SIMULATION OF GROUND-WATER FLOW IN THE WATER-TABLE AQUIFER NEAR BARCELONETA, PUERTO RICO

By Arturo Torres-González

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CONVERSION TABLE

The inch-pound units used in this report can be converted to equivalent SI (metric) units as follows:

Multiply inch-pound unit	By	To obtain SI (metric unit)
inches (in.)	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
mile (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
feet per second (ft/s)	0.3048	meters per second (m/s)
feet per day (ft/d)	0.3048	meters per day (m/d)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
feet squared per day (ft^2/d)	0.0929	meters squared per day (m^2/d)
gallons per minute (gal/min)	0.06309	liters per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)

U.S. DEPARTMENT OF THE INTERIOR · GEOLOGICAL SURVEY

SIMULATION OF GROUND-WATER FLOW IN THE WATER-TABLE AQUIFER NEAR BARCELONETA, PUERTO RICO

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ABSTRACT

A two-dimensional, steady-state digital flow model of the water-table limestone aquifer near Barceloneta, in north-central Puerto Rico, was developed: (1) to estimate the effects of additional ground-water withdrawals on the aquifer water levels and, (2) to determine whether hydraulic gradients relative to mean sea level would be reversed as a result of the additional pumpage, thereby initiating a potential for sea-water intrusion.

The model was calibrated to the ground-water levels of February 1982. Observed heads were within 10 feet of the model-computed heads. Adjusted regional values of aquifer transmissivity ranged from 1,000 to 300,000 feet squared per day. Localized cavernous conditions in the Aymamón Limestone have resulted in aquifer transmissivities in excess of 2,000,000 feet squared per day. Solution conduits, however, were not considered in the steady-state regional ground-water flow analysis of the model. The proximity of the physical boundaries of the aquifer combined with the relative low value of specific yield and high value of transmissivity, causes the ground-water system to reach steady-state conditions within the first 150 days after stresses begin.

Recharge is the most sensitive parameter in the model. Calibrated values of aquifer recharge were as much as 25 inches per year in the outcrop areas of the Aguada Limestone. During any intense drought, ground-water discharges to Caño Tiburones and Río Grande de Manatí will be significantly reduced.

Model results show that if 1982 ground-water withdrawals at Cruce Dávila near the center of the study area are doubled (from 3.5 to 7.0 million gallons per day) water levels would decline a maximum of about 5 feet. A maximum pumpage of 6 million gallons per day would minimize the potential for sea-water intrusion in the Cruce Dávila area.

Simulated pumpage, in addition to the present (1982) pumpage of 11 million gallons per day from the entire study area was varied from 7 to 29 million gallons per day. Additional withdrawal of 7 million gallons per day caused a maximum water level decline of about 4 feet; 17 million gallons per day caused a decline of 16 feet. At an increase in withdrawal of 29 million gallons per day ground water flow to the Caño Tiburones would cease as would flow in the Río Grande de Manatí downstream of Highway 2.

INTRODUCTION

Ground-water withdrawals in the Barceloneta area, in north-central Puerto Rico (fig. 1), have increased dramatically since the early 1970's. Pumpage for industrial and municipal supplies from the water-table limestone aquifer has increased from about 5 Mgal/d in 1972 to about 11 Mgal/d in 1982. Artesian limestone aquifers underlying the shallow aquifers supply about 5 Mgal/d in addition.

Additional ground-water withdrawals in the Barceloneta area have been requested to supply demands of the fast-growing pharmaceutical industry. The Puerto Rico Department of Natural Resources (PRDNR), the Commonwealth agency entrusted with the management of the Island's water resources, is concerned that additional withdrawals may adversely affect the aquifer. Excessive declines in water levels could occur and the potential increased for a reversal of the hydraulic gradient between the water table in the shallow aquifer and the ocean. Such reversal could result in sea-water intrusion to the aquifer.

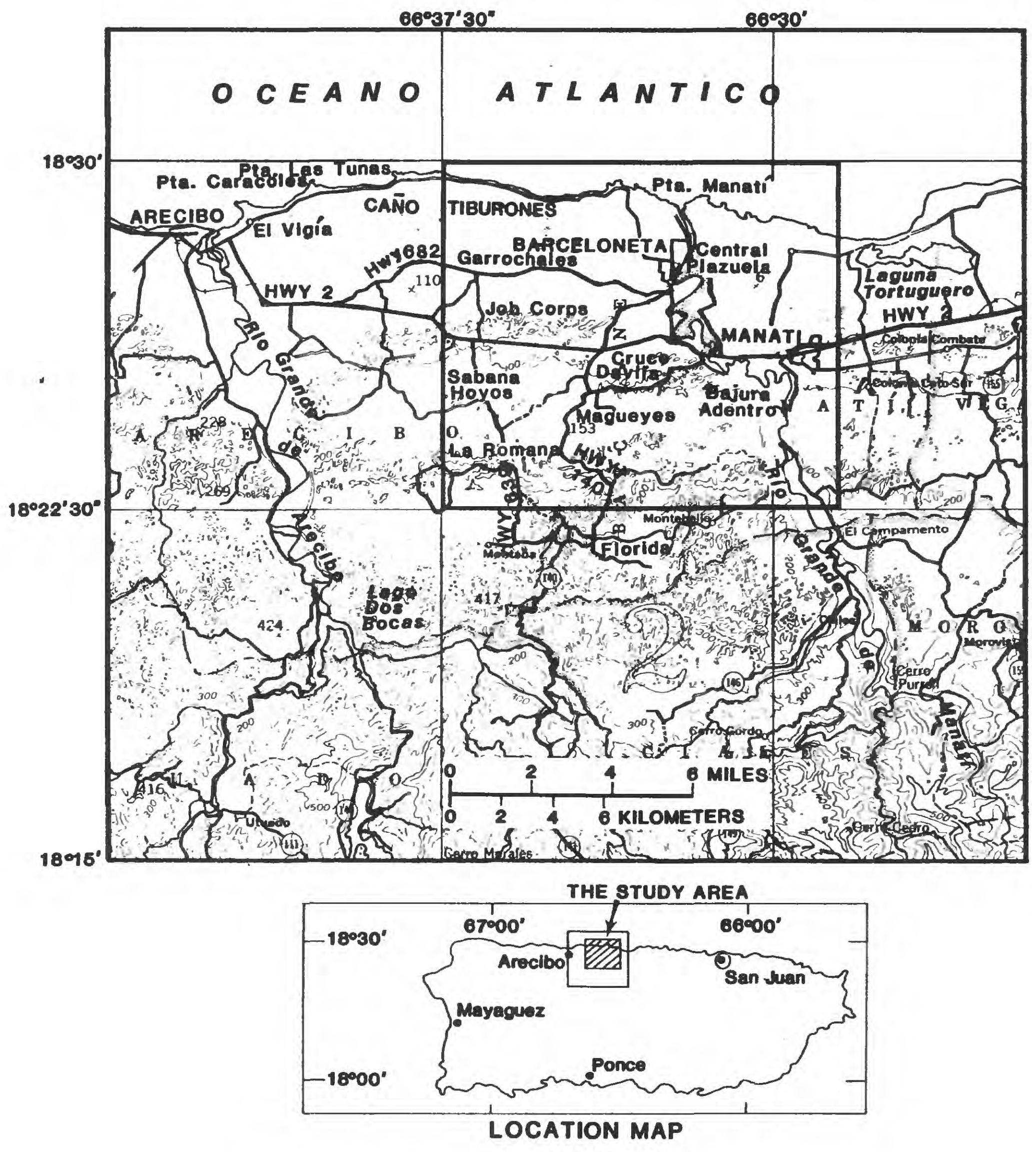


Figure 1.--Location of the study area.

INTRODUCTION-Continued

The U.S. Geological Survey, in cooperation with PRDNR, began in 1980, a project to design, construct, and calibrate a two-dimensional ground-water flow model of the shallow aquifer. The objectives of the model were:

1. To duplicate existing water-level conditions on the basis of aquifer properties, and current ground-water withdrawals.

2. To simulate varied conditions of recharge from precipitation, infiltration from streams, withdrawals from wells, and the effects of these stresses on the current water levels.

3. To provide PRDNR with a means of estimating potential effects of additional ground-water withdrawals in the aquifer water-level configuration and gradients.

The author gratefully acknowledges the assistance of Michael Planert, U.S. Geological Survey, Alabama District Office, in the design, construction, and calibration of the Barceloneta model.

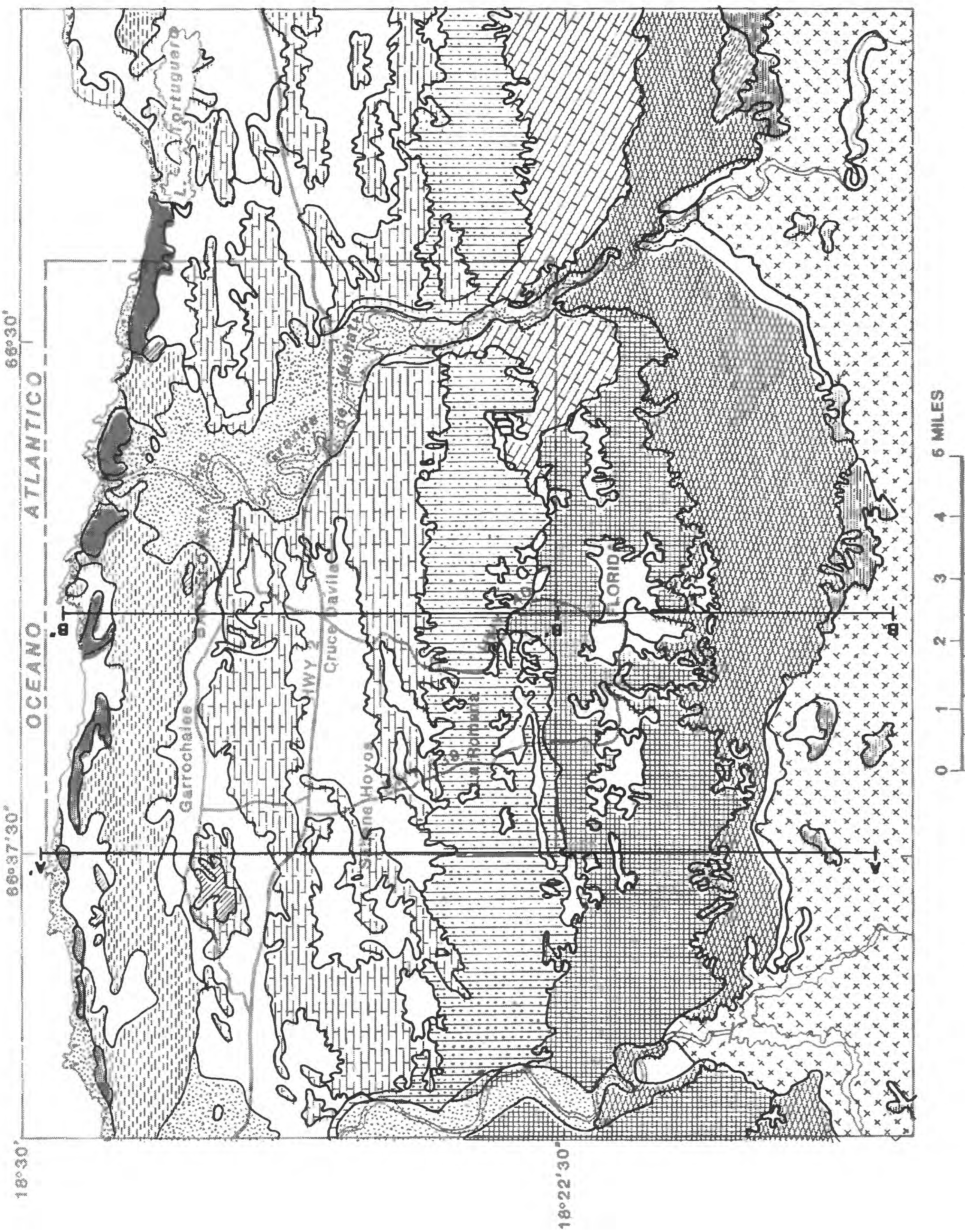
GEOLOGY

Limestone formations of Tertiary age underlie the study area (figs. 2 and 3) to a depth of approximately 5000 feet at the coast line (Gómez-Gómez, and Heisel, 1980). The shallow water-table aquifer in the Barceloneta area occurs mostly within the Aymamón Limestone and underlying Aguada Limestone (figure 4). Artesian conditions occur beneath the Aguada, in the underlying Montebello Limestone Member of the Cibao Formation, and the older Lares Limestone. The artesian-aquifers are separated from the water-table aquifer by a confining layer composed of a chalky marly material 35 to 160 feet thick (Monroe, 1980, p. 39) within the upper part of the Cibao Formation (figs. 4 and 7). Overlying the Aymamón in much of the area are alluvial, swamp and beach deposits referred collectively as surficial deposits. For the purpose of this report, the following descriptions of the surficial deposits are from Briggs (1965, 1966) and of the Aymamón and Aguada have been condensed from Monroe (1976, 1980):

Surficial Deposits

Sand, silt or sandy clay of alluvial or beach origin and organic material associated with swamps collectively are called surficial deposits (fig. 2). The alluvial deposits of fine sand, silt, and clay are found primarily in the valley of the Río Grande de Manatí and may be as much as 200 to 300 feet in thickness in the lower part of the valley. Swamp deposits consisting of peat, clay and fine sand prevail in the Caño Tiburones.

These deposits may be as much as 10 feet thick and occupy what may have been a former channel of either the Río Grande de Arecibo or the Río Grande de Manatí. Blanket sands, as much as 100 feet thick, occupy broad flat areas between the outcrops of the Aymamón and in sinks and valleys in the Aguada. These deposits consist of sand and sand clay and are probably remanents of former ocean beaches (Briggs 1966).


