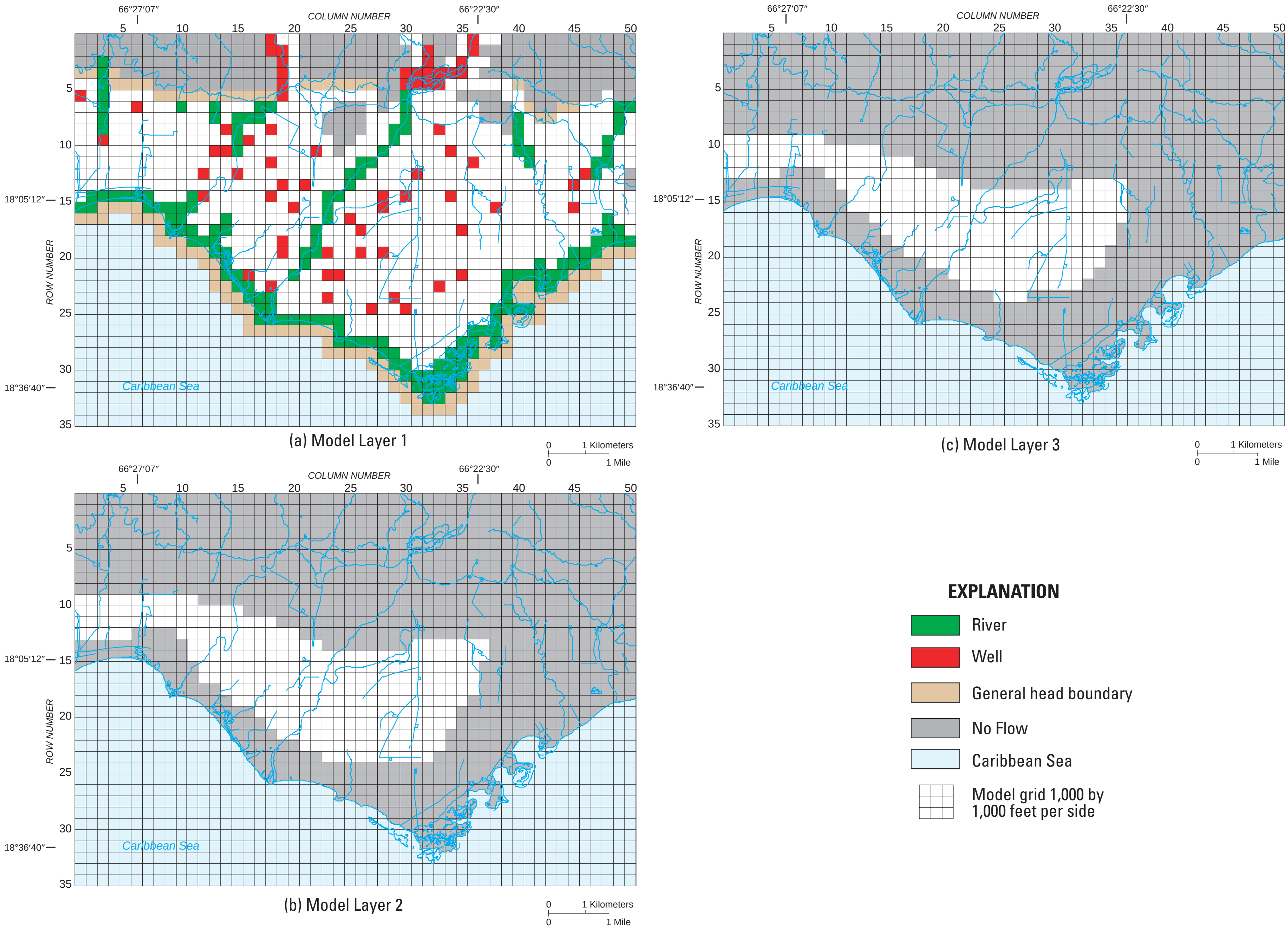


Figure 20. Plan views of model layers and boundary cells.

Boundary Conditions Applied to the Top Layer

Net areal recharge (a percentage of annual rainfall plus the estimated irrigation return flow infiltration) was applied to the top model layer as a specified flux boundary condition. The spatial variation is based on the agricultural field types (figs. 6 and 7), which affects the amount of irrigation return flow that augments the natural net recharge from rainfall.

Streamflow infiltration from the upper river reaches and seepage from the irrigation canals is represented in the model in several ways. In the upper most reaches of the Río Coamo, Río Descalabrado, and Lago Coamo, the estimated lake seepage and streamflow loss was applied with injection wells. In these areas, there is little information on water levels in the aquifer and the reaches are documented always to be losing reaches. The streamflow loss, based on the estimates of streamflow loss described previously, was simulated using injection wells placed along the stream or reservoir with the well package (McDonald and Harbaugh, 1988). The downstream parts of the streams, that generally are losing reaches, were simulated with the river package (McDonald and Harbaugh, 1988). However, the maximum loss to the aquifer by each stream is constrained by setting the river bottom elevation (RBOT in the River Package; McDonald and Harbaugh, 1988) to 1 ft lower than the assigned river stage (RSTAGE in the River Package). The riverbed conductance term is set such that the loss per reach is fixed for each reach by taking the total estimated loss along all of the reaches (table 1) and dividing this by the number of reaches simulated. In this way, the maximum rate of inflow to the aquifer is constrained, but outflow from the aquifer to the river is not constrained. Thus, if water levels rise above the specified river stage in the aquifer during some of the simulations, water can flow from the aquifer to the stream as would naturally occur.

Because the bedrock is highly fractured and may not be totally impermeable, the General-Head Boundary package (McDonald and Harbaugh, 1988) was used to allow leakage from the Juana Díaz irrigation canal along parts of the northern boundary. The specified general head is the elevation of the canal; the conductance term assigned to these model cells is 5 ft^2/d, based on the assumption that the saturated thickness of the general head boundary is 50 ft times a width of 1,000 ft a distance 1,000 ft with a hydraulic conductivity of 0.1 ft/d.

Ground-water withdrawals from the alluvial aquifer were simulated with the well package (McDonald and Harbaugh, 1988), which places the negative pumping rate in the right-hand-side vector of the cell where each well is located. Rather than simulate ET with the ET package, river cells were placed along the inland part of the coast to represent leakage to the clayey unit above the aquifer. The river package was selected rather than the general-head-boundary package in order to allow some leakage to the aquifer when simulated water levels drop, but to be able to constrain the maximum rate of leakage. Parts of this area are mangrove swamps. There is no recharge applied to the cells along the coast and generally there is upward discharge during wet periods. General-head boundary cells were placed at the seaward boundary to allow for discharge or recharge from the sea to the aquifer.

Model Calibration Strategy

Because water-use data and irrigation surveys prior to the one conducted in 1987 are less accurate, the process of model calibration began with developing a steady-state simulation based on the 1987 data that would be used as an initial condition for transient simulation. In 1987, a water-use survey was conducted and 51 water-level measurements from non-pumping wells were collected from March to April 1987 (Rodríguez-del-Río and Gómez-Gómez, 1990). For transient calibration, annual stress periods were set up from 1987 through 2002 with a two-month final stress period representing January and February 2003. For the transient calibration, there is one continuous observation well, Alomar 1 (also locally called HW-87; fig. 2) and a water table map from water levels collected in February 2003. The water-level data collected in 1987 and 2003 are from wells open to the principal flow zone simulated as the top model layer (layer 1).

When calibrating a ground-water flow model, it is important to understand the accuracy and uncertainty of the data used for the model calibration. The match between simulated and observed data should never be closer than the accuracy of the data. Matching inaccurate observations exactly is termed over fitting. It is also important to have estimates of fluxes to and from the ground-water system when calibrating a ground-water flow model, in order to have a unique set of model parameters.

The accuracy for water-level measurements at wells in the relatively flat coastal plain (land-surface altitude 50 ft or less above mean sea level) is known within 2 ft at best (half the contour interval of the 1:20,000 scale topographic map used by Rodríguez-del-Río and Gómez-Gómez, 1990). The accuracy for water-level measurements at wells where the land-surface altitude is greater than about 50 ft above mean sea level are known within 15 ft at best (half the contour interval of the topographic map used by Rodríguez-del-Río and Gómez-Gómez, 1990). Eleven of the 51 water-level measurements have an accuracy of 15 ft and the 40 water-level measurements have an accuracy of 2 ft. The range in the 51 water-level observations is 3 to 98 ft above mean sea level. Thus, the average of the accuracy of these measurements is 4.8 ft, the standard deviation of the accuracy is 5.4 ft, and the root mean square accuracy is 7.2 ft. There is also some error in the location of the water levels for 1987 as these were located without the benefit of modern global positioning systems (GPS). Thus, the initial condition steady-state calibration would be over fit to the water-level data if the standard deviation of observed minus simulated water level is 5.4 ft or less. Because of the additional potential errors in well location for the 1987 data, it was concluded that a good fit to the observed water-level data could have a standard deviation of approximately 11 ft (two times the accuracy standard deviation, which would indicate that approximately two thirds of the residual errors are less than 11 ft). Another useful statistic is the standard deviation of residuals divided by the range in the data. This statistic is dimensionless and should generally be less than one. It is a useful statistic because it takes into account the range of water-level data used for calibration. Generally, if the range of water-level data is large, there is usually a larger standard deviation in residual errors. Thus, a good fit to the data would be reflected if this ratio was approximately 0.1.

There is uncertainty in the estimates of spatially distributed recharge (approximately 5 to 15 percent of rainfall depending on wet or dry year), irrigation return flow (30 to 50 percent of applied water), and ground-water withdrawals for both irrigation (estimated from crop acreage and estimate of amount supplied by rainfall and surface water) and public supply (no requirement for accurate metering).

The range in horizontal hydraulic conductivity of the sediments is probably the best understood property for the upper 200 ft of the alluvial aquifer, but could range from 10-250 ft/d. However, the spatial distribution of small hydraulic conductivity and large hydraulic conductivity should mimic the combined shapes of the hydraulic conductivity map (fig. 13) and the sand and gravel percentage map (fig. 12), with larger hydraulic conductivities in fan-delta deposits and areas of higher sand and gravel percentages and low conductivities in the interlobe areas between the fan-delta lobes.

For the steady-state initial condition calibration, the initial hydraulic conductivity was set at the mid-range value for zones of hydraulic conductivity (fig. 13). Additionally, the ranges in recharge were tested and some of the initial pumping estimates were also reviewed and modified as necessary. Classical sensitivity analysis was performed to gain some insight into which parameters and stresses could be evaluated with parameter estimation. Only those parameters for which the observed data set is sensitive can be estimated with parameter estimation. MODFLOW-2000 with parameter estimation was used to test different zoning schemes of hydraulic conductivity or net recharge (recharge from precipitation and irrigation return flow).

