Geohydrology and Simulation of Ground-Water Flow in the Salinas to Patillas Area, Puerto Rico

By VICENTE QUIÑONES-APONTE, FERNANDO GÓMEZ-GÓMEZ, and ROBERT A. RENKEN

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per month (acre-ft/mo)	1,233	cubic meter per month
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.02832	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
mile per hour (mi/h)	1.609	kilometer per hour
million gallons per day (Mgal/d)	3.785	million liters per day
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	2.590	square kilometer
ton, short	0.9072	megagram

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

$$°F = 1.8 \times °C + 32$$

ACRONYMS USED IN REPORT:

CIRASA	Caribbean Islands Regional Aquifer System Analysis
ESSA	Environmental Science Services Administration
PRASA	Puerto Rico Aqueduct and Sewer Authority
RASA	Regional Aquifer System Analysis
USGS	U.S. Geological Survey

Geohydrology and Simulation of Ground-Water Flow in the Salinas to Patillas Area, Puerto Rico

By Vicente Quiñones-Aponte, Fernando Gómez-Gómez, *and* Robert A. Renken

Abstract

The conceptual model of the aquifer system in the Salinas to Patillas area in southeastern Puerto Rico was modified on the basis of new knowledge and a better definition of geohydrologic and hydraulic conditions. A three-layer ground-water-flow digital model was constructed and calibrated for the aquifer system in the Salinas to Patillas area. The finite-difference modeling technique was used. Predevelopment hydrologic conditions and the effects of water-resources development on the aquifer system from 1890 to 1986 were estimated using the model.

Simulations using the ground-water-flow model indicate a water budget of 43 cubic feet per second for predevelopment hydrologic conditions of the aquifer system. The development of surface-water resources from 1910 to 1960 for irrigation purposes affected the ground-water-flow system by increasing the aquifer's water budget to a maximum of about 126 cubic feet per second, three times the water budget of the aquifer system under natural predevelopment conditions. During 1986, the aquifer's water budget was higher than the predevelopment budget by a factor of two.

The sensitivity analysis was conducted on the ground-water-flow model using the relative sensitivity approach to determine the most relevant hydrologic and geohydrologic factors. This analysis indicates that recharge resulting from irrigation applications, rainfall, and streamflow infiltration through the upper river reaches are the most significant hydrologic factors. The most important hydraulic coefficients are the: hydraulic conductivity of model layer 2, consisting predominately of fan delta and deposits rich in sand and gravel; irrigation canal-bed conductance; transmissivity of model layer 3, which represents the regolith; horizontal anisotropy ratio of model layer 2; and vertical conductance between model layers 2 and 3. The conductance of the sea-face boundary is the most important boundary hydraulic coefficient. The evapotranspiration extinction depth is not an important factor. Altering the value of the streambed conductance for the lower river reaches, which were modeled as drains, results in highly variable head and flux changes.

INTRODUCTION

The U.S. Geological Survey (USGS) began the nationwide Regional Aquifer Systems Analysis (RASA) program in 1977, and in 1986 the Caribbean Islands RASA (CIRASA) study was initiated (Gómez-Gómez, 1987). In Puerto Rico, two major aquifer systems were included as part of this regional assessment: the North Coast Limestone aquifer system and the South Coastal Plain aquifer system. As part of the CIRASA program, a ground-water-flow model was developed for the aquifer contained within the Salinas to Patillas area of the South Coastal Plain aquifer system (fig. 1). Studies of the regional aquifer systems are needed to better understand ground-water flow in the principal aquifer systems in Puerto Rico, to define their hydrologic and geohydrologic characteristics, and to identify areas that require further field investigation.

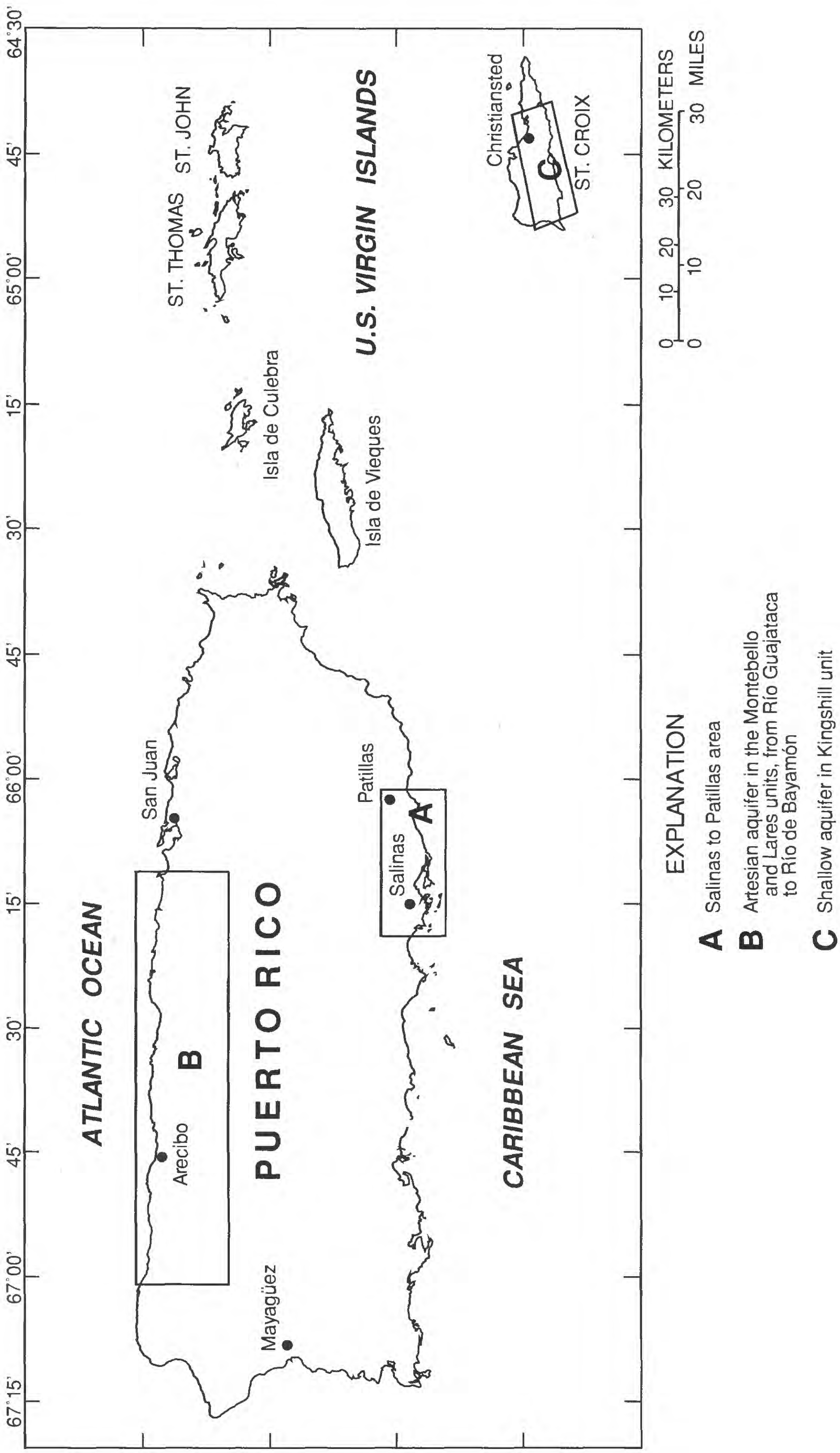


Figure 1. Location of areas modeled as part of the Caribbean Islands Regional Aquifer Systems Analysis.

Purpose and Scope

This report describes the geohydrology of the Salinas to Patillas area of the South Coastal Plain aquifer system (fig. 2) and documents the construction, calibration, and application of a three-layer digital ground-water-flow model. The geohydrology of the Salinas to Patillas area was described in terms of its physical and hydraulic characteristics. These characteristics included thickness, areal extent of the geohydrologic units, and areal variability of hydraulic conductivity values. The characteristics of the aquifer system were reevaluated with more recent data regarding the distribution of aquifer material and hydrologic boundaries.

A digital ground-water-flow model was developed using the MODFLOW computer code (McDonald and Harbaugh, 1988) to represent the aquifer system. Calibration of the digital model was based on the measured and estimated hydrologic conditions for March 1986, and testing was made by incorporating historical hydrologic, water-use, and water-level data from 1900 to 1986 under transient simulations. The model simulated predevelopment conditions (prior to 1890) and provided estimates of the effects of water-resources development on the aquifer system from 1890 to 1986. The model was analyzed for sensitivity to changes in the hydrologic variables and hydraulic coefficients. Model limitations and suggestions for further refinement are included in this report.

Description of Study Area

The Salinas to Patillas area is in the eastern part of the South Coast Ground-Water Province of Puerto Rico, about 28 mi east of Ponce in the South Coastal Plain (fig. 2). The study area extends from 1.5 mi west of Salinas to about 0.7 mi east of Patillas (fig. 2), covering about 196 mi^2. The South Coastal Plain is composed of a series of successive coalescing fan deltas that have an average width of 3 mi. Fan deltas are bordered to the north by intensely faulted low hills that progressively rise in altitude from about 60 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. Steep-gradient intermittent streams with relatively small drainage areas form the individual fan deltas. The coast along the Salinas fan delta is composed of mangrove swamps and tidal flats. Swamps and tidal flats also are present along the coast but are most predominant between Río Salinas (also known as Río Nigua) and Río Guamaní.

Sugar cane cultivation was the principal land use activity in the study area until the 1970's when pharmaceutical and petrochemical industries began operations near Guayama. The diversification of agricultural activities towards commercial production of fruits and vegetables and implementation of drip-irrigation has made agriculture one of the principal land-use activities again.

The mean annual rainfall in the South Coastal Plain is about 45 in. This is generally about 25 in. lower 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 on the northeast trade winds, which produces a rainshadow over the South Coastal Plain. Mean daily temperatures range from 19.5 to 32°C throughout the year. Local wind direction usually is from east to southeast and wind velocities are less than 7 mi/h (McClymonds and Díaz, 1972).

Previous Investigations

The geology of the Salinas to Patillas area is discussed in detail by Berryhill (1960), Berryhill and Glover (1960), Glover (1961a, 1961b), and Monroe (1976, 1980). McClymonds and Díaz (1972) conducted a preliminary appraisal of the water resources in the Salinas to Arroyo area. Bennett (1976) developed a regional-analog model of the South Coast Ground-Water Province. Heisel and González (1979) adapted Bennett's (1976) analog model into a hybrid digital-analog model, and used it to evaluate the water budget and the feasibility of increasing recharge by irrigation (spreading) or by injection of treated wastewater into the South Coast Ground-Water Province.

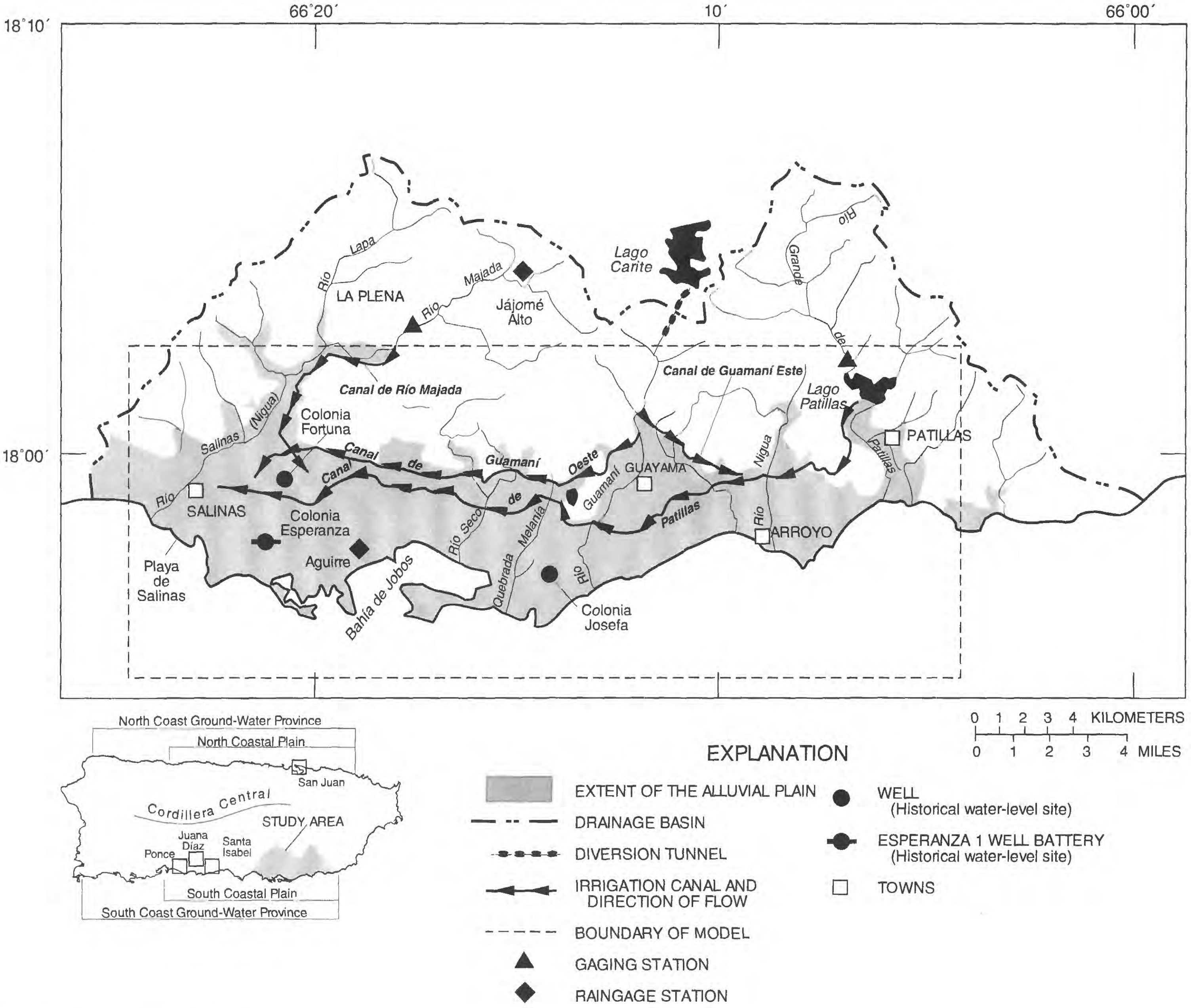


Figure 2. Location of study area.

Hydrologic Setting

The orographic effect of the Cordillera Central mountain range leads to hydrologic conditions typical of a semiarid region in the Salinas to Patillas area. The weather of the area is characterized by a relatively wet season from August through November and a relatively dry season from January through April. Results obtained by McClymonds and Díaz (1972) in their hydrologic analysis in the study area indicated that dry and wet seasons influence ground-water levels more significantly than pumpage. After heavy rains, runoff from the mountains reaches the South Coastal Plain and recharges the aquifer by infiltration through riverbeds. At the upper part of the fan deltas, the riverbeds are composed of coarse gravel that can transmit large amounts of water from streams to the aquifer system. About 5 to 12 percent of the rain in the South Coastal Plain is estimated to result in aquifer recharge (Giusti, 1971; McClymonds and Díaz, 1972; and Bennett, 1976).

Rainfall and Evapotranspiration

Rainfall records obtained since about 1930 indicate that the mean annual rainfall in the Salinas to Patillas area is about 40 in/yr and about 77 in/yr in the mountains. A significant change in the long-term trend in mean annual rainfall occurred during the first 30 years of the present century with an apparent decrease of about 12 in/yr, as interpreted from the 10-year moving average (MA_{10yr}) analysis of the data (fig. 3). The 10-year moving average is determined by applying equation 1 to the time-series data:

$$Y_i(MA_{10yr}) = \frac{(Y_{i-9} + Y_{i-8} + ... + Y_i)}{10}, \qquad (1)$$

where

Y is the mean annual rainfall value; and
i is 1,2,3,...10.

Evapotranspiration (ET) occurs from areas where the aquifer is shallow generally marginal to the coast. ET of 180 acre-feet per month (acre-ft/mo) from the shallow aquifer along the South Coastal Plain was

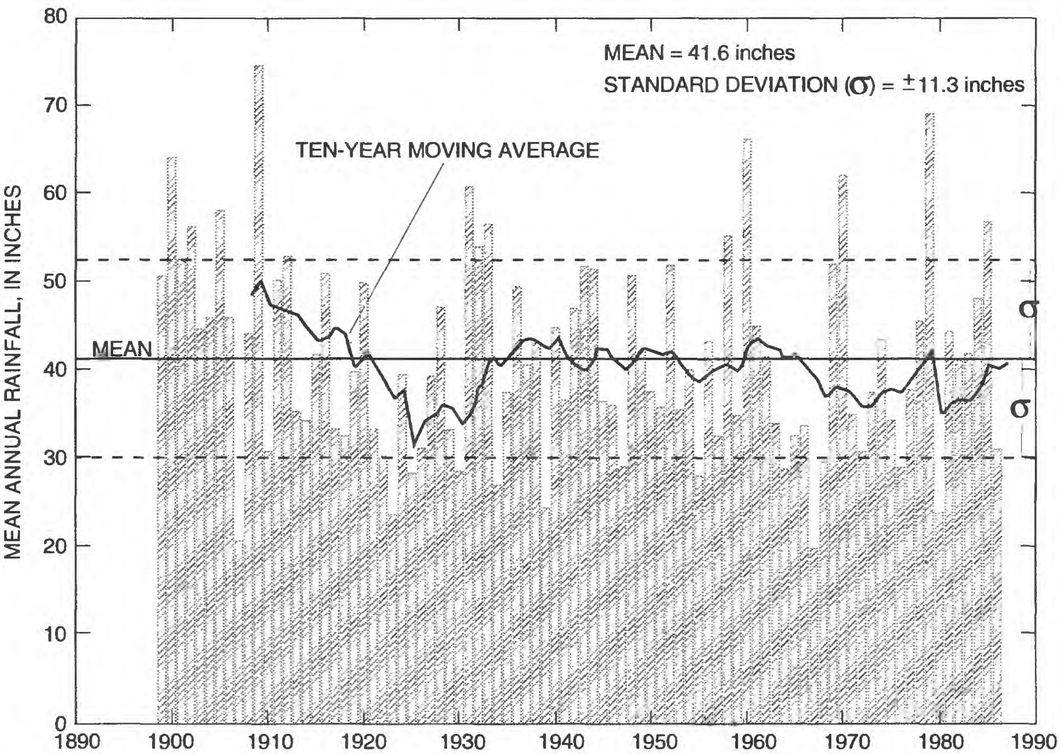


Figure 3. Historical rainfall data at Aguirre, Salinas, Puerto Rico, 1899-1987 (Environmental Science Services Administration, 1930, 1952; U.S. Department of Commerce, 1970).

estimated by Bennett (1976, p. 78) using an electric-analog model. This is equivalent to 2 in/yr, based on an area of about 19 mi^2 for the coastal swamps of the South Coastal Plain. Díaz (1976, p. 92) estimated ET from the shallow aquifer for wet and dry seasons to be 515 and 1,758 acre-ft/yr, respectively, using a high resolution grid spacing electric-analog model of the Guayama-Jobos area. These estimates are equivalent to about 3 and 10 in/yr, respectively. According to Bennett (1976), ET was a significant hydrologic factor throughout the South Coastal Plain until drainage canals were constructed and irrigation pumpage implemented. This caused a general lowering of the potentiometric surface to a position below the evapotranspiration extinction depth resulting in a reduction in ET.