OCEANO ATLANTICO
66°30'
66°37'30'
18°30'
18°22'30'
L. Tortuguero
Garrochales
HWY 2
Cruce Davila
Rio Grande de Manati
Sabana Hoyos
FLORIDA
A
A'
B
B'
0 1 2 3 4 5 MILES
0 1 2 3 4 5 6 KILOMETERS

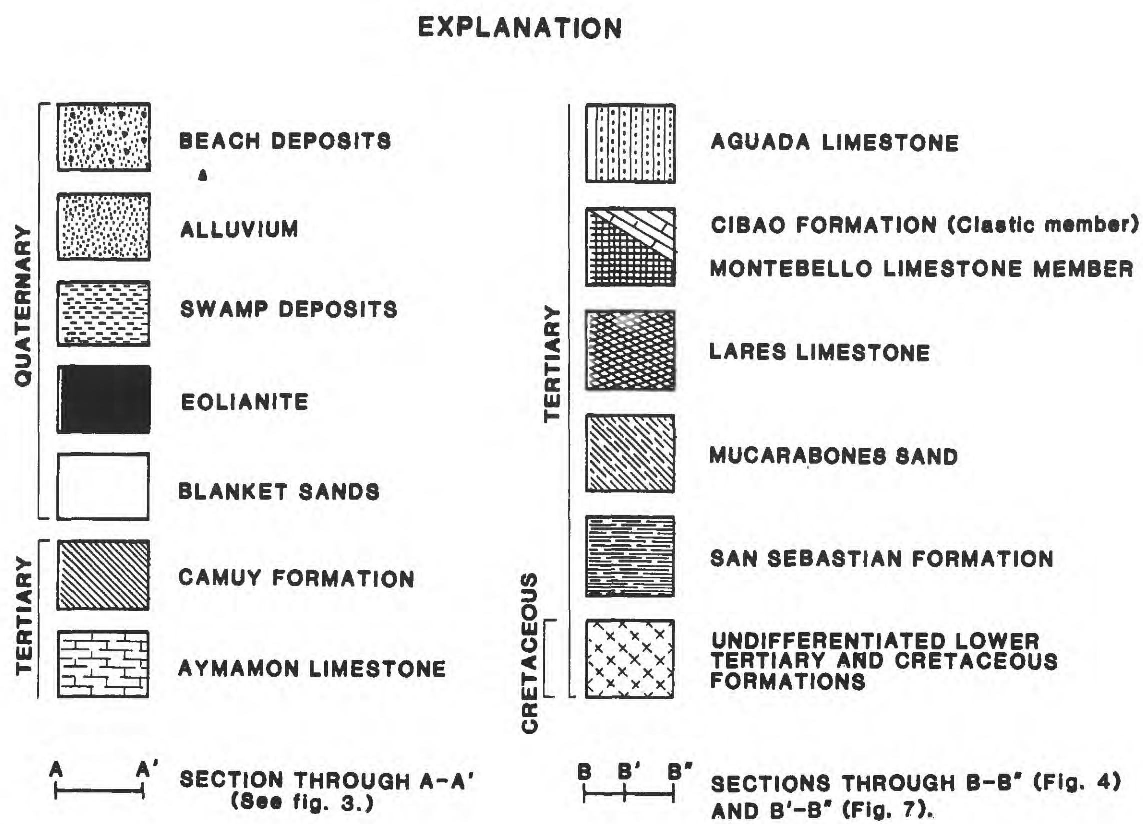


Figure 2.--Geology of the Barceloneta area.
(Adapted from Monroe, 1980.)

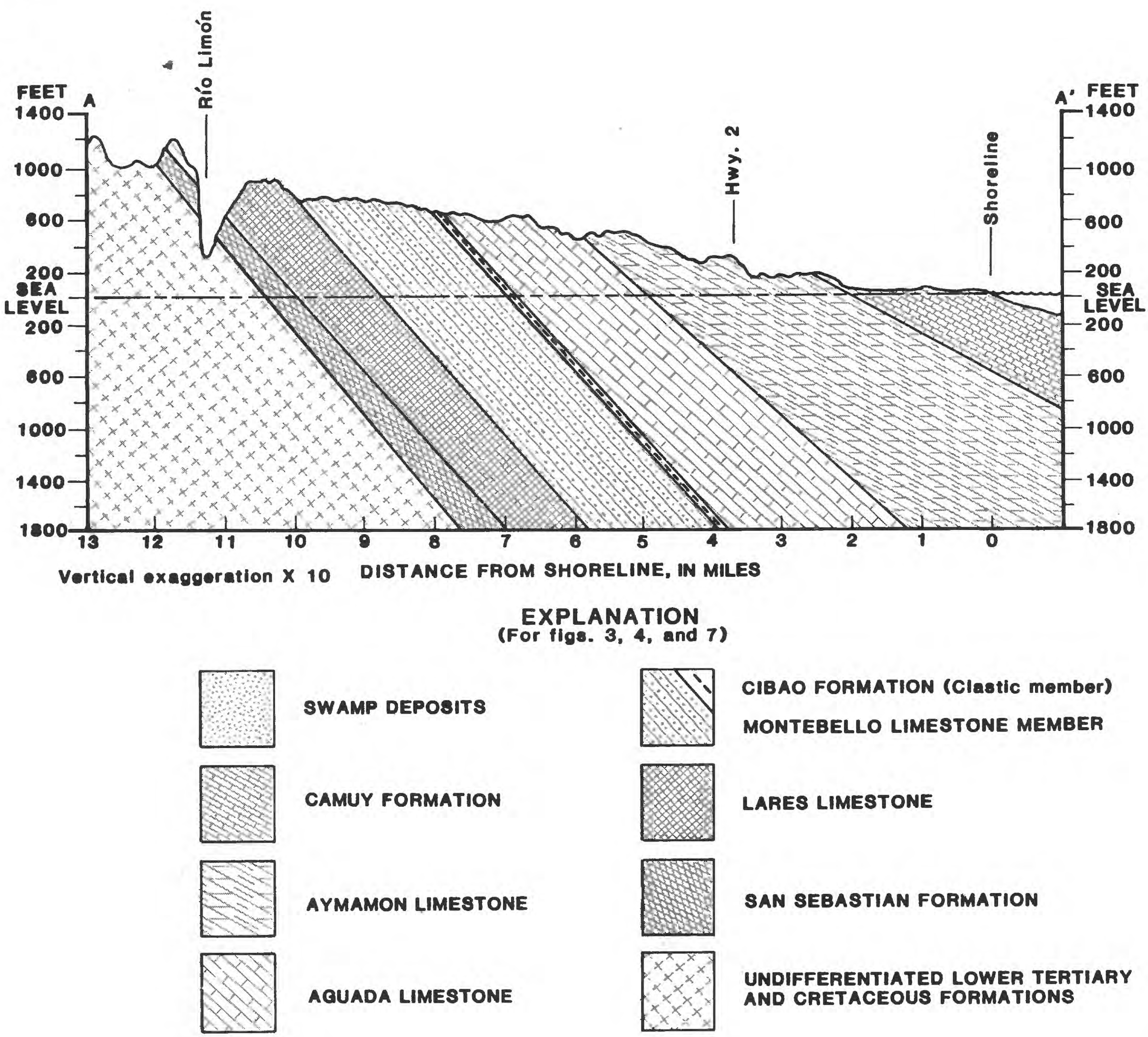


Figure 3.--Geologic section through A-A' near Barceloneta area.
(Modified from Monroe, 1980.)

GEOLOGY-Continued

Aymamón Limestone

The Aymamón Limestone rests conformably on the Aguada Limestone. It is remarkably uniform and consists mainly of thick-bedded to massive commonly quartz-free, very pure limestone. It is the most homogenous formation of middle Tertiary age in northern Puerto Rico. Its thickness ranges from about 620 to 720 feet.

The outcrop topography of the Aymamón is very irregular due to solution and reprecipitation. The typical landform of the Aymamón is the "mogote", a steep-sided conical hill. The mogotes are separated by wide, gently rolling, nearly flat areas, covered by blanket sands (fig. 2). The low permeability of these deposits limits the amount of rainfall that can infiltrate on an areal-wide basis and also provides for some fluvial drainage (Briggs, 1966). Ground-water recharge in these areas also occurs when surface runoff drains into sinkholes and permeable zones at the base of the mogotes.

Aguada Limestone

The Aguada Limestone overlies the Cibao Formation and is almost pure calcium carbonate ($CaCO_3$). It contains chalky beds near the bottom, similar in appearance to those in the Cibao, whereas in the upper part it consists of indurated limestone, resembling the Aymamón. The Aguada varies in thickness, from about 300 feet at the southern edge of the study area to about 380 feet at Cruce Dávila area (Monroe, 1980). Blanket sands occupy dry valleys and other depressions in the Aguada.

The outcrop belt of the Aguada is characterized by very closely spaced sinkholes. It contains few surface streams and all drainage is subterranean in nature.

WATER-TABLE AQUIFER

The water-table aquifer in the Barceloneta area is part of the Puerto Rico north coast aquifer system. It consists mainly of the Aymamón Limestone and Aguada Limestone (fig. 4). The limestones are hydraulically connected to the water-bearing alluvium of the Río Grande de Manatí, surficial swamp deposits in the Caño Tiburones, and the blanket sands (fig. 2). The alluvium of Río Grande de Manatí is about 200 to 300 feet thick and is composed chiefly of fine sands, silt and clay of low hydraulic conductivity (Gómez-Gómez, 1984). The surficial deposits in the Caño Tiburones, a swampy coastal depression, are also of low hydraulic conductivity and may retard water movement through them. The Caño Tiburones's deposits locally behave as confining units (Zack, 1984). Although the blanket sands are not aquifers, they contribute recharge to the underlaying limestones (Heisel, and González, 1983). The low permeability of the blanket sands limits the amount of rainfall that can infiltrate thus some fluvial drainage has evolved in the blanket sands (Briggs, 1966). The fluvial drainage also contributes to recharge, however, as many of the streams, when runoff occurs, drain into sinkholes and permeable zones at the base of the mogotes.

Recharge to the water-table aquifer occurs primarily by direct infiltration of precipitation on the outcrop areas of the Aguada and Aymamón, as well as the fluvial drainage in the blanket sands. The mean-annual rainfall in the study area is about 70 inches (fig. 5). Recharge to the north coast limestone aquifers averages 15 in/yr (Giusti and Bennett, 1976, p.36). Recharge in the outcrop-karstified areas of the Aguada is greater because of higher infiltration rates through sinkholes.

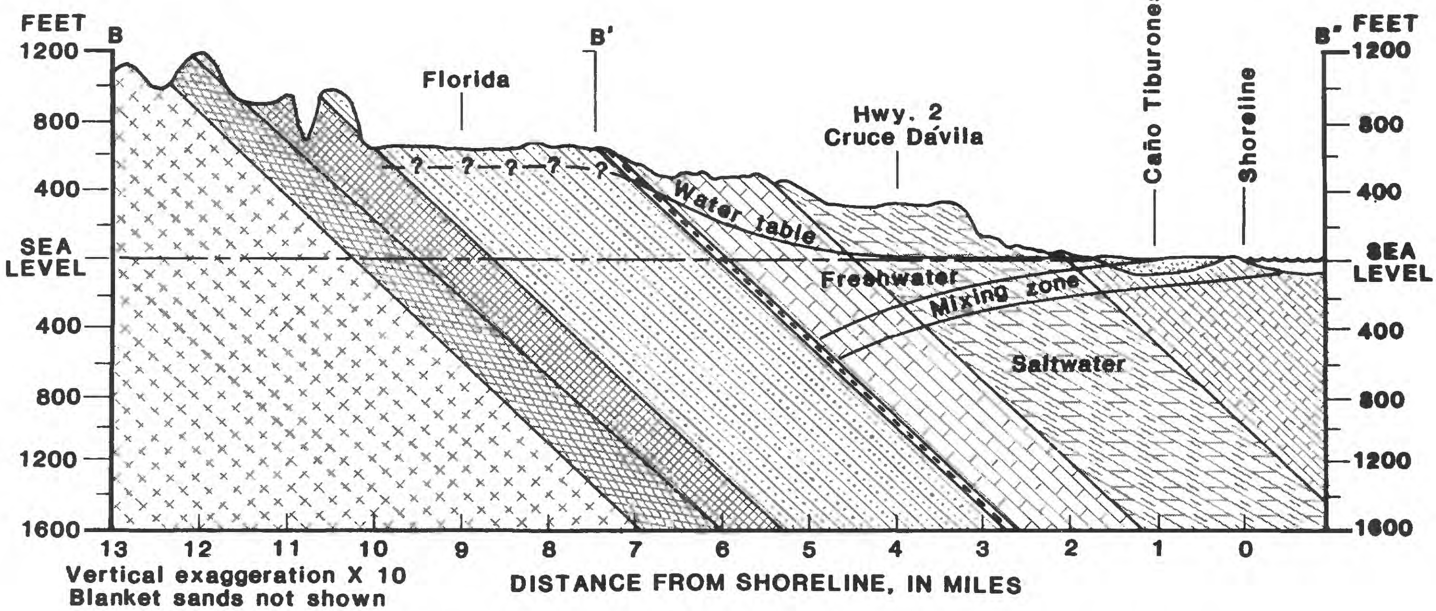
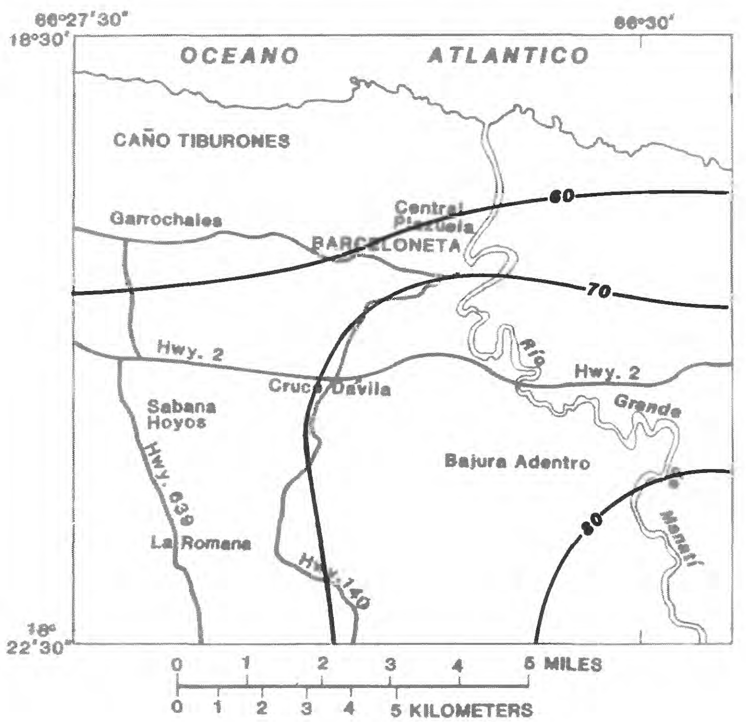


Figure 4.--Geohydrologic section through B-B" in the Florida to Barceloneta area. (See section B'-B" (fig. 7).)



EXPLANATION

——70—— LINE OF EQUAL MEAN-ANNUAL RAINFALL, IN INCHES
Contour interval 10 inches.

Figure 5.--Mean annual rainfall in inches, in the Barceloneta area. (Adapted from Calvesbert, 1970.)

WATER-TABLE AQUIFER-Continued

Water entering the aquifer in the recharge areas of the Aguada generally moves north under hydraulic gradients steeper than those in the Aymamón (figs. 6 and 7). The steep gradient reflects the lower hydraulic conductivity of the saturated Aguada. It is also generally associated with a relatively thin sheet-like flow through the Aguada for which the upper part of the Cibao forms a low permeability base (Giusti and Bennet, 1976, p. 13). Gradients gradually flatten out as ground water moves from the Aguada into the Aymamón. Here the higher hydraulic conductivity of the Aymamón contributes to flatter hydraulic gradients.

Ground-water discharge from the study area (fig. 8) totals about 60 million gallons per day (Mgal/d) (table 1). Ground-water withdrawals from about 50 wells (fig. 9 and table 2) for industrial, municipal and irrigational uses in the area total 11 Mgal/d.