Because the ground-water flow equation is based on Darcy's law, recharge (flux) and hydraulic conductivity are usually correlated in the parameter estimation process and cannot be estimated simultaneously without better prior information (tighter bounds on the estimated parameters or stresses) about recharge and irrigation return flow than previously mentioned. The prior information functions for hydraulic conductivity adequately constrained these parameter estimates. As a result of parameter correlation and poor prior information for net recharge and ground-water withdrawals, attempts to estimate hydraulic conductivity and recharge parameters simultaneously with MODFLOW-2000 resulted in what appeared to be unreasonable recharge rates for the steady-state initial condition.

Figure 21 shows the 1987 simulated water table for the principal flow zone of the alluvial aquifer (the top model layer) and the residual errors (observed minus simulated water level). A positive error means that the simulated water level is too low and a negative error means that the simulated water level is too high. The standard deviation of the residuals was 13.21 ft (original calibration target is a standard deviation of 11 ft) and the mean residual was 8.56 ft (this indicates that there are larger errors in positive residuals). The range in observed water levels was 95 ft, thus the ratio of the residual standard deviation divided by the range is 0.139 (original calibration target was 0.1). Figure 22 is a graph of the observed versus simulated water levels, observed versus residual, and cumulative probability plot of the residuals for the steady-state initial condition. As previously mentioned, the observed versus simulated water levels indicate that the simulated water levels are lower than the observed water levels (more positive residuals). However, the cumulative probability plot has a fairly linear shape, which is desirable.

The final hydraulic conductivity of the top layer for the calibrated model is shown in figure 23. Horizontal hydraulic conductivity ranged from 10 to 150 ft/d in layer 1, is 20 ft/d in layer 2, and is 10 ft/d in layer 3. This final set of aquifer properties was not changed during the transient calibration and was derived by using parameter estimation with MODFLOW-2000 and knowledge about the hydrogeologic framework. Parameter estimation with MODFLOW-2000 indicated a simpler zonation scheme than shown in figure 22. In the simpler zonation scheme, 2 zones were used: 11 ft/d in the two zones contained within the 10 and 20 ft/d (fig. 23) and 72 ft/d in the two zones contained within the 120 and 150 ft/d areas (fig. 23). This simpler scheme provided only a slightly better fit compared to the calibrated values (fig. 23), because the residuals are more normally distributed with a mean error of 2.91 ft and a standard deviation of 13.00 ft. However, this simpler 2-zone scheme does not fit the known geologic framework as well and was not a great improvement in fit to water levels. While the use of MODFLOW-2000 was a valuable tool in the calibration process, the small calibration dataset (51 water levels) and poor bounds on fluxes to and from the aquifer make it impossible to use parameter estimation in a mathematically rigorous manner. The final calibrated hydraulic conductivity values used in the model (fig. 23) are less than the initial estimates shown on figure 13 and include some higher hydraulic conductivity zones near the smaller fan deltas shown on figure 1, which conforms with the information on sand and gravel percentages (fig. 12).

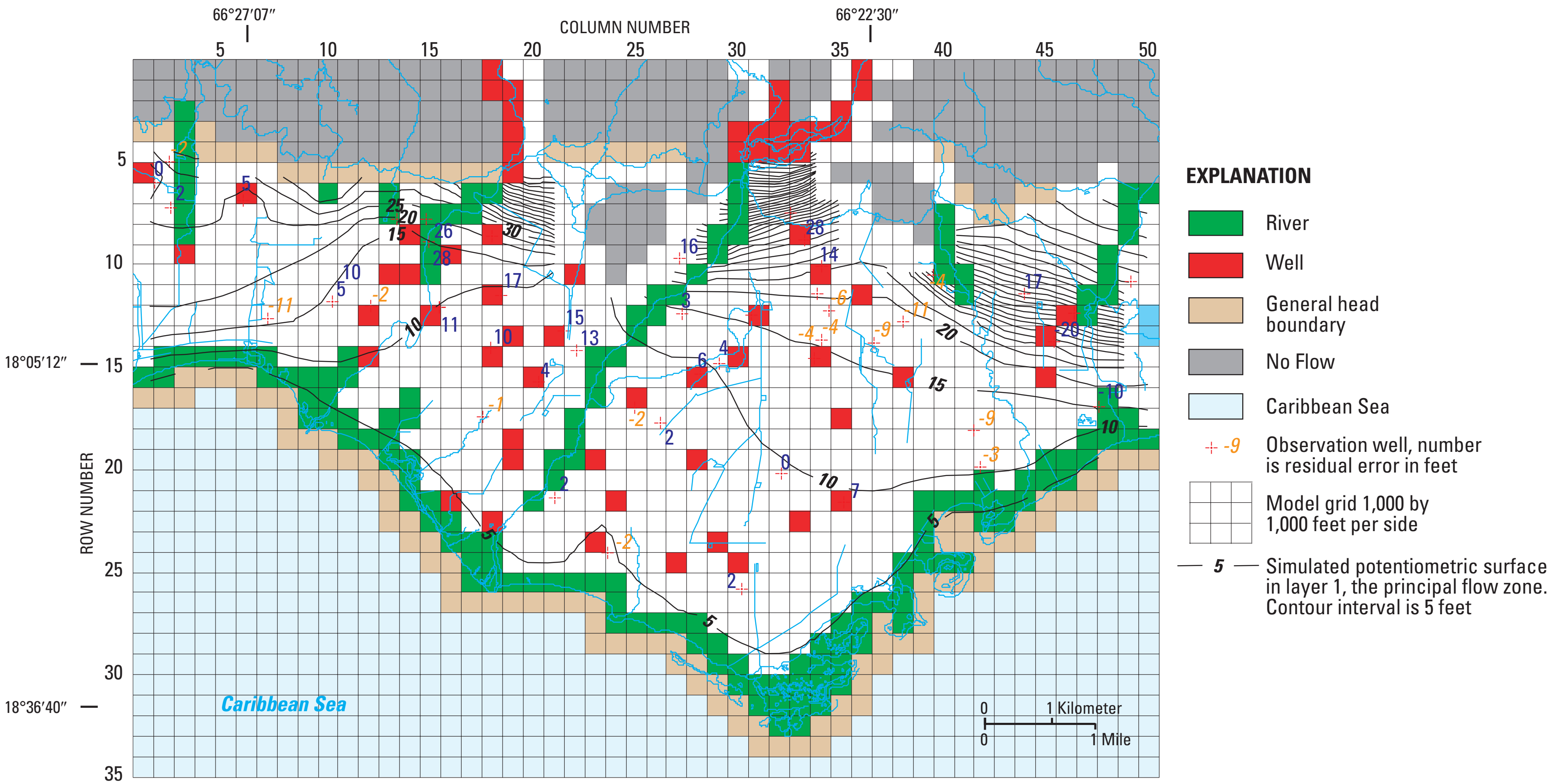


Figure 21. Simulated 1987 potentiometric surface and residual errors at observation wells in the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico.

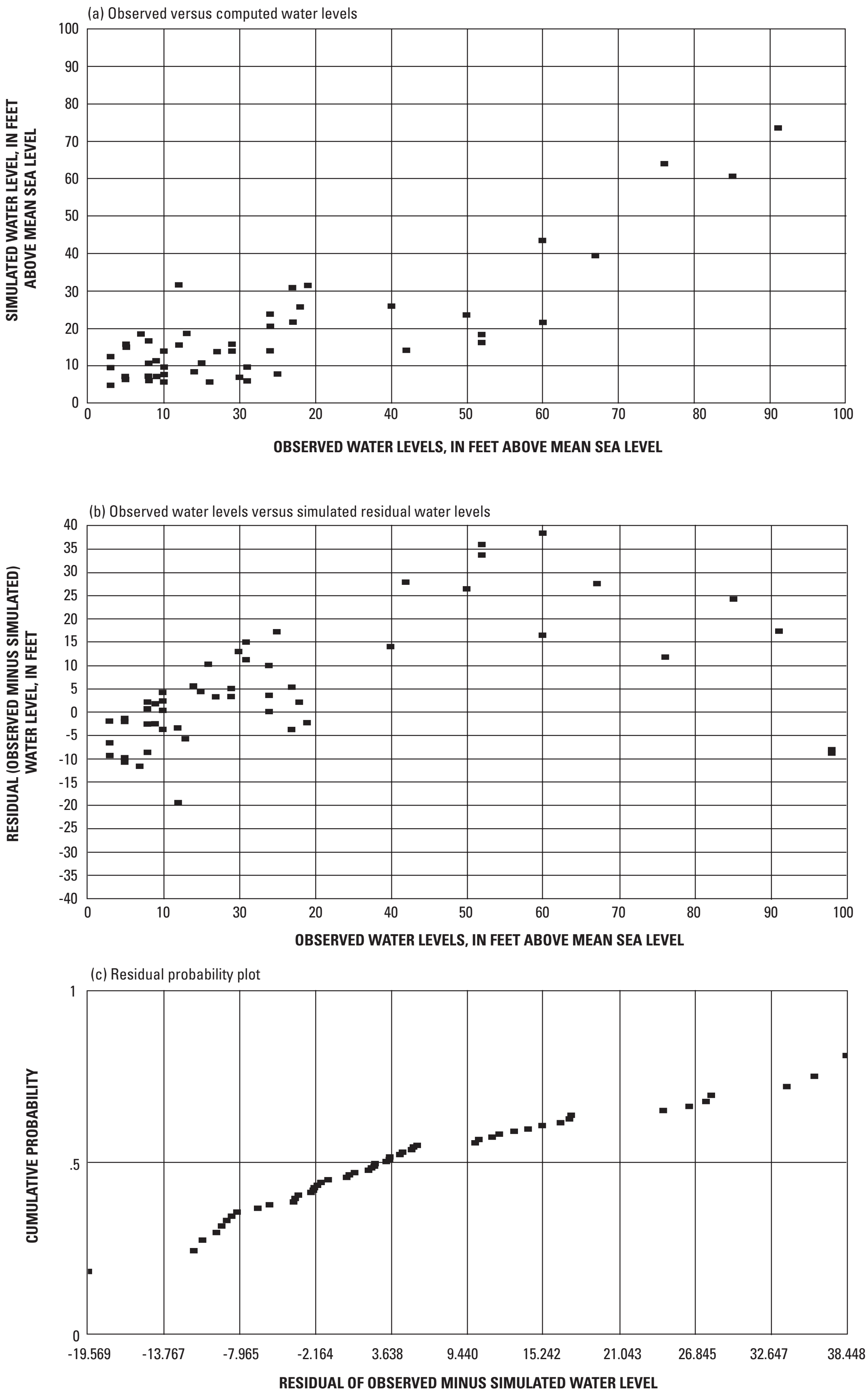


Figure 22. Steady-state model fit to 51 water-level measurements for 1987.

