SIMULATION OF GROUND-WATER FLOW IN THE RIO YAUCO ALLUVIAL VALLEY, YAUCO, PUERTO RICO

By

Vicente Quiñones-Aponte

U.S. GEOLOGICAL SURVEY

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

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

Multiply inch-pound units	By	To obtain SI units
inches (in)	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
mile (mi)	1.609	kilometers (km)
square mile (mi^2)	2.590	square kilometers (km^2)
acre	4047.	square meters (m^2)
acre-feet (acre-ft)	1233.	cubic meters (m^3)
gallon per minute (gal/min)	0.06309	liters per second (L/s)
million gallons per day (Mgal/d)	3785.	cubic meters per day (m^3/d)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
square feet per day (ft^2/d)	0.0929	Square meters per day (m^2/d)

U.S. DEPARTMENT OF THE INTERIOR · GEOLOGICAL SURVEY ·

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ABSTRACT

A digital ground-water flow model of the Río Yauco alluvial valley aquifer was constructed and calibrated utilizing available hydrologic data. The model can be used to evaluate, with reasonable accuracy, the effects of artificial or natural stresses on the aquifer water levels.

The model was calibrated for steady-state and transient conditions. An estimated aquifer water budget as of October 1960 was used in the steady-state calibration. Ground-water levels and surface water data from 1979 to 1983 were used in the transient evaluation.

The sensitivity analysis indicated that the streambed vertical hydraulic conductivity to thickness ratio is the most sensitive hydrologic parameter of the aquifer. Changing the ratio of the streambed vertical hydraulic conductivity to thickness caused significant effects on the rates of water released from streams that affected the entire aquifer at relatively small time periods. Changes of recharge and evapotranspiration rates caused the least significant effects on the aquifer water levels.

Type curves showing the response of the aquifer to various streamflow and pumpage condition were developed with the model. The curves were used for a general evaluation of the aquifer.

INTRODUCTION

The Puerto Rico Department of Natural Resources (PRDNR) began a program in 1973, for the management and conservation of the water resources at selected areas of intense development. Such areas were designated as "critical areas" for the purpose of water use and extraction permits under the Puerto Rico Water Law of 1976. The Río Yauco alluvial valley aquifer, in south-central Puerto Rico (fig. 1) was among the zones designated as critical areas.