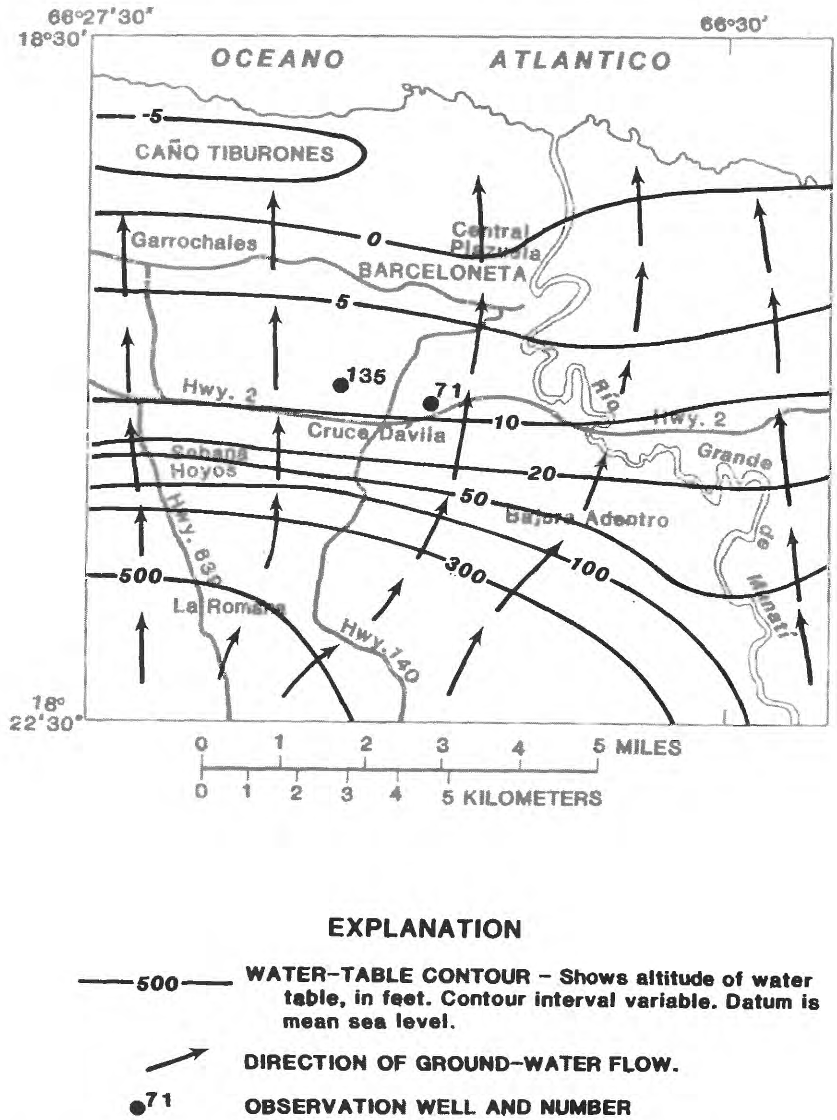


Figure 6.--Generalized ground-water movement in the water-table aquifer near Barceloneta, February 1982.

Table 1. Ground-water discharge from the water-table aquifer in the Barceloneta area.

Discharge Point	Quantity, Mgal/d	Reference
Río Grande de Manatí	22 (1)	Gómez-Gómez, oral commun., 1982
Caño Tiburones (2)	25 (3)	Giusti and Bennett, 1976
Oceáno Atlántico	2	Gómez-Gómez, written commun., 1983
Pumping wells	11	this study, 1982

(1) Ground-water discharges into Río Grande de Manatí occur both as springflow and as areal seepage. Streamflow records and seepage runs show that during low-flow conditions the river augment its flow by as much as 36 ft^3/s (22 Mgal/d) as it crosses the limestone belt.

(2) The Caño Tiburones is a swampy coastal depression extending along the north coast from Río Grande de Manatí to Río Grande de Arecibo (fig. 1).

(3) Ground-water discharges into Caño Tiburones occur also as springflow and as areal seepage. Total areal discharge has been estimated by Díaz (1973) and by Giusti and Bennett (1976, p. 23) as about 60 Mgal/d. The value of 25 Mgal/d reported in Table 1 corresponds to the flow in the Caño Tiburones area defined within the boundaries of the model.

The water-table aquifer in the Barceloneta area behaves as a system under steady-state conditions. Specific yields of the limestones in the study area have been previously estimated at about 10 percent. The relatively low value of specific yield, high value of transmissivity, and the proximity of the aquifer's physical boundaries cause the ground-water system to reach water-level equilibrium in a relatively short time. Water level records of Lederle well 135 (fig. 6), for example, show that the system reaches steady-state conditions within a few weeks after recharge occurs. The cold front of December 12 - 14, 1981, produced as much as 12 inches of rainfall in the Barceloneta area. Water levels in well 135 rose 6 feet in less than 3 days and returned to normal about 8 weeks later (fig. 10). Water levels of other wells in the area, measured more than 10 years ago, were within a few feet of those measured during February 1982.

WATER-TABLE AQUIFER-Continued

The data from Florida Afuera well 71 (fig. 6), show the stability of the ground-water system to long-term water-level fluctuations (fig. 11). Applying the Theis non-equilibrium flow equation (Lohman, 1972) to the water-table aquifer of the Barceloneta area, it is estimated that the entire ground-water system reaches steady state in about 150 days after any stress event. The values of specific yield and transmissivity used in the estimate were 0.1 and 20,000 feet squared per day (ft^2/d), respectively.

In coastal aquifers where the fresh-water head is as low as in the Cruce Dávila area (5 to 10 feet above mean sea level), sea-water intrusion can occur by two mechanisms. Lowering of the water-table below sea level would reverse the water-table gradient, inducing movement of the freshwater-saltwater mixing zone to the pumping areas. Where the salt-water zone occurs inland but deep in the aquifer, overpumpage and high drawdowns can induce salt-water upconing toward the bottom of the well. Data from wells 20, 22, 25, 30, and 32 (fig. 9) suggest that upconing is probably occurring in the Cruce Dávila area. In these wells, chloride concentrations are from 10 to 50 times higher than the background level of about 20 milligrams per liter (mg/L).

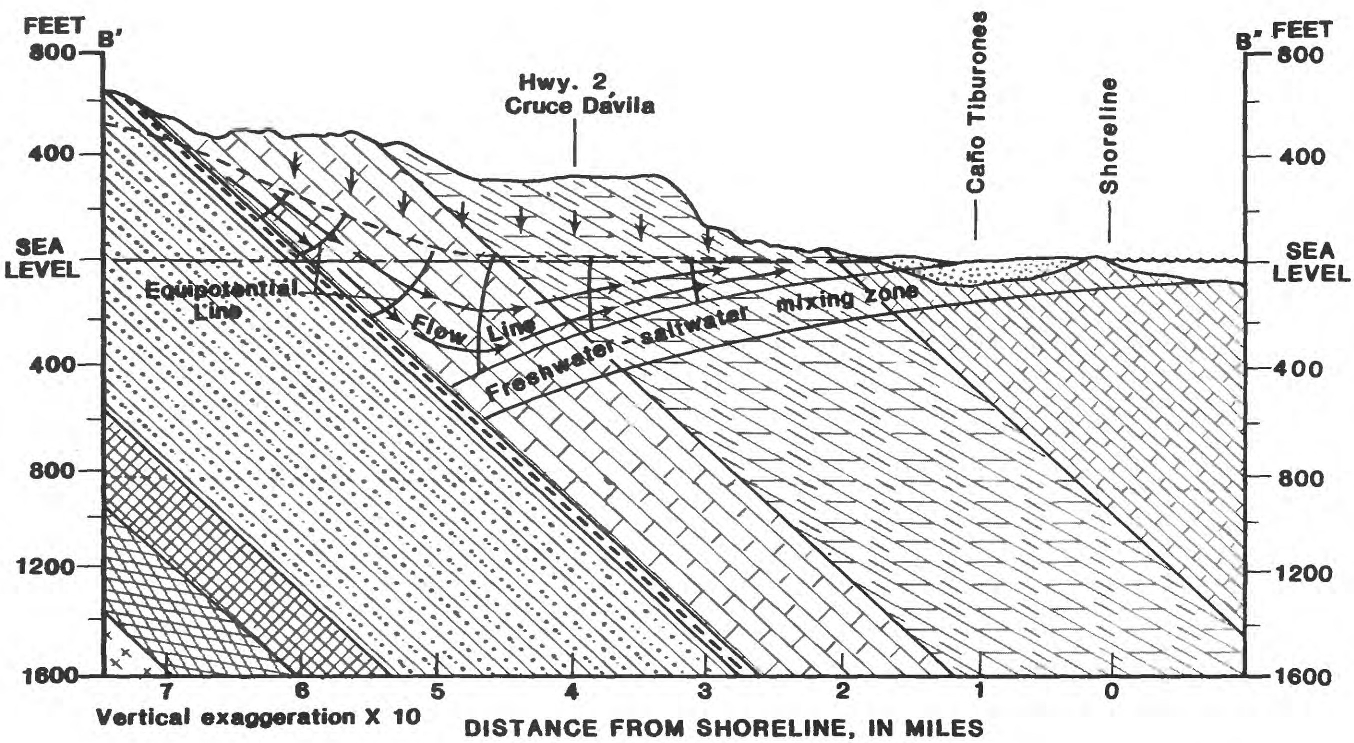


Figure 7.--Generalized ground-water movement across geologic section B'-B" in the Barceloneta area. (See fig. 2 for location of section.)

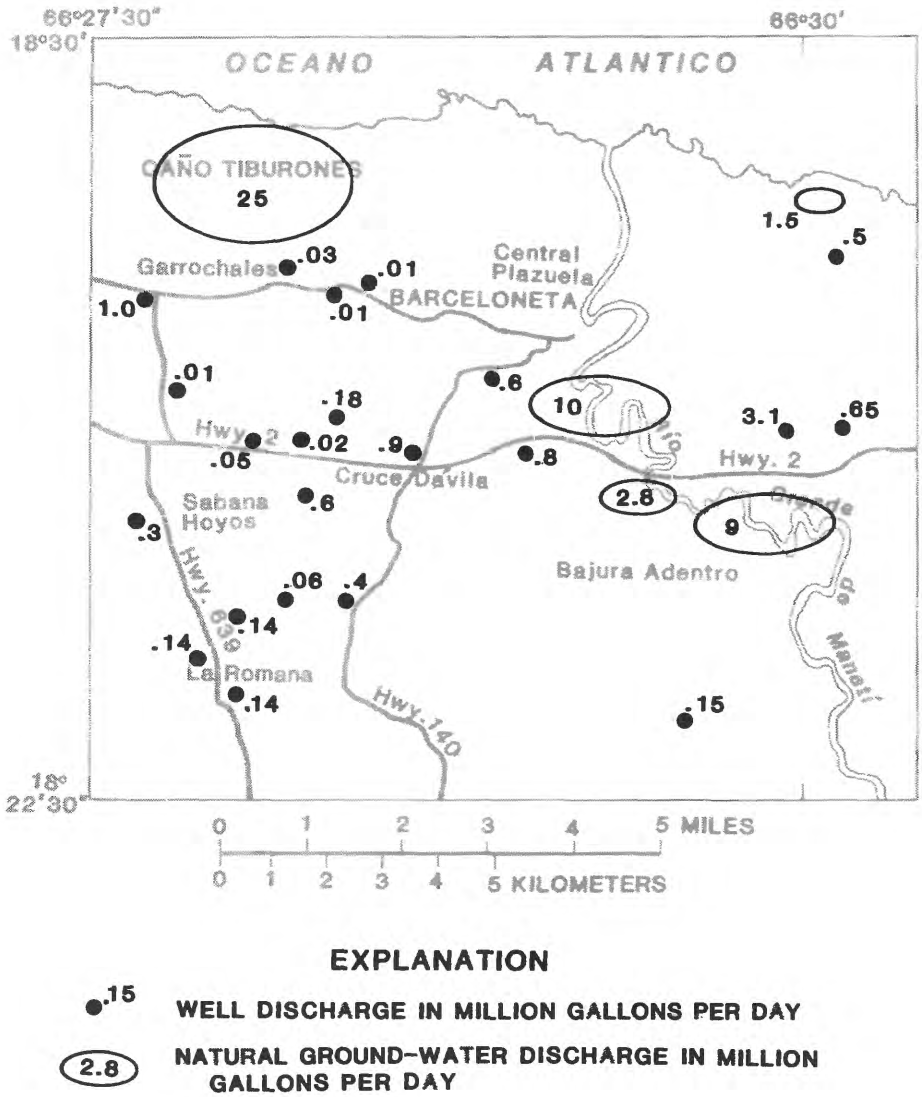
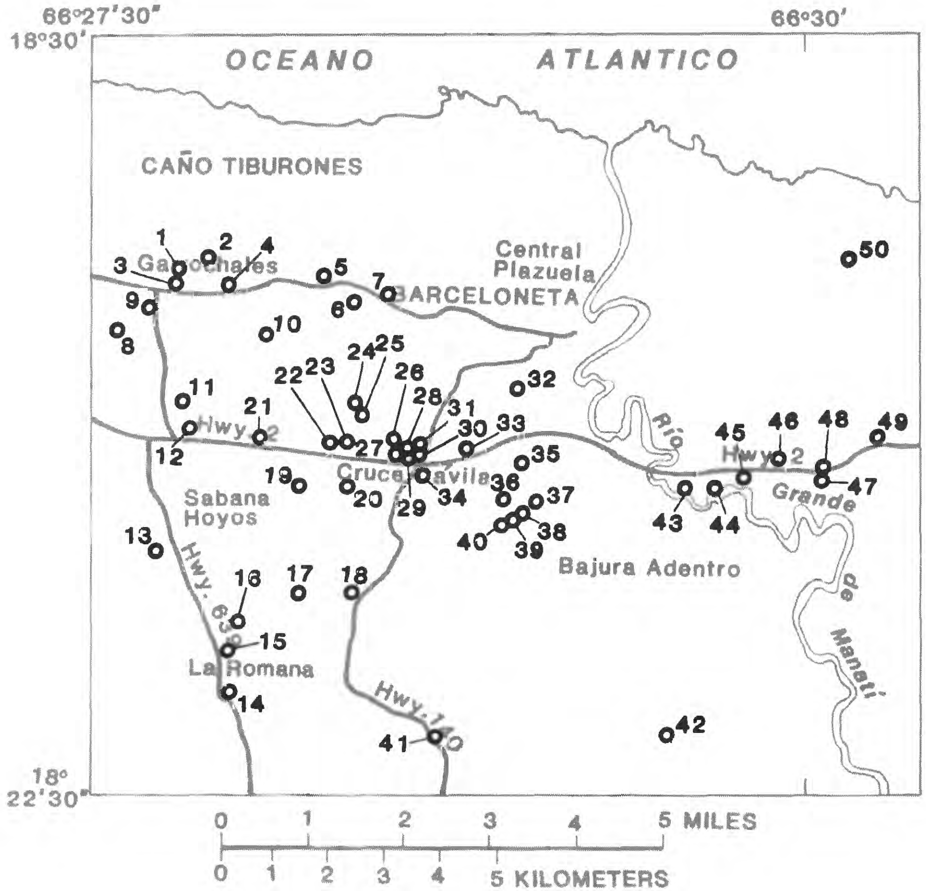


Figure 8.--Ground-water discharge from the water-table aquifer in the Barceloneta area, February 1982.



EXPLANATION

o[42] WELL AND WELL NUMBER (For identification of wells see table 2.)

Figure 9.--Producing wells in the water-table aquifer.

Table 2. Water-table wells in the Barceloneta area, February 1982.