Streamflow

The principal streams in the Salinas to Patillas area from west to east are the: Río Nigua (also known as Río Salinas), Río Seco, Quebrada Melanía, Río Guamaní, Río Nigua (at Arroyo), and Río Grande de Patillas (fig. 2). The Río Nigua at Salinas has the largest drainage basin, which covers 52.6 mi^2, and Quebrada Melanía has the smallest of only 4.6 mi^2 (table 1). The Río Nigua at Salinas is composed of two main tributaries, the Río Majada and the Río Lapa (table 1), and some smaller tributary streams. Water is exported across the insular hydrologic divide from Lago Carite (in the Río de La Plata Basin) to the Río Guamaní Basin (fig. 2). Almost all these streams loose their flow completely between the mid- and upper valley reaches as they enter the fan deltas.

Table 1. Hydrologic data for selected streams in the Salinas to Patillas area

[Mean annual precipitation estimated by Calvesbert (1970). mi^2, square mile; in., inch; ft^3/s, cubic foot per second]

Stream name and station No.	Drainage area (mi^2)	Mean annual precipitation (in.)	Mean annual base flow (ft^3/s)
Río Majada (50-100450)	16.7	65	[1]3.7
Río Lapa[2]	9.92	50	[3]2.2
Río Guamaní[2]	12.8	70	[3]2.9
Quebrada Melanía[2]	4.6	52	[3]1.0
Río Seco[2]	11.4	50	[3]2.5
Río Nigua at Arroyo[2]	5.8	65	[4]1.3
Río Grande de Patillas (50-92000)	29.0	85	[3]6.5

[1] Estimated from hydrograph in 1989.

[2] Not a formal gaging station site. Drainage area estimated for area contributing to the stream before or above the point where the stream enters into the coastal plain.

[3] Mean annual base flow estimated by multiplying the mean annual base flow to drainage area ratio for Río Majada by the drainage area of the given stream.

[4] Estimate based on similar calculation as in ([3]), but using drainage-area ratio for Río Grande de Patillas.

Field inspections and streamflow measurements indicate that stream courses usually maintain perennial flow downstream to the point where they enter the fan deltas. During a concurrent hydrologic investigation of the upper reach of the Río Nigua (the Río Salinas), it was estimated that the stream lost about 5 ft^3/s of flow in a short segment of its reach starting at about 6.2 mi upstream from the river's mouth (Ramos-Ginés, 1990). These highly permeable reaches usually coincide with streambeds composed of coarse gravel and boulders and occur where the underlying thickness of unconsolidated deposits increases abruptly due, possibly, to down-block faulting. The occurrence of down-block faulting in the Salinas to Patillas area has been documented by Renken and others (1991). This high streambed leakage indicates that streamflow plays an important role as a source of ground-water recharge. Most of these stream channels re-wet near the coastal reaches, and according to isotopic and water-quality data (Fernando Gómez-Gómez, U.S. Geological Survey, written commun., 1989), the return flow does not represent the same water previously infiltrated but, instead, local ground-water discharge.

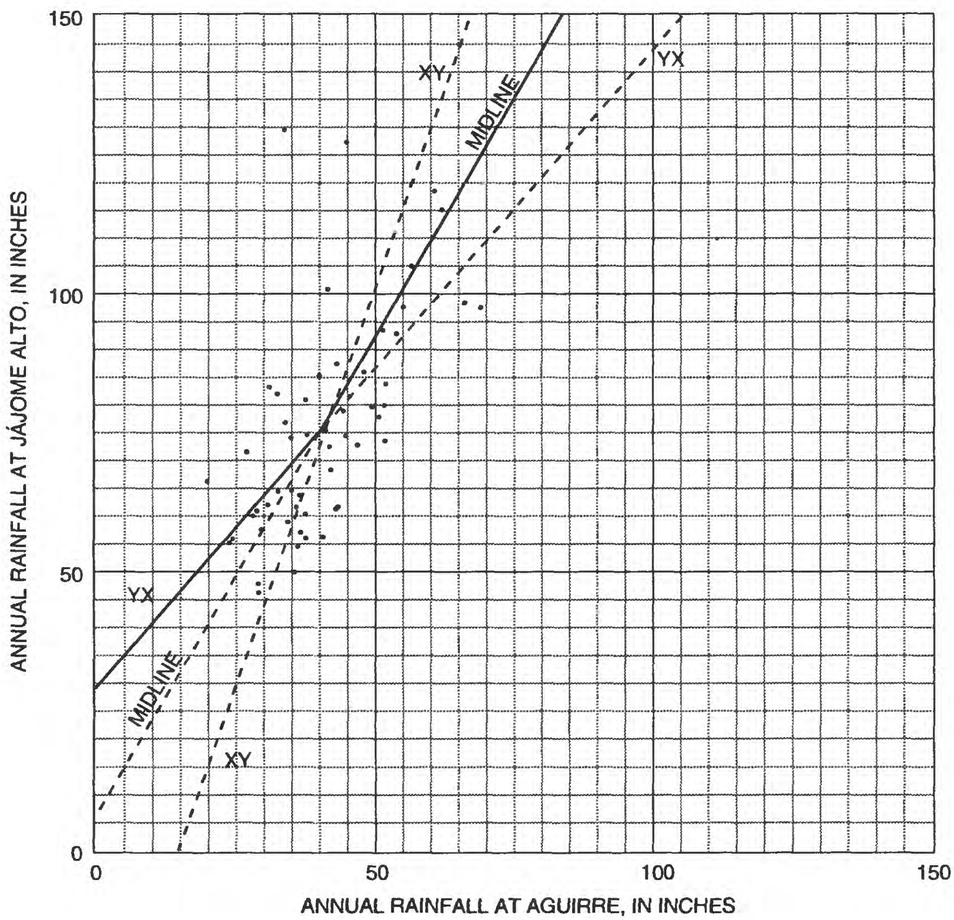
Synthetic streamflow data were generated for the Río Majada because its streamflow is a major source of recharge to the aquifer system and because a sufficient number of years of streamflow records are not available for a conventional streamflow analysis. To generate synthetic long-term (1899-1986), streamflow data for the Río Majada, it was necessary to estimate the long-term annual-rainfall trend at the Jájome Alto raingage in the Río Majada Basin. The computation of synthetic streamflows at the Río Majada at La Plena gaging station, requires synthetic annual rainfall data for the Jájome Alto raingage (fig. 2) from 1899 to 1930. The least-square linear regression technique was used to correlate annual rainfall data from the Aguirre raingage (period of record 1899-86) with data from the Jájome Alto raingage (period of record from 1930 to 1986). Although the relation between rainfall events at the two recording sites is probably not linear, a linear model was assumed sufficiently accurate as an estimate of mean annual runoff at the Río Majada at La Plena gaging station. Different linear models were generated (fig. 4); (1) *Y* on *X* (line *YX* in figure 4, *X* as the independent variable or abscissa and *Y* as dependent variable or ordinate), (2) *X* on *Y* (line *XY* in figure 4; *Y* as independent variable and *X* as the dependent variable or ordinate), and (3) the midline method (Cummings, U.S. Geological Survey, written commun., 1978), which is defined as the line that bisects the angle formed by the intersection of the regression lines of *YX* and *XY*. Here *X* represents annual rainfall at Aguirre and *Y* represents annual rainfall at Jájome Alto. The slope of the midline regression equation is:

$$b_{mid} = \tan\left[0.5\left(\tan^{-1}b_{YX} + \tan^{-1}b_{XY}{}^{-1}\right)\right], \qquad (2)$$

where

b_{mid} is the line that bisects the angle between regression lines *YX* and *XY*;
b_{YX} is the slope of the regression line *YX*; and
b_{XY} is the slope of the regression line *XY*.

Because the correlation coefficient (r=0.63) was judged to be a relatively poor correlation between annual rainfall at Aguirre and Jájome Alto, an optimization procedure was used in the linear models in order to produce the most accurate estimate possible. The optimization procedure was performed using the RMSD (root-mean-square difference):



EXPLANATION

Solid line represents regression model 4, which combines the upper part of model 3 with the lower part of model 1 (see table 2)

Figure 4. Regression curves for annual-rainfall data at Aguirre and Jájome Alto raingages (data from Environmental Science Services Administration, 1930, 1952, and U.S. Department of Commerce, 1970).

$$\mathrm{RMSD} = \left(\left(\frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{N}\right)\right)^{\frac{1}{2}}, \qquad (3)$$

where

Y_i is the measured annual rainfall;
$\hat{Y}_i$ is the estimated annual rainfall; and
N is the number of observations.

Five different combinations of the three regression models were tested producing RMSD values ranging from 15.27 to 23.54 (table 2). Models 1 (*YX*) and 4 (a combination of models 1 and 3, shown as a solid line in figure 4) produced the lowest RMSD, 15.27 and 15.56, respectively (table 2). Although model 1 produced the lowest RMSD, it also produced the most biased estimates for the higher values. Regression model 4 produced the least biased estimates for the entire data set (fig. 4). Synthetic annual rainfall data for the Jájome Alto raingage was computed (fig. 5*A*) from 1899 to 1930 using regression model 4. It showed a trend that, as expected, was similar to that observed at the Aguirre raingage (fig. 3).

A polynomial regression model was made on the basis of a correlation between monthly rainfall at the Jájome Alto raingage and the total monthly runoff at the Río Majada at La Plena gaging station (figs. 2 and 6), from October 1988 to September 1989. This polynomial regression model was used to construct a synthetic hydrograph for the Río Majada at La Plena from 1899 to 1987 (fig. 5*B*). The general streamflow trend of the Río Majada at La Plena was represented by the 10-year moving average of the synthetic records (fig. 5*B*). The trend was used for estimating river baseflow.

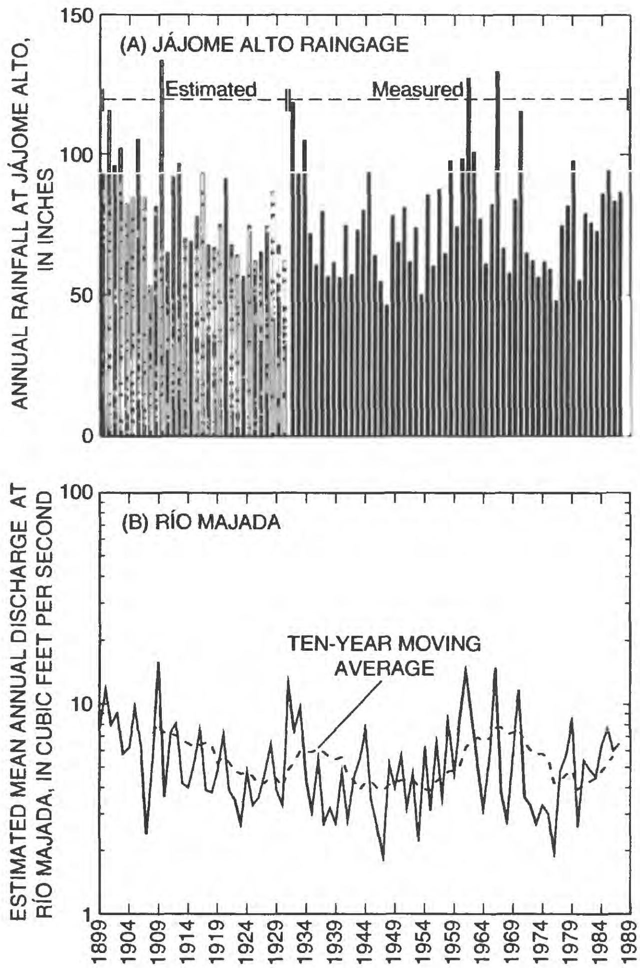


Figure 5. Measured and estimated rainfall at Jájome Alto and estimated discharge at Río Majada at La Plena.

Table 2. Linear regression models of annual-rainfall data from Aguirre and Jájome Alto raingages

[Data from the Environmental Science Services Administration, 1930; 1952; U.S. Department of Commerce, 1970. RMSD is root mean square difference; *YX* is regression model in which *X* is treated as independent variable while *Y* is treated as dependent variable; *XY* is regression model in which *Y* is treated as independent variable while *X* is treated as dependent variable; and MIDLINE is the line that bisects the angle formed by the intersection of regression lines *YX* and *XY*; <, actual value is less than value shown; >, actual value is greater than value shown; *, multiply by]

Model No.	Type	Regression equation	RMSD (inches)
1	*YX*	*Y*=29.73+1.14**X*	15.27
2	*XY*	*Y*=-40.87+2.85**X*	23.54
3	Midline	*Y*=6.19+1.71**X*	16.22
4	*YX* and Midline	model 1 for *X* < 40 model 3 for *X* > 40	15.56
5	*XY* and *YX*	model 2 for *X* < 40 model 1 for *X* > 40	19.91

History of Water-Resources Development

Reconstruction of the history of water-resources development in the Salinas to Patillas area is possible due to the availability of information in letters, internal reports, data summaries, and other unpublished documents that are under the custody of the Engineering Department of Central Aguirre Sugar Mill at Salinas (formerly known as Luce & Co.); the Puerto Rico Electric Power Authority, Guayama, Puerto Rico; and the Puerto Rico Aqueduct and Sewer Authority.

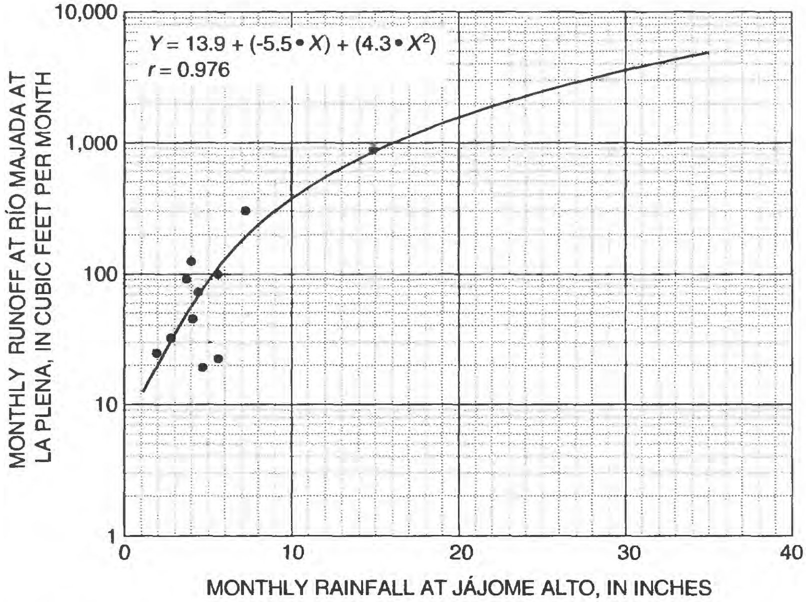


Figure 6. Regression curve for monthly rainfall at Jájome Alto raingage and monthly runoff at Río Majada at La Plena, 1988-89.

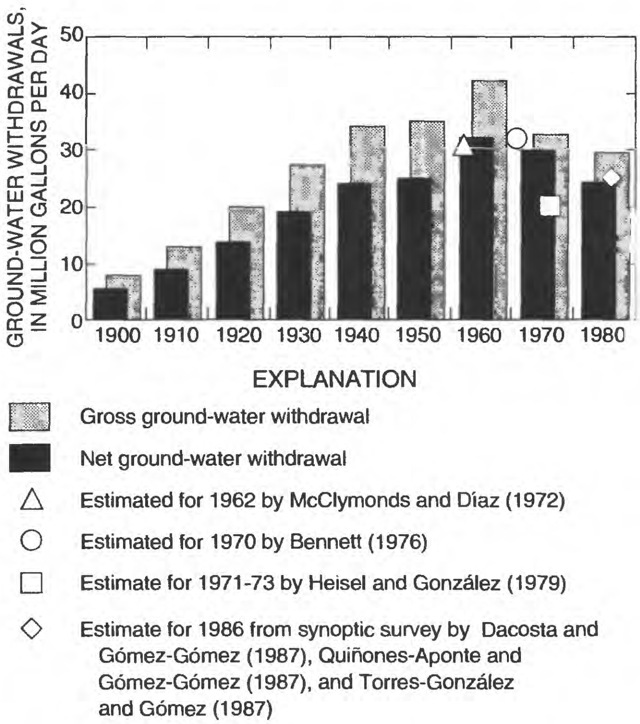


Figure 7. Estimated average ground-water withdrawals by decade from the Salinas to Patillas area.

The water resources of the Salinas to Patillas area have been continuously developed and the hydrologic conditions modified beginning with streamflow diversions, for irrigation purposes, by Spanish colonizers during the mid-19th century on relatively small acreage. Water for irrigation was routed from streams through small diversion canals that conveyed the water to farm fields by gravity. In 1861, the Lapa and Majada diversion canals began conveying water from the Río Lapa and the Río Majada (fig. 2) to farms located northeast of the town of Salinas. Both diversion canals had a maximum combined conveying capacity of about 13 ft^3/s (9,400 acre-ft/yr). As of 1986, only the Majada diversion canal was in operation with an estimated flow rate averaging about 1 ft^3/s (720 acre-ft/yr) from the Río Majada.

Steam-driven centrifugal pumps were used to withdraw water from the shallow part of the aquifer system during the first decade of the 1900's. This was the beginning of large-scale ground-water withdrawals from the South Coastal Plain of Puerto Rico. The historical development of ground-water withdrawals can be traced by the following: (1) improvements in pumps and ground-water withdrawal technology, (2) development of surface-water reservoirs and canals for irrigation purposes, (3) use of electricity to power pumps, and (4) expansion of sugar cane cultivation as the principal agricultural land-use activity throughout the entire South Coastal Plain.