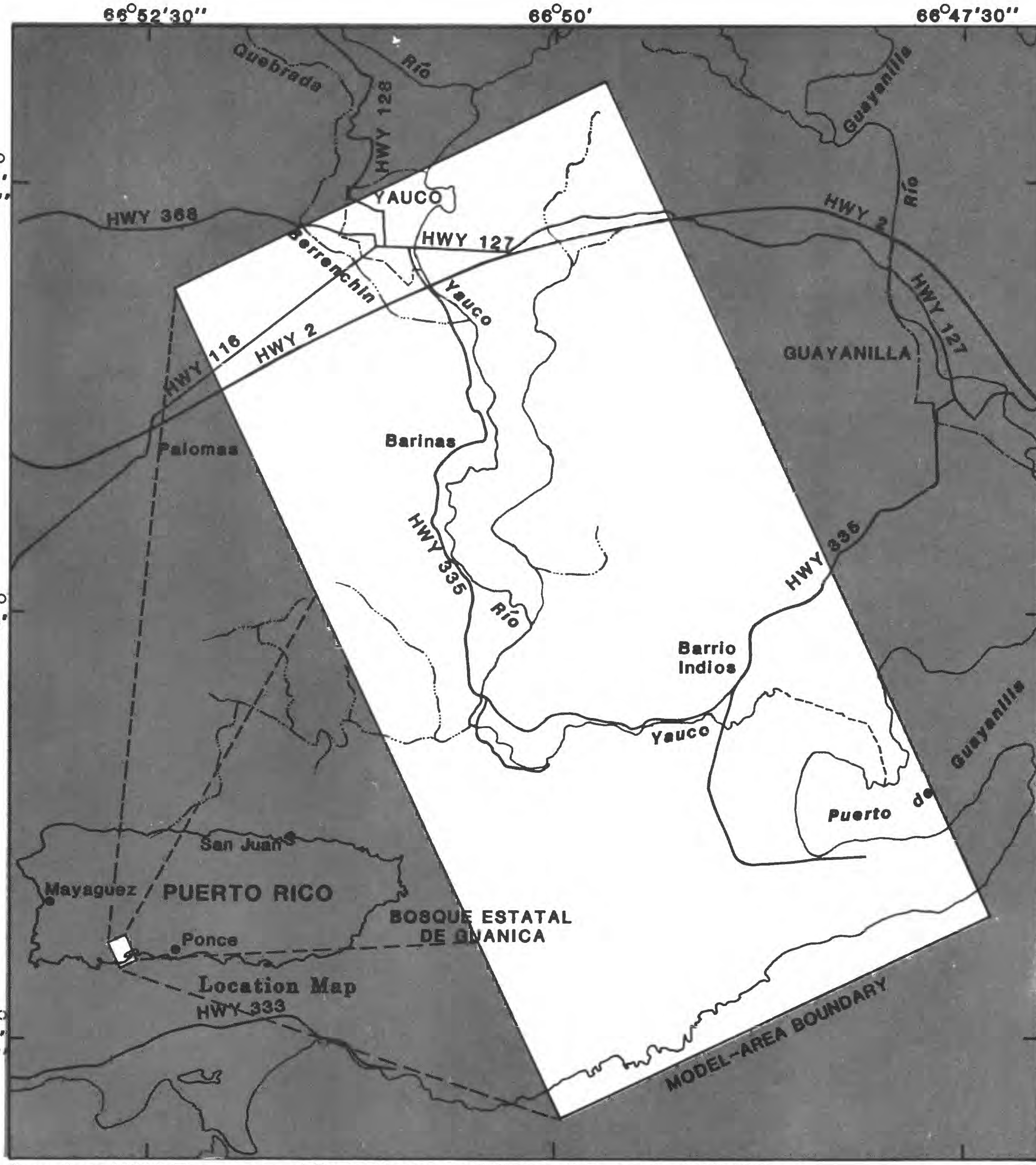
Salt-water contamination of the Yauco alluvial aquifer was reported in the early 1970's as result of ground-water withdrawals of approximately 8 million gallons per day (Mgal/d). The aquifer was almost depleted of freshwater by a combined effect of ground-water withdrawals, diversion of streamflow for irrigation, and a localized drought.

The vulnerability of the Yauco alluvial aquifer to salt-water intrusion has been recognized by both the PRDNR and the principal industrial users in the area. Based on that, the PRDNR implemented regulatory measures to prevent future improper use of the ground-water in the valley. However, ground-water withdrawals declined from an average of 6 Mgal/d in 1981 to about 2 Mgal/d in 1984 as a result of declining industrial operations. Salt-water contamination is no longer a major problem in the aquifer.

In 1980, the U.S. Geological Survey (USGS), in cooperation with the PRDNR, began a project to design, construct, and calibrate a two-dimensional ground-water flow model of the aquifer within the Río Yauco alluvial valley. The objectives of the project were to construct and calibrate a digital-computer model of the Río Yauco alluvial valley aquifer using available hydrologic data and, provide the PRDNR with a management instrument to estimate potential effects of additional water withdrawal in the hydrologic system (aquifer and river) of the Río Yauco alluvial valley.

Data from previous investigations were used as a base for the conceptualization, construction, and calibration of the Río Yauco alluvial valley aquifer model. The hydrology of the valley was described by Crooks and others (1968). Bennett (1976) developed a regional analog model of the south coast alluvial aquifers including the Río Yauco alluvial valley. Heisel and Gonzalez (1979) developed a hybrid digital-analog model to evaluate the water budget and the feasibility of increasing recharge by irrigating or injecting treated wastewater into the south coast alluvial aquifers. The geology of the general area is discussed in detail by Monroe (1976, 1980).

The assistance of the PRDNR is gratefully acknowledged for providing information on water levels and yields for various wells located throughout the valley. Special thanks to Engineer Raymond Acevedo for making available most of the data necessary for the transient calibration of the model.



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000.

Figure 1.--Location of study area.

LOCATION AND DESCRIPTION OF THE STUDY AREA

The Río Yauco alluvial valley is located on the south coast of Puerto Rico, 16 miles (mi), west of Ponce (fig. 1). The alluvial valley is approximately 24,000 feet (ft) long by 2,000 ft wide and irregular in shape. Río Yauco flows through a narrow canyon bounded by steep-walled limestone ridges on which karst topography is being developed. The valley has a moderate topographic relief. Near the coast Río Yauco has formed an alluvial fan which merges with the Río Guayanilla fan.