WELL NUMBER	WELL IDENTIFICATION	DISCHARGE (MILLION GALLONS PER DAY)
1	Vaquería Ramón Delgado	0.025
2	Vaquería Ramón Delgado	0.025
3	PRASA Garrochales 2	0.576
4	PRASA Garrochales 3	Not in operation
5	Morales Well	0.005
6	Vaquería Efrain Martínez	0.012
7	Vaquería Mena	0.012
8	Vaquería Rivera	0.012
9	PRASA Garrochales 1	0.432
10	Job Corps	0.36
11	Betania	0.012
12	Mita	0.005
13	PRASA Sabana Hoyos 4	0.331
14	PRASA Sabana Hoyos 1	0.144
15	PRASA Sabana Hoyos 2	0.144
16	PRASA Sabana Hoyos 3	0.144
17	Mr. Pike Well	0.030
18	PRASA Magueyes	0.29
19	UPJOHN	0.576
20	RCA	Backup
21	WALCOTT (Land Authority)	0.045
22	A.H. Robins	0.003
23	Hillside Motel	Less than 0.003
24	Pollera	0.034
25	PRASA Tiburones	0.144
26	Pfizer	Backup
27	Casera 1	0.035
28	Casera 2	0.035
29	Industria Alimenticia (Nescafe)	0.024
30	Abbott (south)	0.400
31	Abbott (north)	0.400
32	PRASA Fortuna	0.643
33	PRASA Cruce Dávila 2	0.643
34	Winthrop Lab	0.020
35	Lotus	0.120
36	Bristol	Backup
37	Merck, Sharp & Dohne	Backup
38	Frito Lay	0.045
39	Union Carbide	0.011
40	Union Carbide	0.011
41	PRASA Pajonal X	0.20
42	PRASA Montebello 4 (Riachuelo)	0.144
43	Vaquería	0.01
44	Vaquería	0.09
45	Vaquería	0.01
46	Inland Chemical	1.2
47	PRASA Manatí 2	1.0
48	PRASA Manatí 1	1.5
49	PRASA Oficina Manatí	0.65
50	PRASA Boquillas	0.50
	Total =	11.00 Mgal/d

WATER-TABLE AQUIFER–Continued

The water-table aquifer in the study area is at present heavily stressed. Although the system has historically maintained a quasi-equilibrium state (fig. 11), additional ground-water withdrawals could disturb the system's stability in relation to long-term water-level fluctuations. If the potential recharge cannot balance the additional well discharges, water will be diverted from the areas of natural discharge (Río Grande de Manatí and Caño Tiburones). This condition could increase the possibility for lateral sea-water intrusion in the area. Sea-water upconing into individual wells can also occur in a coastal aquifer system like the Barceloneta area. This will probably occur if water levels in wells are lowered near or below sea level thus causing a disruption of the freshwater-saltwater equilibrium. Water levels in some wells in the area are at present, depressed. These wells represent therefore potential sites for sea-water intrusion.

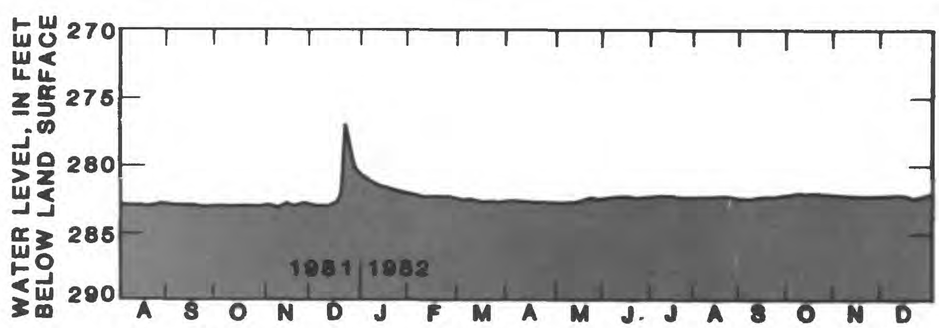


Figure 10.--Ground-water levels at well 135 (Lederle) at Barceloneta.

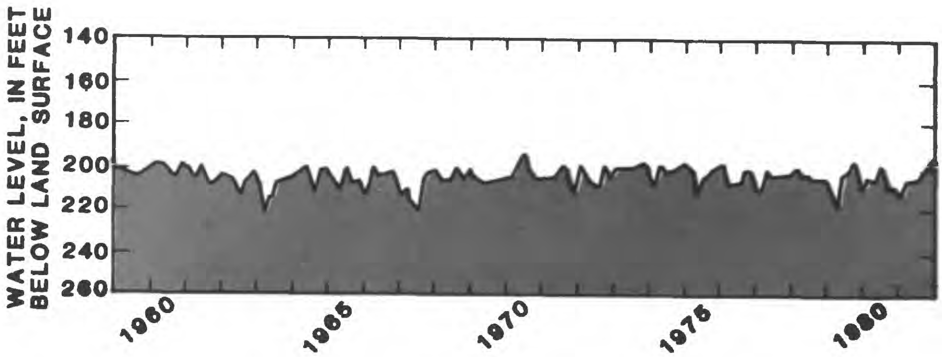


Figure 11.--Ground-water levels at well 71 (Florida Afuera) near Barceloneta from 1959 to 1981.

GROUND-WATER FLOW SIMULATION

Two-Dimentional Finite-Difference Model

The finite difference aquifer model of McDonald and Harbaugh (1984) was used to simulate the two-dimensional ground-water flow in the Barceloneta water-table aquifer. The model uses finite-difference techniques to solve the ground water flow equation for two or three-dimensional, steady or transient flow in an anisotropic, heterogenous ground-water system.

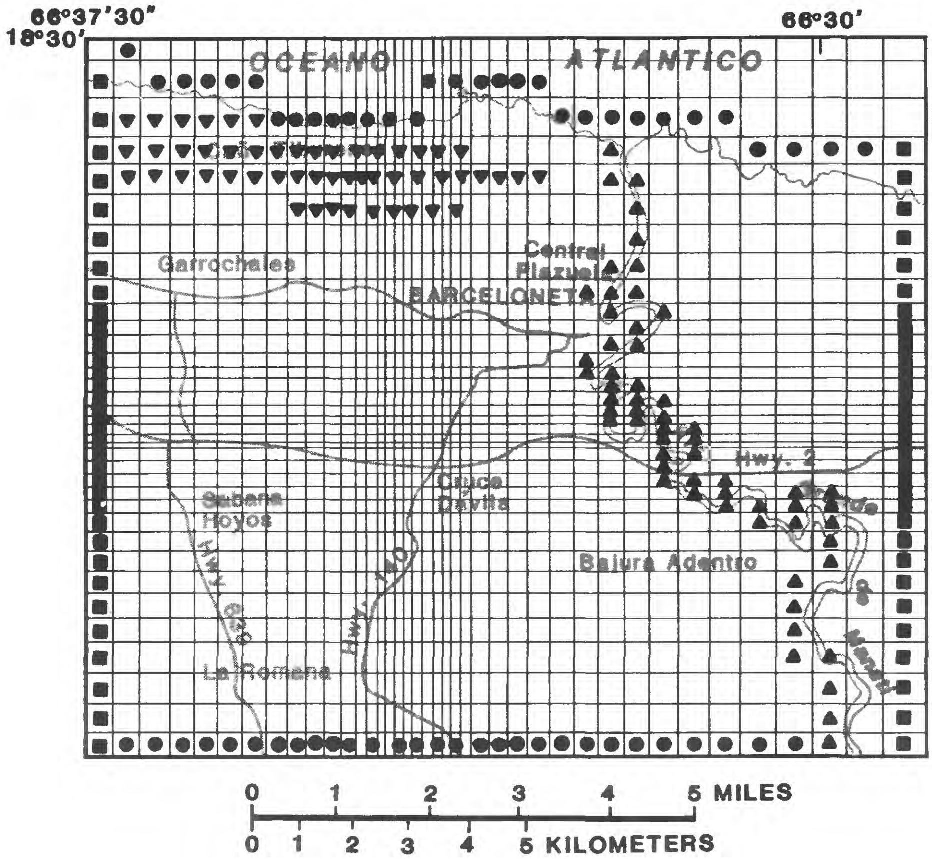
The model simulates ground-water flow in a horizontal plane with no vertical flow; an accurate simplification of the real system. In the north coast limestone water-table aquifer, horizontal hydraulic conductivity (Kx) is significantly larger than vertical hydraulic conductivity (Kv) by a ratio of about 10 to 1 (Bennett and Giusti, 1972, p. 11). The simplified system assuming zero vertical flow could result in local erroneous water-level predictions if interaquifer water movement to the water-table aquifer, through improperly sealed or abandoned wells completed in the artesian aquifers, is significant. Although interaquifer water movement through these wells is probable, it has never been confirmed.

The model also assumes that pumping wells are completed through the entire saturated thickness of the aquifer and that well losses during pumping were assumed insignificant.

Model Construction

The finite-difference technique requires that the ground-water system be divided into nodes or blocks. Average values of parameters (hydraulic conductivity, recharge, water-table elevations) are assigned to every block in the finite-difference grid. The Barceloneta model covers an area of approximately 75 square miles (mi^2) and has a grid of 36 by 40 blocks (fig. 12). The blocks were dimensioned according to the accuracy of existing data and concentration of pumping wells. The smallest blocks (535 by 515 feet) are located in the vicinity of Cruce Dávila. The size of the blocks was increased away from this pumping center. The largest block (2133 by 2077 feet) is located in the northeastern corner of the model.

The base of the aquifer (south of Highway 2) was defined as the top clastic member of the Cibao Formation (fig. 4) as described by Briggs (1965). Seaward from Highway 2, the top of the freshwater-saltwater mixing zone (chloride concentrations greater than 500 mg/L was considered as the base of the aquifer. Location of the mixing zone was determined from well logs and water-quality data. The contour lines representing the base of the water-table aquifer (fresh-water zone) are shown in figure 13.



EXPLANATION

FINITE-DIFFERENCE BLOCK

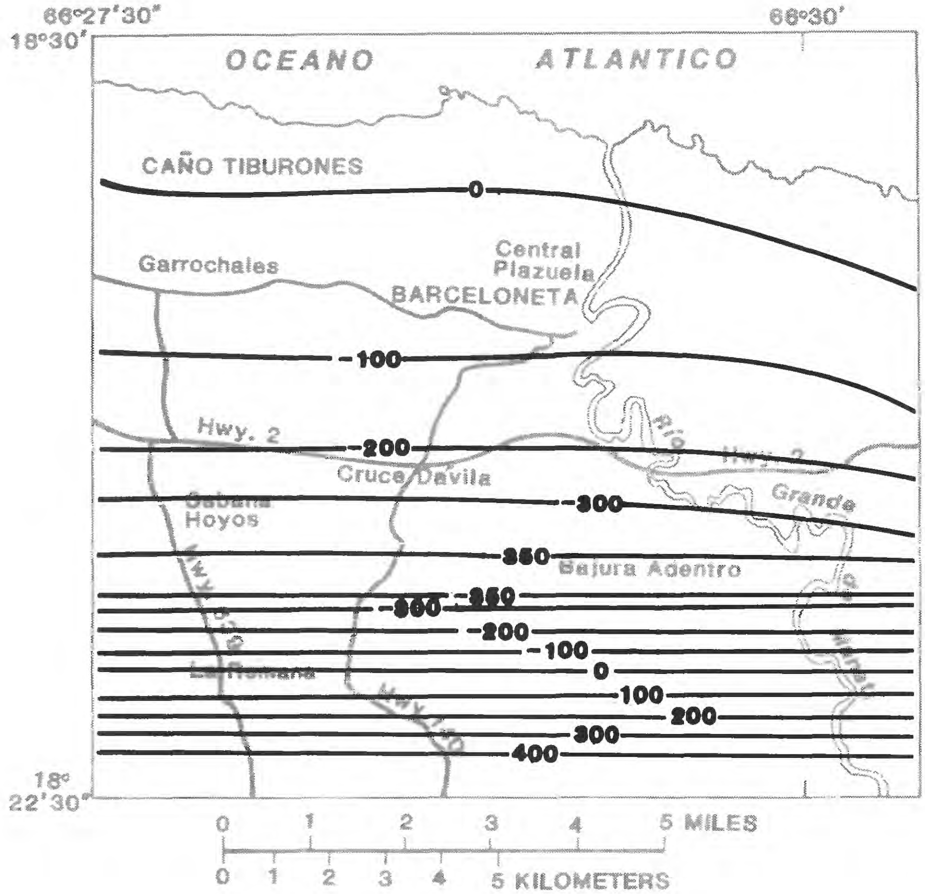
● CONSTANT HEAD NODE

■ NO-FLOW BOUNDARY NODE

▲ STREAM NODE (Río Grande de Manatí)

▼ STREAM NODE (Caño Tiburones)

Figure 12.--Finite-difference grid and boundary condition used in model.



EXPLANATION

——100—— **HYDROGEOLOGIC CONTOUR - Shows altitude of base of water-table aquifer, in feet. Interval 50 and 100 feet. Datum is mean sea level.**

Figure 13.--Altitude of base of the water-table aquifer.

Model Construction–Continued

Average values of hydraulic conductivity initially assigned to the Aymamón and Aguada were 535 and 87 ft/d, respectively (fig. 14). These were calculated by Giusti and Bennett (1976) from well performance data. Initial estimates of aquifer transmissivity (fig. 15) were computed as the product of the average values of hydraulic conductivity and saturated thickness of each unit. The saturated thickness of the water-table aquifer (freshwater zone) in the Barceloneta area is shown in figure 16.

The southern edge of the study area and the Oceano Atlantico on the north represent areas of constant hydraulic head (fig. 12). The southern edge is considered a constant head boundary to allow movement of ground water from the Montebello Limestone Member under unconfined conditions into the Aguada. The areas are simulated in the model by assigning constant hydraulic heads to the nodes which represent them.