Data from a well performance pumping test conducted on February 1, 1900, obtained from files of the Engineering Department of the Central Aguirre Sugar Mill, indicate that a well installed in Hacienda Carmen, 4,000 ft northeast of the town of Salinas, was supplying water to one of the first large-yield steam-driven pumps in the area. Other wells operated by steam-driven pumps were constructed from 1905 to 1910 in Colonias Fortuna, Esperanza, and Josefa, withdrawing about 8 million gallons per day (Mgal/d) (fig. 7). About 18 wells operated by steam-driven pumps were constructed during 1900-15. Those pumps withdrew ground water from well batteries at rates ranging from 500 to 2,700 gallons per minute (gal/min). Most of the steam-driven pumps consisted of a battery of several relatively shallow wells (depths less than 40 ft) connected by a header to a centrifugal pump typically sited in an excavated pit 20 ft below land surface. During the mid-1920's, the steam-driven pumps were replaced by more efficient kerosene-driven pumps and ground-water withdrawals increased to about 28 Mgal/d (fig. 7). In the 1930's, the kerosene-driven pumps were replaced by deep turbine pumps, operated by electric motors. This trend of increasing ground-water withdrawals continued to about 1947 when a campaign to reduce irrigation costs by controlling the pumpage of ground water was put into effect by the major irrigation company in the area (Luce and Co.), due to the high coast of electricity. From the late 1950's and early 1960's, submersible pumps also were installed as part of the implementation of the public-water supply system by the Puerto Rico Aqueduct and Sewer Authority (PRASA). Total ground-water withdrawals were then about 40 Mgal/d (fig. 7). Early in the 1970's, the local sugarcane industry registered a significant decline in sugar production which was paralleled by a reduction in ground-water withdrawals from about 42 to 33 Mgal/d (fig. 7). Net ground-water withdrawals shown in figure 7 represent 70 percent of the gross withdrawals because, according to previous investigations (Giusti, 1971; Bennett, 1976), 30 percent of the water applied as furrow irrigation returned to the aquifer by infiltration.

Large-scale use of surface water for irrigation in the Salinas to Patillas area started in 1914 with the beginning of water deliveries from the Patillas and Carite reservoirs (fig. 2). The initial deliveries from the two principal irrigation canal systems (Canal de Patillas and Canal de Guamaní) was about 65,000 acre-ft/yr of water to the agricultural areas. Prior to the use of these principal irrigation canals, no more than 10,000 acre-ft/yr of streamflow was diverted from the Río Majada and Río Lapa to agricultural lands in the Salinas area. A 10-year moving average of the water-deliveries data from the Canal de Patillas and Canal de Guamaní shows the following trends (fig. 8): (1) fairly steady rates of deliveries from 1914 to the mid-1930's (about 65,000 acre-ft/yr), (2) a decrease in delivery rates from the mid-1930's to late 1940's (from 65,000 to about 51,000 acre-ft/yr), (3) an increase from to the late 1940's to the late 1950's (from 51,000 to 61,000 acre-ft/yr) possibly related to the increasing cost of electricity as previously described, (4) a short steady period from the late 1950's to the mid-1960's (61,000 acre-ft/yr), and (5) a significant decrease from the mid-1960's to 1986 (from 61,000 to 32,000 acre-ft/yr) generally related to a decrease in sugarcane production.

The construction of a series of drainage canals and pumping stations in swampy areas was a significant modification to the hydrologic system. The drainage canals were constructed as a consequence of irrigation practices in the Salinas to Patillas area. The poor drainage characteristics of soils along the coastline, combined with surplus irrigation water, produced water-logging problems. Late in the

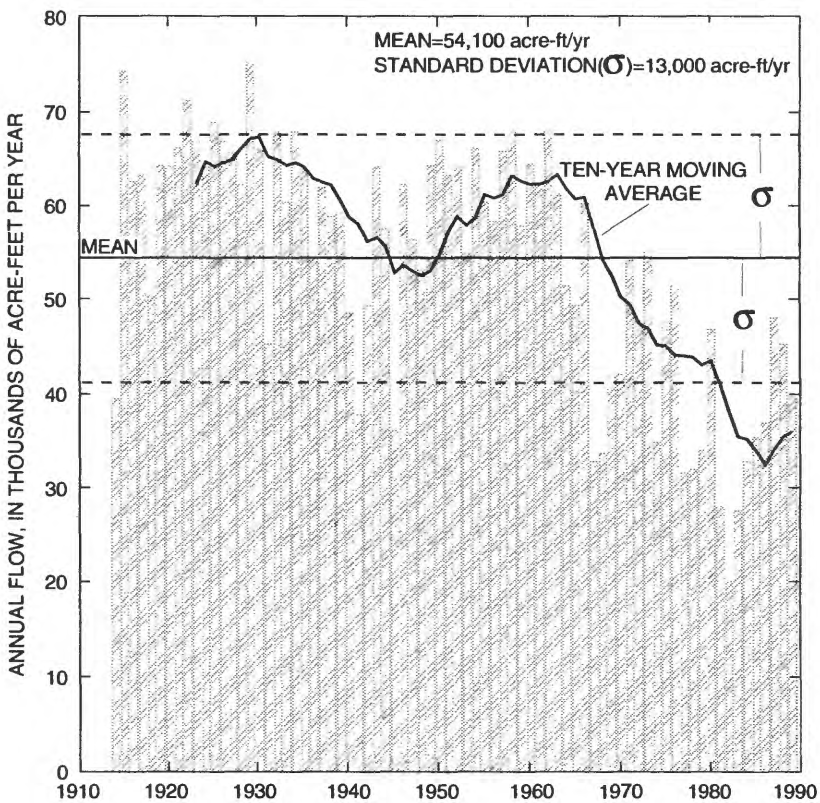


Figure 8. Total irrigation water released from Canal de Patillas and Canal de Guamaní, 1914-89. (Data from the Puerto Rico Electric Power Authority, formerly Puerto Rico Water Resources Authority, unpublished files.)

1930's, a network of drainage canals was installed through the swampy areas of the South Coastal Plain to recover land for agriculture. In the Playa de Salinas community, drainage pump stations were installed to control the water-table altitude and avoid the formation of swamps in an effort to control the spread of malaria.

During the 1970's, ground-water withdrawals increased by about 3 Mgal/d in the area southwest of Guayama for industrial purposes. Also, the Aguirre thermoelectric powerplant at Salinas increased ground-water withdrawals to about 1.5 Mgal/d.

Changes in crop type, primarily with the decrease in sugarcane production and increase in vegetable crops, also have modified ground-water withdrawal patterns. Drip irrigation is being implemented at some farms in the Salinas to Patillas area. Drip irrigation diminishes recharge to the aquifer by nearly the total amount applied in this fashion (Yamauchi, 1984). Under the present furrow irrigation methods, only about 30 percent of the total applied water in the Salinas to Patillas area recharges the aquifer.

Geologic and Physiographic Setting

In their preliminary appraisal of the water resources of the Salinas to Patillas area, McClymonds and Díaz (1972) separated the study area into two principal physiographic regions; low foothills, and the Cordillera Central mountain range rising to nearly 3,000 ft above mean sea level and forming the insular drainage divide. These highland areas are underlain by a highly faulted sequence of volcanic breccia, lava, volcanogenic sandstone and siltstone, minor limestone, and local igneous intrusive and hydrothermally altered rocks of Cretaceous to lower Tertiary age (fig. 9). These older

SYSTEM	SERIES		GEOLOGICAL UNIT	GEOHYDROLOGICAL UNIT	MODEL LAYER
Quaternary	Holocene		Mangrove swamp, beach, tidal and supratidal flat deposits	Shallow coastal water table and confining clay	Model layer 1
	Pleistocene		Fan-delta and alluvial deposits	Principal flow zone (unconsolidated deposits)	Model layer 2
Tertiary	Pliocene		Alluvial deposits infilling graben structures		
	Miocene	Upper			
		Middle			
		Lower	Volcanic, volcaniclastic, siltstone, minor limestone, and igneous rocks of Cretaceous to Tertiary age	Regolith	Model layer 3 (unknown thickness)
	Oligocene	Upper			
		Middle			
		Lower			
	Eocene				
	Paleocene				
Cretaceous	Upper				
	Lower				

Figure 9. Relation of geologic and geohydrologic units and model layers (R.A. Renken, U.S. Geological Survey, written commun., 1993).

rocks extend southward toward the coast beneath a low-lying coastal plain of unconsolidated to poorly consolidated boulder, cobble, pebble, sand, silt, and mud deposits. A weathered bedrock (regolith) of silty clay and silty limestone locally separates older rock from the younger, overlying deposits (fig. 9).

A series of coalescing alluvial fan deltas form the coastal plain and are largely of Quaternary age, but could be of Miocene age where the deltas lie in the deeper subsurface (fig. 9). The deltas are characterized by a fan-like shape and are separated from the Caribbean Sea by a narrow transitional zone of marsh, mangrove swamp, beach, tidal, and supratidal flat deposits. Local bedrock hills protrude above the alluvial cover near the foothills and in one coastal locality near the Central Aguirre sugar mill.

An understanding of local and regional tectonics and depositional patterns has proven useful in explaining the variation in thickness of the fan-delta sequence and the pattern of lithofacies (Renken and others, 1990) (fig. 10). Sand-and-gravel percentage lithofacies maps show that a coarse-grained facies of sand- to boulder-sized material extends coastward from the fan apex as a narrow channel from the highlands and spreads out in mid-fan areas (fig. 10). The thickest fan-delta deposits occur in infill cross-cutting graben structures. The pattern of these grabens and associated horst structures (fig. 11) probably is related to the divergence and convergence of parallel to subparallel strike-slip faults that are part of the Great Southern Puerto Rico Fault zone (Glover, 1971). R.A. Renken (U.S. Geological Survey, written commun., 1993) said the "Horst and graben fault blocks, formed by movement along the great southern Puerto Rico fault zone, were subjected to subaerial erosion, then buried and preserved as a series of paleotopographic ridges and valleys." They also mentioned that structure and paleotopographic "Highs and lows may not necessarily correspond." In much of the study area, the thickness of the fan-delta sequence is less than 100 ft. The deposits are thicker coastward, reaching maximum depths beneath the coast at Salinas fan delta where they could exceed 200 ft (fig. 11).

GEOHYDROLOGY

The geohydrologic characteristics of aquifers in the South Coastal Plain vary considerably. In the Salinas to Patillas area, the lithology is a key factor in defining the aquifer system and, for model simulation purposes, it can be simplified and represented by three lithologic sequences. These sequences form distinct geohydrologic units (fig. 9): (1) the shallow water table and confining clay geohydrologic unit (shallow coastal water-table aquifer) composed of sand, gravel, and clay; (2) the principal ground-water-flow zone geohydrologic unit (principal flow zone) composed of fan deltas and alluvial deposits; and (3) the regolith geohydrologic unit (regolith) composed of weathered bedrock of varied types. The shallow coastal water-table aquifer extends areally from Río Nigua (of Salinas) to Río Guamaní, is not present in the Guayama area, and is again present along the Arroyo fan delta. This geohydrologic unit is present along the coastline extending from 1 mi (at Bahía de Jobos) to 4 mi (in the Salinas fan delta) inland. The shallow coastal water table and confining clay unit is present from the land surface to about 75 ft below land surface, along the coastline, and from 10 to 40 ft below land surface along its northern limit. The thickness of the confining clay occurring at the lower section of the geohydrologic sequences could be as much as 40 ft. The shallow coastal water-table aquifer is not important as a ground-water source, supplying water only to some domestic wells with yields ranging from 5 to 10 gal/min.

The principal flow zone represents the main geohydrologic unit and its areal extent can be closely traced by the shaded areas in figure 10, which are areas in which unconsolidated deposits are present. The thickness of the principal flow zone is highly variable and is mainly determined by the position of horst and graben structures (fig. 11). The principal flow zone could be as much as 350 ft thick in the southeast part of the Salinas fan delta where the structural floor is about 400 ft below mean sea level (fig. 11). The principal flow zone is the most productive aquifer zone in the Salinas to Patillas area providing water for most agricultural, industrial, and public water-supply wells in this area. Wells tapping the principal flow zone can yield water at rates ranging from 100 to 2,700 gal/min.

The regolith composes the lower geohydrologic unit and its top is defined by the position of the horst and graben structures (fig. 11). It occurs in the upper section of the bedrock structure, where many fractures have accelerated the weathering process. The regolith crops out along the northern border of the alluvial deposits. Few wells withdraw water from this geohydrologic unit exclusively and those that do yield an average of about 100 gal/min.

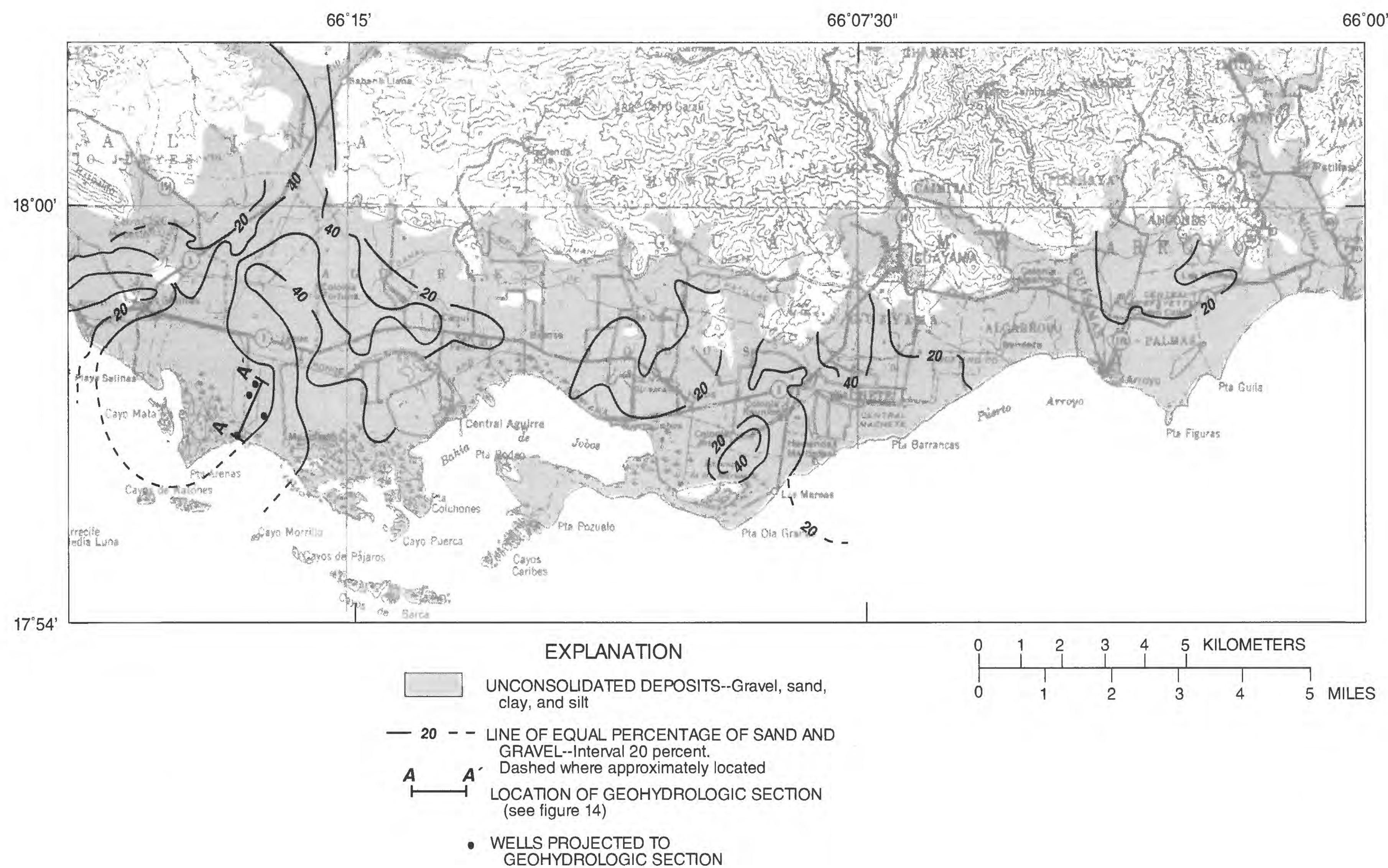


Figure 10. Unconsolidated deposits and percentage of sand and gravel distribution in the Salinas to Patillas area (modified from Renken and others, 1991).

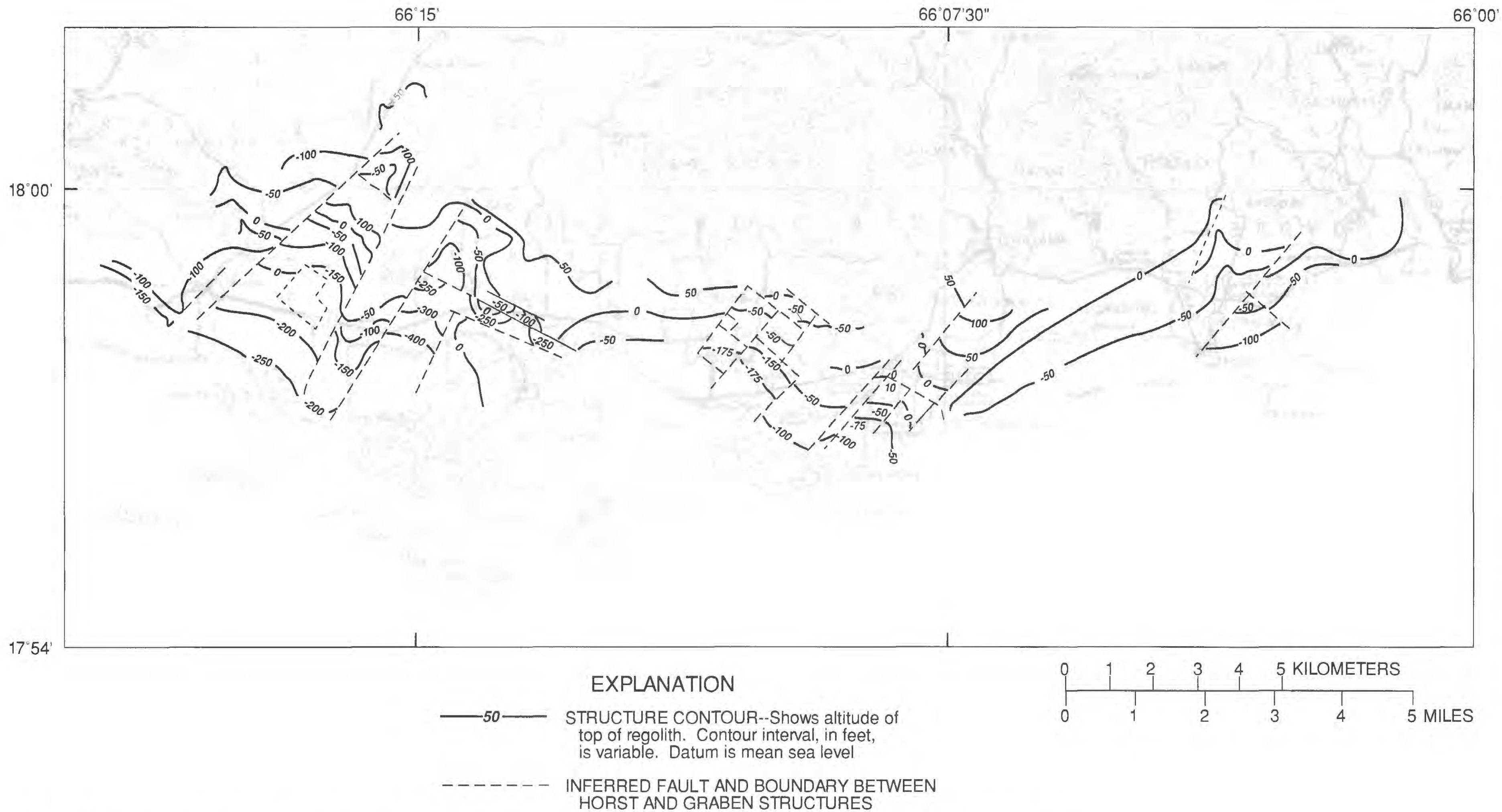


Figure 11. Generalized top of regolith and inferred faults in Salinas to Patillas area. (Modified from Renken and others, 1991).