The mean-annual rainfall is less than 40 inches (in.), (Calvesbert, R.J., 1970), while temperatures range from 24 to 32 degrees celsius (°C), the potential evapotranspiration is above 100 percent of the rainfall (Crooks and others, 1968, p. 13). Evapotranspiration from the alluvial aquifers in the south coast was a major mechanism of ground-water discharge until intense ground-water withdrawals began (Bennett, 1976, p. 7). The pumpage has reduced the evapotranspiration by lowering the altitude of the water table.

Agriculture has been the only activity within the valley due to periodic flooding. Traditionally most of the tillable land was dedicated to sugarcane cultivation. In 1982, the Central Guánica sugar mill closed operations. As of 1984, about 50 percent of the land in the valley had been left fallow.

Geology

The general geology in the study area includes three principal lithologic units: 1) the river alluvium, 2) the Ponce Limestone, and 3) the Juana Díaz Formation. The area covered by the model grid is predominately alluvium and Ponce Limestone (fig. 2). The Juana Díaz Formation is exposed only near the northern boundary of the study area (fig. 2).

The alluvium is composed of sand, gravel, clay, and silt. Sand and gravel are poorly sorted and also intermixed with finer sediments. Clay and silt occur along the entire length of the valley but mainly in the lower part. Thickness of the alluvium ranges from a few feet along the edge of the valley to as much as 200 ft as noted in logs of wells located near the center of the valley.

The Ponce Limestone overlies the Juana Díaz Formation and is in itself overlain by the alluvial sediments in the valley area. This middle Tertiary formation crops out at numerous places along the south coast of Puerto Rico. It consists of yellowish-orange, chalky limestone and is very fossiliferous. Unlike the Tertiary limestones deposits of northern Puerto Rico, the Ponce Limestone has apparently not developed a high degree of secondary porosity and is not a significant source of ground water in this area. Within the valley, the thickness of the Ponce Limestone could be in excess of 650 ft (Monroe, 1980, p. 81).

The Juana Díaz Formation underlays the Ponce Limestone. This formation is composed of conglomerate, sandstone, sandy limestone, and some shale (Crooks and others, 1968, p. 34). The Juana Díaz Formation is not important as a source of water due to its low permeability and for the most part contains saline water even at the outcrop areas.

There are others less important lithologic units within the study area (fig. 2). The limited areal extention of the beach, dune, and colluvial deposits and the very low permeability of the cretaceous rocks make such formations nonimportant as sources of water.