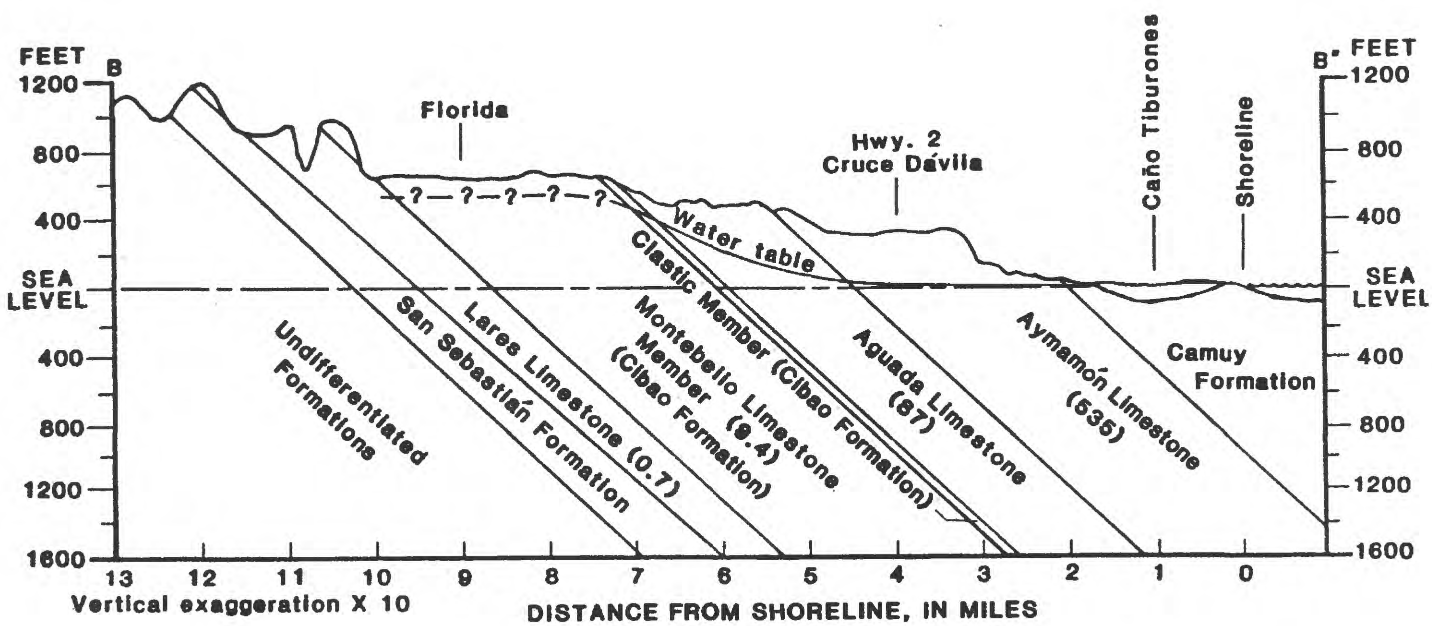
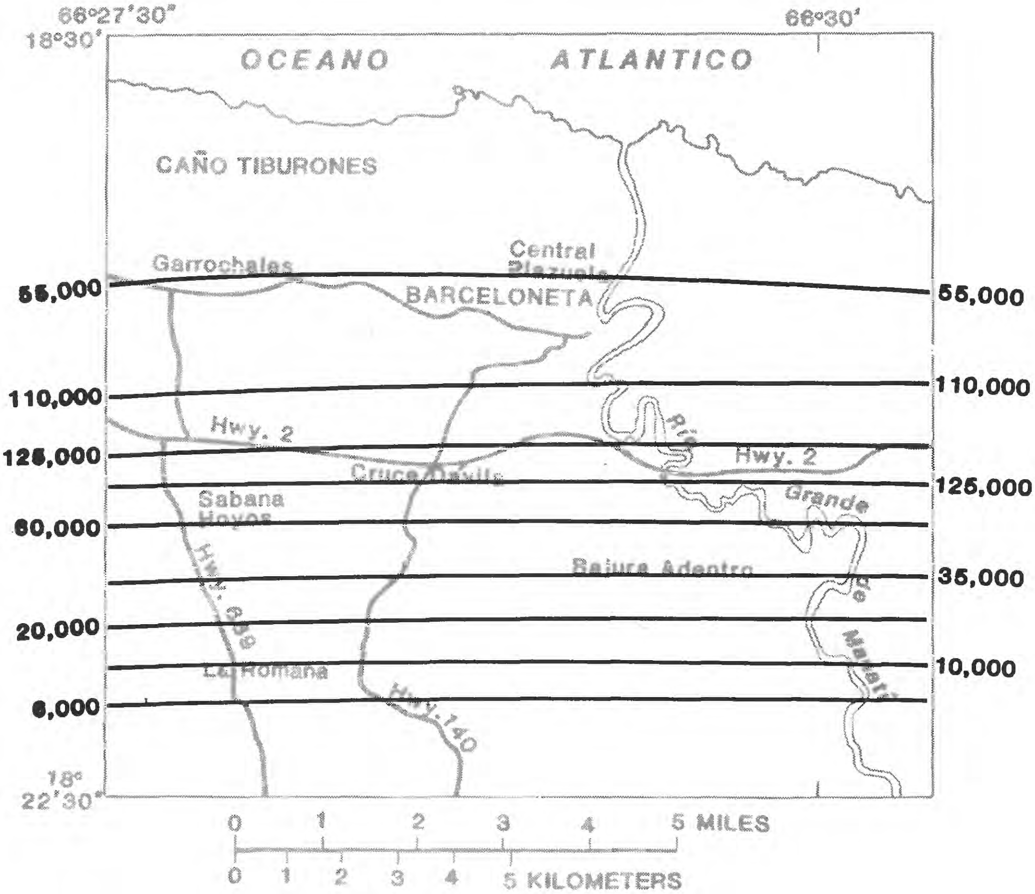


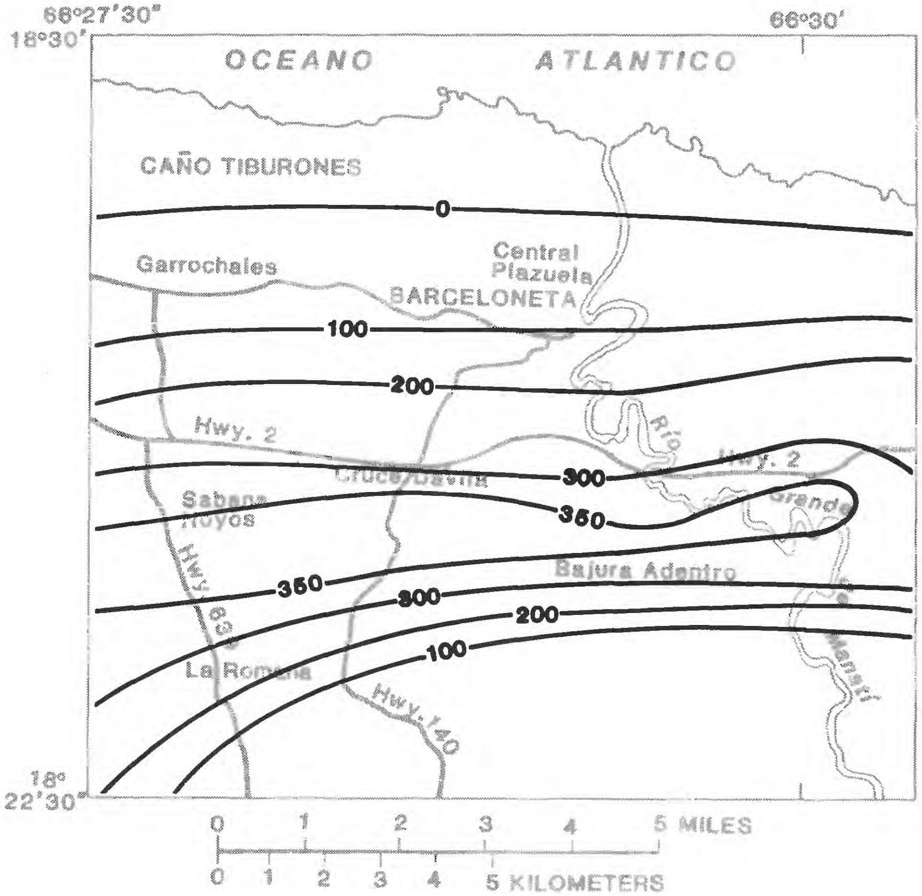
Figure 14.--Estimated average hydraulic conductivity in feet per day through cross section B-B" in the Cruce Dávila area.
(Modified from Giusti and Bennett, 1976.)
(See fig. 2 for location of section.)



EXPLANATION

—— 20,000 LINE OF EQUAL TRANSMISSIVITY, IN SQUARE FEET PER DAY, INTERVAL VARIABLE

Figure 15.--Estimated transmissivity of the water-table aquifer.
(Based on Giusti and Bennett, 1976.)



EXPLANATION

——100—— LINE OF EQUAL SATURATED THICKNESS, IN FEET. Interval 50 and 100 feet.

Figure 16.--Saturated thickness of the water-table aquifer (fresh-water zone) in the Barceloneta area.

Model Construction–Continued

The exchange of water between the streams (Río Grande de Manatí and Caño Tiburones), and the aquifer in the study area (stream-aquifer leakage) occurs through the streambed and is simulated in the model (fig. 12) according to the following equation:

$$Q = k'/b' \ (Hs - Ha) \ A$$

where

Q = rate of leakage, in cubic feet per second;

k'/b' = streambed leakance, or ratio of hydraulic conductivity of streambed, in feet per day, to thickness of streambed, in feet;

Hs = elevation of stream stage, in feet;

Ha = elevation of water table, in feet; and

A = wetted area of streambed reach, in square feet

Well discharge data used in the model (average daily) was obtained from the Puerto Rico Department of Natural Resources, Puerto Rico Aqueduct and Sewer Authority, Geological Survey files and from industries in the area. Field inspections were conducted to verify most of the reported values.

Pumping wells were simulated assuming fully penetrating conditions (screened or opened through the entire saturated thickness of the aquifer) and 100 percent efficiency. As they are not, the observed pumping water levels in actual wells are proportionally lower than the water levels predicted by the model. Well logs from the Barceloneta area indicate that 9 of 21 wells penetrate 75 percent or more of the saturated thickness of the aquifer(fig. 17).

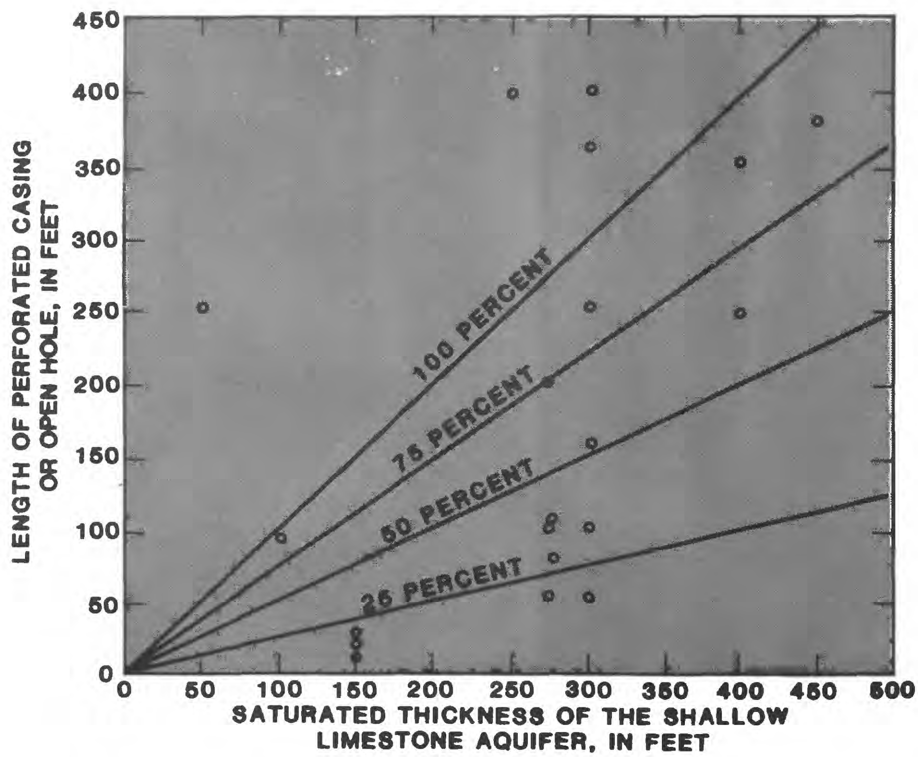


Figure 17.-- Percentage of penetration of pumping wells in the water-table aquifer.

Model Construction–Continued

Because all wells in the model were assumed to be fully penetrating, water-level declines indicated by the model should be corrected for effects of partial penetration. In the Barceloneta area, the corrections are not expected to be significant because the aquifer has a very high transmissivity. Wells 3, 4, and 9, at Garrochales for example, (fig. 9) penetrate less than 25 percent of the entire saturated thickness of the aquifer. Nevertheless, when these wells are pumped at rates exceeding 1,000 gallons per minute (gal/min), water-level declines are negligible (less than 0.5 ft). Drawdowns could have been less if the wells would have been fully penetrating. Computed transmissivity from these wells is very high, over 100,000 ft^2/d.

A recharge value of 15 in/yr from precipitation was initially assumed in the model. The model does not differentiate between sources of recharge. Although precipitation accounts for the largest percentage of recharge, some vertical water movement through improperly sealed artesian wells might exist, which will therefore be included in this overall value of recharge.

The eastern and western limits of the study area were considered as no-flow boundaries (fig. 12). Water-table contour maps (fig. 6) show that ground-water flow lines run parallel to the boundaries. As previously described, the base of the model (figs. 4 and 7) was determined by both the locations of the confining bed (Cibao Formation) beneath the Aguada and the top of the freshwater-saltwater mixing zone. The confining bed provides hydraulic non-continuity between the deep Montebello artesian aquifer and the shallow water-table aquifer. The freshwater-saltwater mixing zone was also considered as an impermeable boundary because flow lines are generally parallel to it (fig. 7).

Model results near the Cruce Dávila area, the largest pumping center in the Barceloneta area (fig. 1), will not be significantly affected by the location of the boundaries. However, near the boundaries location, pumpage simulations should be cautiously analyzed. A model, using the Río Grande de Arecibo as the western boundary, would reduce problems arising from the effects of boundaries.

Model Calibration

Model calibration is the process by which simulated aquifer parameters are modified to obtain a match between the water levels computed by the model and observed ground-water heads. The model of the water-table aquifer in the Barceloneta area was calibrated to water levels of February 1982 by adjusting, within reasonable limits, values of hydraulic conductivity, recharge, and altitude of the bottom of the fresh-water zone in the aquifer. Ground-water discharges to Caño Tiburones and Río Grande de Manatí were adjusted to historically known rates of discharge by modifying the hydraulic connection between the streambeds and the aquifer.

Hydraulic Conductivity

The first estimates of hydraulic conductivity initially used in the model (Aymamón 537 ft/d and Aguada 87 ft/d) were obtained from Giusti and Bennett (1976). These values of hydraulic conductivity were modified in the model because in the real system variations in conductivity with depth exist in each of the limestone formations (fig. 18). Hydraulic gradients in the Aymamón are expected to be flatter than in the Aguada, at the same rate of ground-water discharge, because of higher values of hydraulic conductivity in the Aymamón. Although the relative value of head gradients of the two formations was properly simulated by the model, computed heads in the Aguada were generally lower than the measured heads. Some head differences were also evident in the area where the water table reflects the hydraulic properties of both formations. Values of hydraulic conductivity were therefore adjusted throughout the model (fig. 19) taking into consideration that the hydraulic conductivity varies with depth in each formation.

The adjustments in the values of aquifer hydraulic conductivities (fig. 19) enabled a closer approximation of the computed and observed heads. Reductions were significant in the values of hydraulic conductivity in the outcrop area of the Aguada to account for larger hydraulic gradients in the recharge area. Values of hydraulic conductivity as low as 10 ft/d were determined for the Aguada (fig. 19). Although the new simulated heads were closer to the real values, additional adjustments to refine the calibration were required. However, no further adjustments in the values of hydraulic conductivity were attempted because they would have exceeded the values shown in figure 18 beyond reasonable limits.