For purposes of analysis, the aquifer system consisting of these three geohydrologic units in the Salinas to Patillas area can be divided into six independent aquifer subsystems based on local geohydrologic characteristics. These subsystems can be classified into three groups.

The first aquifer group includes the Salinas fan delta, the Jobos area, and the Arroyo fan-delta subsystems. The aquifers in these areas fill structurally low areas. The aquifers are confined near the coast by a fine-grained, poorly permeable clay or silt bed (from 5- to 45 ft thick) ranging in altitude from 5 ft above mean sea level to 25 ft below mean sea level. This confining unit extends almost continuously along the coast and as much as 2 mi inland. Fan-delta and alluvial deposits below the confining unit constitute the principal flow zone of the aquifer group and contain water under confined conditions. However, this principal flow zone extends to the upper part of the fan deltas where ground water occurs under unconfined conditions. A weathered regolith lies beneath the principal flow zone.

The second aquifer group is represented by a single subsystem in the narrow Patillas Valley, an alluvial valley that extends south towards the coast. In this valley, the aquifer consists of fine to coarse sand, pebbles, and cobbles, and is 30 ft thick and less than 0.6 mi wide. The principal flow zone in this aquifer is about 20 ft thick and is confined. The maximum well yield in this aquifer is about 500 gal/min.

The third aquifer group is characterized by structurally high areas where the alluvial cover is thin. Two subsystems are present; one in the Bahía de Jobos area between Barrio Coqui and Barrio Villodas, and the other in the Guayama area between Río Guamaní to Quebrada Corazón. In both of these subsystems, the principal flow zone is a thin water-bearing zone (about 10 ft thick) consisting of weathered bedrock or alluvial material underlying clayey deposits (50 ft thick). The aquifers in this third group are confined and well yields probably do not exceed 100 gal/min.

Hydraulic Characteristics

This section provides a description of the hydraulic characteristics of the aquifer, which include: transmissivity, hydraulic conductivity, storage coefficient, specific yield, and horizontal and vertical anisotropies. The transmissivity of the fan-delta deposits is greatest (about 70,000 ft^2/d) where thick alluvial deposits fill graben structures. The transmissivity of these deposits, first studied by McClymonds and Díaz (1972), has been reevaluated by Fernando Gómez-Gómez (U.S. Geological Survey, written commun., 1987), who used drillers logs and specific-capacity data from more than 130 wells to determine the areal distribution of hydraulic conductivity. Although areal variations in transmissivity present an overall view of the hydraulic properties of the aquifer system, the hydraulic conductivity provides a better representation of the hydraulic characteristics of this aquifer system because of the irregular thickness of permeable deposits in the Salinas to Patillas area. A map showing the distribution of hydraulic conductivity in the fan-delta and alluvial deposits of the principal flow zone was constructed (fig. 12). Hydraulic conductivity values for aquifers in the Salinas to Patillas area range from 1 to 550 ft/d. The higher values occur in the principal flow zone geohydrologic unit in the Salinas fan (fig. 12). Data from 104 wells were used as control points to construct the hydraulic conductivity map. In general, the distribution of hydraulic conductivity (fig. 12) compares well with the previously presented map showing percentage of sand and gravel distribution (fig. 10).

Quiñones-Aponte (1989) estimated a storage coefficient of 0.0003 from an aquifer test conducted in the southeastern corner of the Salinas fan. This storage coefficient value represents confined conditions that occur in the lower fan areas along the coast. A layer of clay at about 35 ft below land surface confines the aquifer in this area. Specific yield of about 0.25, representative of unconfined conditions in the principal flow zone unit, is assumed for the upper fan-delta areas where the confining unit is nonexistent.

The aquifer test in the southeastern corner of the Salinas fan also revealed an apparent horizontal anisotropy ratio of 1.62 to 1.00, with the major principal transmissivity axis oriented north 28° west (Quiñones-Aponte, 1989). Bennett and Giusti (1971) estimated a vertical to horizontal anisotropy ratio of 1:1,000 for the Ponce area (15 mi west of Salinas), which has geohydrologic conditions similar to those of the Salinas to Patillas area.

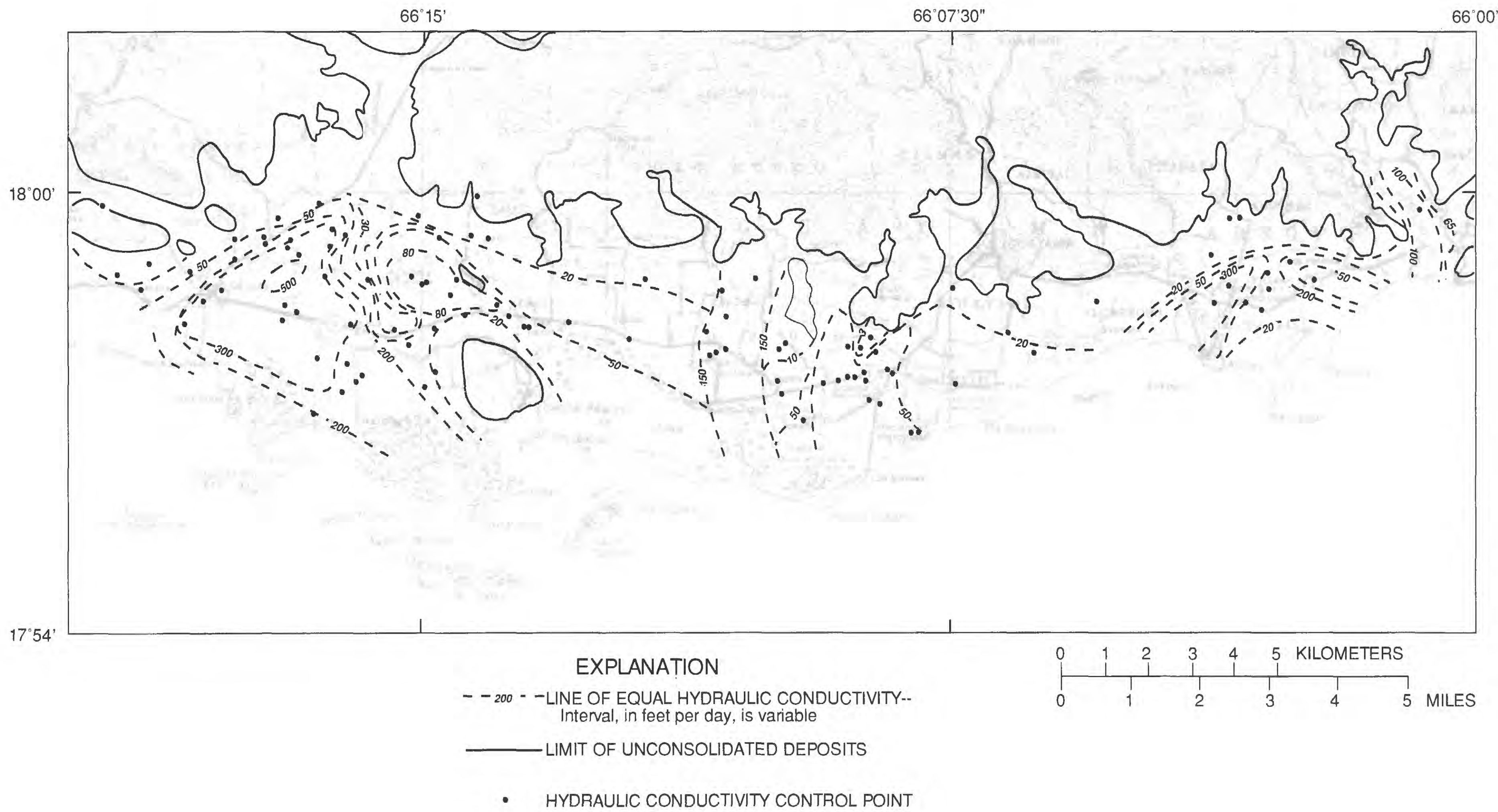


Figure 12. Generalized distribution of hydraulic conductivity of the fan-delta and alluvial deposits in the principal flow zone, Salinas to Patillas area.

Ground-Water-Flow Patterns

According to the configuration of the potentiometric surface (Dacosta and Gómez-Gómez, 1987; Quiñones-Aponte and Gómez-Gómez, 1987; Torres-González and Gómez-Gómez, 1987), ground-water flow in the Salinas to Patillas area closely follows the topographic patterns. A cone of depression has formed in the Central Aguirre area because of pumpage from a well field that lies to the north. In 1986, these wells pumped about 5 Mgal/d (Torres-González and Gómez-Gómez, 1987). Under current hydrologic conditions, recharge to the aquifer system comes from streamflow seepage near the fan apex, rainfall, irrigation canal seepage, and return flow from areal furrow irrigation applications. Stream seepage to the aquifer system 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. Based on hydrologic investigations in other areas of Puerto Rico, it is estimated that long-term recharge from rainfall in the Salinas to Patillas area is from 2.00 to 5.40 in/yr, which is from 5 to 12 percent of the mean annual rainfall, respectively. About 30 to 50 percent of the water, used for irrigation percolates into the principal flow zone of the aquifer system (McClymonds and Díaz, 1972, p. 14). Recharge to the regolith geohydrologic unit (fig. 9) occurs in the hills and at the foot of the mountains in the northern part of the study area. Some water can be induced into the principal flow zone by pumpage from the lower regolith and the shallow water table (through the leaky confining clay). Ground-water discharge occurs principally to wells, by way of diffuse upward leakage to springs and swamp areas, to lower river reaches, and to the seabed. Discharge from the regolith geohydrologic unit occurs to some wells, to the fan-delta and alluvial deposits (principal flow zone), and to the sea.

SIMULATION OF GROUND-WATER FLOW

A computer-based model was constructed and used to conduct simulations of ground-water flow in the aquifer system in the Salinas to Patillas area. The model was used to test the sensitivity of the aquifer system to changes in various hydrologic and geohydrologic factors to determine the relative importance of each factor. Different boundary conditions also were tested. The model also was used to estimate the predevelopment conditions of the aquifer system and to evaluate the effects of the historical water-resource development operations on the water budget of the aquifer system. Some of the original concepts used by Bennett (1976) in his electric-analog model of the aquifer system were incorporated into this model, and other concepts were modified on the basis of new data.

The MODFLOW modular finite-difference code by McDonald and Harbaugh (1988) was used to approximate the quasi-three-dimensional constant density, horizontally isotropic and heterogeneous ground-water-flow equation for the Salinas to Patillas area digital model. For unconfined conditions, the following equation is represented:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h^2}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h^2}{\partial y}\right) \pm L_E \pm W = S_y\frac{\partial h}{\partial t} \qquad (4a)$$

and for confined conditions:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) \pm L_E \pm W = S_s\frac{\partial h}{\partial t} \qquad (4b)$$

where

K_{xx} and K_{yy} are the hydraulic conductivity along the x and y coordinate axes, assuming the axes are parallel to the major axes of hydraulic conductivity (LT^{-1});

h is the potentiometric head (L);

L_E is the vertical leakage term and represents flow across the layers interface or confining units (per LT^{-1});

W is a volumetric flow per unit volume and represents sources and/or sinks of water (T^{-1});

t is time (T);

S_y is the specific yield of the aquifer matrix;

T_{xx} and T_{yy} are the transmissivity along the x and y coordinate axes, assuming the axes are parallel to the major axes of transmissivity (L^2T^{-1}); and

S_s is the specific storage of the aquifer matrix (L^{-1}).

Equations (4a and 4b) are solved by a finite-difference approximation technique using a backward-difference scheme (McDonald and Harbaugh, 1988). The strongly implicit procedure is used to solve the system of finite-difference equations by matrix algebra (McDonald and Harbaugh, 1988).

Model Conceptualization and Construction

In the conceptual model, three model layers are used to represent the geohydrologic units that form the aquifer system in the Salinas to Patillas area (fig. 9). The top layer (model layer 1) represents the shallow coastal water-table aquifer that occurs from 20 ft above to 20 ft below mean sea level. A thin clay unit underlies the water-table aquifer, partially isolating it from the lower principal ground-water-flow zone. The altitude of the top of the clay unit ranges from 20 to 50 ft below mean sea level throughout the area. Water can leak through the clay unit from the shallow coastal water-table aquifer downward to the principal flow zone, or in the opposite direction, but the confining clay unit controls the rate of leakage.

Model layer 2 represents the principal flow zone which consists of fan-delta and alluvial deposits. The principal flow zone occurs from 40 to 140 ft below mean sea level and constitutes the most important geohydrologic unit in the aquifer system. The principal flow zone has a large range of variation in hydraulic conductivity that is associated with the areal distribution of sand and gravel, which was controlled by the dynamics of fan-delta and alluvial geomorphological

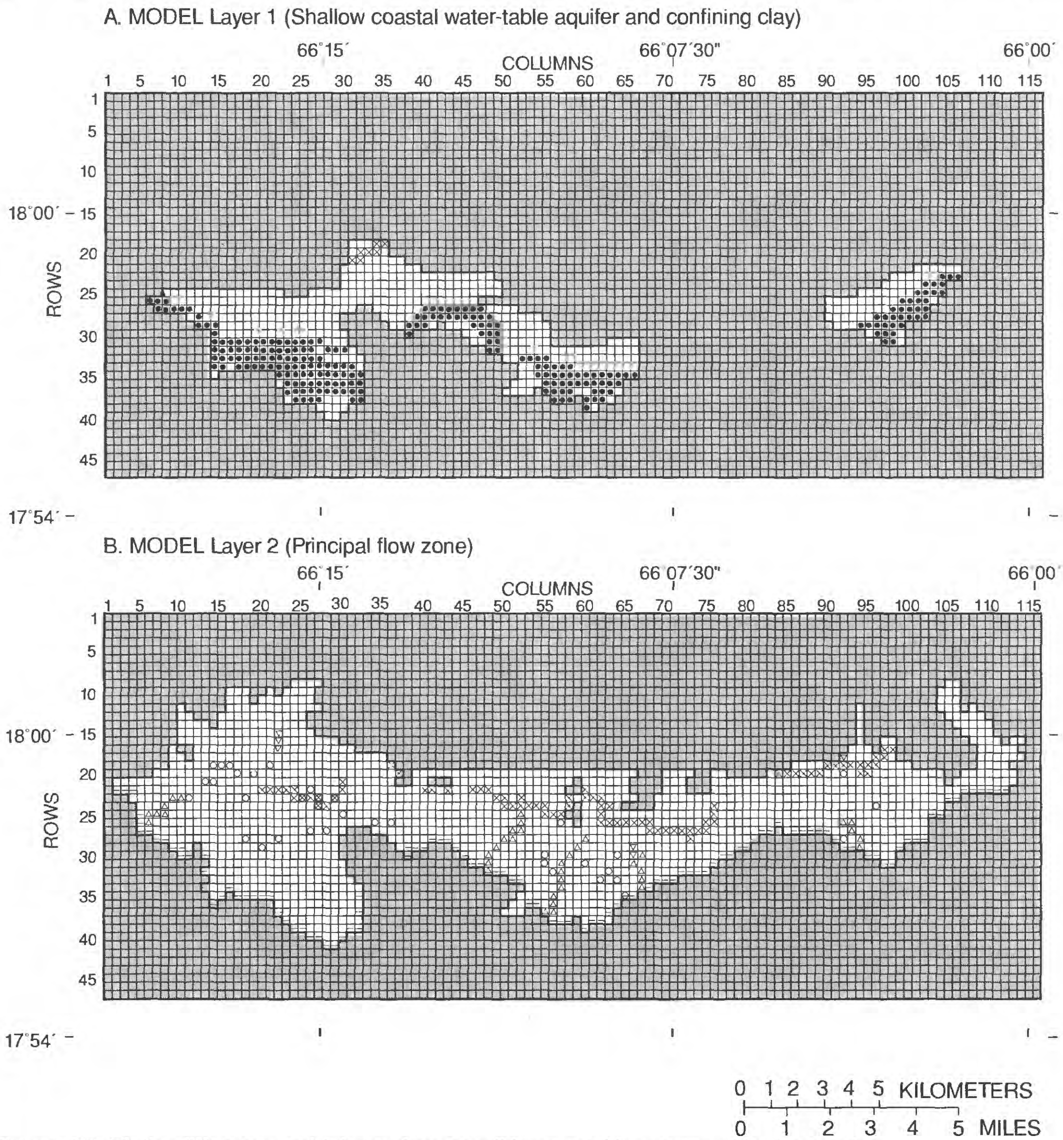


Figure 13. Finite-difference grid, boundary conditions, and layers used in the model.

processes. The principal flow zone crops out in the central and northern parts of the coastal plain. At its bottom, the principal flow zone is bounded by regolith.