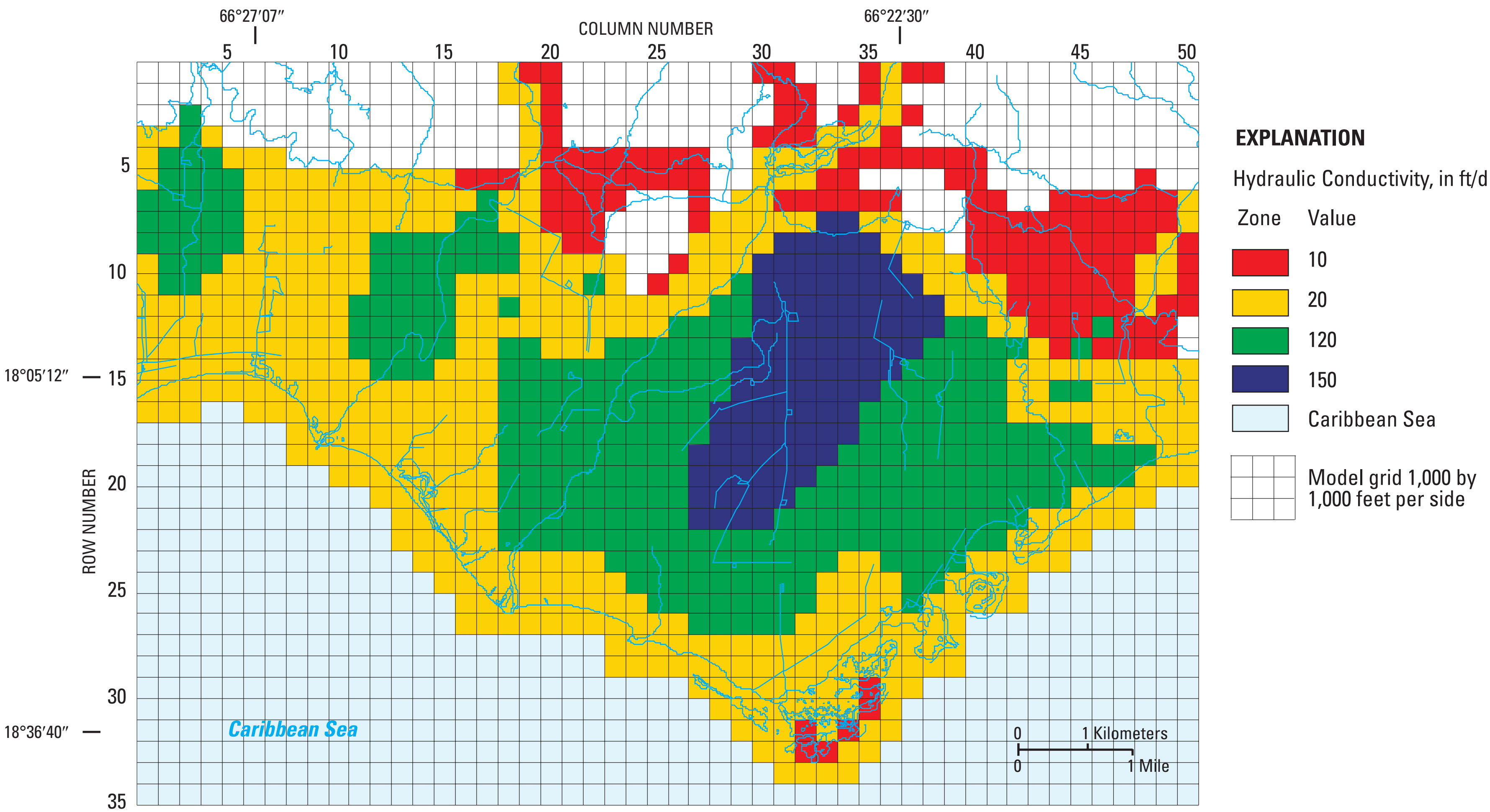


Figure 23. Final horizontal hydraulic conductivity used in the simulations for the principal flow zone (layer 1) of the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico.

After conducting the steady-state calibration, transient data were prepared for 1987 through February 2003 and simulation started with the simulated 1987 steady-state water levels as the initial condition. The only parameters modified for the transient calibration were net recharge (percent of total precipitation for each year) and storage coefficient. Through a trial and error transient calibration, the best fit to the ground-water-level trend from observation well Alomar 1 (fig. 1) occurred when the specific yield of the unconfined aquifer was set to 0.1, storage coefficient for lower layers was left at the original estimate of 0.0003, irrigation return flow for micro-drip fields was zero, and irrigation return flow from furrow irrigation was 30 percent of the applied water. Additionally, the simulated hydrograph matched better if for years in which annual rainfall was less than 30 inches, net recharge was estimated as 4 percent of annual rainfall; for years in which annual rainfall exceeded 40 inches, net recharge was estimated as 12 percent of annual rainfall; and for average years in which annual rainfall was between 30 to 40 inches, net recharge was estimated as 8 percent of annual rainfall. From 1987 through 2001, average annual reported rainfall at Santa Isabel was 32.45 inches and the average recharge applied in the simulation was 2.43 inches or 7.5 percent of the average annual rainfall reported for Santa Isabel 1987-2001. For 2002, rainfall data for the Santa Isabel station were not available and recharge applied in the simulation was estimated from average long-term annual rainfall at Santa Isabel (fig. 2). For January and February 2003, the recharge rate applied was half the historical average annual rate, because this is the relatively dry season of the year. Because of the limited streamflow loss studies, the inflows to the model from surface-water losses from the major streams, irrigation canals, and Lago Coamo were kept at the average rate for the transient simulation by not changing the injection rates of the wells or the conductances of the river cells and general-head boundary cells. The simulated changes in inflow for each annual stress period is mainly from the loss of irrigation return flow and the change in estimated recharge as a percent of annual precipitation.

Figure 24 shows the observed versus simulated hydrograph at observation well Alomar 1 (also referred to as HW-87) for the period from 1987 through February 2003. The standard deviation for the residual water level (observed water level minus simulated water level) at Alomar 1 is 3.17 ft, the mean residual is -1.66 and the range in observed values is 23.88 ft. Thus, the standard deviation of residual divided by the range is 0.133. This was considered a fairly good fit of the data at Alomar 1, because the altitude of the water level above or below mean sea level is known within 2 ft and the observed water levels are affected by pumping from nearby irrigation wells.

Water levels were measured in February 2003 in the Santa Isabel area and compared to the simulated water levels for February 2003 (fig. 25). The altitude of land surface was obtained from 1:20,000 scale topographic maps as before. However, the geographic location of each well was obtained using handheld GPS. Thus, the locations of observation wells are more accurate for the data collected in 2003. Of the 57 observations, the maximum water-level altitude was 62.9 ft and the minimum was -20.1 ft (range of 83 ft). The maximum simulated water-level altitude was 45.1 ft and the minimum was -19.5 ft. The standard deviation of the residuals (observed minus simulated water level) was 9.22 ft with a mean residual of 8.50 ft. The statistics are affected by one outlier residual of 57.4 ft (fig. 25). If this outlier is removed, the standard deviation drops to 6.51 ft and the mean error to 7.63 ft. The standard deviation of all of the wells divided by the range in observations is 0.111. This was considered an acceptable fit to the February 2003 data given that recharge for 2002 and 2003 could not be estimated from actual precipitation data.

Sensitivity Testing and Analysis

Ground-water modeling results are affected by various modeling parameters, stresses, and assumptions, including: (1) geometry of the geohydrologic units; (2) vertical and horizontal spacing of the model grid; (3) types and locations of model boundaries; (4) magnitudes and areal distributions of stresses such as ground-water recharge and withdrawals; (5) conductance of river and general head boundary cells; and (6) horizontal and vertical hydraulic conductivities of aquifers and confining units. Transient simulation results are affected by the time-step size, number of stress periods, or the storativity of the aquifers and confining units. Ideally, a complete sensitivity analysis would determine model sensitivity to all of these parameters and assumptions, but only model sensitivity to the parameters and stresses were determined for the Santa Isabel model. For ground-water flow models, the model response is the simulated water level and flow through the system. For the Santa Isabel model, it is considered sensitive to a parameter or stress when a small change (perturbation) of the parameter or stress causes a large change in the simulated water level (observation dataset is water levels). Sensitivity analysis is useful for indicating where errors in the calibrated set of parameters and stresses are more likely. If the model is sensitive to changes in the parameter or stress, the calibrated value is more likely to be accurate or can be accurately estimated through simulation. If the model is insensitive to changes in a parameter or stress, then it is not known if the calibrated value is close to the actual value, and that parameter or stress cannot be estimated through simulation or the use of automated parameter estimation.

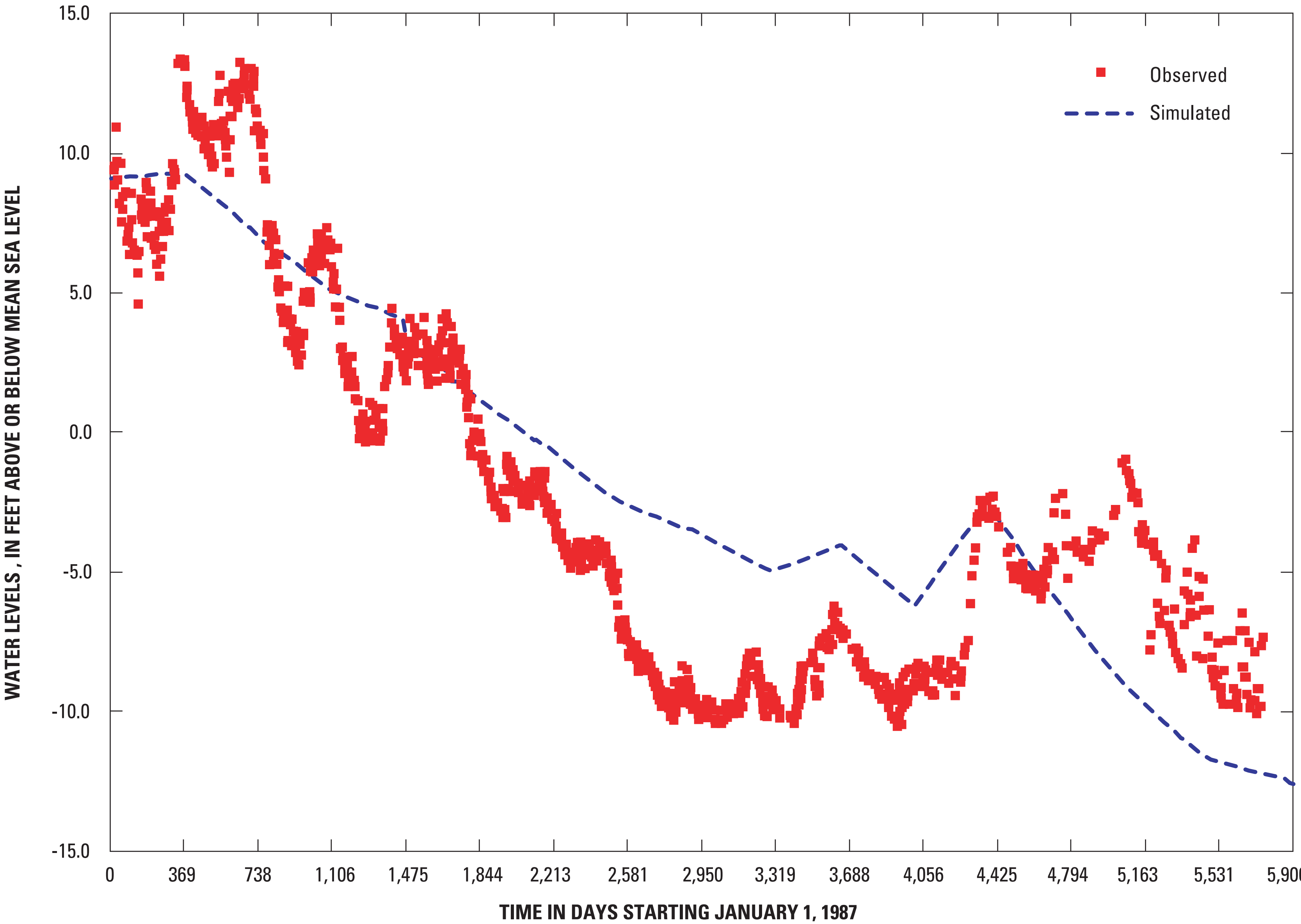


Figure 24. Observed and simulated water levels at well Alomar 1 for January 1987 through February 2003.