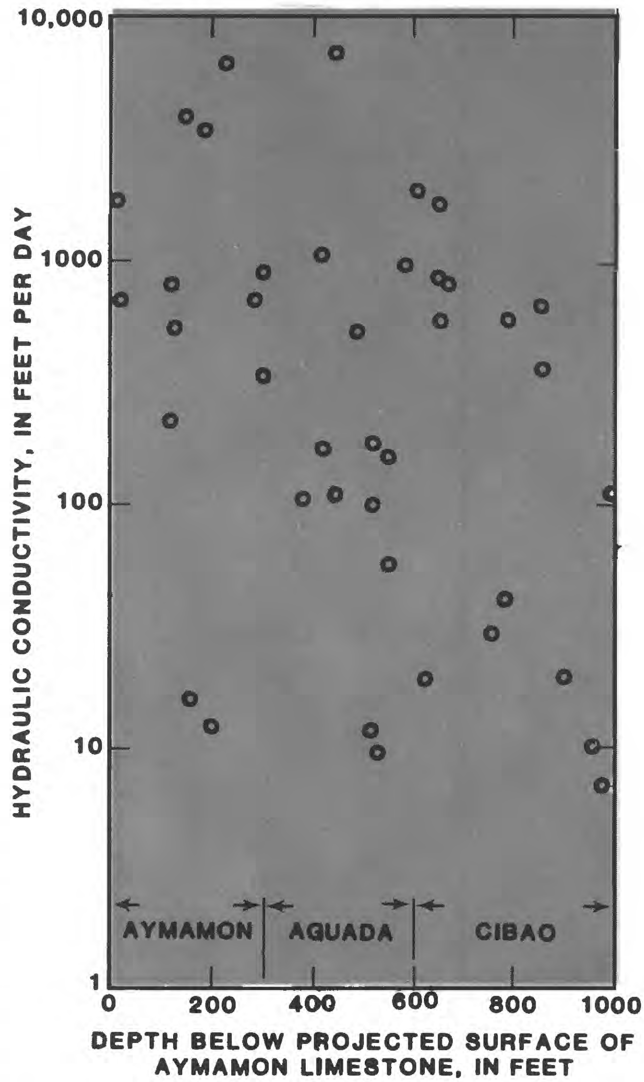
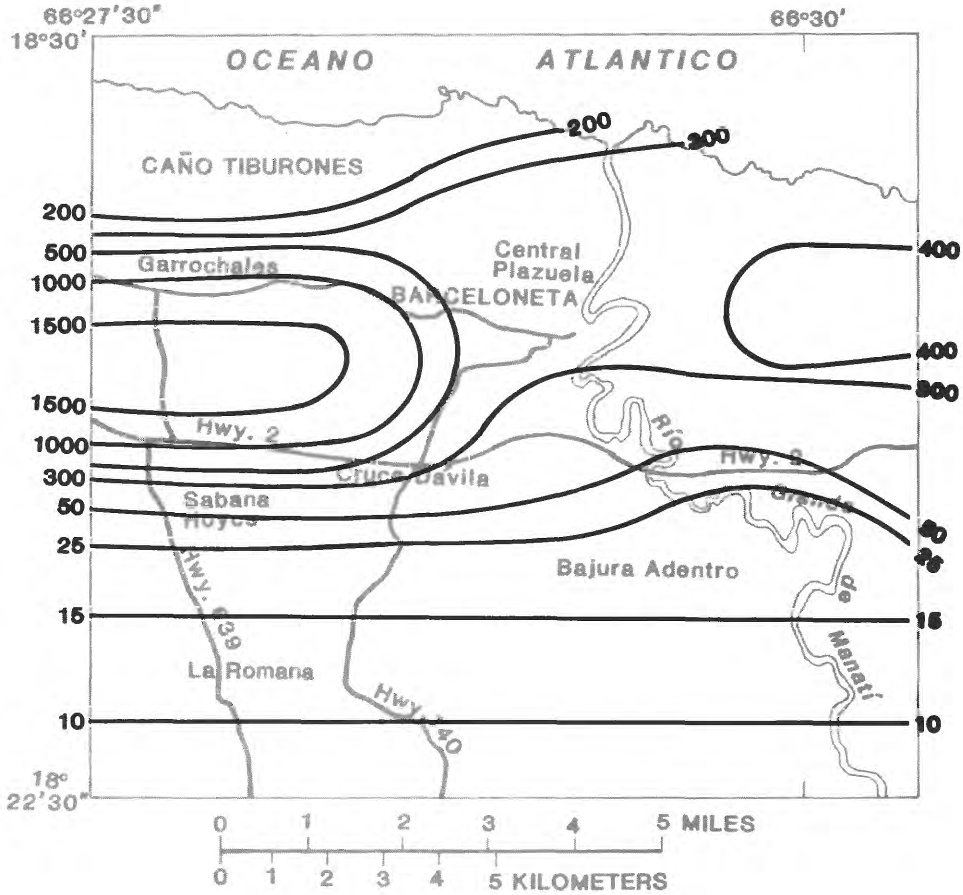


Figure 18.--Hydraulic conductivity of limestone relative to stratigraphic depth. (Modified from Giusti and Bennett, 1976.)



EXPLANATION

10———10 LINE OF EQUAL HYDRAULIC CONDUCTIVITY, IN FEET PER DAY. INTERVAL VARIABLE.

Figure 19.--Simulated values of hydraulic conductivity in the water-table aquifer.

Aquifer Recharge

The mean-annual rainfall in the Barceloneta area is about 70 inches (fig. 5). A uniform recharge rate of 15 in/yr (Giusti and Bennett, 1976, p. 36), was initially assumed in the study area. This assumption was modified during the calibration process because aquifer recharge varies with the amount of precipitation. Rainfall in the Barceloneta area is not uniformly distributed. It varies from about 75 in/yr in the southern boundary, to less than 60 in/yr along the shoreline (fig. 5). Also a uniform recharge rate throughout the outcrop area cannot be applied because of the existing topographic features in the area. The outcrop areas of the Aguada are characterized by a very rugged karst terrane with no surface drainage. Closely-spaced sinkholes are abundant, acting as effective ground-water recharge conduits. In the outcrop area of the Aymamón, however, the topography is different. The land is characterized by steep-sided conical hills (mogotes) with blanket sand deposits filling the valleys between them. The deposits provide some surface drainage and probably a greater chance for evaporation to occur, thus reducing the amount of runoff available for recharge. Recharge rates in these areas within the Aymamón outcrops were therefore considered less than in the outcrop of the Aguada.

Agreement between the simulated and the observed heads was finally achieved by gradually increasing the recharge rate. Recharge was increased to 20 in/yr on the Aymamón outcrop, and to 25 in/yr on the Aguada outcrop (fig. 20). Recharge was assumed to be negligible near the shoreline because the Caño Tiburones is an area of natural ground-water discharge.

Well Discharge

Well discharge rates simulated by the model include only ground-water withdrawals from the water-table aquifer. All wells shown in figure 9, except 14, 41, and 42 comply with this requirement. These wells were previously reported to be completed in the water-table aquifer, however, their construction logs show that they tap both the water table and upper artesian (Montebello Limestone Member) aquifers. With no other data available, discharges of wells 14, 41, and 42 were adjusted in the model according to the percentage of the well opened to the water-table aquifer. Model computed heads and drawdowns improved significantly in these wells after the above adjustments.

Stream-Aquifer Leakage

The exchange of water between the streams and the aquifer in the Barceloneta area was accurately simulated by the model. Streambed hydraulic conductivity values of 3 and 1 ft/d were used for Río Grande de Manatí and Caño Tiburones, respectively. A streambed thickness of 1 ft was assumed for the streams. These values were derived by trial and error simulations attempting to approximate the historical rates of ground-water discharge in the streams (table 1).

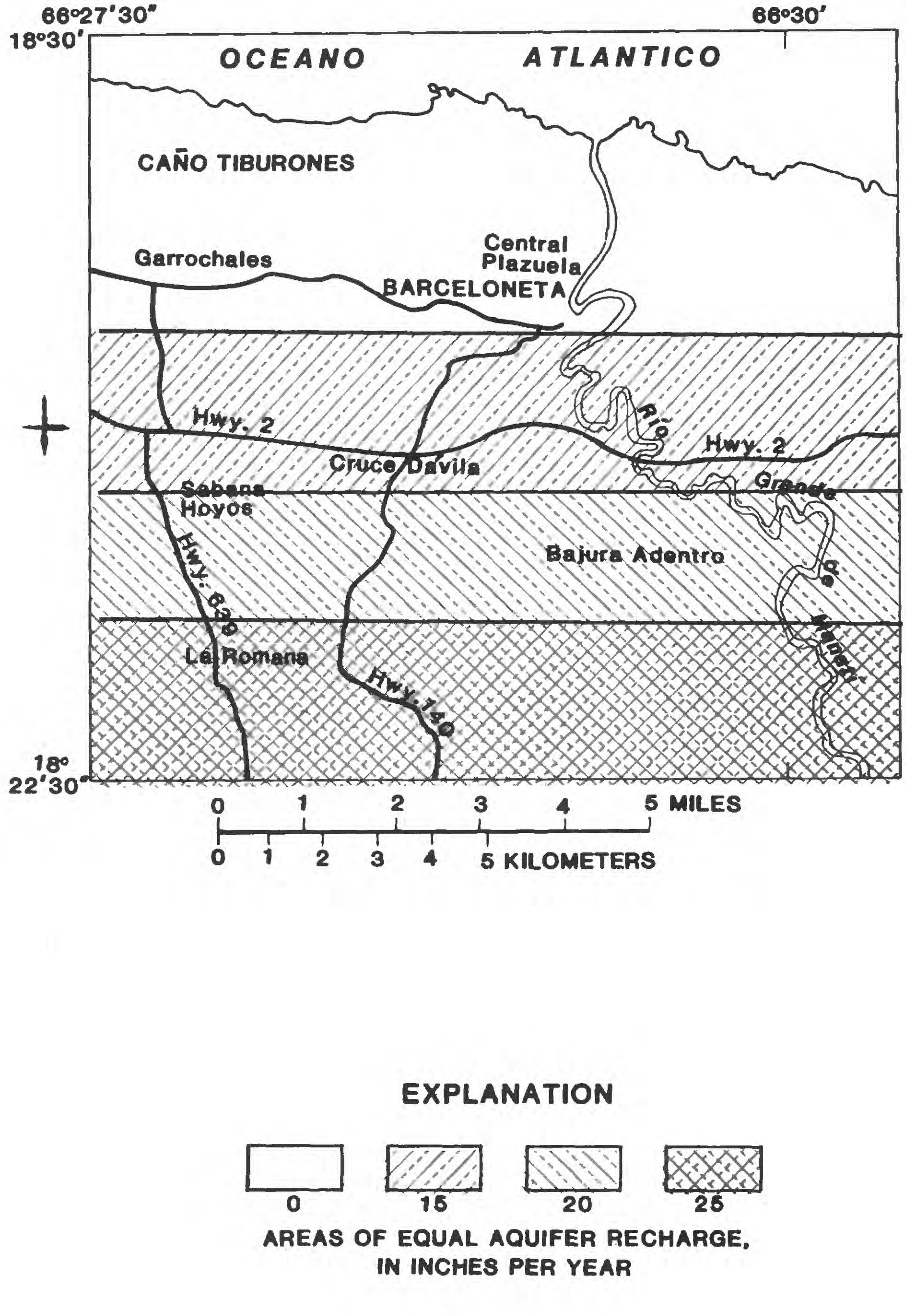


Figure 20.--Simulated aquifer recharge.

Calibrated Potentiometric Surface and Transmissivity

The potentiometric surface simulated by the model (fig. 21) closely approximated the water levels measured in February 1982 (fig. 6). Most of the observed heads were within 10 feet of the model-computed heads.

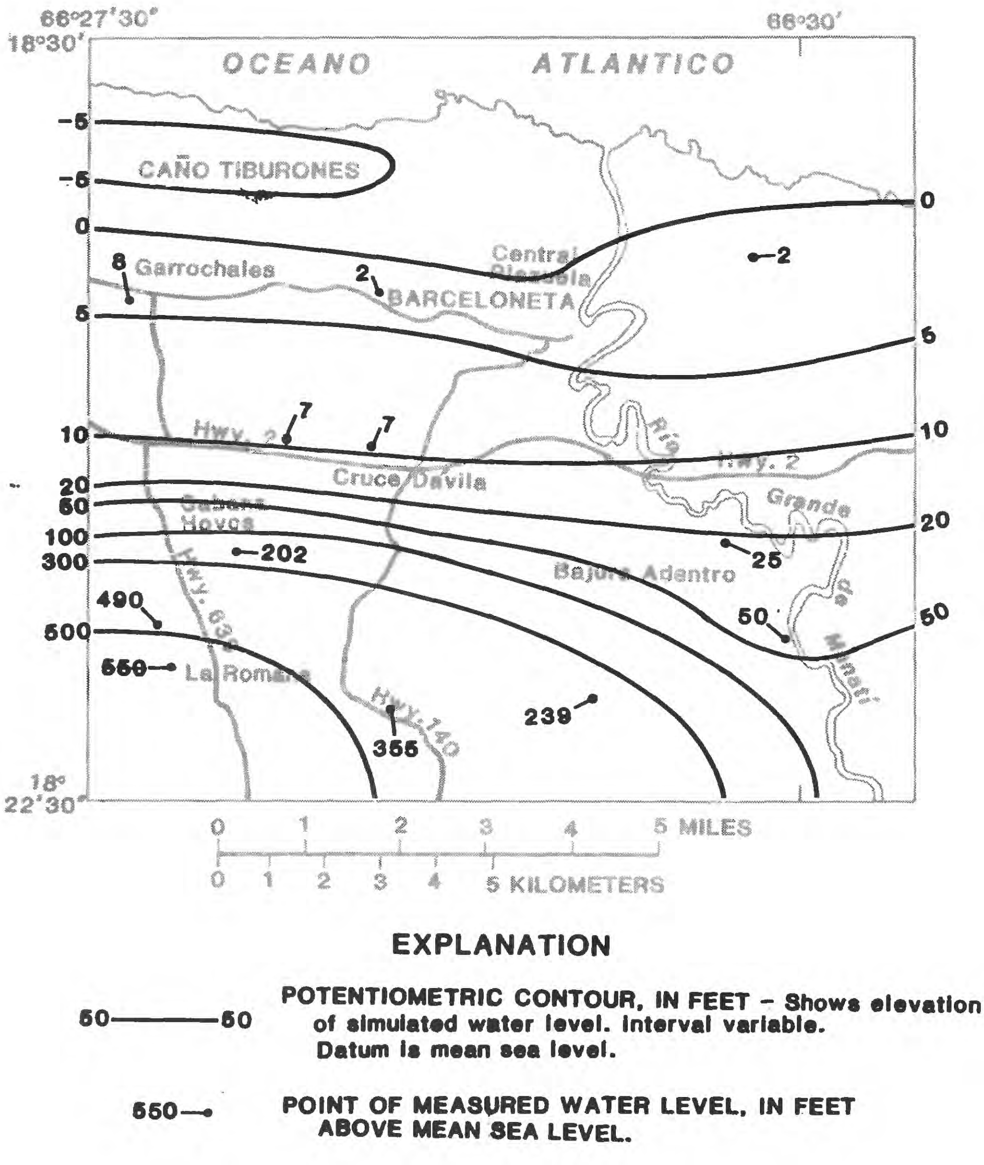
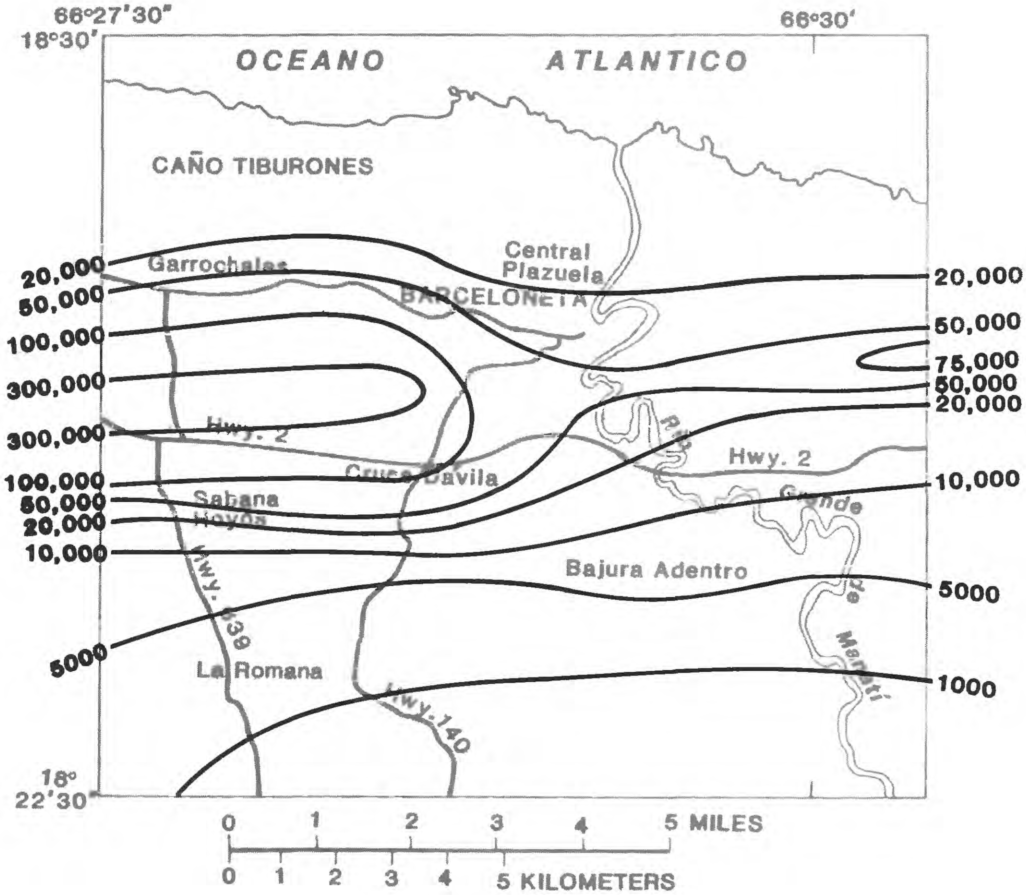