The regolith is represented in the model by model layer 3. The thickness of the regolith is unknown, but it is apparently highly fractured in the subsurface and crops out in the northern part of the study area.

In the model, areal recharge to the aquifer system is represented by rainfall and irrigation water infiltration through the outcrops of the regolith and principal flow zone geohydrologic units. Streamflow infiltration in the upper river reaches and seepage from irrigation canals also are represented in the model. Discharge from the aquifer system is represented in the model as: (1) pumpage from wells tapping the principal flow zone and the regolith, (2) ET, drains, swamps, and springs in the shallow coastal water-table aquifer, (3) seepage to the lower stream reaches, and (4) leakage to the seabed through the boundaries of the principal flow zone and the regolith.

A grid was constructed covering an area of 196 mi^2 and consisting of 47 rows, 116 columns, and three layers (fig. 13). All the rectangular cells have sides of 1,000 ft. The boundaries and flow components of the model are different for each layer (fig. 13).

Model layer 1, the upper layer, contains 533 active cells covering an area of 19 mi^2 along the coastal plain, mainly less than 3 mi of the shoreline (fig. 13*A*). In general, the shallow coastal water-table aquifer and underlying clay unit occur within the first 50 ft below land surface. However, near the shoreline this unit is present at as much as 80 ft below land surface (fig. 14). The extent of the shallow coastal water-table aquifer and the clay unit was delineated with the aid of soil survey maps showing the outcrop locations of these clay units (Boccheciamp, 1977).

The lateral boundaries of model layer 1 coincide with the lateral extension of this geohydrologic unit and are simulated as no-flow boundaries. An initial estimate of hydraulic conductivity of 20 ft/d was used for the shallow coastal water-table aquifer. The vertical

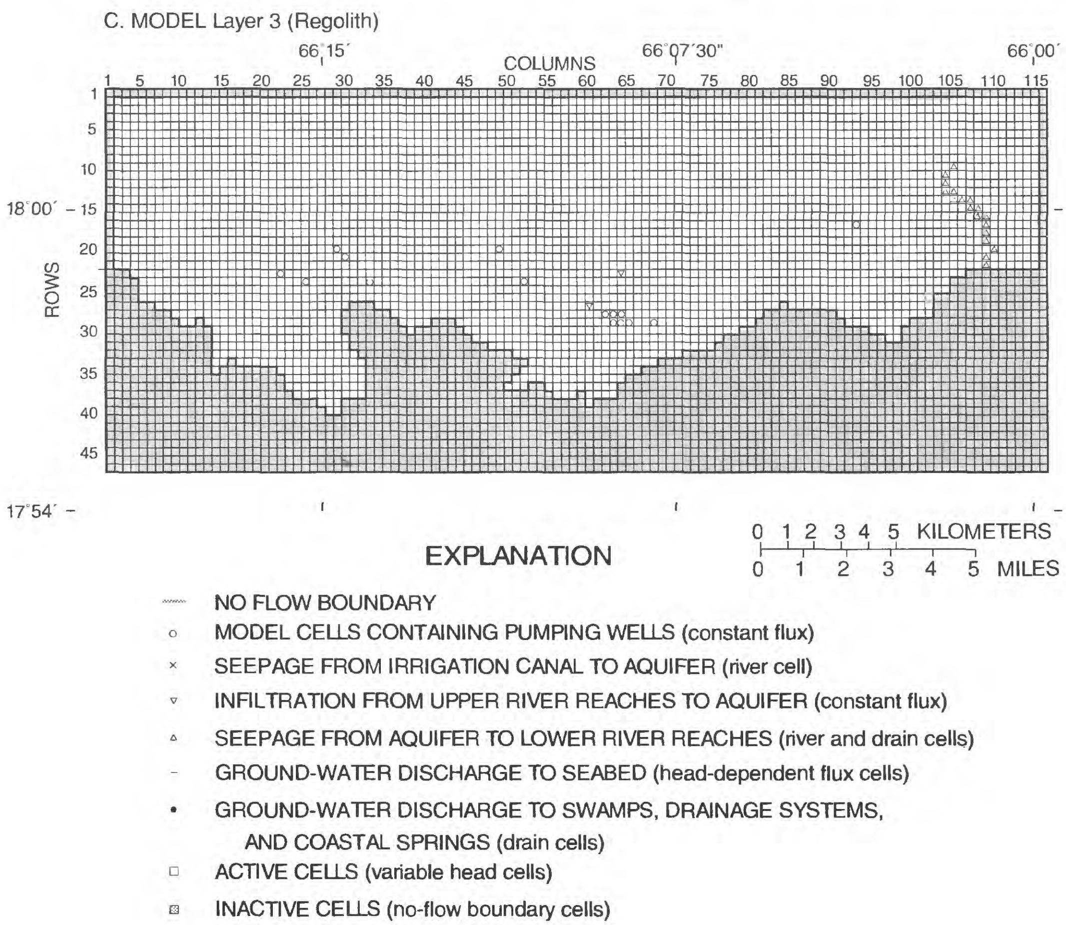


Figure 13. Finite-difference grid, boundary conditions, and layers used in the model—*Continued.*

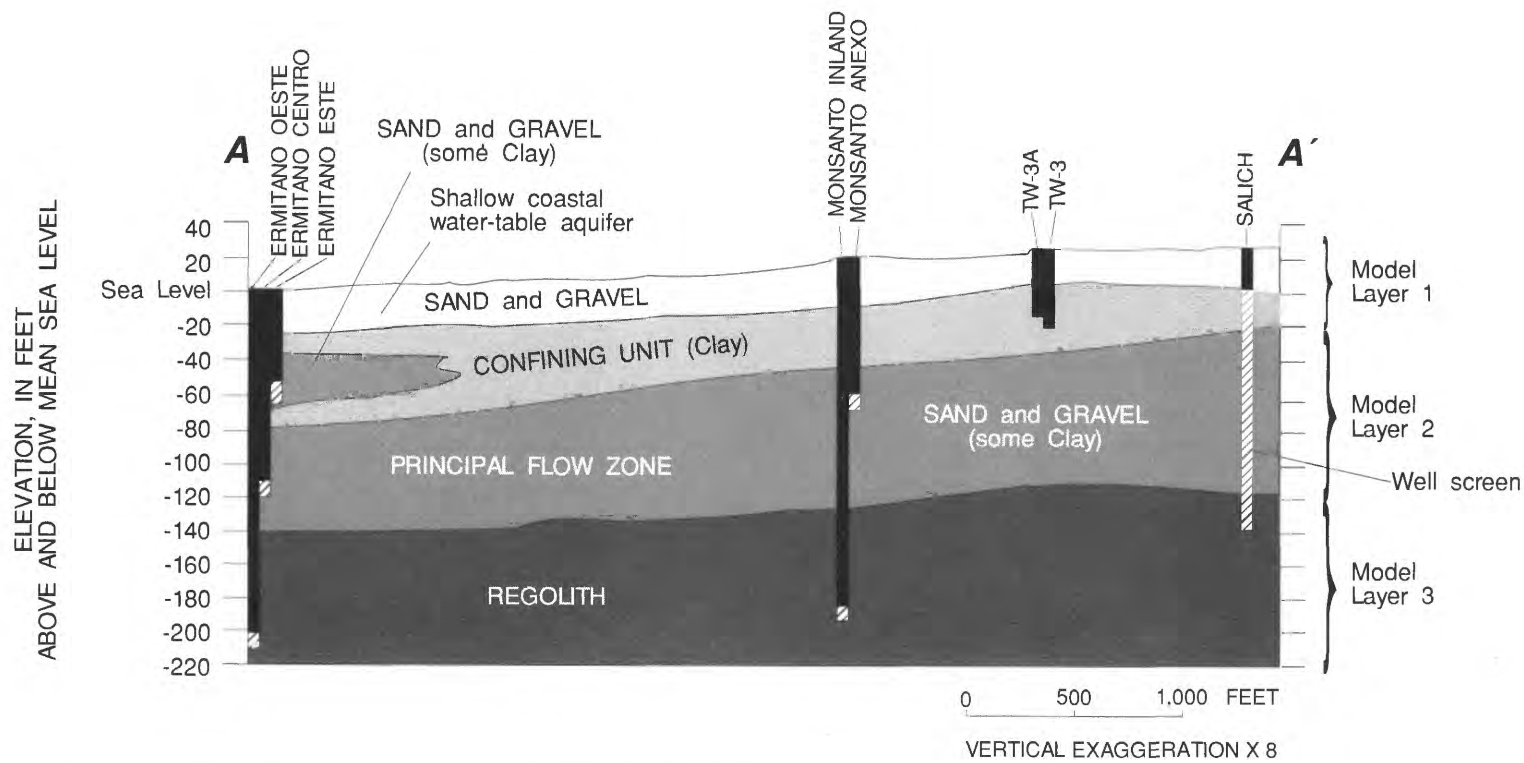


Figure 14. Geohydrologic section *A-A'* in the Salinas fan. Refer to figure 10 for geographic location.

hydraulic conductivity (*k´*) of the confining clay was initially estimated as 0.27 ft/d on the basis of an aquifer test conducted on the southeastern part of the Salinas fan delta (Quiñones-Aponte, 1989). Assuming that the average thickness (*b´*) of the confining clay is about 35 ft, the vertical conductance per unit area (*Vcon*) is computed by:

$$Vcon = k'/b',$$
$$Vcon = (0.27 \text{ ft/d})/(35 \text{ ft}),$$
$$Vcon = 0.0077 \text{ d}^{-1}.$$

Flow to and from the shallow coastal water-table aquifer and through the clay unit (model layer 1) is generally simulated in the vertical direction. The flow-driving mechanics in model layer 1 are ET and a series of drainage canals. These were simulated using the Drain and ET packages of McDonald and Harbaugh (1988, p. 9-1 and 10-1). A maximum of 533 model cells can potentially represent ET. However, the actual number of cells representing ET vary depending on the altitude of the water table. The maximum ET rate varies seasonally and was estimated to range from about 3.0 to 10.0 in/yr (Díaz, 1976, p. 92). Maximum ET, as simulated in the model, occurs when the water table is at land surface and decreases, linearly, until the ET extinction depth (depth at which ET from the water-table surface is assumed to be zero) is reached. An initial extinction depth of 6.0 ft below land surface was used as suggested by Bennett (1976, p. 62). Flow to the drainage network was simulated by 236 cells in model layer 1 (fig. 13*A*). These drain cells simulate flow of surplus irrigation water and ground-water discharge to swampy areas on the coast.

Model layer 2 represents the principal flow zone (figs. 13*B* and 14). The variability of hydraulic conductivities and the bottom of the principal flow zone were represented using discrete model cells in model layer 2 (figs. 10 and 12, respectively). Hydraulic conductivities in the Salinas to Patillas area, along the northern limit of the unconsolidated deposits, are less than 10 ft/d, and are greater than 500 ft/d in the central area of the Salinas fan delta (fig. 12). Flow in model layer 2 is simulated in the horizontal plane and water can move down to model layer 3 and up to the active cells of model layer 1. The northern limit of model layer 2 represents the limit of the principal flow zone and is simulated as a no-flow boundary. At the southern limit of model layer 2, where discharge to the seabed is simulated, a head-dependent flow boundary along the shoreline is used (general-head boundary, McDonald and Harbaugh, 1988, p. 11-1 to 11-4). Previous studies estimated ground-water flow to the seabed along the coast from Salinas to Patillas to range from 5.6 ft^3/s (Bennett, 1976, p. 58-59) to 18 ft^3/s (McClymonds and Díaz, 1972, p. 31). For model calibration purposes, an intermediate estimate of 11.5 ft^3/s was assumed based on data from Heisel and González (1979).

Streamflow infiltration to the principal flow zone (model layer 2) is simulated only in the upper river reaches. An injection-well function was used to simulate stream loss to the aquifer system due to the very good hydraulic connection between the stream and the aquifer system and the abrupt increase in aquifer hydraulic diffusivity (transmissivity divided by storage coefficient) along the upper river reaches where grabens occur. Along the lower reaches, which are simulated using the River package option of MODFLOW (McDonald and Harbaugh, 1988, p. 6-1 to 6-13), streams gain water from the aquifer system. Stream gains on the lower reaches of the Río Nigua at Salinas were simulated using the Drain package option of MODFLOW (McDonald and Harbaugh, 1988, p. 9-1 to 9-6). Limitations in the River package option of McDonald and Harbaugh (1988) preclude its use in simulating leakage when the potentiometric surface gradient is not controlled by the stream as a result of the high hydraulic conductivity of the aquifer. Discharge from wells in layers 2 and 3 was simulated by specifying the pumping rate at model cells where the wells are located (table 3).

Model layer 3 represents the regolith, which has relatively low permeability compared to the principal flow zone (figs. 13*C* and 14). The top of model layer 3 is represented by the top of the regolith (fig. 11). Because the thickness of the regolith is unknown, a transmissivity value of 1,000 ft^2/d was used as a first approximation. Vertical movement of water between model layers 2 and 3 is controlled by *Vcon* (McDonald and Harbaugh, 1988, p. 5-11 to 5-24), which was initially estimated as 0.00086 d^{-1}. The regolith, as simulated in the model by layer 3, extends inland beyond the alluvial deposits forming the foothills and is assumed to be recharged by rainfall infiltration throughout the foothills. Flow from the regolith discharges to the principal flow zone at variable rates controlled primarily by the head differences between the two units.

Recharge from rainfall and irrigation was simulated by delineating areas where irrigation water was applied. Recharge was applied to the uppermost active cells of the three layers.

Table 3. Pumping rate for wells during March 1986 in the Salinas to Patillas area

[Withdrawals in cubic feet per second represent the equivalent pumping rate for 24 hours. Mgal/d, million gallons per day; ft^3/s, cubic foot per second; --, no data]

Well No. (fig. 15)	Location in model grid		Pumping rate	
	Row	Column	Mgal/d	ft^3/s
1	25	10	0.29	0.45
2	23	11	1.00	1.55
3	23	12	.80	1.24
4	19	15	.50	.78
5	20	15	.46	.71
6	19	16	.16	.25
7	20	16	.77	.19
8	24	16	2.16	3.34
9	20	18	.32	.49
10	26	19	.96	1.48
11	33	19	--	--
12	20	20	1.87	2.89
13	22	20	.62	.96
14	29	21	1.44	2.23
15	19	22	.53	.82
16	30	22	.09	.14
17	28	23	.86	1.33
18	25	26	.60	.93
19	22	27	.46	.71
20	23	28	1.50	2.32
21	20	30	.14	.22
22	23	31	.40	.62
23	25	31	.92	1.42
24	26	33	.86	1.33
25	26	34	.08	.12
26	25	35	.08	.12
27	26	36	2.45	3.79
28	27	36	1.44	2.23
29	26	38	.15	.23
30	27	44	.00	.00
31	27	52	.52	.80
32	32	57	.23	.36
33	31	61	.57	.89
34	30	65	.36	.56
35	35	66	.48	.74
36	28	71	.05	.08
37	17	93	.09	.14
38	21	93	.17	.26
39	19	96	.14	.23
40	25	97	.18	.28
41	24	98	.05	.08
42	24	99	.15	.23
43	24	102	.16	.25

Model Calibration

In small aquifer systems under significant stress, it is difficult to determine a water-level configuration that accurately represents the system in a steady-state condition. This is explained by the fact that boundaries and sink-source features are located relatively close to each other, making the system sensitive to small stress changes. In small aquifer systems, it is less probable that the system approximates a steady-state condition because any given stress would rapidly affect the entire aquifer. Because of this sensitivity and relative instability of the source-sink conditions, a modeling approach was used in which the same, or more, weight was given to the ground-water hydraulic coefficients and water-use data than to the potentiometric levels and flow components.

Preliminary calibration was done by setting all better-known variables and adjusting the less well-known variables within the uncertainty of their estimated values. Because of the short-term cyclic trends of ground-water levels in the aquifer system, the steady-state assumption is not suitable for model calibration purposes. During the calibration process, difficulties were met when trying to minimize the number of model iterations required to achieve convergence of the matrix solution and at the same time satisfy the steady-state assumption in which the inflow minus outflow must approach zero. This can be explained by the fact that in this model almost all the variables are explicitly represented. Model variables were not altered unrealistically far from their actual or most reliable values while attempting to satisfy the steady-state calibration requirements. This preliminary calibration was performed attempting to match the hydrologic conditions of March 1986 (Dacosta and Gómez-Gómez, 1987; Quiñones-Aponte and Gómez-Gómez, 1987; and Torres-González and Gómez-Gómez, 1987).