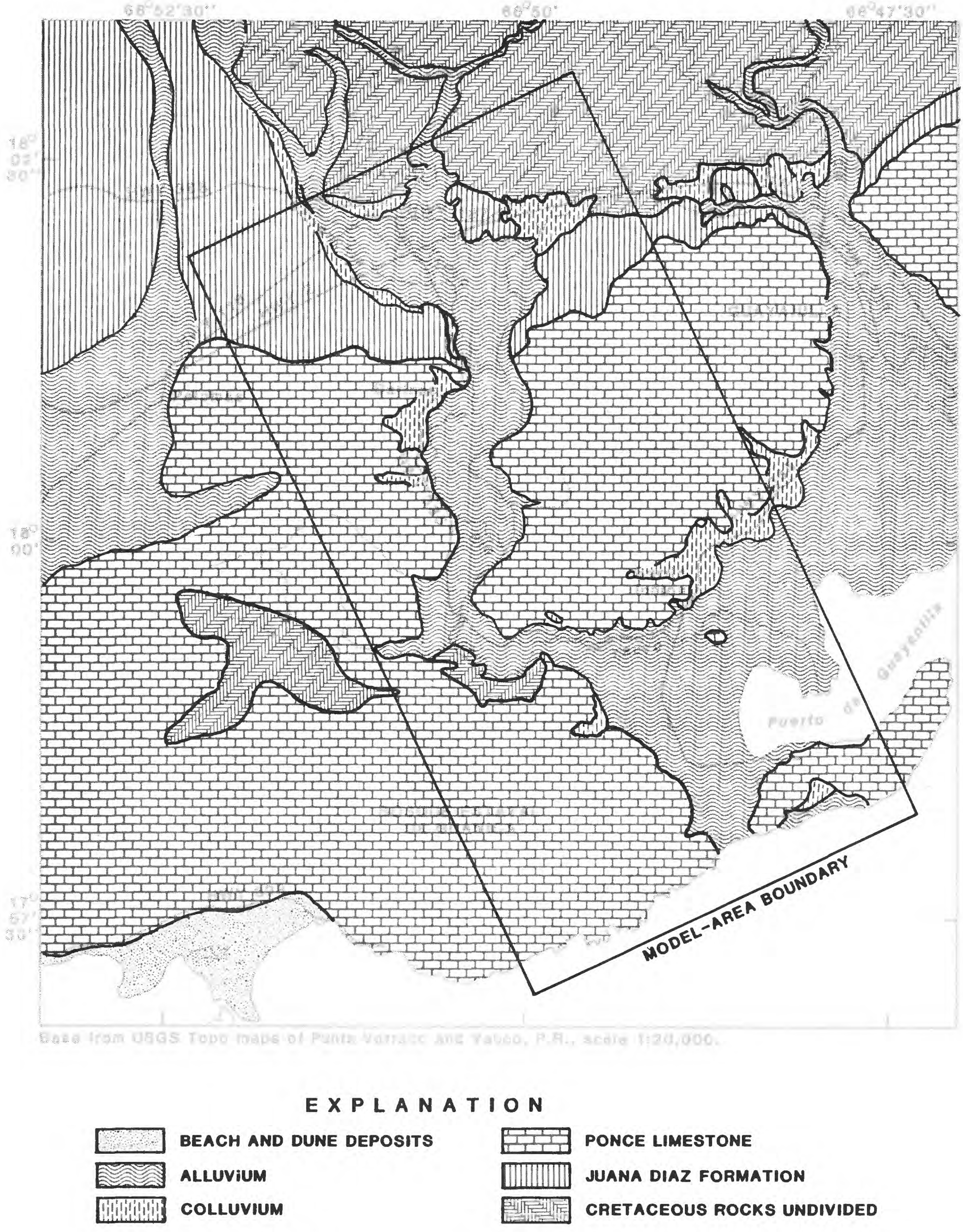


Figure 2.--Geology of the Yauco area. (Adapted from Crooks and others, 1968).

Surface-Water Hydrology

Río Yauco is the major drainage feature in the basin. Headwaters of Río Yauco originate on the rugged south slopes of the Cordillera Central, approximately 9 mi. northwest of the town of Yauco. Total basin drainage area is about 46 square miles (mi^2).

Lago Lucchetti reservoir (fig. 3) is the major and most important flow-regulation structure within the basin. It has a drainage area of 17.3 mi^2 and a storage capacity of about 16,450 acre-ft (Crooks and others, 1968, p. 18). Water from various reservoirs in the Río Grande de Añasco basin is diverted by tunnel to Lago Lucchetti. This flow is used at a hydroelectric plant located on the north shore of Lago Lucchetti (fig. 3). Most of this water is then diverted through another tunnel to a second hydroelectric plant and later discharged to Lago Loco (fig. 3). A lesser amount of water is released through the Lago Lucchetti dam to satisfy streamflow appropriation rights from Río Yauco (1.9 cubic feet per second (ft^3/s), U.S. Corps of Engineers, (USCOE), 1979, p. 21).

The other important hydrologic structure is the irrigation canal system which diverts water from Río Yauco at different points along the alluvial valley (fig. 3). Streamflow diverted through canals has been used for sugarcane irrigation in the central and lower parts of the Río Yauco alluvial valley for several years. The irrigation canal system has a maximum combined conveyance capacity of 17 ft^3/s (Crooks and others, 1968, p. 37).

Differences in the mean-annual discharge of Río Yauco (1978 to 1982), between the two USGS gaging stations, 50126150 and 50128000, (fig. 3) indicate that stream leakage combined with a consistent withdrawal of water from the river through the irrigation canals amounted to about 5 ft^3/s. Moreover, an analysis of flow-duration curves for the two stations show stream leakage combined