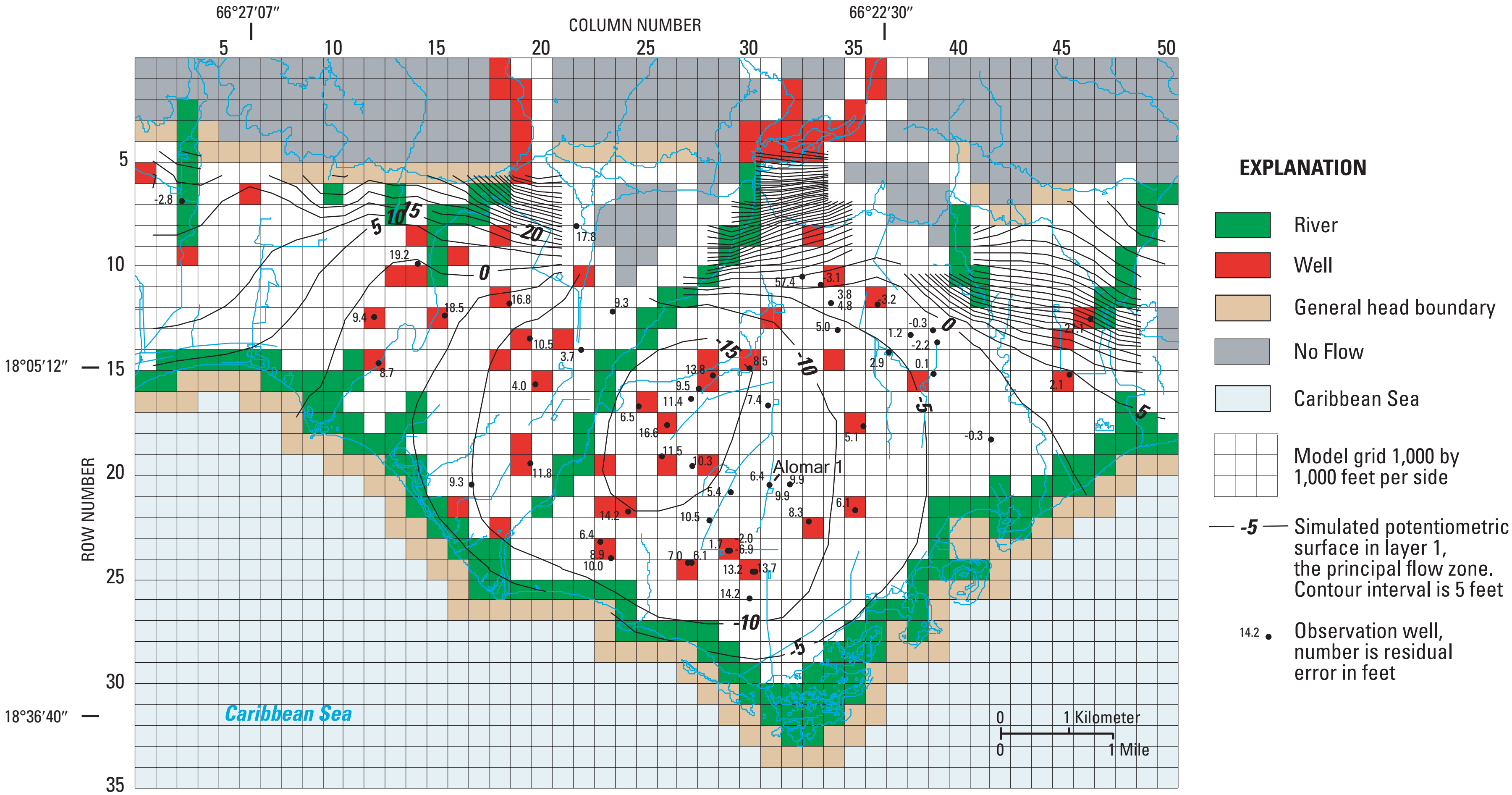


Figure 25. Simulated February 2003 potentiometric surface and residual errors at observation wells in the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico.

The sensitivity testing of the steady-state model was accomplished by using the sensitivity process of MODFLOW-2000. Table 3 shows the composite scaled sensitivities of various parameters and stresses for the initial steady-state condition. For this reason, no storativity values are shown. Composite-scaled sensitivities are calculated for each parameter using the scaled sensitivities for all observations, and indicate the total amount of information provided by the observations and the parameter. They are calculated at the set of calibrated values, are independent of the observed values, and are dimensionless (Hill, 1998). When the sensitivity process is used with the final set of parameters that are used in the calibrated model, the sensitivities indicate which parameters will result in the greatest change in observation types. For the steady-state model, only 51 water-level observations were available. Thus, the sensitivity testing provides information on how the parameters and stresses affect water levels. While 11 of the measurements were plus or minus 15 ft, and 40 were plus or minus 2 ft, weighting was not used in the sensitivity analysis. Weighting is critical for calibration and sensitivity analysis if there are different observation types, such as flux observations, water levels, or water-level differences. For the Santa Isabel model, all of the observations were water levels. For this case, weighting the observations does not provide more information about sensitivity, although weighting would have given the appearance of better calibration statistics since the worst residual errors were at wells that had the least accuracy. The larger the composite scaled sensitivity number the greater the model sensitivity for that parameter.

The steady-state model is most sensitive, in decreasing order, to ground-water withdrawals, recharge, river reach conductance, recharge along reaches simulated with injection wells, and horizontal hydraulic conductivity. The steady-state model is relatively insensitive to vertical hydraulic conductivity and the general head boundary conductance. The recharge zones in table 3 are based on the agricultural areas shown in figure 7 for 1987. The vertical hydraulic conductivity zones are numbered the same as the horizontal hydraulic conductivity zones shown in figure 23.

Table 3. Composite scaled sensitivity for the steady-state calibrated model for 1987.

[ft^3/d, cubic feet per day; ft/d, feet per day]

Parameter name	Parameter value (units variable)	Description	Composite scaled sensitivity (dimension less)
wel1	variable discharge ft^3/d	Pumping wells at 1987 rates	40.071
rch4	0.00320 ft/d	Furrow irrigation area (fig. 6)	13.894
riv0	1,000 to 19,100 ft/d	Riverbed conductance	13.480
wel2	variable recharge ft^3/d	Injection wells for Lago Coamo and upper reaches of Río Descalabrado	10.163
rch2	0.00151 ft/d	12 percent of 1987 annual precipitation, vegetable crop area falllow (fig. 6)	9.955
kx3	10 ft/d	Horizontal conductivity (fig. 23)	8.896
kx4	20 ft/d	Horizontal conductivity (fig. 23)	7.517
rch3	0.00145 ft/d	Less than 12 percent of 1987 annual precipitation, vegetables drip area (fig. 6)	6.768
kx6	150 ft/d	Horizontal conductivity (fig. 23)	4.430
kx5	120 ft/d	Horizontal conductivity (fig. 23)	3.369
ghb0	5 or 5000 ft/d	General head conductance	0.308
kz4	2 ft/d	Vertical conductivity 1/10(kx4) (fig. 23)	0.118
kz3	1 ft/d	Vertical conductivity 1/10(kx3) (fig. 23)	0.005
kz5	12 ft/d	Vertical conductivity 1/10(kx5) (fig. 23)	0.005
kz6	15 ft/d	Vertical conductivity 1/10(kx6) (fig. 23)	0.001

Sensitivity of the computed water levels to storativity was determined with the transient simulation using a trial and error calibration process. The model is somewhat sensitive to the specific yield for the unconfined top layer and insensitive to the storage coefficient used in all layers. Specific yield was initially set to 0.25; however, the final value used for the calibrated model is 0.10. The storage coefficient was not changed from the initial value of 0.0003, because the model is insensitive to this parameter. Decreasing the specific yield during the analysis affected the water levels by increasing the change in slope of the computed hydrograph, which improved the fit to the observed hydrograph. The greatest changes in the computed hydrograph resulted from changes in recharge and ground-water withdrawals, during calibration simulation trials, similar to the steady-state sensitivity analysis.

Effects of Water-Resources Development

How water-resources development has affected the ground-water system in the Santa Isabel area is best described by examining changes in the ground-water flow model derived water budgets. The water budget for the steady-state model is shown in table 4. Recharge from rainfall and irrigation return flow is the greatest contributor of inflows (60 percent of total inflows), followed by the inflows from surface-water losses from the major streams, irrigation canals, and Lago Coamo (40 percent of total inflows; 23 percent from river cells plus 16 percent from injection wells plus 1 percent from general head cells). Ground-water withdrawals from wells are the greatest outflow from the system (75 percent of total outflows). Discharge to the river cells along the coast represents evapotranspiration and is almost an order of magnitude less than ground-water withdrawals (14 percent of total outflows). The majority of discharge to the general-head boundary cells represents freshwater discharge to the coast and is also an order of magnitude smaller than ground-water withdrawals (11 percent of total outflows).

The water budget for the last stress period of the transient simulation, which represents January through February 2003, is shown in table 5. This represents a short relatively dry period and total inflow rates were 28 percent less than the 1987 steady-state simulation. As a result, there is less inflow to the model. The inflows from surface-water losses from the major streams, irrigation canals, and Lago Coamo were held constant and they represent the majority of the inflows (55 percent). However, a significant amount of inflow is supplied from storage in the unconfined aquifer simulated as layer 1 (18 percent). Recharge is 15 percent of the total inflow. Additionally, for the last stress period, the general head boundary along the coast, which represents exchange of water with the sea supplies 10 percent of the total inflows and the inland river cells representing the swamps along the coast now provide 2 percent of inflows. In the steady-state simulation of 1987, there was no inflow to the model from the general head boundary or the river cells along the coast (table 4c). The lowering of the water table below sea level has reversed the gradient and induced inflow to the aquifer. Outflow rates for the last stress period are quite different from the 1987 steady-state simulation. For the last stress period of the transient simulation, ground-water withdrawals from wells represent 96 percent of the total outflows, rivers only 2 percent, and general heads along the coast only 2 percent of the total. The total ground-water withdrawals during the last stress period (January through February 2003) are about 8 percent less than the steady-state simulation for 1987.