The calibration to the March 1986 hydrologic conditions was done by initially modifying only the least certain hydrologic factors. Recharge from rainfall was calibrated to a value of 2.5 in/yr, which is about 6.3 percent of the mean annual rainfall. Recharge from irrigation applications was simulated for areas delineated during the March 1986 survey (fig. 15). Recharge resulting from irrigation was initially estimated to be about 19 in/yr, assuming that 30 percent of the total applied water recharges the aquifer system. No changes in recharge from irrigation were required during the calibration process. Conductance values (which is the product of hydraulic conductivity and cross-sectional area of flow divided by the length of the flow path) for the

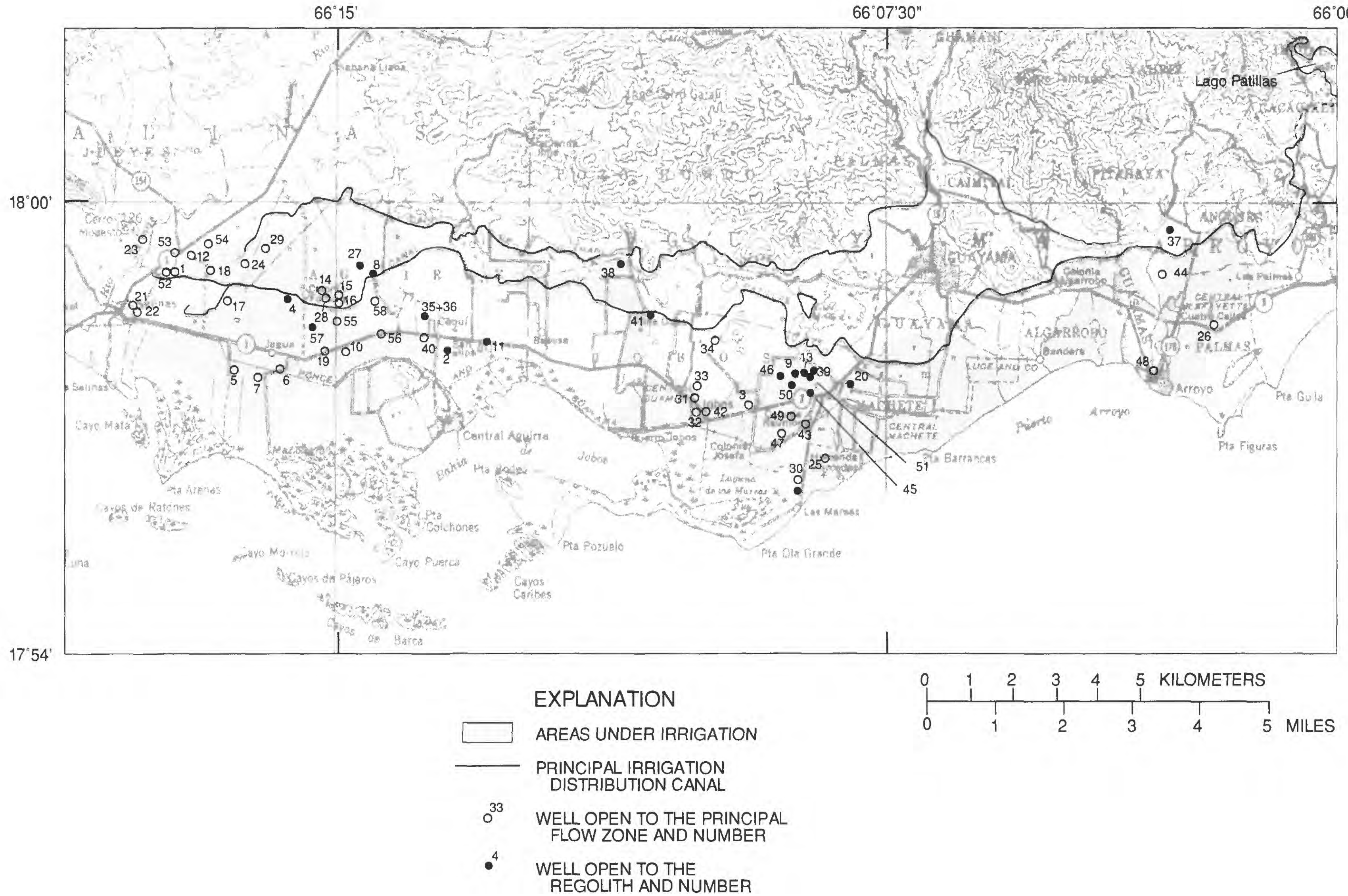


Figure 15. Irrigation canals, areas under irrigation, and wells in the Salinas to Patillas area, March 1986.

lower river reaches (modeled as drains) were adjusted until a total discharge rate of 8.0 ft^3/s measured during the March 1986 hydrologic survey was approximated by the model. After final model parameter adjustments, the total ground-water discharge to these lower river reaches was simulated at about 12.5 ft^3/s.

Aquifer evapotranspiration in the study area ranged from 3 to 10 in/yr during wet and dry seasons, respectively, according to Díaz (1976, p. 92). For the March 1986 conditions, ET was calibrated at 6.5 in/yr using an ET extinction depth of 6 ft below land surface.

Estimates of ground-water flow to the seabed were made from previous investigations (McClymonds and Díaz, 1972; Bennett, 1976; and Heisel and González, 1979) (table 4). The head-dependent flow boundary option of MODFLOW (McDonald and Harbaugh, 1988) was used to simulate ground-water flow to the seabed. Conductance values along the seabed boundary (head dependent flow array) were adjusted until a flow of 10 ft^3/s was obtained, which fell within the previously mentioned range of 5.6 to 10 ft^3/s. Obtaining acceptable head matches and potentiometric contour configurations was another constraint used for calibrating the conductance of the seabed boundary. Adjustments to the conductance values for the simulation of ground-water flow to the seabed were made using the hydraulic conductivity values of the principal flow zone along the shoreline (fig. 12). Conductance values were modified upward from initial input values for the area between Río Guamaní and Quebrada Branderi. The physiographic conditions of the shoreline in this area are characterized by scarps along the shoreline that appear to be serving as drains for the shallow coastal water-table aquifer.

Seepage from the Canal de Patillas to the aquifer system was simulated using the River Package option of MODFLOW (McDonald and Harbaugh, 1988, p. 6-1). A series of canal-flow measurements, made as part of the

Table 4. Summary of estimated ground-water budgets from previous investigations and simulated budgets for this report

[*, undistinguished fraction of total recharge; --, not considered in this model; x, does not apply for this model]

Budget component	McClymonds and Díaz (1972)	Bennett (1976)	Heisel and González (1979)	This report: Steady-state model 1986	This report: Steady-state model predevelopment (1890-1900)
Inflow (cubic feet per second)					
Areal recharge:					
Rainfall	42.5	38	49.5	48.1	30.0
Irrigation	23.5	*	*	[1]30.0	30.0
Seepage	19.0	*	*	18.1	x
Northern boundary	--	5.4	15.4	--	--
Streamflow	11.0	--	--	15.3	13.0
Irrigation canal seepage	--	--	--	19.0	x
TOTAL INFLOW	53.5	43.4	64.9	82.4	43.0
Outflow (cubic feet per second)					
Pumpage	[2]36.0	[2,3]37.8	23.5	43.2	x
Evapotranspiration	--	[4]9.6	[5]8.0	6.2	3.0
Drains, swamps, and coastal springs	--	--	--	18.9	25.0
Lower stream reaches	--	--	[6]22.0	6.5	8.0
Flow to seabed	18.0	5.6	11.5	7.6	7.0
TOTAL OUTFLOW	54.0	53.0	65.0	82.4	43.0

[1] Area receiving recharge includes the low hills in the study area.
[2] Net pumpage = total pumpage times 0.65.
[3] Includes evapotranspiration and drains.
[4] Includes drains.
[5] Estimated using a rate of 5 in/mo (Díaz, 1976).
[6] Includes drains and lower river reaches.

March 1986 survey, were used to estimate seepage from the canal to the aquifer system. Seven canal-flow measurements, made during the March 1986 survey, ranged from 37.1 ft^3/s at the entrance to the Arroyo fan delta to zero at the middle of the Salinas fan delta. Although it is not known if canals delivered water to farms during the time of the survey, these data were used to identify areas where large seepage rates occurred. Estimated canal seepage ranged from 0.75×10^{-4} to 9.06×10^{-4} $ft^3/s/ft^{-1}$ (cubic feet per second per foot of canal length), which would correspond to a rate of 1.0 to 10.0 ft/d. High seepage rates occurred along areas north of the western part of Bahía de Jobos to areas southwest of the town of Guayama and from the entrance to the middle of the Salinas fan delta, where the canal is usually dry.

No changes were required for hydraulic conductivity values input to model layer 1 (shallow coastal water-table aquifer) from the initial value of 20 ft/d. Modifications to the hydraulic conductivity of model layer 2 (principal flow zone) were required only at some localities. Changes near the apex of the Salinas fan delta, were made from an initial range of 10 to 180 ft/d to a range of 50 to 300 ft/d. This change is justified by the high percentage of sand and gravel present (fig. 10) and high rates of streamflow infiltration in this area. Some other minor changes in the hydraulic conductivity of model layer 2 were made for the Jobos area. The transmissivity of model layer 3, which represents the regolith, was calibrated to 1,500 ft^2/d from an initial value of 1,000 ft^2/d. Calibration of transmissivity for model layer 3 was performed by comparing simulated heads against measured heads at wells tapping the lower geohydrologic unit (fig. 16). The conductance value used to simulate the drainage system along the swamp areas was the most uncertain parameter and was adjusted during the final stage of the model calibration process.

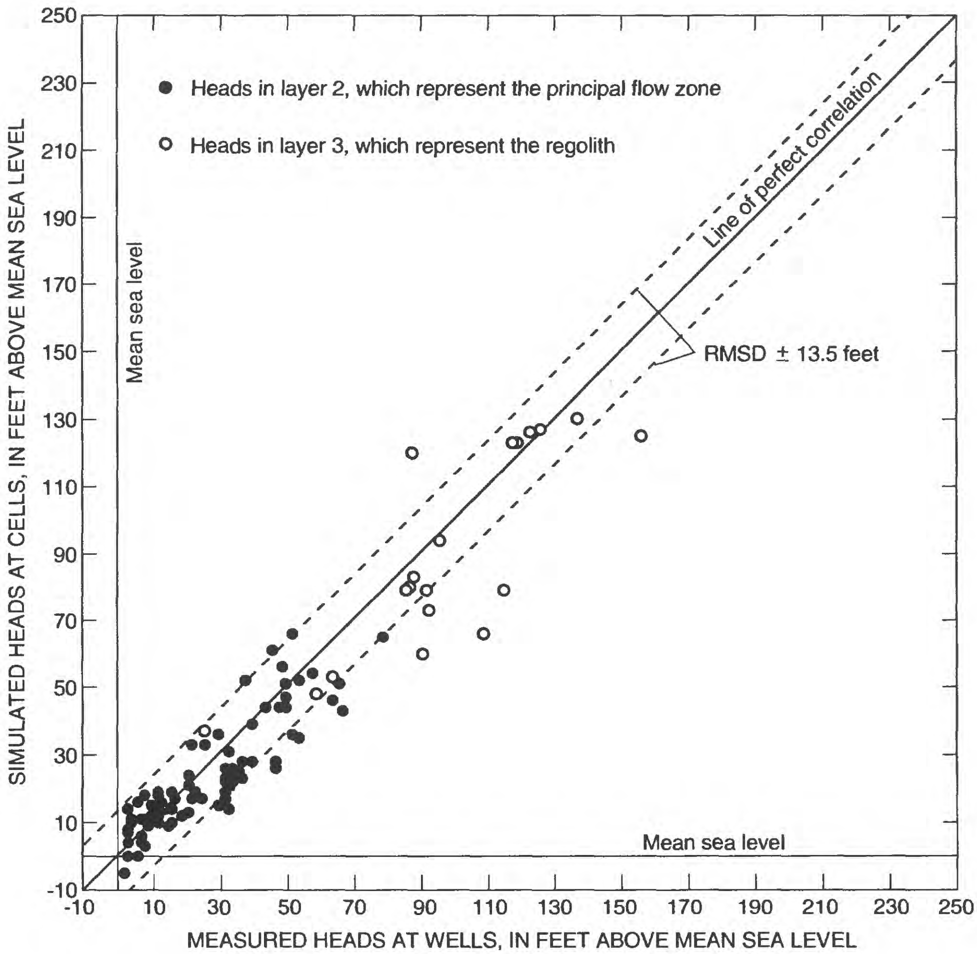
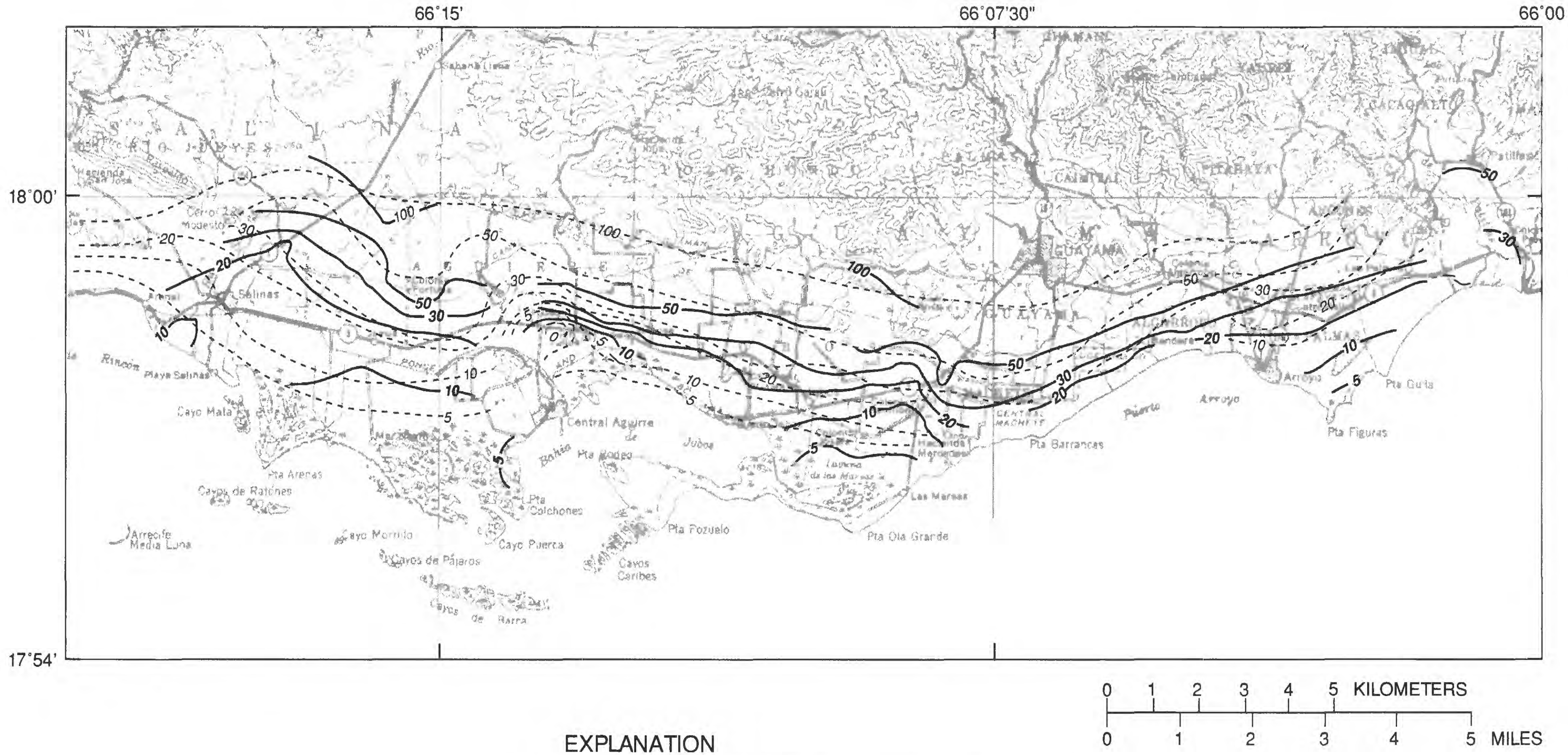


Figure 16. Correlation between heads measured in wells and simulated heads for model cells containing the corresponding wells.



EXPLANATION

POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is mean sea level

- - 30 - - Measured

—30— Simulated

Figure 17. Measured and simulated potentiometric contours for the principal flow zone (model layer 2), during March 1986.

Conductance values for the agricultural drainage system were adjusted until the potentiometric contours for the principal flow zone along the lower part of the fan deltas followed the configuration of contours drawn on the basis of actual water-level measurements (fig. 17). Changes in the drainage system flow were controlled so as not to affect the other previously calibrated flow components. A uniform conductance value of 0.029 per second (s^{-1}) was used for the drains in the calibrated model.

In general, simulated potentiometric contours followed the configuration of contours drawn from actual potentiometric level data (fig. 17). Some minor discrepancies are reflected in the southwestern part of the Salinas fan delta where the model-simulated heads are higher than the measured heads.

The overall model calculated water budget for the March 1986 steady-state conditions was 82.4 ft^3/s. This is higher than the estimated water budgets of previous investigations, which range from about 40 to 65 ft^3/s (table 4). Differences are suspected to be due to the fact that some of the water-budget components were not considered in the previous estimates (table 4). Also, the area modeled in this study includes the outcrop area of the regolith (foothills), not included in previous investigations, but which contribute to the aquifer system water budget.

A correlation between heads measured at shut-off pumping and non-pumping wells and model-simulated heads for cells containing the corresponding wells reveals that about 76 percent of the measurements falls within the RMSD band (RMSD = $\pm$13.5 ft) projected from a line of perfect fit for the 95-percent confidence interval (fig. 16). Larger deviations were observed for wells tapping the regolith, probably because of a greater uncertainty in the variables used for simulating that geohydrologic unit. A RMSD value of 20.8 ft was computed for model arrays representing measured and simulated heads at wells tapping only the principal flow zone. The latter RMSD value could be subject to error introduced while interpolating measured heads from wells to cells or to errors in the interpretation made to develop potentiometric contours representing actual measurements. Model finite-difference cell size also introduces errors because of variation of the actual head values within the area covered by a cell. In the calibration process, further refinement of the calibrated parameters should not be attempted if the differences between initial and simulated head values are within the range of variability of actual heads in the area covered by a cell.

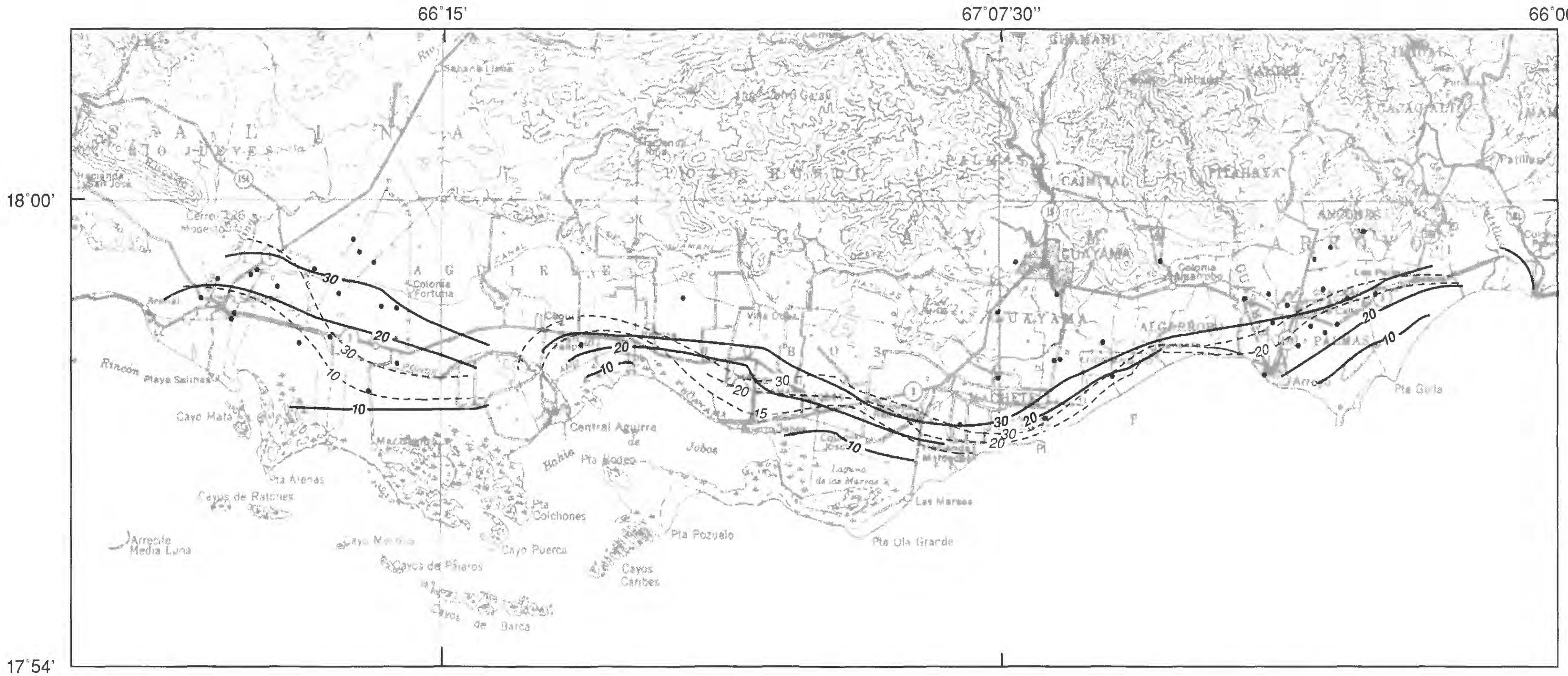
Model Testing and Simulation of Effects of Water-Resources Development on the Aquifer System

The model was tested by simulating natural and man-made changes in hydrologic conditions in the aquifer system from 1890 to 1986. An estimated potentiometric surface for the nonirrigation (near predevelopment) geohydrologic conditions of 1890 was used to represent the initial heads in the transient simulation (fig. 18). These data were obtained from records of wells drilled from 1900 to 1920. The records are in the custody of the Engineering Department of Central Aguirre sugar mill.