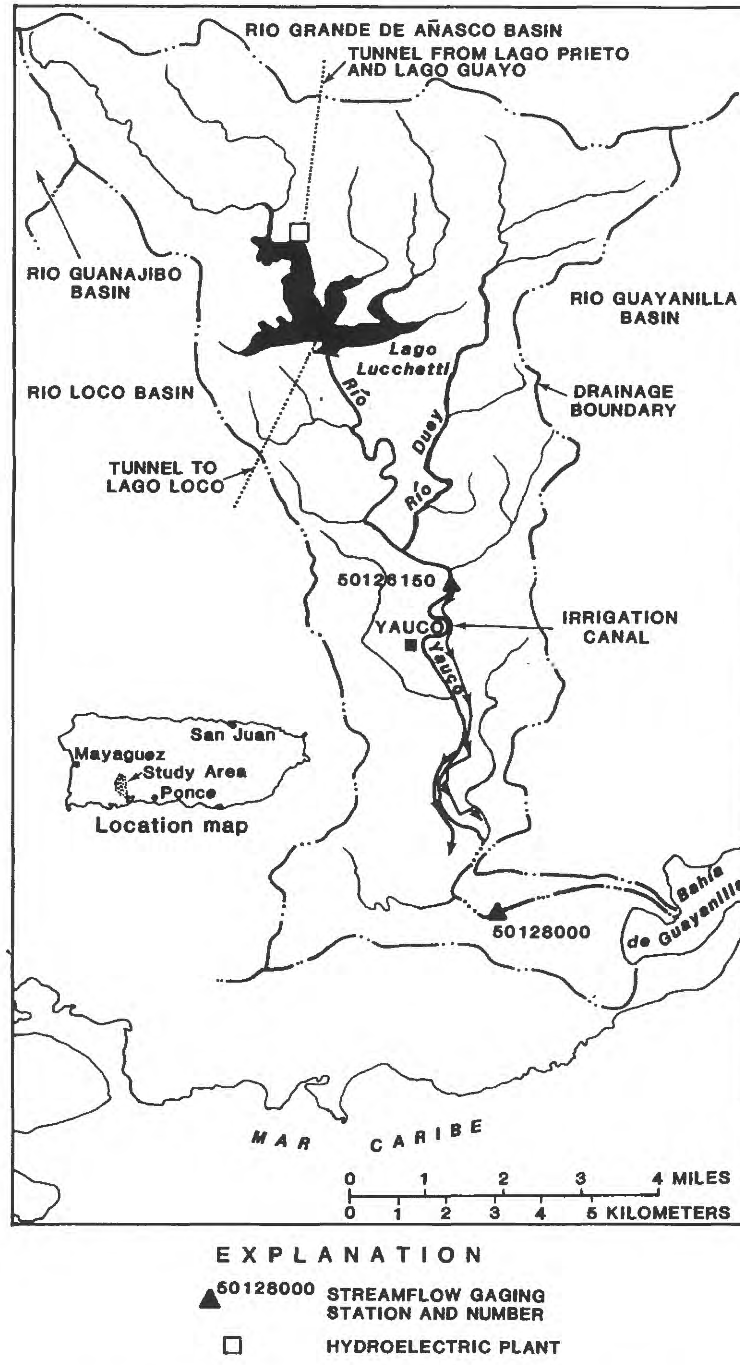


Figure 3.--Hydrologic features within Río Yauco basin..

with withdrawals through the irrigation canals that fluctuate from 1.3 ft^3/s during 98 percent of the time to 12 ft^3/s during 13 to 25 percent of the time (fig. 4). The largest streamflow losses produced by the combined effect of stream leakage and withdrawals through irrigation canals (12 ft^3/s, during 13 to 25 percent of the time) occur when streamflow entering to the valley is between 15 to 30 ft^3/s and the water table is lower than the stream surface. When streamflow is greater than 30 ft^3/s the water table approaches the altitude of the stream surface. As the difference in head decreases, the leakage to the aquifer decreases. Streamflow losses from the combined effect of leakage and withdrawals can dry the river along the central and upper parts of the valley when streamflow entering the valley is less than 6 ft^3/s (fig. 4).