As discussed earlier, the change to more efficient irrigation practices in the Santa Isabel area has decreased ground-water withdrawals for irrigation. However, public supply withdrawals have increased to almost offset the reduction in ground-water withdrawals for irrigation. The efficiency of the micro-drip irrigation results in zero irrigation return flow. The primary effect of the changes in agricultural practices is a reduction in recharge to the aquifer from the loss of irrigation return flow. The combination of total ground-water withdrawals increasing to almost the same rate as 1987 and the decreased recharge from the loss of irrigation return flow has resulted in a lowering of the water table below sea level throughout most of the Santa Isabel area, which has been duplicated by simulation (fig. 25).

Another effect of the lowering of the water table is that some water is removed from storage in the alluvial aquifer. The transient simulation cumulative water budget indicates 30,562 acre-ft of water came out of storage (1,892 acre-ft/yr) between 1987 and February 2003. Along with the reduction in storage is a reduction in transmissivity, because the saturated thickness of the aquifer is reduced. At the Alomar 1 observation well (row 21 column 31 of the model), the simulated saturated thickness changes from 172 ft in 1987 to 150 ft in February 2003. The hydraulic conductivity of the aquifer in this area is 150 ft/d. Thus, the transmissivity in the model at Alomar 1 is 25,800 ft^2/d in 1987 and 22,500 ft^2/d in February 2003, a 13 percent reduction in transmissivity.

Lowering the water table below sea level reverses the natural discharge of ground water along the coast and can result in the inland movement of seawater or upconing of poorer quality water. The inland movement of seawater may result in increased salinity of the aquifer, as has occurred in other parts of the South Coastal Plain Aquifer (Díaz, 1974, 1979b). Local farmers indicate that some wells have increased in salinity, approaching the limit of salinity useful for irrigation of banana crops. However, the current salinity conditions are not a problem for other crops, such as onions and peppers (R. Richards, U.S. Geological Survey, written commun., 2003).

Table 4. Mass balance summary for 1987 steady-state initial condition.

[ft^3/d, cubic feet per day; ft^3/s, cubic feet per second]

(a) Summary of entire model	Inflows			Outflows	
	ft^3/d	ft^3/s		ft^3/d	ft^3/s
river	573275.89	6.64	river	353792.74	4.09
general head	14906.78	0.17	general head	265817.60	3.08
well	388200.00	4.49	wells	1829545.20	21.18
recharge	1471911.00	17.04			
Total in	2448293.67	28.34	Total out	2449155.54	28.35

Percent Mass Balance Error -0.04

(b) Exchange between layers	Inflows			Outflows	
	ft^3/d	ft^3/s		ft^3/d	ft^3/s
Summary for layer 2					
from layer 1	248249.85	2.87	to layer 1	248423.90	2.88
from layer 3	49990.94	0.58	to layer 3	49963.38	0.58
Summary for layer 3					
from layer 2	49963.38	0.58	to layer 2	49990.94	0.58

(c) Summary of general head cells at coast	Inflows			Outflows	
	ft^3/d	ft^3/s		ft^3/d	ft^3/s
general head	0.00	0.00	general head	265817.60	3.08

(d) Summary of inflows by surface water loss to aquifer by river cells, and injection wells, general head cells, and injection wells, in ft^3/s	
Río Cañas	1.39
Río Descalabrado	2.58
Río Coamo and Lago Coamo	5.60
Río Jueyes	0.42
Irrigation Canals	1.28
Total	11.27

Table 5. Mass balance summary for February 2003 from the transient simulation.

[ft^3/d, cubic feet per day; ft^3/s, cubic feet per second]

(a) Summary of entire model	Inflows			Outflows	
	ft^3/d	ft^3/s		ft^3/d	ft^3/s
storage	315389.99	3.65	storage	581.41	0.01
river	612268.06	7.09	river	38592.26	0.45
general head	184802.62	2.14	general head	33527.59	0.39
well	388200.00	4.49	wells	1683555.79	19.49
recharge	255586.00	2.96			
Total in	1756200.00	20.33	Total out	1756300.00	20.33
Percent Mass Balance Error	-0.01				

(b) Exchange between layers	Inflows			Outflows	
	ft^3/d	ft^3/s		ft^3/d	ft^3/s
Summary for layer 2					
storage	321.30	0.00	storage	1.10	0.00
from layer 1	343766.22	3.98	to layer 1	344376.28	3.99
from layer 3	81138.16	0.94	to layer 3	80848.26	0.94
Summary for layer 3					
storage	290.49	0.00	storage	0.64	0.00
from layer 2	80848.26	0.94	to layer 2	81138.16	0.94

(c) Summary of general head cells at coast	Inflows			Outflows	
	ft^3/d	ft^3/s		ft^3/d	ft^3/s
general head	168278.94	1.95	general head	33527.59	0.39

(d) Summary of inflows by surface water loss to aquifer by river cells, general head cells, and injection wells, in ft^3/s		
Río Cañas		1.39
Río Descalabrado	2.58	
Río Coamo and Lago Coamo	5.6	
Río Jueyes		0.42
Irrigation Canals	1.28	
Total		11.27

Alternative Strategies for Ground-Water Management

Based on the simulation results and the estimated water budget (fig. 2), current withdrawals slightly exceed recharge much of the time. The main concern in the Santa Isabel area is lateral seawater intrusion, which may degrade water quality by increasing the salinity of ground-water supplies. The first alternative evaluated for mitigating this problem is to reduce ground-water withdrawals, which may be accomplished by using surface water from existing reservoirs, water conservation, or a combination of conservation and surface-water use. The second alternative evaluated is to use artificial recharge (diverting storm runoff to spread over agricultural fields and allowing this water to percolate into the aquifer). The third alternative evaluated is to take treated wastewater from the Santa Isabel wastewater treatment facility and inject this water near the coast to increase the water level in the aquifer above sea level along the coast. The fourth alternative evaluated is to place dams or weirs in the stream channels, which would help store storm runoff and then inject the storm runoff into wells located along the stream channels near the dams and weirs.

The first alternative was tested by simply reducing the ground-water withdrawals at each well, simulating average recharge conditions, and determining what reduction in ground-water withdrawals resulted in water levels returning to sea level or greater throughout most of the area. The calibrated transient model was run with a final 15-year stress period added with recharge set to 2.76 inches/yr. Through trial and error, the percent reduction required to raise water levels at or above sea level was determined. Figure 26 shows the simulated hydrograph at the Alomar 1 well. The model simulations indicate that a 27 percent reduction in ground-water withdrawals would result in an increase in water levels to sea level throughout most of the model area in about 13 years if precipitation is average during that period (fig. 27).

The second alternative using artificial recharge would be more difficult to implement in the Santa Isabel area. Areas of land adjacent to canals or stream channels that can be flooded must be determined, then permission to flood these areas obtained, and finally hydraulic structures and pumps constructed to direct flood waters, which normally flow out to the sea, to these areas. This second alternative involves determining the rate of increased recharge near fields adjacent to the streams and canals that will raise water levels above sea level. A transient simulation was started using the water levels from the last stress period of the calibrated model for the initial condition. The transient simulation had one 15-year stress period with ground-water withdrawals set at the 2003 rates. The number of cells in agricultural fields and the increased rate of recharge required to raise water levels to sea level were determined by trial and error. If recharge is increased from the average rate of 0.00063 to 0.0022 ft/d over 8,950 acres, water levels will rise to near sea level throughout most of the area in about 15 years (fig. 28). The simulated infiltration area required may not be available, but the additional annual recharge required was approximately 1,700 million gallons. The excess recharge rate is the equivalent of about 0.6 ft of water applied over the 8,950 acres. However, the actual amount applied might have to be increased, because there may be some evapotranspiration losses. The area where simulated net recharge was increased covers most of the central agricultural fields (fig. 28).

The third artificial recharge alternative would require the installation of injection wells near the coast and injection of tertiary treated wastewater into these wells. This alternative was tested with a simulation strategy similar to the second alternative, except the objective of the hypothetical simulation was to determine the spacing and rate of injection required while maintaining the ground-water pumping rates for public and irrigation supply wells at 2003 rates. Through trial and error scenario testing it was determined that eight wells were not adequate to achieve the simulation goal, but 11 wells placed along the coast brought water levels to acceptable altitudes. Initially a 0.1 Mgal/d injection rate was applied at all wells, but the rate had to be increased at some of the 11 wells to 0.4 Mgal/d at six wells and 0.2 Mgal/d at one well for a total of 3 Mgal/d in order to maintain water levels above or near sea level along the coast (fig. 29). This is equivalent to 1,095 million gallons of injected water per year, which is less than one-half of the 2003 ground-water withdrawals for public supply.

The fourth artificial recharge alternative was simulated similar to the second and third alternative, except that the location of injection wells near the downstream segments of the Río Descalabrado and Río Coamo and at some of the irrigation canals was determined through trial and error scenario testing. Surface water or treated wastewater would have to be imported from other areas for injection or dams could be placed in the stream channels to help store some of the storm runoff for injection or increase infiltration water along the stream channel. Ground-water levels returned to sea level if 27 injection wells pumping at 0.2 ft^3/s were placed as shown in figure 30. The 3.5 Mgal/d of freshwater injected would have to be imported from another watershed or stored in channel dams or reservoirs. However, considering the high sediment loads of the streams, in-stream dams or structures may be impractical as they may require frequent dredging in order to function.

It was beyond the scope of this investigation to determine costs or feasibility associated with the alternatives simulated. Additionally, some combination of the simulated alternatives, such as a reduction in ground-water pumpage and artificial recharge over a smaller area, or reduction in ground-water pumpage near the coast and artificial recharge by the use of injection wells, could be implemented as a ground-water management strategy to mitigate seawater intrusion.