Figure 21.--Simulated potentiometric surface with measured water levels in the water-table aquifer, February 1982.

Calibrated Potentiometric Surface and Transmissivity–Continued

Calibrated values of regional aquifer transmissivity (fig. 22) are significantly different than those initially estimated (fig. 15) using average values of hydraulic conductivity as determined by Giusti and Bennett. The principal reason for this discrepancy was previously discussed in the hydraulic conductivity section. The computed transmissivities in the Aguada (fig. 22) are generally less than the initial estimates whereas in the Aymamón they are larger. Calibrated values of regional transmissivity in the Aymamón were as high as 300,000 ft^2/d in the northwestern part of the study area. Local transmissivities in excess of 2,000,000 ft^2/d have been determined from aquifer tests at specific sites in the same area.



EXPLANATION

5000 ———— 5000 LINE OF EQUAL TRANSMISSIVITY, IN FEET SQUARED PER DAY. INTERVAL VARIABLE.

Figure 22.––Simulated transmissivity of the water-table aquifer near Barceloneta.

Calibrated Potentiometric Surface and Transmissivity–Continued

Final computed heads in the Aymamón, however, are still about 3 to 7 feet higher than the real heads. These computed heads could be better approximated if localized highly transmissive features, like solution conduits known to exist in the area, could be incorporated in the model.

Sensitivity Analyses

The capacity of the model to simulate field conditions and changes can be appraised from sensitivity analyses. In this procedure, modeled hydrologic parameters are varied over a range of values and the model response is compared to field conditions.

Values of aquifer hydraulic conductivity, streambed hydraulic conductivity, and recharge rates were varied to test their effects on the model results (tables 3, 4, and 5; simulations 10 to 15 and figure 23). The most significant effects on ground-water discharge and water heads were caused by variations in recharge (Table 5 and fig. 23a). If recharge is either increased or reduced by 50 percent over the entire model area, water levels fluctuate (1) about 5 ft in the Cruce Dávila area and, (2) as much as 20 ft in La Romana and Cruce Magueyes areas (fig. 1 and table 4, simulation 14 and 15). Reductions in recharge significantly affect ground-water discharge into Caño Tiburones and Río Grande de Manatí (table 5, simulation 14).

Variations in streambed hydraulic conductivity caused the least significant head changes on the model (fig. 23b). This parameter was varied by a factor of 10 and produced water level changes in the Cruce Dávila area of only 4 feet (table 4, simulations 12 and 13). Ground water discharge into Caño Tiburones and Río Grande de Manatí was affected by less than 10 percent (table 5, simulations 12 and 13).

Changes in aquifer hydraulic conductivity (table 3, simulations 10 and 11) affected the ground-water discharges to the streams by less than 10 percent (table 5, simulation 10 and 11). These variations in hydraulic conductivity, however, significantly affected the water heads in the Cruce Dávila and La Romana areas by as much as 7 feet and 30 feet, respectively, when conductivity was decreased by 50 percent. When the hydraulic conductivity was increased by 50 percent heads were affected in the Cruce Dávila and La Romana areas by 2 feet and 12 feet, respectively (table 4, simulations 10 and 11, fig. 23c).

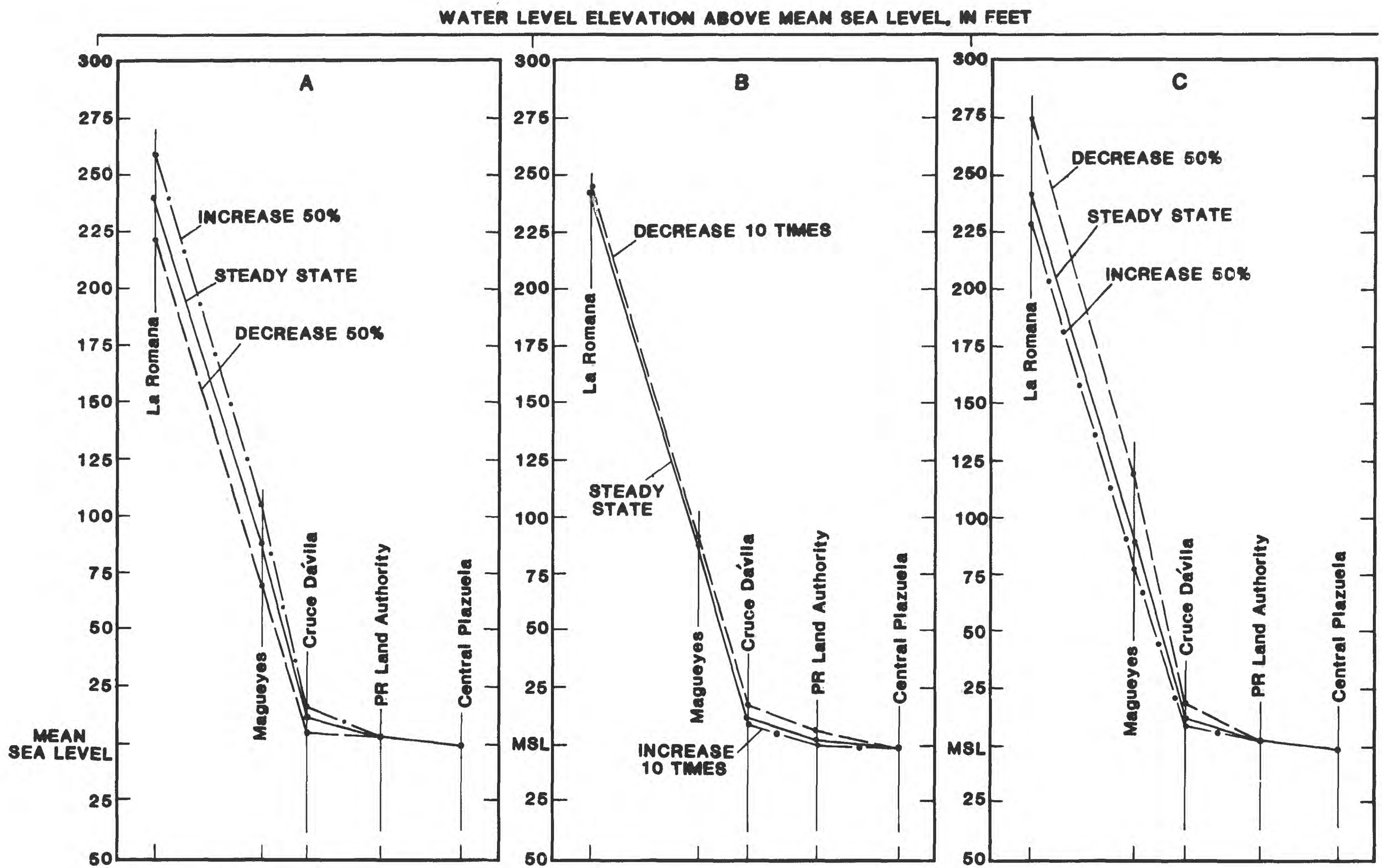


Figure 23.--Results of sensitivity analyses for: A – Aquifer recharge,
B – Streambed vertical hydraulic conductivity, and
C – Aquifer horizontal hydraulic conductivity.

Table 3. Aquifer simulations.

Simulation	Description
1	Discharge of wells 30 and 31 as of 1982, increased from 0.8 to 1.8 Mgal/d. Total pumpage in the Cruce Dávila area increased to 4.5 Mgal/d.
2	Discharge of selected wells in the Cruce Dávila area, as of 1982, increased from 1.5 to 4.5 Mgal/d: wells 30 and 31 increased by 1.0 Mgal/d, well 33 (0.5 Mgal/d), well 27 (0.5 Mgal/d), well 39 (0.5 Mgal/d) and well 34 (0.5 Mgal/d).
3	Same as simulation 2 plus a line of 18 hypothetical wells (along Highway 2) pumping at a rate of 550 gal/min (1982 pumpage increased by 17 Mgal/d).
4	Withdrawal rates of February 1982 plus a line of 18 hypothetical wells (along Highway 2) pumping at a rate of 550 gal/min (1982 pumpage increased by 14 Mgal/d).
5	Same as simulation 4 but 17 wells instead of 18 wells and pumping at rates of 550 gal/min (1982 pumpage increased by 13.4 Mgal/d).
6	Discharge of the 17 hypothetical wells increased from 550 to 800 gal/min (1982 pumpage increased by 19.6 Mgal/d).
7	Discharge of the 17 wells increased to 1,200 gal/min (1982 pumpage increased by 29.4 Mgal/d).
8	Substitution of the 17 wells by 6 wells spaced 1 mile apart and pumping at rates of 825 gal/min (1982 pumpage increased by 7 Mgal/d).
9	Withdrawal rates of February 1982 plus 1 hypothetical well in the river valley Near Highway 2 bridge. Pumping rate is 800 gal/min.
10	Values of aquifer hydraulic conductivity decreased by 50 percent.
11	Values of aquifer hydraulic conductivity increased by 50 percent.
12	Streambed vertical hydraulic conductivity decreased by a factor of 10.
13	Streambed vertical hydraulic conductivity increased by a factor of 10.
14	Values of aquifer recharge decreased by 50 percent.
15	Values of aquifer recharge increased by 50 percent.
16	Withdrawal rates of February 1982 plus 2 hypothetical wells: one located in the river valley near Highway 2 bridge (400 gal/min) and the other east of the Cruce Dávila (400 gal/min).
17	Same as simulation 16 but well near river valley pumping at 850 gal/min.
18	All pumping wells removed from the aquifer.
19	Same as simulation 18 but with one hypothetical well at Cruce Dávila area pumping at a rate of 500 gal/min.

Table 4. Simulated water-level elevations.

NUMBER OF SIMULATION[a]	SITES[b]						
	JOB CORPS	CENTRAL PLAZUELA	ABANDONED PRLA[c] WELL	CRUCE DAVILA	CRUCE MAGUEYES	BAJURA ADENTRO (Cortes Well)	LA ROMANA (Sabana Hoyos)
1	4.6	-0.4	2.9	10.9	88.2	37.4	242
2	4.1	-0.5	2.8	8.7	87.1	37.4	242
3	-0.2	-0.6	2.2	1.2	82.3	36.7	241
4	0.6	-0.6	2.3	4.8	84.2	36.8	241
5	1.0	-0.6	2.3	5.0	84.3	36.8	241
6	-0.8	-0.6	2.0	1.6	82.3	36.5	240
7	-3.8	-0.8	1.6	-4.0	79.0	36.0	239
8	2.8	-0.5	2.6	8.4	86.3	37.1	242
9	4.9	-0.4	2.9	12.0	88.6	37.3	242
10	8.8	-0.3	2.9	18.8	118.0	57.3	275
11	3.7	-0.5	2.9	9.9	77.4	30.0	230
12	11.0	0.8	7.3	16.8	91.7	38.9	244
13	3.5	-0.5	2.2	11.2	88.0	37.2	242
14	1.5	-0.6	2.5	6.6	68.8	23.0	220
15	8.2	-0.3	3.3	17.4	106.0	48.6	263
16	4.8	-0.4	2.8	11.9	88.5	37.4	242
17	4.8	-0.4	2.8	11.9	88.5	37.4	242
18	6.6	-0.3	3.1	15.4	93.4	39.4	250
19	6.5	-0.4	3.1	14.6	93.1	39.3	250
CALIBRATED WATER LEVELS STEADY-STATE	4.9	-0.4	2.9	12.0	88.6	37.5	242

Table 5. Simulated ground-water discharges.

NUMBER OF SIMULATION[a]	DRAINING FEATURE				
	Ocean Discharge into Caño Tiburones	Ground-water Discharge into Caño Tiburones	Ground-water Discharge into Ocean on Northeastern part of Río Grande de Manatí Valley	Ground-water Discharge into Río Grande de Manatí, downstream of Highway 2	Ground-water Discharge into Río Grande de Manatí, upstream of Highway 2
1	1.5	23.8	2.5	12.0	11.1
2	1.5	23.8	2.4	10.5	11.1
3	1.5	11.8	2.5	8.1	10.3
4	1.8	16.0	2.4	5.1	10.2
5	1.5	16.3	2.6	4.0	10.4
6	1.5	8.2	2.4	1.1	10.1
7	1.6	0.5	2.5	-7.0	9.5
8	1.5	17.4	2.4	8.1	10.8
9	1.4	24.5	2.0	11.9	10.7
10	2.0	22.2	1.1	13.5	14.7
11	1.5	25.6	3.7	12.0	7.9
12	0.1	23.0	2.5	9.8	12.7
13	10.0	32.6	1.7	13.4	10.3
14	1.5	13.1	1.7	3.0	1.5
15	1.5	36.1	3.1	22.7	21.5
16	1.5	22.6	2.9	10.9	11.1
17	1.5	23.2	2.4	11.2	11.1
18	1.5	30.1	4.1	15.5	18.4
19	1.5	29.8	4.1	14.3	18.4
CALIBRATED STEADY-STATE WATER LEVELS	1.5	24.6	2.5	13.6	11.2

EXPLANATION
(For tables 4 and 5)

a – Description of simulations in Table 3.
b – See Fig. 1 for location of these sites.
c – Puerto Rico Land Administration.