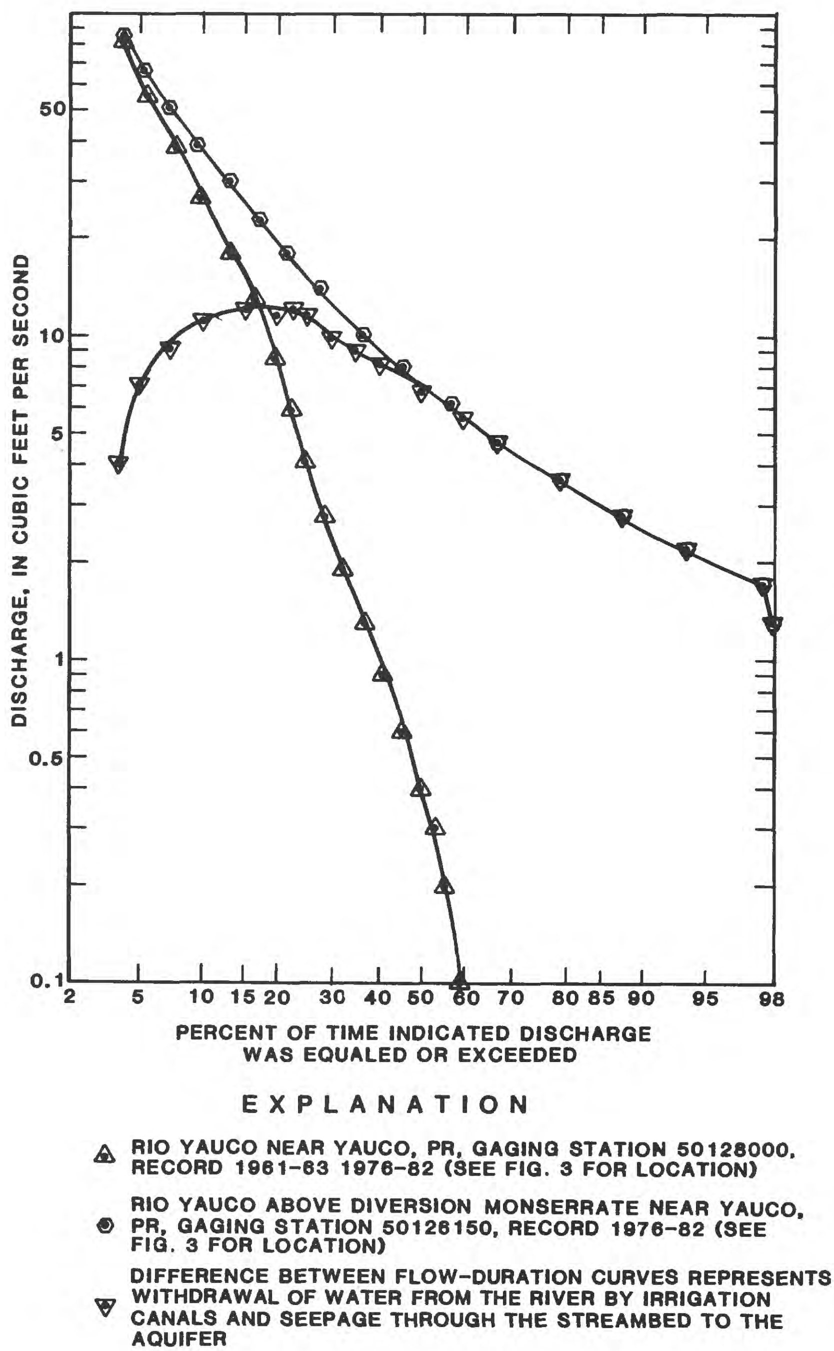


Figure 4.--Flow-duration curves of daily values and difference between flow-duration curves for Río Yauco.

GEOHYDROLOGY

Ground water is assumed to occur only within the unconsolidated alluvial deposits of the Río Yauco valley. The Ponce Limestone is an important source of water to wells in certain localities of the south coast of Puerto Rico, but in the study area it is not very productive (Crooks and others, 1968, p. 33). The Juana Díaz Formation yields only small quantities of saline water along the south coast of Puerto Rico and in most areas is not considered an aquifer (Crooks and others, 1968, p. 34).

The alluvial aquifers along the south coast of Puerto Rico are, in general, under water-table conditions (Crooks and others, 1968, p.28). Some flowing artesian wells have been reported within the south coast, however, these wells are in isolated localities and therefore it is assumed that artesian conditions are not regional in nature.