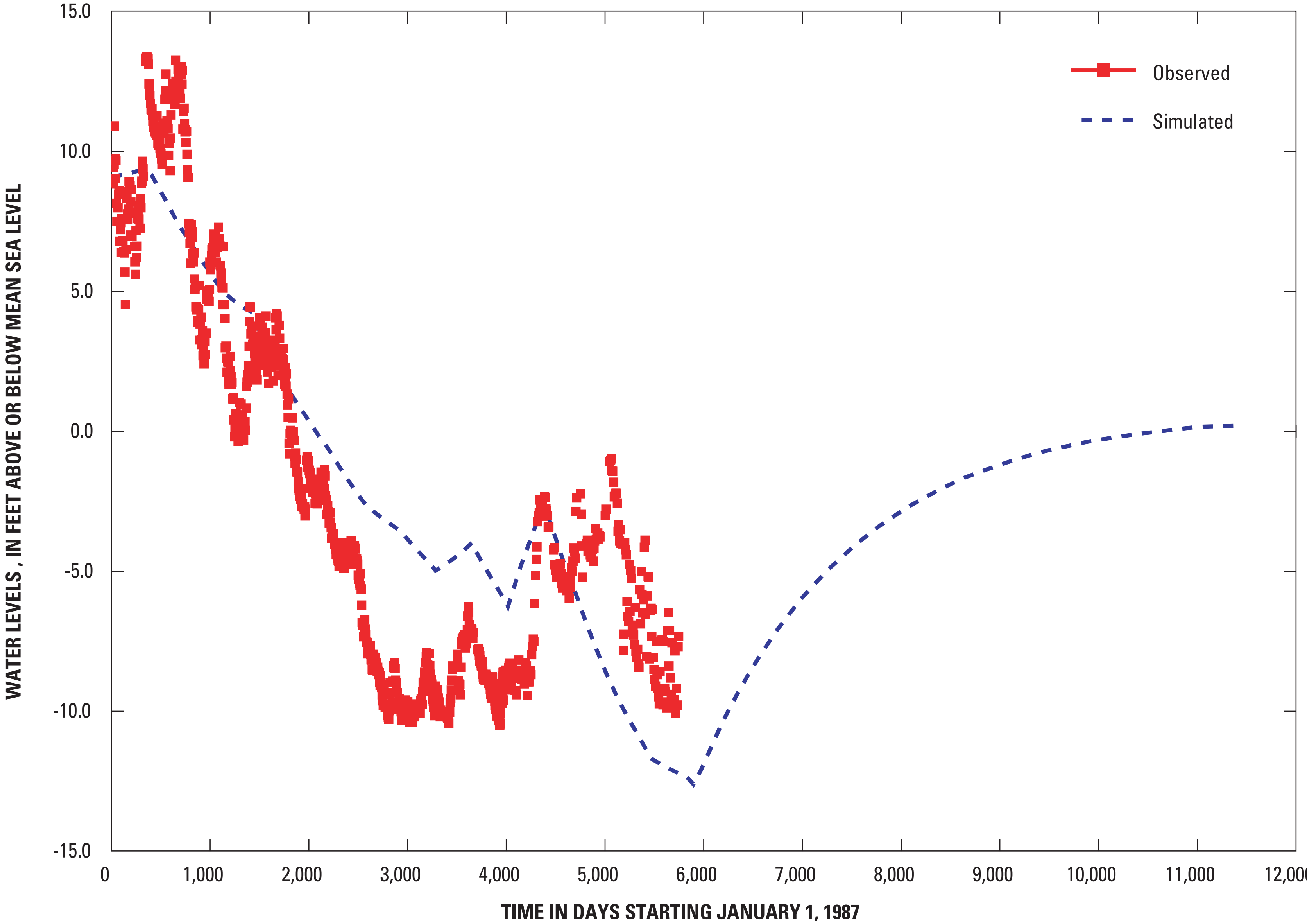


Figure 26. Observed and simulated water level at observation well Alomar 1 when future pumpage is reduced by 27 percent from the 2003 states.

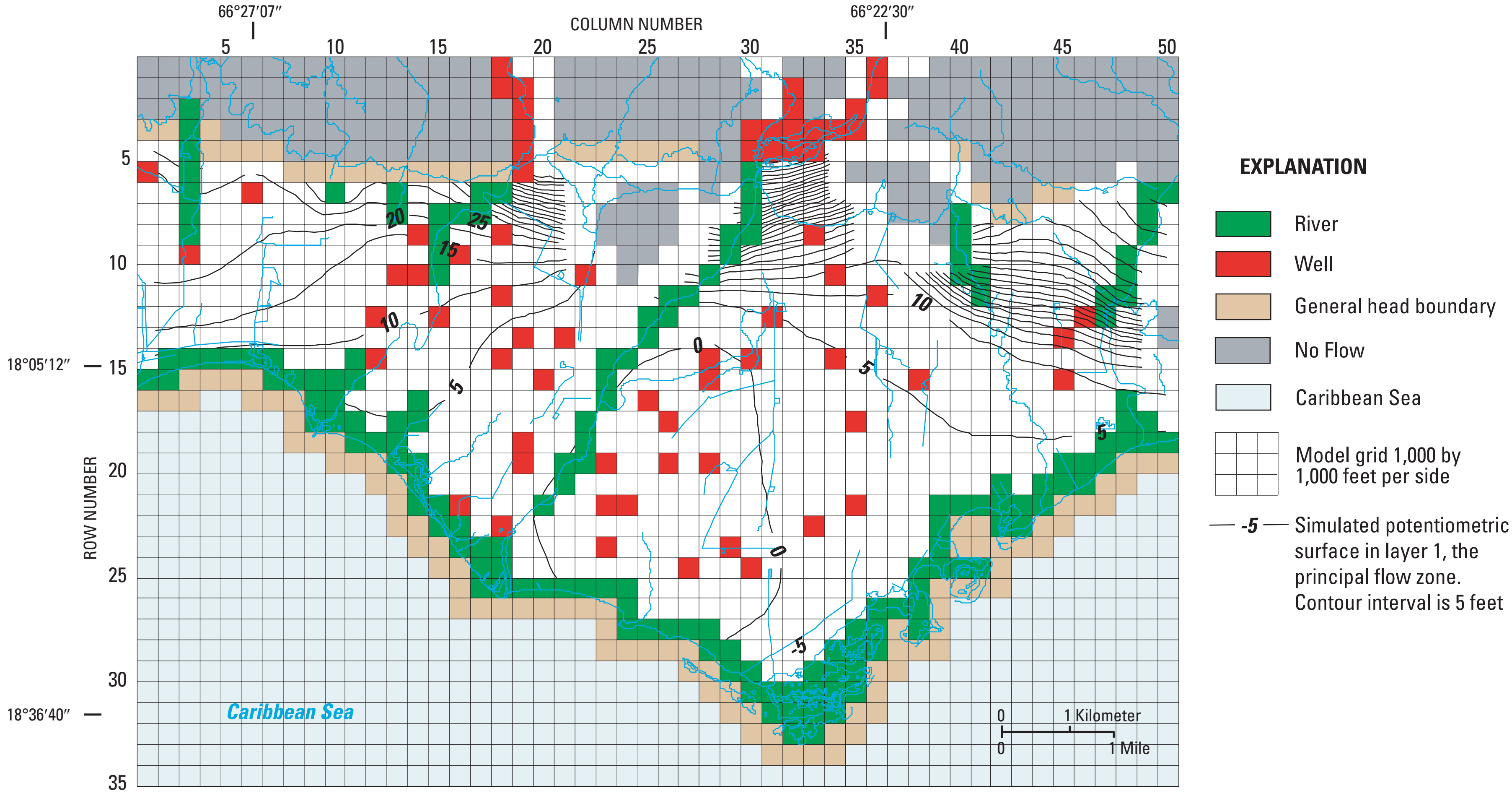


Figure 27. Simulated potentiometric surface of the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico, after 15 years from February 2003 with average recharge and a 27 percent reduction in pumpage.

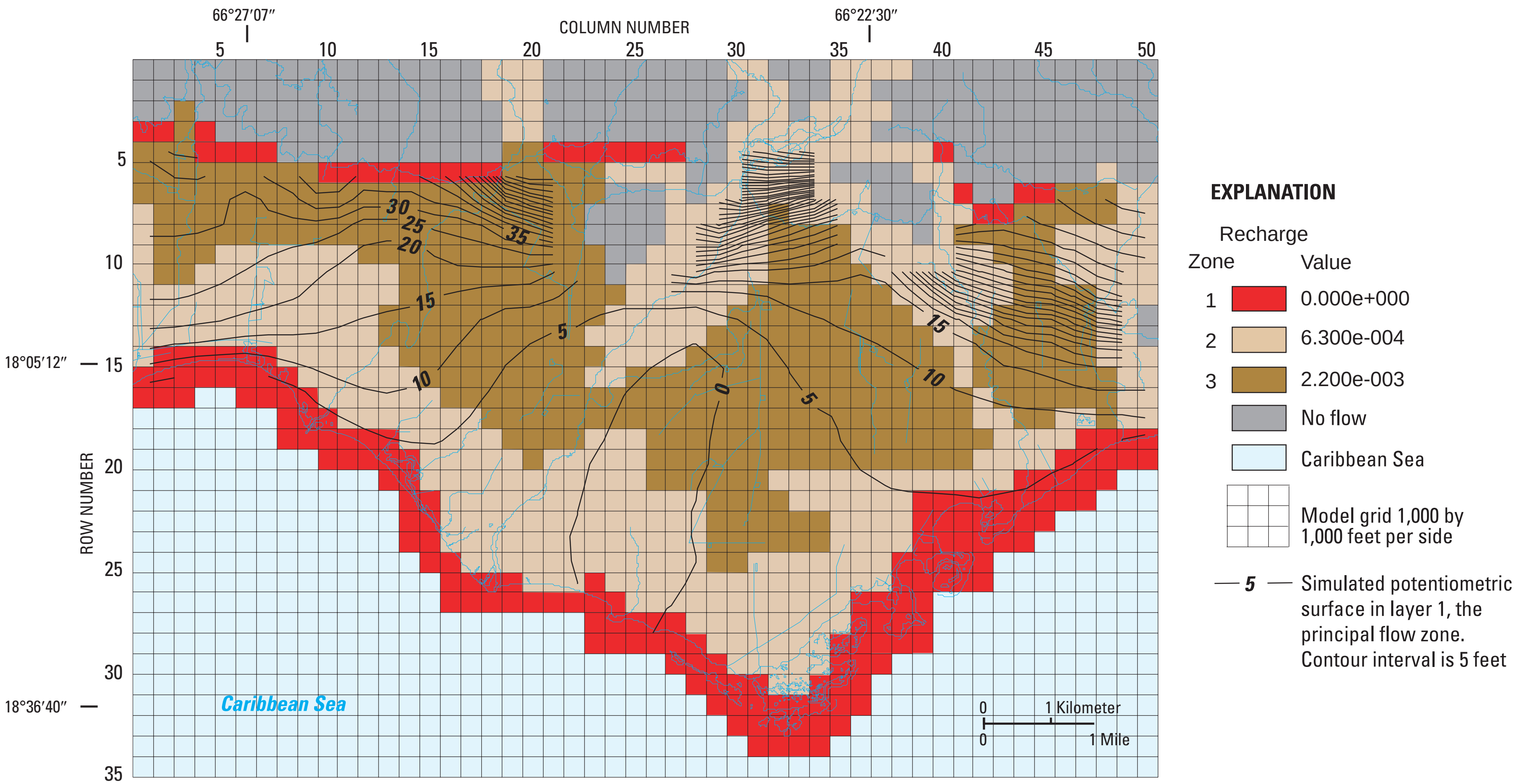


Figure 28. Simulated potentiometric surface of the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico, after 15 years of average recharge with artificial recharge applied over agricultural areas.