Beginning in 1890, nine stress periods were used to simulate changes in the inflow and outflow components of the aquifer system (fig. 19). Each period was 10 years in duration, except the last interval of 1970-86. Average input values for pumpage, recharge from rainfall infiltration, recharge from irrigation, and river seepage were used to represent each stress period.

Irrigation canal deliveries were based on data presented in figure 8; historical rainfall data and estimates of rainfall were taken from figures 3 and 5 to estimate rainfall recharge rates; streamflow seepage to the aquifer system was derived from baseflow estimates given in table 7 and adjusted slightly to account for relatively wet and dry rainfall periods; irrigation wells return flow (ground-water recharge) was calculated from withdrawals minus net withdrawals as given in figure 7; and ET rates along coastal areas were estimated. Baseflow estimates for streams other than the Río Majada were extrapolated using the discharge to drainage area ratio of the Río Majada (table 1). Estimates of withdrawals from wells used for irrigation purposes were made on the basis of 7.2 hours of pumping per day. This is equivalent to an average of 2,640 hours per year for active sugarcane irrigation wells as documented in files at the Central Aguirre sugar mill. Withdrawals from wells for public-supply purposes were estimated on the basis of 24 hours of pumping per day.

The model-simulated heads were compared to reconstructed ground-water level fluctuations at a well for which sporadic manometer readings were made over a 76-year period (1910-86) (Esperanza 1 well battery, figs. 2 and 20). Manometer readings were correlated to water-level measurements at a piezometer installed at the same location. The well and the piezometer tap the principal flow zone. Conductance values of drains and coastal river reaches were adjusted until simulated and observed



EXPLANATION

PREDEVELOPMENT POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is mean sea level.

- - 30 - - Approximate--Measurements were made during well drilling. Wells drilled from 1900 to 1920

—30— Simulated

• MEASURED WATER-LEVEL CONTROL POINT

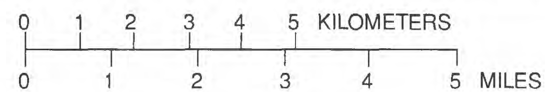


Figure 18. Approximate and simulated predevelopment potentiometric contours for the principal flow zone (model layer 2). Represents average conditions during the 1900-20 period. Water-level information is from Engineering Department of Central Aguirre sugar mill.

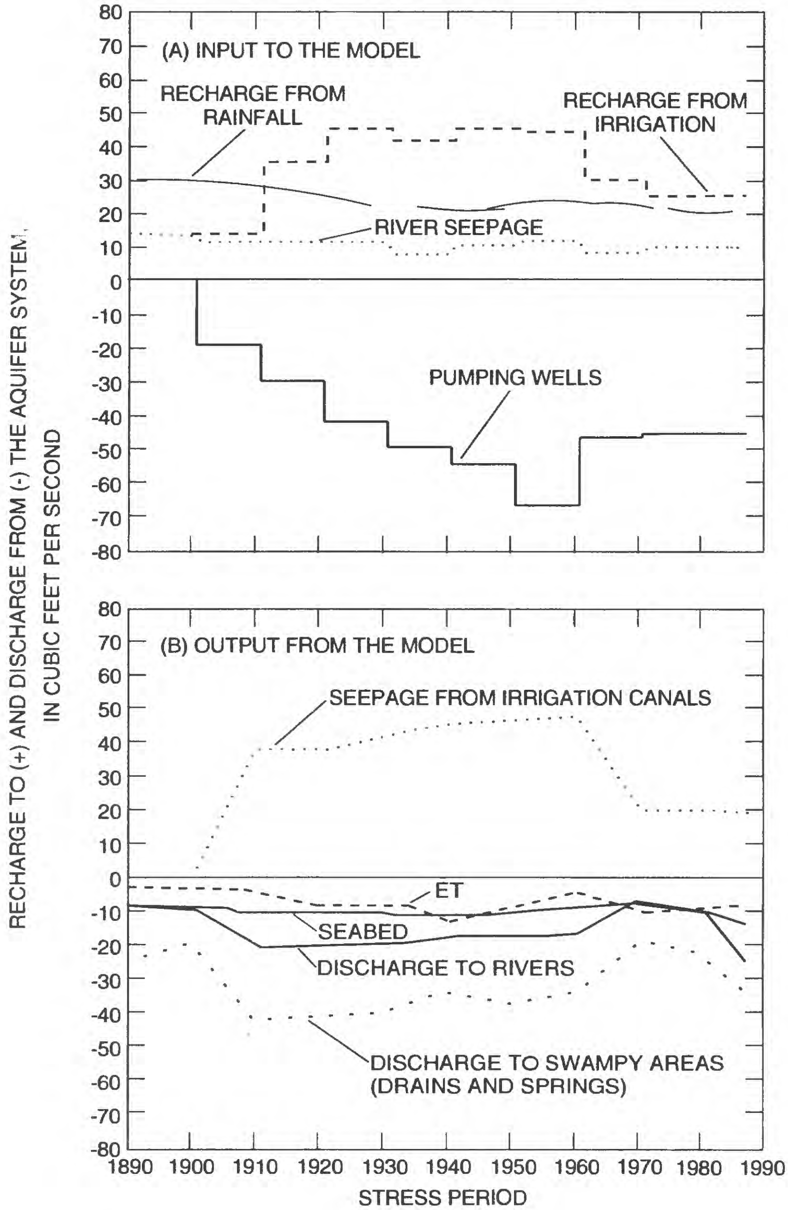


Figure 19. Simulation of hydrologic conditions in the Salinas to Patillas area, 1890-1986, showing changes in (*A*) model input and (*B*) model output during each stress period.

ground-water-level fluctuations at the Esperanza 1 well battery were closely matched, and the conditions existing during March 1986 were approximated.

The transient simulation indicates that the simulated head at the Esperanza 1 well battery follows the trend of the water-level altitudes (fig. 20). Discrete measurements are not closely approximated by the model because input values to the model are representative of average conditions during each decade and extreme ground-water levels represent conditions occurring during discrete time periods or seasons. In general, the simulated well hydrograph approached the actual values represented by the March to April dry season measurements.

Based on the model results, the aquifer system had two important sources of recharge during predevelopment conditions; rainfall (30 ft^3/s) and streamflow seepage through the upper river reaches (13 ft^3/s). In addition, the aquifer system had four discharge components during this time (fig. 19*B* and table 4) that consisted of: (1) discharge to coastal swamps and springs (25 ft^3/s), (2) seepage to coastal river reaches (8 ft^3/s), (3) flow to the seabed (7 ft^3/s), and (4) discharge as ET (3 ft^3/s). The model-estimated steady-state predevelopment water budget was about 43 ft^3/s.

The following is a summary of the hydrologic conditions from 1890 to 1986 based on the transient simulation. With the beginning of pumping during the first decade of this century, natural discharge to swamp areas along the coast was reduced due to interception of water by wells. In 1914, with the beginning of large-scale irrigation deliveries, recharge to the aquifer system increased. Relatively high aquifer recharge from irrigation applications occurred during the decades of the 1910's and 1920's. These high recharge rates combined with relatively low ground-water withdrawal rates, produced high discharges rates to swampy areas (drainage systems and coastal springs), coastal river reaches and the seabed; and, increased ET as a result of high ground-water levels near the coast. The high ground-water levels near the coast led to the construction of the coastal drainage systems and dewatering pumping stations during the latter part of

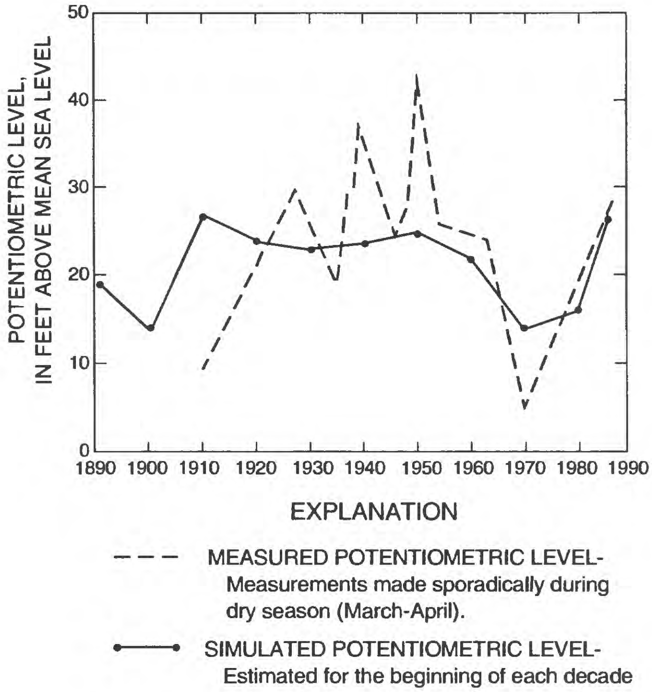


Figure 20. Measured and simulated ground-water-level fluctuations at Esperanza 1 well battery near Salinas (see figure 2 for location).

the 1930's. Infiltration from areal irrigation applications and seepage from the irrigation canals, which reached a maximum of 45 ft³/s from 1920 to 1960 (fig. 19*B*), sustaining year-round swampy areas, increased discharge to the seabed, and increased ET.

During the 1960's and 1970's, net ground-water withdrawals increased, largely due to withdrawals for public supply. Although public-supply wells in Puerto Rico typically have smaller yields than irrigation wells, public-supply wells usually operate 24 hours per day, 7 days per week, whereas furrow irrigation wells usually operate from 8 to 10 hours a day, 5 days per week. Results obtained with the ground-water-flow model indicate that an increase in net ground-water withdrawals led to a decrease in discharge to coastal drains, which included swamps and springs, coastal river reaches, and also to a decrease in ET rates (fig. 19*B*). A reduction in surface-water diversion for irrigation, from 65,000 to 35,000 acre-ft/yr, occurred from 1970 to 1980. Also, withdrawals from irrigation wells decreased by about 14,500 acre-ft/yr and caused a decrease in total aquifer recharge of about 13,300 acre-ft/yr. Recharge rates from irrigation canal seepage and areal irrigation applications were reduced by about 50 percent each. As a consequence, discharge to coastal drains and springs, coastal river reaches, and to ET declined to near their predevelopment rates (fig. 19*B*). Only ET rates remained slightly higher, probably because application of water for irrigation facilitated ET (fig. 19*B*).

In general, the increased use of surface water for irrigation purposes from the 1920's to the 1960's increased the ground-water flow through the aquifer system by about a factor of three (126 ft³/s). In 1986, the aquifer system had a larger water budget than the water budget estimated for predevelopment conditions by about a factor of two (88 ft³/s). From the analysis of the water budget for the transient model simulation, and assuming that: (1) the drip irrigation technique is fully implemented, (2) ground-water withdrawals are maintained at the same rate, and (3) surface-water withdrawals from the reservoirs and the Río Guamaní are discontinued, recharge to the aquifer system could be decreased by about 60 percent. If this occurs, it can result in large ground-water-level declines and possibly saltwater upconing and/or intrusion.

Sensitivity Analysis

A sensitivity analysis was done on the Salinas to Patillas area model to determine the model's response to changes in hydrologic and geohydrologic factors. Sensitivity analysis is used to determine the range within which hydrologic factors can be changed without significantly affecting the model responses. This type of analysis also helps to determine the most significant hydrologic or geohydrologic factors. Field efforts then can be focused toward the better definition of these factors.

For the sensitivity analysis of this study, the hydrologic and geohydrologic factors were divided into three categories: hydrologic variables, hydraulic coefficients, and boundary hydraulic coefficients. For the purpose of this section the word "parameter" is used when making a general reference to the hydrologic and geohydrologic factors.

In the typical sensitivity analysis, parameters are individually increased and decreased by some specified percent from their calibrated value. In this study, the dimensionless relative sensitivity approach (Simon, 1988) was applied. In this approach, an objective function represents the overall head or flow changes. The objective function used for this sensitivity analysis was the dimensionless relative mean square differences (DRMSD) which was originally proposed by Ibbitt and O'Donnell (1971) as:

$$\mathrm{DRMSD} = \frac{\left[n \sum_{i=1}^{n} (hc_i - hr_i)^2 \right]^{1/2}}{\sum_{i=1}^{n} hc_i}, \quad (5)$$

where

- n is the number of observations;
- hc_i is the calibrated value;
- hr_i is the response value; and
- i is 1, 2, 3, ... n.

Rates of change of the objective function were related to the rates of change of the parameter by determining relative changes of the objective function with respect to the change imposed to the parameter. The relative changes of the objective function (SREL_i) were determined using the approach proposed by Simon (1988):

$$SREL_i = \frac{\Delta SR_i}{\Delta PR_i}, \quad (6)$$

in which

$$\Delta SR_i = \frac{(SS_i - SST)}{SST}, \quad (7)$$

$$\Delta PR_i = \frac{(PR_i - PR_c)}{PR_c}, \quad (8)$$

where

- SS_i is the value of the objective function modified by the change in the parameter;
- SST is the objective function value of calibrated parameter;
- PR_i is the modified parameter value;
- PR_c is the calibrated parameter value;
- ΔSR_i is the relative change in the objective function; and
- ΔPR_i is the relative change of the parameter.

Values of the relative sensitivity for the range ±20 to ±80 percent change from the calibrated parameter are defined by:

$$\Delta SR_i = \frac{(SS_i - SS_{(i-1)})}{SST}, \quad (9)$$

and

$$\Delta PR_i = \frac{(PR_i - PR_{(i-1)})}{PR_c}. \quad (10)$$

Because detailed hydrologic characteristics and heads in model layers 1 and 3 are not well-defined, the objective function representative of the response surface was defined using only heads in model layer 2. However, parameters of model layers 1 and 3 were evaluated as part of the sensitivity analysis. The same objective function was used to represent flows to and from all hydrologic features (canals, rivers, and others).

The following terminology is used to classify the behavior of the parameters as they are changed from their calibrated value: active parameter, inactive parameter, and nuisance parameter. The activity or inactivity of a parameter is determined by the location of the objective function value of head or flow responses, for increased or decreased parameters, from the objective function of the calibration results. In the graph shown in figure 21, the value zero represents the calibration results. As the objective function value from results of a modified parameter depart from zero, the parameter is said to be active. The farther the objective function plots from zero, the more active the parameter is considered to be. If the objective function remains close to zero, the parameter is classified as inactive and is, therefore, less important to the model. Nuisance parameters are those that do not show a functional behavior. The activity of nuisance parameters increase and decrease without a defined pattern.