Water levels throughout the Río Yauco alluvial valley aquifer have fluctuated from 10 to 36 ft below land surface during the last ten years. These fluctuations can be associated with ground-water withdrawals within the valley and a reduction of streamflow leakage to the aquifer by diversion of river flow through irrigation canals. About 30 percent of the water used for irrigation was estimated to percolate and recharge the water-table aquifer (Giusti, 1971, p. B250)

Recharge to the aquifer is higher in areas where the river loses water (leakage), or in sugarcane fields due to irrigation. There is visual evidence that Río Yauco lost more water to the aquifer, in the upper part of the valley than in any other place, however, the river is really gaining rather than losing in the lower alluvial fan. The maximum recharge rate from irrigation is assumed to be from 25 to 30 percent of the total water applied to the sugarcane fields, which are located in the central and lower parts of the valley.

Direct evapotranspiration (ET) from the aquifer (0.0006 ft/d) occurs mainly in the lower part of the valley due to the location of the water table in relation to the ET extension depth (depth to which ET is effective). Rates of evaporation from the ground-water surface were found to be insignificant at depths in excess of 6 feet from the ground surface (Gardner and Fireman, 1958).

Ground-water recharge from rainfall is minimal because the frequency, intensity, and duration of the typical rainfall events are low and short.

The freshwater saturated thickness of the alluvial aquifer ranges from 5 ft in the vicinity of Yauco where the alluvium pinches out to as much as 170 feet near the central part of the valley.

Alluvial Aquifer Properties

Aquifer properties of the Río Yauco alluvial valley aquifer were obtained from previous investigations or estimated from existing field data. The hydraulic conductivity of the alluvium varies, increasing inland from 13 feet per day (ft/d) near the coast to 200 ft/d at the northern part of the study area (Bennett, 1976, p. 19). On this basis, the aquifer was assumed to be heterogeneous horizontally. Hydraulic conductivity was assumed to be uniform at different depths. Values of hydraulic conductivity were estimated from specific capacity data of wells (Bennett, 1976, p. 8). The aquifer can be considered isotropic because the narrow width of the valley resulted in uniform deposition of sediments during the formation of the alluvial valley.

The specific yield of the alluvial aquifer was estimated as 0.15. This value was estimated by Giusti (1971, p. B249) for the Coamo fan deposits which are similar to those in the Río Yauco valley.

GROUND-WATER FLOW SIMULATION

Digital models for ground-water flow simulation are being increasingly used as an aid in the management of water resources. The model is just a simple mathematical representation of the actual hydrologic environment within the aquifer. A calibrated model (a model for which all the parameters estimated are acceptable) can be utilized to design a water development plan and establish critical conditions or limits providing a measure for aquifer management through planned withdrawals of water.

There are three principal steps in the preparation process of a model for the simulation of ground-water flow: 1) conceptualization, 2) construction, and 3) calibration. The conceptual model is a number of assumptions which make it possible to approximate the behavior of ground-water flow systems mathematically. The construction of the model is the process of representing the model in a numerical form. The calibration procedure involves the process of adjusting the hydrogeologic parameters in order to obtain a good match between observed and simulated water levels, and stream-aquifer interaction.

Two-Dimensional Finite-Difference Model

Ground-water flow and stream-aquifer leakage in the Río Yauco alluvial valley aquifer were simulated using the modular finite-difference model of McDonald and Harbaugh (1984). The program computes finite-difference approximations of the partial differential equation for ground-water flow. The computational process is described in the program documentation (McDonald and Harbaugh, 1984). The model can be used to compute steady-state or transient flow in an anisotropic-heterogenous aquifer, for two-dimensional or three-dimensional flow conditions.

Only the two-dimensional flow option of the model was necessary in evaluating the Río Yauco alluvial valley aquifer.

The principal limitations of the model are:

1) Precision with which the model can predict aquifer responses is directly related to the accuracy and adequacy of the input data.

2) For evaluations of present conditions of the aquifer it is necessary to update the information on pumpage, streamflow, and other water budget items.