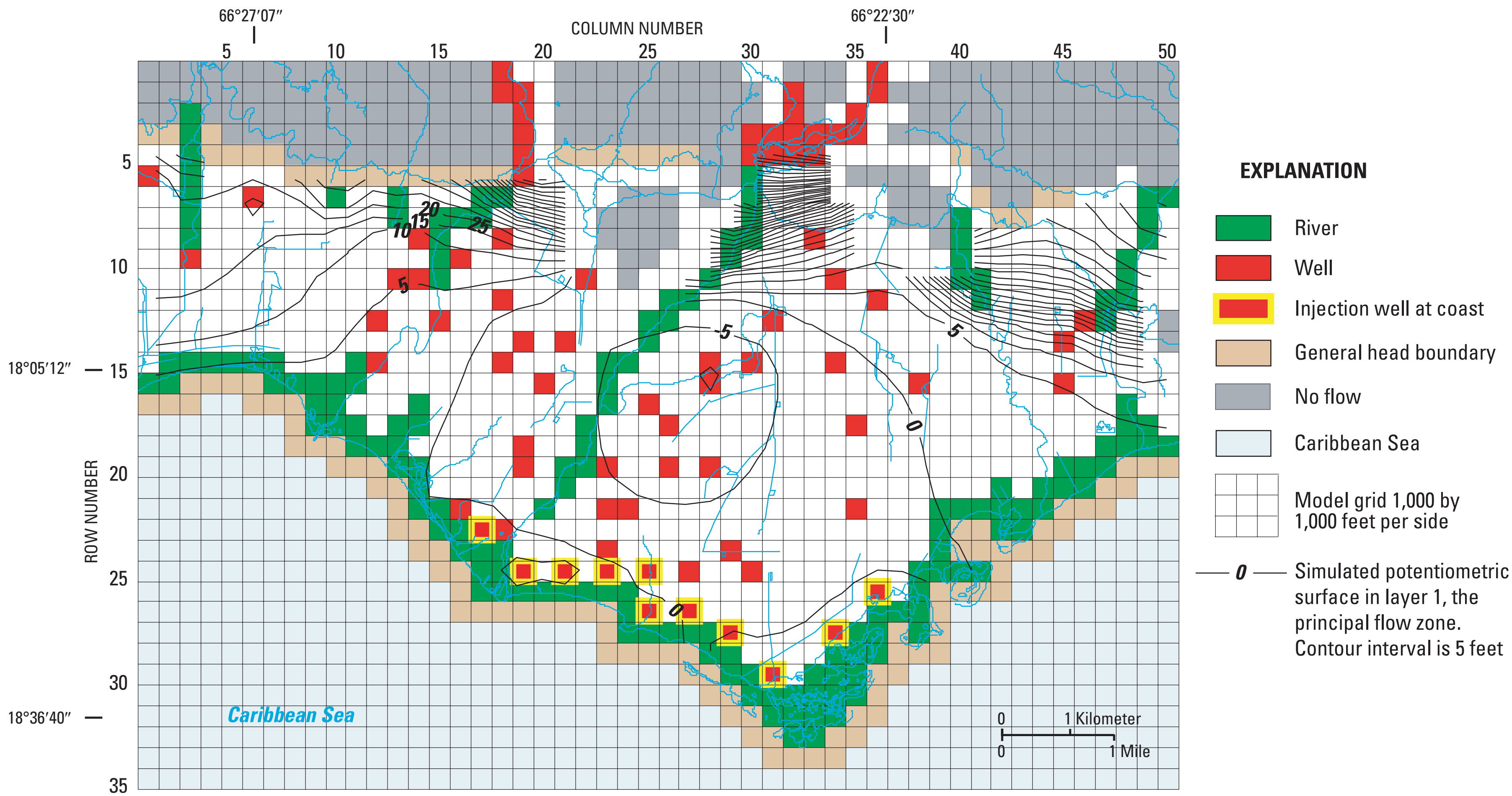


Figure 29. Simulated potentiometric surface of the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico, after 15 years of average recharge and 2003 pumpage with injection wells along the coast.

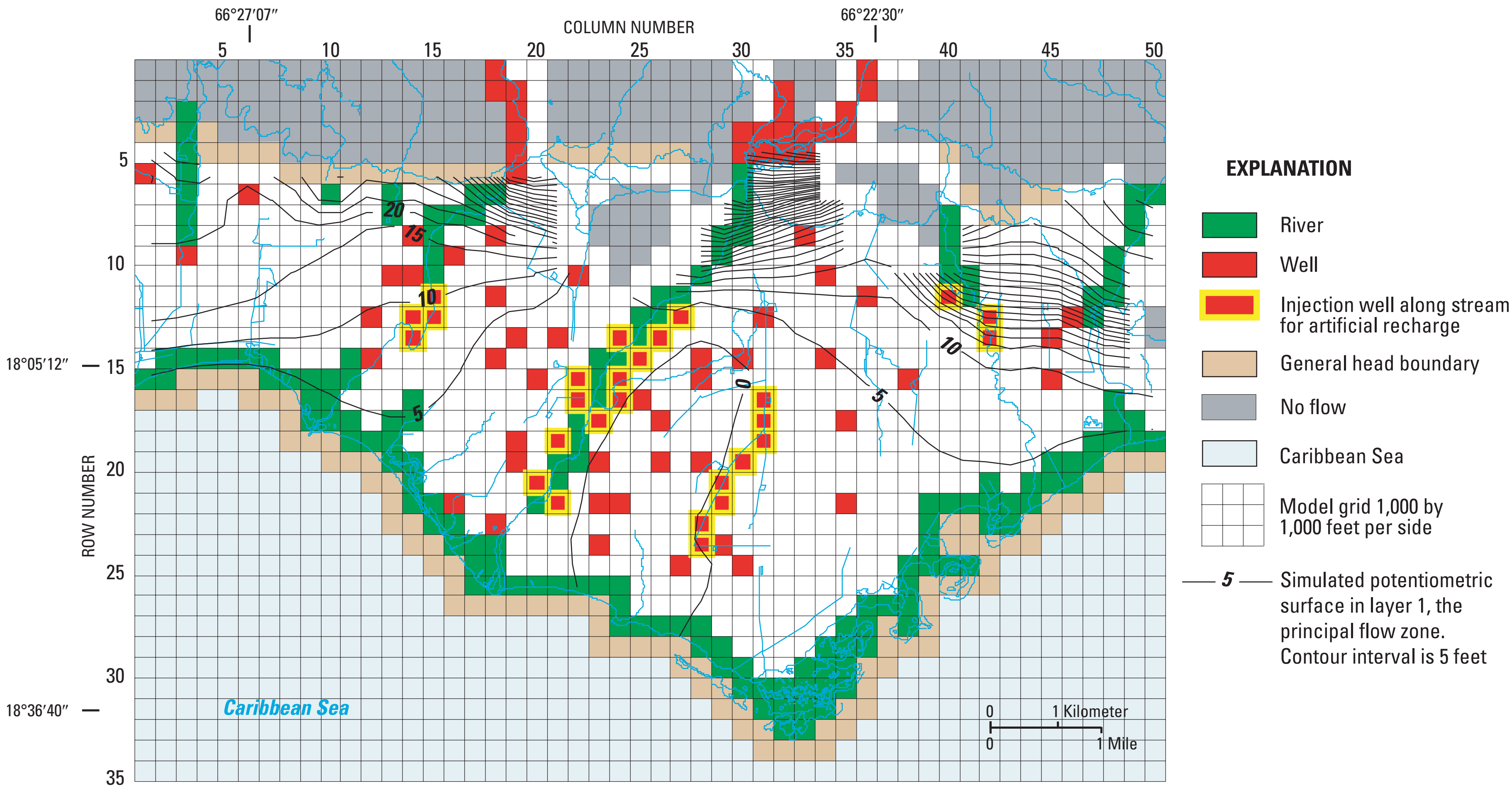


Figure 30. Simulated potentiometric surface of the South Coastal Plain aquifer in the vicinity of Santa Isabel, Puerto Rico, after 15 years of average recharge and 2003 pumpage with injection wells along streams and canals.

Limitations of the Model

All ground-water flow models involve simplification of the actual aquifer system. Three of the simplifications involved in this modeling effort are: (1) simplified homogeneous hydraulic conductivity zones for the three model layers; (2) the use for the freshwater/saltwater interface as a no-flow boundary for a constant density model, as is common practice (Reilly, 2001), rather than using a variable density model code; and (3) use of non-varying general head boundaries along the coast. However, the greatest source of errors in the model calibration, which limits the usefulness of tests of the alternatives for mitigating seawater intrusion, are a result of the lack of metered ground-water withdrawals, especially from irrigation wells, and the lack of continuous streamflow gaging on streams that lose flow to the alluvial aquifer or the Juan Díaz canal.

There probably is greater heterogeneity in the hydraulic conductivity of the principal flow zone (top layer) than the final simple zones of hydraulic conductivity used in the calibrated model. However, the final distribution of hydraulic conductivity for the principal flow zone is within reasonable ranges of the known distribution. No aquifer-test data for establishing hydraulic conductivities for the lower two layers of the model were available. However, the water budgets indicate that the majority of the flow in the aquifer is through the top layer and the lack of sensitivity of vertical hydraulic conductivity is a result of the fact that only a relatively small amount of the flow system occurs in the lower layers. Thus, poor estimates of the hydraulic conductivity of the lower two layers would have little effect on the simulations.

The errors introduced by approximating the freshwater/saltwater interface as a no-flow boundary are believed to be small (Reilly, 2001). This is common practice and no effort was made to test this boundary condition.

The non-varying general head boundary in the top layer along the coast may have some effect on the leakage to or from the alluvial aquifer to the sea. The conductance term is calculated from the estimates of horizontal hydraulic conductivity of the alluvial aquifer divided by 10 (to represent vertical hydraulic conductivity) and the cell area. Since the grid spacing is fairly small, 1,000 by 1,000 ft, the conductance terms are not large; thus they, will not result in forcing a constant head and should provide a reasonable estimate of ground-water flow to or from the coast (Kuniansky and Danskin, 2003). The specified head at the coast is set to sea level even though the head would rise and fall with the tides. However, over the annual stress period, the non-varying specified head is a reasonable approximation.

The greatest limitations of this modeling effort are a result of the lack of metered ground-water withdrawals and lack of continuous streamflow gaging on streams. Calibration of the model would be greatly improved with accurate information on these major components of the water budget. Better knowledge of these fluxes would help constrain the model calibration and provide much more confidence in the calibrated set of aquifer properties and net recharge because this information would lead to a unique set of model parameters and stresses. However, the final estimates of these components of the water budget are reasonable given the intermittent data that have been collected in the study area about streamflow losses and ground-water withdrawals.