Simulated Stresses and Responses

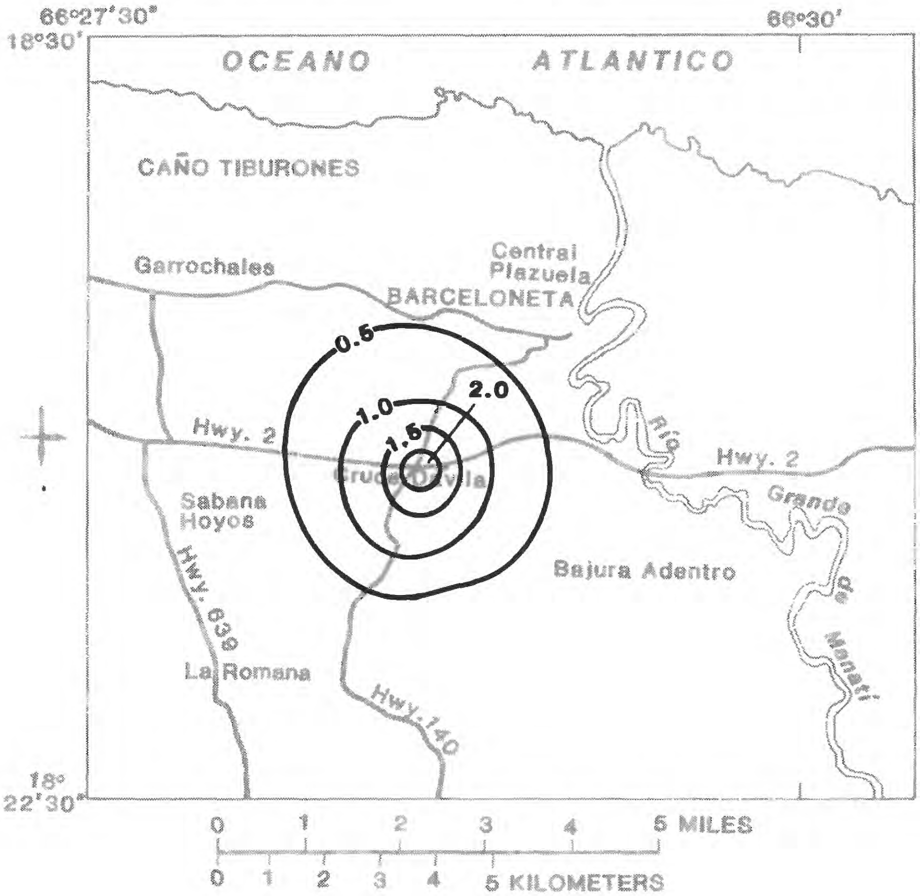
The Barceloneta model was designed to simulate the ground-water flow system and to determine the effects of additional ground-water withdrawals on the water-table altitude. Having accomplished a reasonable simulation of the ground-water flow system, various pumping scenarios were imposed on the model to analyze the effects of additional ground-water withdrawals.

As previously described, the proximity of the aquifer's physical boundaries, the relative low value of specific yield, and the high value of transmissivity of the limestones in the study area permits the ground-water system to reach steady-state conditions within 150 days from the start of any aquifer stress. The Theis non-equilibrium flow equation also indicates that production wells in ground-water systems similar to the Barceloneta area will probably attain about 95 percent of the head changes near the well within the first month of pumping.

Ground-water withdrawals as of 1982 (water-table aquifer) in the vicinity of Cruce Dávila were about 3.5 Mgal/d and totaled about 11 Mgal/d for the entire area. Several pumping scenarios were designed for the Cruce Dávila area (table 3, simulations 1, 2, 16, and 19) because it is the largest pumping center. In simulations 1 and 2 combined withdrawals of pumping wells 27, 29, 30, 31, 33, and 34 in Cruce Dávila area (fig. 9) were increased by 1 and 3 Mgal/d, respectively. Model results indicate that water-level declines of 1 to 2 feet will result for simulation 1 (fig. 24), whereas drawdowns of as much as 3 feet will occur from simulation 2 (fig. 25). Pumping tests conducted in wells 30 and 31, (Mar 15, 1982) duplicated pumping conditions of simulation 1. The drawdown measured, when pumping rate of well 31 was increased from 300 to 600 gal/min, was about 4 feet. This drawdown reasonably compares with the 2 feet predicted by the model. Better approximations could be obtained if model results were adjusted for well inefficiencies and partial penetration.

A line of hypothetical wells located along Highway 2 was used to simulate the maximum permissible pumpage from the aquifer prior to a reversal of the water-table gradient (table 3, simulations 3 to 8). Total discharge of the wells, in addition to existing pumpage as of February 1982 (11 Mgal/d), was varied from about 7 Mgal/d to about 29 Mgal/d. If ground-water withdrawals as of 1982 are increased by 7 Mgal/d (table 3, simulation 8), water-level declines in the Cruce Dávila area will be about 4 feet (table 4). If withdrawals are increased to 29 Mgal/d (table 3, simulation 7), water-level declines will be as much as 16 feet (fig. 26 and table 4).

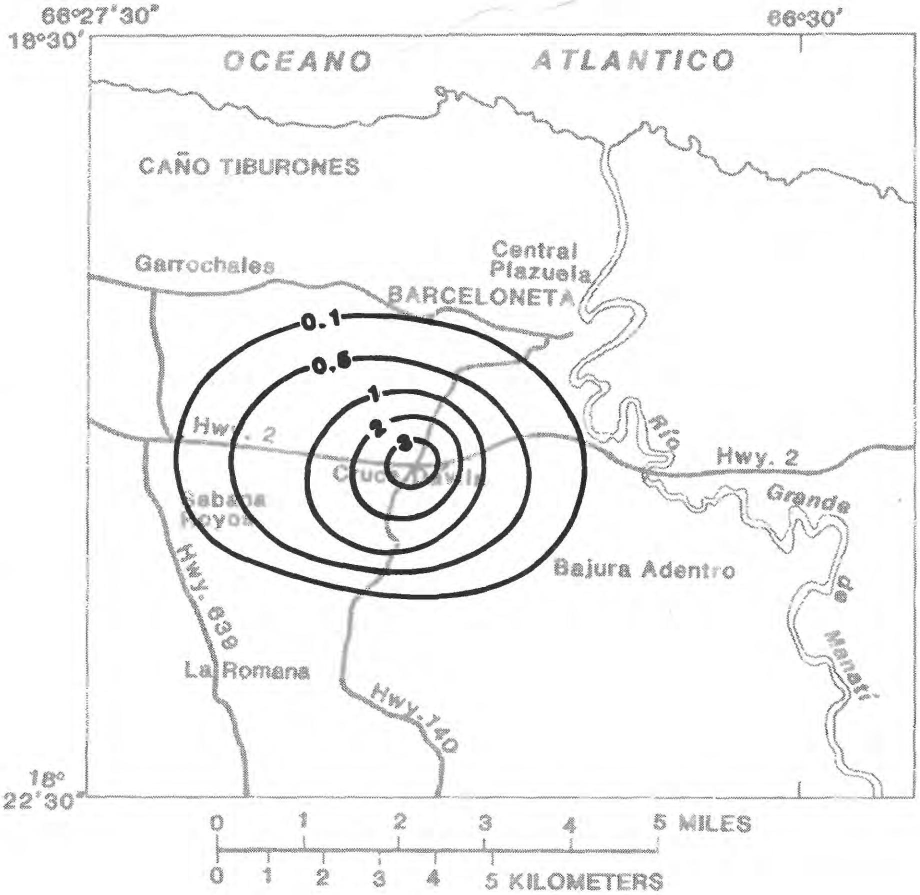
Simulations 10 to 15 (table 3) are related to the model-sensitivity analyses and were previously discussed. Simulations 9, 16, and 17 describe possible effects of water supply wells located east of the center of pumping at Cruce Dávila or in the valley of the Río Grande de Manatí.



EXPLANATION

——1.0—— **LINE OF EQUAL WATER-LEVEL DECLINE, IN FEET. Interval 0.5 feet.**

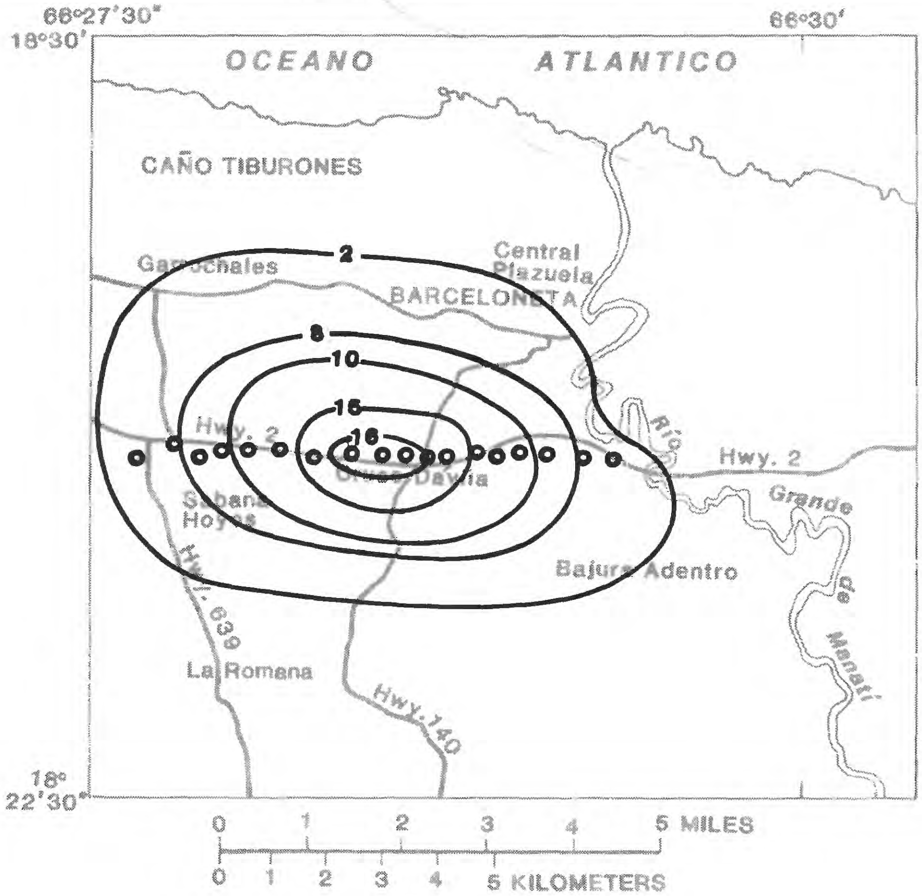
Figure 24.--Computed steady-state water-level declines in the water-table aquifer of Barceloneta for simulated ground-water pumpage increase of 1 million gallons per day (total pumpage 4.5 million gallons per day), Cruce Dávila area, 1982.



EXPLANATION

——3—— **LINE OF EQUAL WATER-LEVEL DECLINE, IN FEET. Interval variable.**

Figure 25.--Computed steady-state water-level declines in the water-table aquifer at Barceloneta for simulated ground-water pumpage increase of 3 million gallons per day (total pumpage 6.5 million gallons per day), Cruce Dávila area, 1982.



EXPLANATION

——15—— LINE OF EQUAL WATER-LEVEL DECLINE, IN FEET. Interval variable. Datum is mean sea level.

o SIMULATED HYPOTHETICAL WELL.

Figure 26.—Computed steady-state water-level declines in the water-table aquifer at Barceloneta for simulated ground-water pumpage increase of 3 million gallons per day at Cruce Dávila area and 14 million gallons per day along Highway 2, 1982. (Total pumpage 29 millon gallons per day.)

Simulated Stresses and Responses–Continued

The most significant result of the steady-state simulations is that in a dry year, when recharge from precipitation is less than normal, water-level declines in the Cruce Dávila area may result in increases in chloride concentrations at some wells. The model suggests that under existing ground-water withdrawals, water levels in the Cruce Dávila area could decline as much as 5 to 7 feet if rainfall conditions of 1957 (which were 65 percent of normal) are repeated. Water-quality data indicates that wells 20, 22, 25, 27, 28, 29, 30, 31, 32, 33, and 34 (fig. 9) would be most likely to be affected by salt-water upconing. For specific events such as this one, transient-state simulations are suggested to confirm the results of the steady-state simulations. To minimize the potential for salt-water intrusion in the Cruce Dávila area, pumpage of 6 Mgal/d or less would be desirable. Exceeding the 6 Mgal/d rate likely would increase the possibility of salt-water intrusion by upconing.

The steady-state simulations also indicate that ground-water discharges to Río Grande de Manatí and Caño Tiburones will be reduced significantly during dry periods and also by increases of ground-water withdrawals from the aquifer. In simulation 7 (table 3), where withdrawals as of 1982 were increased by 29 Mgal/d, ground-water flows to Caño Tiburones would cease as would flows in the Río Grande de Manatí downstream of Highway 2. Flow reductions of this magnitude will (1) affect potential freshwater use in the area, and (2) increase the saltwater encroachment problems in Caño Tiburones and lower parts of the river valley.

SUMMARY AND CONCLUSIONS

A two-dimensional finite-difference model was calibrated to simulate the steady-state ground-water flow in the limestone water-table aquifer near Barceloneta. The model can be used to simulate the effects on the aquifer of additional ground-water withdrawals from the area.

The proximity of the aquifer's physical boundaries, the relative low value of specific yield, and the high value of aquifer transmissivity of the limestones allow steady-state conditions to prevail in about 150 days, even after large ground-water withdrawals.

The model was calibrated to observed ground-water levels of February 1982. The model-computed heads were within 10 feet of the observed heads. Calibrated values of regional aquifer transmissivity in the Aguada were lower than values previously reported in the literature. For the Aymamón, the resulting calibrated values generally were higher. In the Aymamón, aquifer transmissivity in excess of 2,000,000 ft^2/d have been obtained where localized cavernous conditions exist. Solution conduits, however, were not considered in the steady-state regional ground-water flow analysis of the aquifer.

SUMMARY AND CONCLUSIONS–Continued

Recharge appears to be the most sensitive parameter in the model. Variations in recharge, from precipitation, will significantly affect the water levels in the aquifer and the flow in areas of natural ground-water discharge. Calibrated values of recharge were as much as 25 in/yr in the outcrop area of the Aguada Limestone. Simulation of a very intense drought (through limited recharge) would reduce significantly ground-water flows to the Caño Tiburones and Río Grande de Manatí. The amount of recharge occurring during any particular year, can be used to provide management guidelines (through control of pumpage) in reducing salt-water intrusion in the aquifer. In a dry year, for example, ground-water levels and withdrawals could be closely monitored to safely maintain the water levels in the aquifer above sea level.

Results of the simulations suggest that in order to minimize the potential of salt-water intrusion in the Cruce Dávila area, the present center of pumpage (1982), pumpage of 6 Mgal/d (an increase of 2.5 Mgal/d) or less would be desirable.

The maximum simulated pumpage, plus existing pumpage of 11 Mgal/d, based on a line of wells along Highway 2 was varied from 7 to 29 Mgal/d. Additional withdrawal of 7 Mgal/d would cause maximum water-level declines of about 4 feet. If withdrawals were increased by 29 Mgal/d, water-level declines will be as much as 16 feet and ground-water flow to the Caño Tiburones would cease, as would flow in the Río Grande de Manatí downstream of Highway 2. Saltwater encroachment problems would increase proportionately.

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