Hydrologic variables included in the analysis were recharge from rainfall (RCHRAIN), recharge from irrigation applications (RCHIRRG), evapotranspiration rates (ET), evapotranspiration extinction depth (ETDEPTH), and streamflow infiltration to the aquifer system at the upper river reaches (STREAMIN). According to head and flow responses, recharge from irrigation applications is the most active hydrologic parameter for the entire range of parameter changes. The activity of RCHIRRG decreased at slow rates for the flow response when the RCHIRRG increased or decreased as well as for the head response when the RCHIRRG is increased (figs. 21*A* and 21*B*). A high rate of increase in RCHIRRG activity is reflected by the head response when the RCHIRRG is decreased (fig. 21*A*). Recharge from rainfall (RCHRAIN) is the second most active hydrologic variable. Occasionally, RCHRAIN becomes less active than streamflow infiltration at the upper river reaches (STREAMIN) and

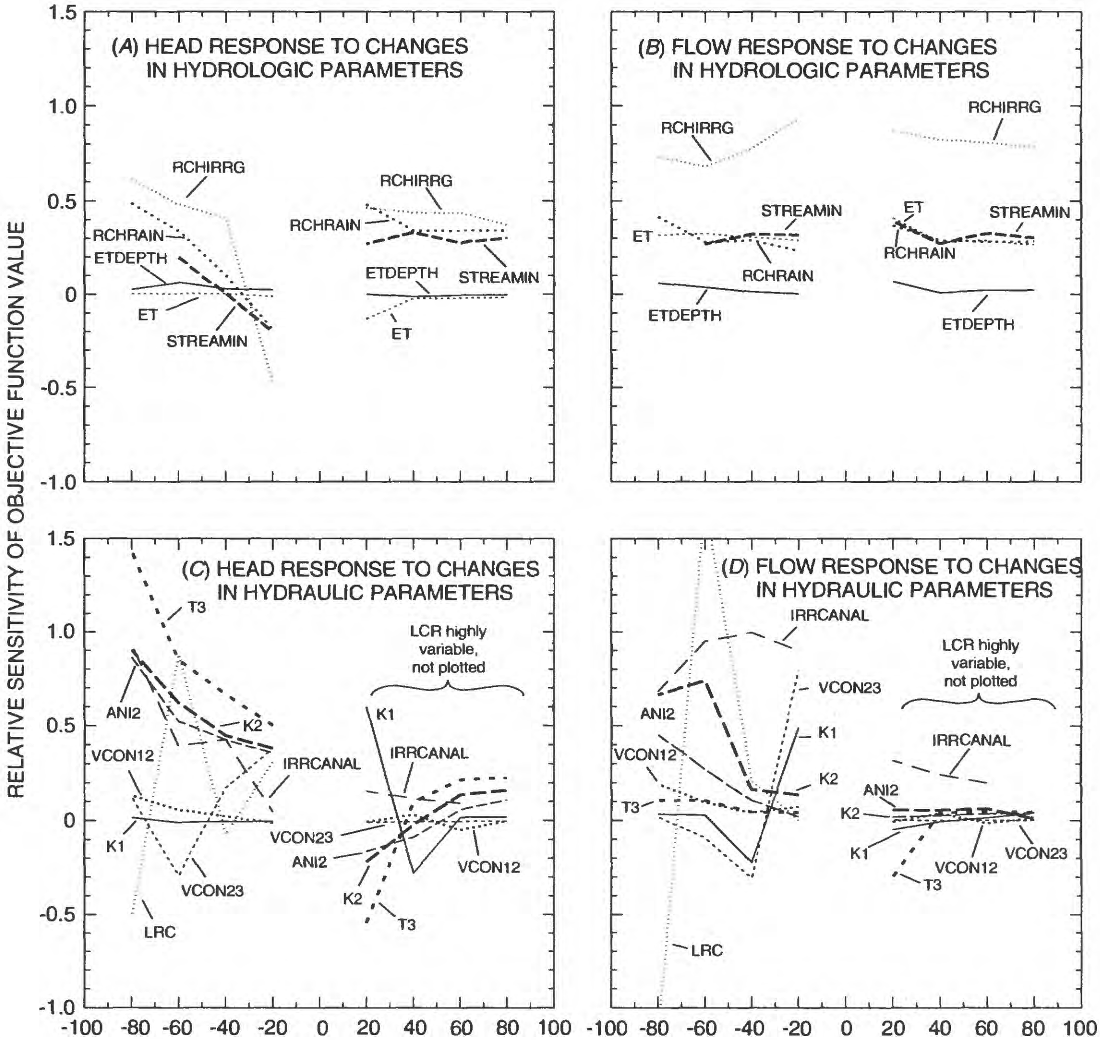
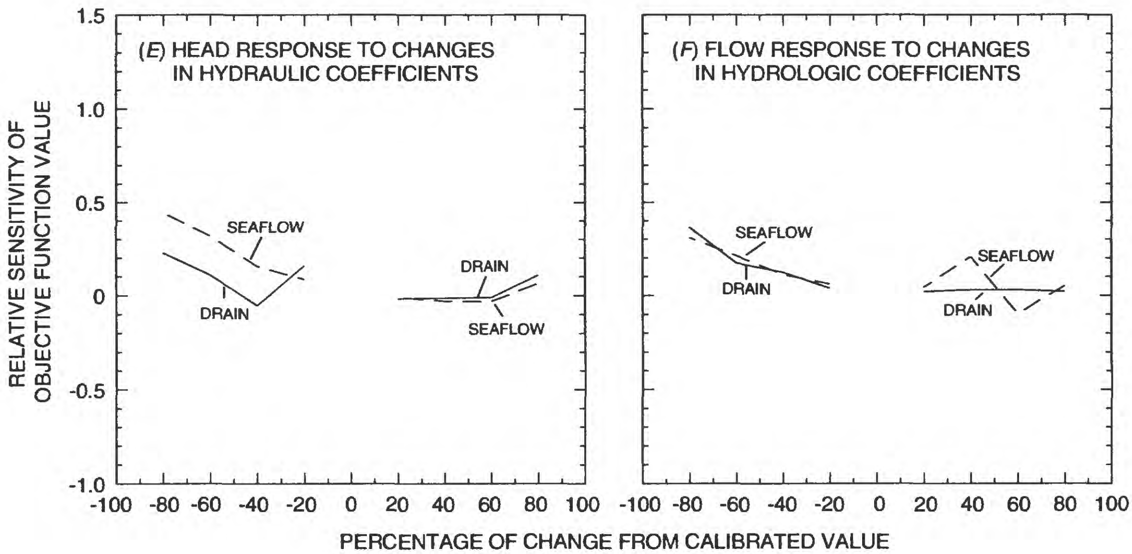


Figure 21. Relative sensitivity of objective function values representative of head and flow responses to variations in hydrologic, hydraulic, and boundary hydraulic parameters.

evapotranspiration rates (ET). But RCHRAIN showed more activity from the head response when the parameter was decreased (figs. 21*A* and 21*B*). Streamflow infiltration at the upper river reaches (STREAMIN) is the third most active parameter within the hydrologic variables followed by ET, which reflected some activity from the flow response but almost no activity from the head response (figs. 21*A* and 21*B*). The ET extinction depth ETDEPTH did not show significant activity either from the head response or from the flow response, which indicated that the model is not sensitive to this parameter.

Hydraulic coefficients included in the analysis were the hydraulic conductivity of model layer 1 (K1), hydraulic conductivity of model layer 2 (K2), transmissivity of model layer 3 (T3), vertical conductance between model layers 1 and 2 (VCON12), vertical conductance between model layers 2 and 3 (VCON23), horizontal anisotropy ratio of model layer 2 (ANI2), irrigation canal-bed conductance (IRRCANAL), and streambed conductance of lower stream reaches (LRC). IRRCANAL, K2, and T3 are the most active parameters within the hydraulic coefficients group. If the interpretation is made on the basis of the head response, T3 is the most active parameter followed



EXPLANATION

RCHIRRG	Recharge from irrigation applications
RCHRAIN	Recharge from rainfall
ET	Evapotranspiration
ETDEPTH	Evapotranspiration extension depth
STREAMIN	Streamflow infiltration to the aquifer
IRRCANAL	Conductance of irrigation canal bottom
VCON12	Vertical conductance per unit area between layers 1 and 2
K1	Hydraulic conductivity of layer 1
K2	Hydraulic conductivity of layer 2
T3	Transmissivity of layer 3
ANI2	Horizontal anisotropy ratio of layer 2
LRC	Lower river reach conductance

Figure 21. Relative sensitivity of objective function values representative of head and flow responses to variations in hydrologic, hydraulic, and boundary hydraulic parameters—*Continued.*

by K2, ANI2, and IRRCANAL (fig. 21*C*). But if the flow responses are used to rank the parameters, IRRCANAL is the most active followed by K2 and ANI2, whereas T3 shows relatively low activity (fig. 21*D*). If the two interpretations are combined, it can be concluded that K2 is, in general, the most active parameter followed by IRRCANAL, T3, ANI2, VCON23, and K1. The least active parameter is VCON12 and LRC is a nuisance parameter (figs. 21*C* and 21*D*).

Only two parameters were included for the analysis of boundary hydraulic coefficients: conductance of drainage canal network (DRAIN) and conductance of the flow through sea-face boundary (SEAFLOW). From the head response, it can be inferred that SEAFLOW is most active when the parameters are decreased and the two (SEAFLOW and DRAIN) are about equally active when the parameters are increased (fig. 21*E*). From the flow response, both parameters are equally active and increase in activity as the magnitude of the parameters are decreased (fig. 21*F*). From the flow response, DRAIN is shown to be almost inactive and SEAFLOW behaves as a nuisance parameter when its magnitude is increased.

Model Limitations and Suggestions for Further Refinements

Some of the more relevant limitations of the Salinas to Patillas area model are in the simulation of ground-water flow to the seabed, generalization of the principal horizontal hydraulic conductivity components, and the inability of the computer code to rewet dry cells in model layers 1 and 2. The use of the head-dependent flux routine to simulate ground-water flow to the seabed might introduce some errors in the predicted heads along this boundary due to the effect of variation in water density in this area.

The generalized orientation of the principal horizontal transmissive components seems to have produced acceptable results for regional simulation purposes. However, for localized and detailed simulations of the variability in the direction of the principal transmissive components, this generalization could produce considerable bias in predicted heads or flow components.

Some limitations of the computer code used for this study (MODFLOW, version 1638, McDonald and Harbaugh, 1988) preclude the resaturation of model cells that become dry in model layers 1 and 2 during simulation. This can happen in some localities because these model layers are thin and cells can dry during the iterative solution process or as result of a stress imposed on the model. It is suggested to use a small acceleration parameter in the solver package that defines the magnitude and frequency of oscillations during the iteration process (McDonald and Harbaugh, 1988, p. 12-28). Although a small acceleration parameter requires more iterations to achieve convergence, it produces smaller oscillations, preventing cells from drying out in areas of thin saturated thickness.

The fact that the transient model was calibrated using extrapolated average flow values to represent discrete conditions during ten-year intervals, implies that the model must be either re-calibrated or re-tested if shorter time periods are used. Detailed data representing a shorter time period scenario would be required.

CONCLUSIONS

Among the most relevant conclusions and findings of this study were the following:

1. Previous studies considered the evapotranspiration rates to be higher during predevelopment conditions. The model indicates, however, that lower evapotranspiration rates occurred during predevelopment and early development conditions. The model also indicates that later areal applications of irrigation water, combined with the generally small vertical hydraulic conductivity of the confining clay and alluvial deposits, produces relatively high water-table altitudes resulting in high evapotranspiration rates.

2. The implementation of the new geohydrologic framework, developed by Renken and others (1991), allows for the simulation of internal boundaries and the representation of the partial isolation of the ground-water basins located within deposits infilling graben structures.

3. A reevaluation of the areal variability of the hydraulic conductivity in the principal flow zone was made, which considered the control data points, stream depositional patterns, dip of bedrock surface, and other geomorphologic factors. This new representation of the hydraulic conductivity distribution provided greater detail and a better definition of the hydraulic characteristics, yielding more realistic results. In general, the map showing distribution of hydraulic conductivity correlates well with a map of the areal distribution of percentage of sand and gravel.

4. The drainage system, implemented in the digital model, discharges about 23 percent of the water budget from the aquifer system.

5. During the peak of water deliveries from irrigation, the water budget of the aquifer system, under natural conditions, was increased by a factor of three and for 1986 it was higher by a factor of two. The ground-water system has been undergoing artificial recharge since about 1910.

6. Streamflow infiltration to the aquifer system was an important hydrologic factor during predevelopment conditions and accounted for about 29 percent of the water budget. However, in the 1970-86 period, streamflow infiltration was only 19 percent of the water budget. Some of the water that was formerly supplied by streamflow leakage is now supplied through infiltration from irrigation applications and seepage from irrigation canals.

SUMMARY

The geohydrology of the Salinas to Patillas area of southeastern Puerto Rico was studied. The study included a review of previous investigations and modification of the conceptual model of the aquifer system on the basis of new knowledge and data. A digital model was constructed, calibrated, and used to test the conceptual model of the aquifer system, to evaluate the effect of historical water-resources development on the water budget of the aquifer system, and to estimate the predevelopment conditions of the aquifer system.

The Salinas to Patillas area is located in the eastern part of the South Coast Ground-Water Province of Puerto Rico, about 28 mi east of Ponce in the South Coastal Plain. The study area extends from 1.5 mi west of Salinas to about 0.7 mi east of Patillas, covering about 196 mi^2. The South Coastal Plain is composed of a series of successive coalescing fan deltas that have an average width of 3 mi. Fan deltas are bordered to the north by low hills and to the south by the Caribbean Sea. In general, agriculture has been the principal land-use activity in the Salinas to Patillas area.

The mean annual rainfall in the South Coastal Plain is about 45 in/yr. An analysis of mean annual rainfall data for the Central Aguirre raingage was made using the 10-year moving average. The only significant change in the mean annual rainfall trend occurred from 1900 to 1930. Actual mean annual rainfall values ranged from 20 to 75 in., but moving average values were within 30 to 50 in. Evapotranspiration from the aquifer has been estimated to range from 2 to 10 in/yr along its nearshore area.

More than 5 ft^3/s of streamflow can infiltrate into fan-delta deposits from the Río Nigua at the northern part of the Salinas fan delta. These highly permeable river reaches usually coincide with stream channels composed of coarse gravel and boulders and are located at sites where the thickness of the underlaying sediments increase abruptly due to the occurrence of the grabens discussed by Renken and others (1991). Synthetic mean annual rainfall data for the Jájome Alto raingage and synthetic mean annual discharge data for the Río Majada at La Plena were made using regression techniques and used to generate a base flow hydrograph of the Río Majada. Estimates of base flow discharge for the Río Majada were used to obtain estimates for other streams and these discharge rates used to estimate historical stream infiltration rates in the ground-water-flow model.

The history of water-resources development in the Salinas to Patillas area was reconstructed using information from historical data files, which are under the custody of private companies and local State government agencies. In the Salinas to Patillas area, the development of water resources and modification of hydrologic conditions that begun in the mid-19th century are associated with the agricultural irrigation practices of the Spanish colonizers. In 1861, the Lapa and Majada diversion canals began conveying water from the Río Lapa and Río Majada to farms located northeast of the town of Salinas. The two canals combined conveying capacity was about 13 ft^3/s. During the first decade of the 1900's, steam-driven pumps were used to withdraw water from dug wells at rates ranging from 500 to 2,700 gal/min. During the mid-1920's, the steam-driven pumps were replaced by more efficient kerosene-powered pumps increasing ground-water withdrawals to about 28 Mgal/d. Early in the 1930's, the kerosene-powered pumps were replaced by turbine pumps, operated by electric motors. The peak in total ground-water withdrawals occurred during the 1960's averaging about 40 Mgal/d. During the 1970's, additional ground-water development took place when new industries started operations in the Jobos area. These industries could have been withdrawing about 3 Mgal/d.

Large-scale use of surface water for irrigation in the Salinas to Patillas area started in 1914 with water deliveries from the Patillas and Carite reservoirs. The initial deliveries from the Canal de Patillas and Canal de Guamaní to the agricultural areas was about 65,000 acre-ft/yr. Since the beginning of surface-water distribution through the irrigation canals the 10-year moving average indicates a decreasing trend in their annual flow. Surface-water deliveries have decreased from 65,000 to 32,000 acre-ft/yr from 1917 to 1989.

Three lithologic sequences define distinct geohydrologic units: (1) shallow coastal water-table aquifer, composed of sand, gravel, and clay; (2) principal flow zone composed of fan delta and alluvial deposits; and (3) regolith composed of weathered bedrock of varied types. These units represent the aquifer system in the study area.

The Salinas to Patillas area can be divided into six aquifer subsystems. These subsystems are classified into three groups. The first group includes the Salinas fan delta, the Jobos area (from Barrio Villodas to the Río Guamani), and the Arroyo fan delta. In this group, water-bearing beds that underlie these areas, infill a structurally low area. In each of these three areas the aquifer is confined near the coast by a fine-grained, poorly permeable clay or silt bed of less than 45 ft thick that lies at a depth of 35 ft below land surface. This confining unit extends nearly continuously along the coast and extends inland 2 mi. Well yields in this group are as high as 2,700 gal/min.

The second aquifer group includes the aquifer in the Río Grande de Patillas valley. This aquifer occurs in a narrow valley and is composed of sand and gravel deposits less than 0.6 mi width and 30 ft thick. Maximum well yield is about 500 gal/min.

The third aquifer group is characterized by structurally high areas where the alluvial cover is thin. Aquifer subsystems of this group occur (1) in the Bahía de Jobos area between Barrio Coquí and Barrio Villodas, and (2) in the Guayama area between the Río Guamaní and Quebrada Corazón. A thin water-bearing bed (approximately 10 ft thick) consisting of regolith (weathered bedrock) or alluvial material underlies clayey deposits of about 50 ft thick. The aquifer in this area is confined, and well yields probably do not exceed 100 gal/min.

Hydraulic conductivity values for aquifers in the Salinas to Patillas area range from 1 to 550 ft/d. The higher values occur in the principal flow zone in the Salinas fan. The storage coefficient of the confined parts of the principal flow zone was determined to be 0.0003. A specific yield value of 0.25 was used to represent unconfined conditions. The principal flow zone has an apparent horizontal anisotropy ratio of 1.62 to 1.00, with the major principal transmissivity axis oriented north 28° west. A vertical to horizontal anisotropy of 1:1,000 was adopted from a study in the Ponce area.

An updated interpretation of the areal variability of hydraulic conductivity of fan-delta and alluvial deposits, and of the altitude of the regolith surface, was used in the development of a digital ground-water-flow model using MODFLOW, a modular finite-difference code. A three-layer model in which each layer represented distinct geohydrologic units was constructed, covering an area of about 196 mi^2. The model was calibrated using the March 1986 hydrologic conditions and tested using a transient simulation from 1890 to 1986.

The transient simulation was used to estimate the predevelopment ground-water-flow conditions and the effects of water-resources development on the aquifer system. An estimate of predevelopment conditions is based on a conceptual ground-water-flow model having two sources of recharge (upper river reaches seepage and recharge from rainfall) and four discharge components (coastal swamps and springs, seepage to lower river reaches, discharge to the seabed, and evapotranspiration near the coast). Results obtained with the ground-water-flow model indicate that the predevelopment water budget was about 43 ft^3/s. The development of water resources in the Salinas to Patillas area may have increased the water budget by a factor of three from 1920 to 1965 to 126 ft^3/s. In 1986, the water budget of the aquifer system remained higher than the predevelopment budget by a factor of two.

A sensitivity analysis, using the dimensionless relative sensitivity approach, was done on the model to identify the hydrologic and geohydrologic factors that are most relevant to the model and to assess the effect of their variability or uncertainty on the reliability of the model's response. For purposes of the sensitivity analysis, the hydrologic and geohydrologic factors were divided into three categories or groups: (1) hydrologic variables, (2) hydraulic coefficients, and (3) boundary hydraulic coefficients.

The sensitivity analysis indicated that the most active of the hydrologic factors group are recharge from irrigation applications, recharge from rainfall, and streamflow infiltration at the upper river reaches. From the hydraulic coefficients group, the hydraulic conductivity of model layer 2 is the most active followed by the irrigation canal-bed conductance, transmissivity of model layer 3, horizontal anisotropy ratio of model layer 2, and vertical conductance between model layers 2 and 3. The conductance of the sea-face boundary is the most active parameter within the boundary hydraulic coefficients group. The evapotranspiration extinction depth was determined to be an inactive parameter in all cases and is not important in simulations. The streambed conductance of lower river reaches is a nuisance parameter and the possibility of withdrawing its representation from the model can be considered in future simulations.

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