Because of the uncertainty in major components of the water budget, the ground-water management alternatives examined are mainly illustrative of how seawater intrusion could be mitigated. The rates of ground-water withdrawal reduction, rates of net recharge applied, and injection rates determined from the simulation of the three alternatives are not exact numbers. For example, a reduction in ground-water withdrawals of only 20 percent may be all that is necessary rather than the 27 percent suggested by the simulation. However, the relative rates of ground-water withdrawal reduction versus net recharge or injection required to mitigate seawater intrusion should prove useful in evaluating the alternatives. Additionally, both alternatives three and four involve the use of injection wells and the amount of injected water required is similar. However, it takes fewer injection wells and less injected water to achieve water levels above sea level along the coast for alternative three than alternative four. Thus, alternative three would have a lower well construction and water conveyance cost than alternative four.

Summary

The alluvial aquifer in the area of Santa Isabel is located within the South Coastal Plain aquifer of Puerto Rico. Variations in precipitation, changes in irrigation practices, and increasing public-supply water demand have been the primary factors controlling water-level fluctuations within the aquifer. Until the late 1970s much of the land in the study area was irrigated using inefficient furrow flooding methods that required large volumes of both surface and ground water. A gradual shift in irrigation practices from furrow systems to more efficient micro-drip irrigation systems occurred between the late 1970s and the late 1980s. Irrigation return flow from the furrow-irrigation systems was a major component of recharge to the aquifer. By the early 1990s, furrow-type systems had been replaced by the micro-drip irrigation systems. Water levels declined about 20 feet in the aquifer from 1985 until present (February 2003).

The main effects of the changes in agricultural practices are the reduction in recharge to the aquifer and total irrigation ground-water withdrawals. Ground-water withdrawal increases for public supply offset the estimated reduction in irrigation ground-water withdrawals such that the total ground-water withdrawal rate in 2003 was only 8 percent less than in 1987. Installation of micro-drip irrigation systems has resulted in the loss of irrigation return flow to the aquifer. These changes resulted in lowering the water table below sea level throughout most of the Santa Isabel area. By 2002, the lowering of the water table reversed the natural discharge along the coast and resulted in the inland movement of seawater, which may result in increased salinity of the aquifer water, as has occurred in other parts of the South Coastal Plain aquifer.

Management alternatives for the South Coastal Plain aquifer in the vicinity of Santa Isabel include limiting ground-water withdrawals or implementing artificial recharge measures. Another alternative for the prevention of saltwater intrusion is to inject freshwater or treated sewage effluent into wells along the coast. A digital ground-water flow model was developed to provide information for water managers to evaluate some of these alternatives. After calibration of the ground-water model to historical data, four simulations of ground-water management strategies were performed: ground-water conservation, surface infiltration over existing agricultural fields, or infiltration along streams and canals, or injection wells along the coast.

Simulations of four alternative water management strategies indicate that this condition can be reversed by: (1) reduction in 2003 pumping rates by approximately 27 percent; (2) application of about 1,700 million gallons per year of artificial recharge over more than half of the current agricultural areas; or (3) injection of about 3 Mgal/d of freshwater in wells distributed along the coast; or (4) injection of about 3.5 Mgal/d of freshwater in wells distributed along canals and streams.

It was beyond the scope of this study to evaluate the costs of constructing injection wells systems, in stream dams, reservoirs, or weirs for implementing artificial recharge. However, the relative rates of ground-water withdrawal reduction versus net artificial recharge or injection required to mitigate seawater intrusion should prove useful in evaluating the feasibility of ground-water resource management alternatives for the Santa Isabel area.

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Appendix. Lithologic Description for Test Boring at Santa Isabel, Puerto Rico, Dual Tube Drilling (March 19-20, 1987, Boring SC-4, location shown on figure 11a)

Lithologic Description for Test Boring at Santa Isabel, Puerto Rico, Dual Tube Drilling (March 19-20, 1987, Boring SC-4)
Lithologic description by Jesús Rodríguez-Martínez
Latitude 175738 Longitude 662411, North American Datum 1927; Land Surface about 20 feet above mean sea level

Depth interval, feet	Lithologic description
0-5	Clayey siltstone, moderate yellowish brown, locally pebbly and sandy.
5-10	Sand - fine grained, locally silty and pebbly.
10-20	Volcanic pebbles, gravel with a fine to very coarse grained, grained moderate yellowish brown volcanic to quartzose (Qt-zose) sand as a matrix.
20-25	Sand, pebbly, very coarse grained, volcanic with a minor amount of quartz, poor sorting.
25-35	Sand - Qt-zose and volcanic, medium to very coarse grained, clayey poor to moderate sorting.
35-53	Claystone - moderate - dark yellowish brown, predominantly soft?, locally sandy.
53-58	Sand, loose, poorly consolidated, medium to very coarse grained, volcanic to Qt-zose in a minor clayey matrix (saturated at 53 ft).
58-80	Claystone - moderate to dark
80-90	Generally as above, locally pebbly and sandy.
90-95	Sand - dark yellowish brown to moderate brown, with volcanic pebbles and cobbles, medium to very coarse grained volcanic Qt-zose.
95-103	Volcanic cobbles and pebbles, angular-subangular, with a minor coarse grained sand matrix.
103-110	Claystone - moderate brown, slightly soft, indurated, wet.
110-115	Claystone - moderate yellowish brown, locally silty and sandy, locally with limestone clasts.
115-125	Limestone - pale orange to moderate yellowish brown, locally argillaceous, biosparite wackstone, fragmented, fairly high to med grained-coarse grained porosity with mollusks.
125-135	Claystone - moderate to dark brown, moderately indurated, generally slightly calcareous, locally black mottled, also pale yellow mottled locally, locally with volcanic chips, pebbly and sandy locally.
135-146	Gravel, sandy, dark reddish brown, dark gray, black, yellowish orange, volcanic.
143-152	Claystone - moderate yellowish brown, semi-plastic, semi-wet, silty in part, locally volcanic pebbly.
152-161	Altered in clayey limestone clasts (fragmental, reef?)
161-164	Sandstone - clayey, medium to coarse grained, volcanic and Qt-zose.
164-171	Sand - predominantly very coarse, also medium grained, loose to slightly indurated, locally with volcanic pebbles and cobbles.
171-180	Locally volcanic pebbles.
180-197	Generally as above.

Depth interval, feet	Lithologic description
197-204	Claystone - moderate brown to dark yellowish brown, locally silty with pebbles, dark yellow and black mottled locally.
204-211	Sand - dusky brown, fine to very coarse grained, volcanic sand, poorly sorted.
211-214	Generally as above, with a clayey matrix.
214-219	Claystone - moderate yellowish brown, generally slightly calcareous, locally black particles (oxides, mollusks), pebbly locally.
219-228	Sand - fine to very coarse grained, volcanic and Qt-zose, pebbly, locally volcanic cobbles.
228-235	Claystone - moderate yellowish brown to moderate brown, slightly to moderately indurated, pebbly with isolated volcanic cobbles, locally black mottled.
235-242	Claystone as above, also fairly well indurated, pebbly in part, silty and sandy in part (Qt-zose and feldspar?).
242-255	Claystone - pale grayish brown, moderately to well indurated, pale yellow mottled, black and white mottled locally, strongly calcareous (oxides - black mottled, calcareous veinlets, tiny shell debris?), locally silty and sandy.
255-258	Generally as above with clayey siltstone, very calcareous.
258-260	Limestone cobbles, clayey, fragmental, locally recrystalized, reef structure, with high solution porosity.
260-264	Sandstone - clayey ans silty fine grained, moderate brown, Qt-zose to volcanic, calcareous (limestone chips), locally grades top silty and sandy calystone, locally with Qt-zose, volcanic and limestone chips.
264-268	Sand as above, with limestone cobbles - biospar to biomicrospar, dense-wackstone, light gray localized little moldic porosity.
268-279	Sand with no limestone cobbles.
279-284	Limestone - pale gray, fragmental, biospar-biomicrospar - wackstone, clayey with included volcanic pebbles and Qt-zose, locally black vein with localized diseminated pyrite.
284-291	Claystone - grayish orange, pale yellow and creamy white mottled, strongly calcareous, locally with volcanic pebbles, moderately to well indurated.
291-304	Sand, fine to very coarse grained volcanic Qt-zose sand, pebbly, locally with volcanic pebbles.
304-312	Claystone - sandy and silty, moderate yellowish brown, locally pebbly (internally dried).
312-322	Sand, losse, dark yellowish brown, fine to very coarse grained, volcanic and Qt-zose.
322-340	Claystone - dark yellowish brown, white and locally pale yellow mottled, black nodules and black mottled (oxides?) silty and locally sandy, moderately to strongly calcareous.
340-343	Generally as above, but less white and black mottled, calcareous.
343-356	Claystone - silty and sandy (Qt-rose and volcanic chips), moderate brown, black mottled and bonded, non to locally moderately calcareous.
356-370	Claystone - moderately yellowish brown, creamy white and pale yellow mottled, strongly calcareous, volcanic pebbles.
370-376	Claystone - sandy and pebbly, locally white mottled, calcareous, partially wet.
376-380	Sand - clayey, fine to coarse grained - volcanic Qt-zose, pebbly.
380-389	Claystone - dark yellowish brown, sandy occasionally pebbly, slightly to moderately calcareous.

Depth interval, feet	Lithologic description
389-399	Sand, loose, dark yellowish brown, pebbly, fine to very coarse grained, volcanic with a minor fraction of quartz.
399-405	Volcanic cobbles and pebbles with sand as above.
405-416	Claystone - silty, locally sandy, with volcanic pebbles, non to locally slightly calcareous, Qt-zose and volcanic pebbles, moderate brown to moderate yellowish brown.
416-430	Claystone - moderately indurated, silty and sandy (Qt-zose), color as above.
430-440	Sand - fine to very coarse volcanic sand (poor quality sample) volcanic and Qt-zose sand, locally pebbly and cobbles.
440-464	Claystone - sandy and silty, pale yellowish brown to moderately brown (true color) moderately to well indurated, predominantly dried, locally white and pale to medium yellow mottled (highly carcareous in these areas), locally black mottled, with clayey and altered limestone cobbles, white to pale yellow concave fractures, reef coral clasts locally (at 457 ft).
464-472	Claystone - moderate to dark yellowish brown, silty and sandy, calcareous, volcanic and locally Qt-zose, calcite and limestone chips.
472-485	Sand - pebbly fine to very coarse grained, volcanic and calcareous chips (limestone?).
485-494	Claystone - silty and sandy moderate brown, pale yellow and creamy white locally black, mottled locally, slightly to locally highly calcareous, volcanic pebbles and limestone chips.
494-498	Sand - dark yellowish brown, volcanic and Qt-zose with pebbly fine to coarse grained limestone chips.
498-508	Claystone - dark yellowish brown, moderately indurated, silty and sandy, slightly calcareous.
508-514	Claystone - as above, locally pebbly (volcanic), poor quality sample.
514-525	Claystone - genrally as above, light brown mottled internally, silty in part, slightly calcareous.
525-530	As above, pale yellow and locally black mottled, volcanic pebbly in part.
530-532	As above.

FINAL DEPTH 532 ft

District Chief
Caribbean District
U.S. Geological Survey
Water Resources Division
GSA Center, Suite 400-15
651 Federal Drive
Guaynabo, Puerto Rico 00965-5703

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