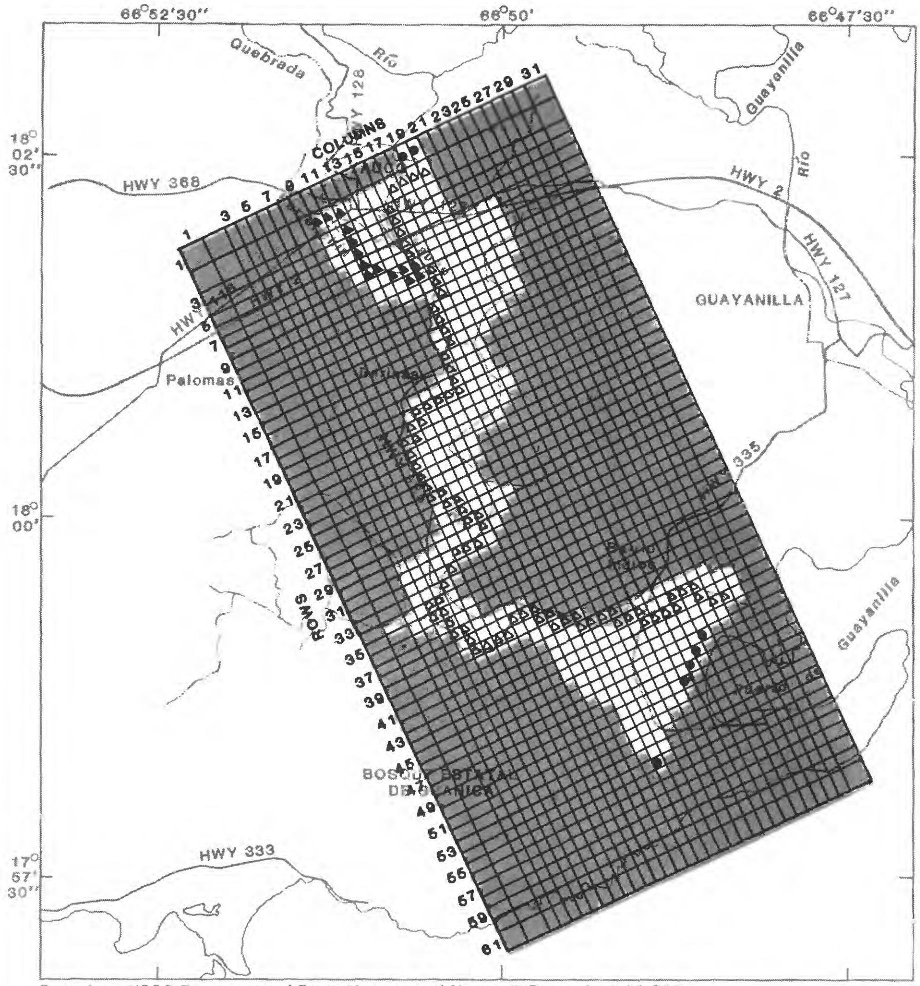
3) The model does not consider changes in the location of a moving freshwater-saltwater interface.

4) The model does not account for evaluation of salt-water intrusion induced by pumpage.

5) The computations of the model assume that pumping wells are fully penetrating the ground-water system and are 100 percent efficient.

Model Construction and Conceptualization

A finite-difference grid was constructed subdiving the study area into rectangular blocks (fig. 5). The grid covers an area of 17.5 mi^2 and consists of 61 rows by 31 columns. Cell sizes in columns 1, 2, and 31, and rows 1, 2, and 61 are 1,000 by 500 feet. All other cells are squares having sides of 500 feet (fig. 5).



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000

EXPLANATION

- ☐ FINITE-DIFFERENCE BLOCK (VARIABLE HEAD)
- ● CONSTANT HEAD CELL
- ☐ NO-FLOW BOUNDARY CELL
- △ STREAM CELL (RIO YAUCO)
- ▲ STREAM CELL (QUEBRADA BERRENCHIN)

Figure 5.--Finite-difference grid and boundary conditions used in the model.

Model Construction and Conceptualization (Continued)

The model utilizes two types of boundaries: 1) no-flow boundaries and 2) constant head. The no-flow boundaries usually are set at cells within the model grid representative of impermeable areas. The constant-head boundaries are used to simulate the ground water entering or exiting the aquifer by natural action.

The no-flow boundaries of the alluvial aquifer model were selected based on the altitude of the top of the Ponce Limestone - used to delineate the bottom of the aquifer (fig. 6). This surface defined the bottom of the alluvial aquifer everywhere in the study area, except in the lower part of the valley where the freshwater-saltwater mixing zone (Díaz, 1974, p. 8), was used to define the bottom of the aquifer. The lateral boundaries of the model were located at the outcrops of the Ponce Limestone and the Juana Díaz Formation (fig. 2), and treated as no-flow. Constant head boundaries were located in the upper and lower reaches of the valley (fig. 5) to represent areas of ground-water flow in and out of the aquifer model. The Guayanilla Bay, for example, was represented as a constant head boundary (fig. 5).

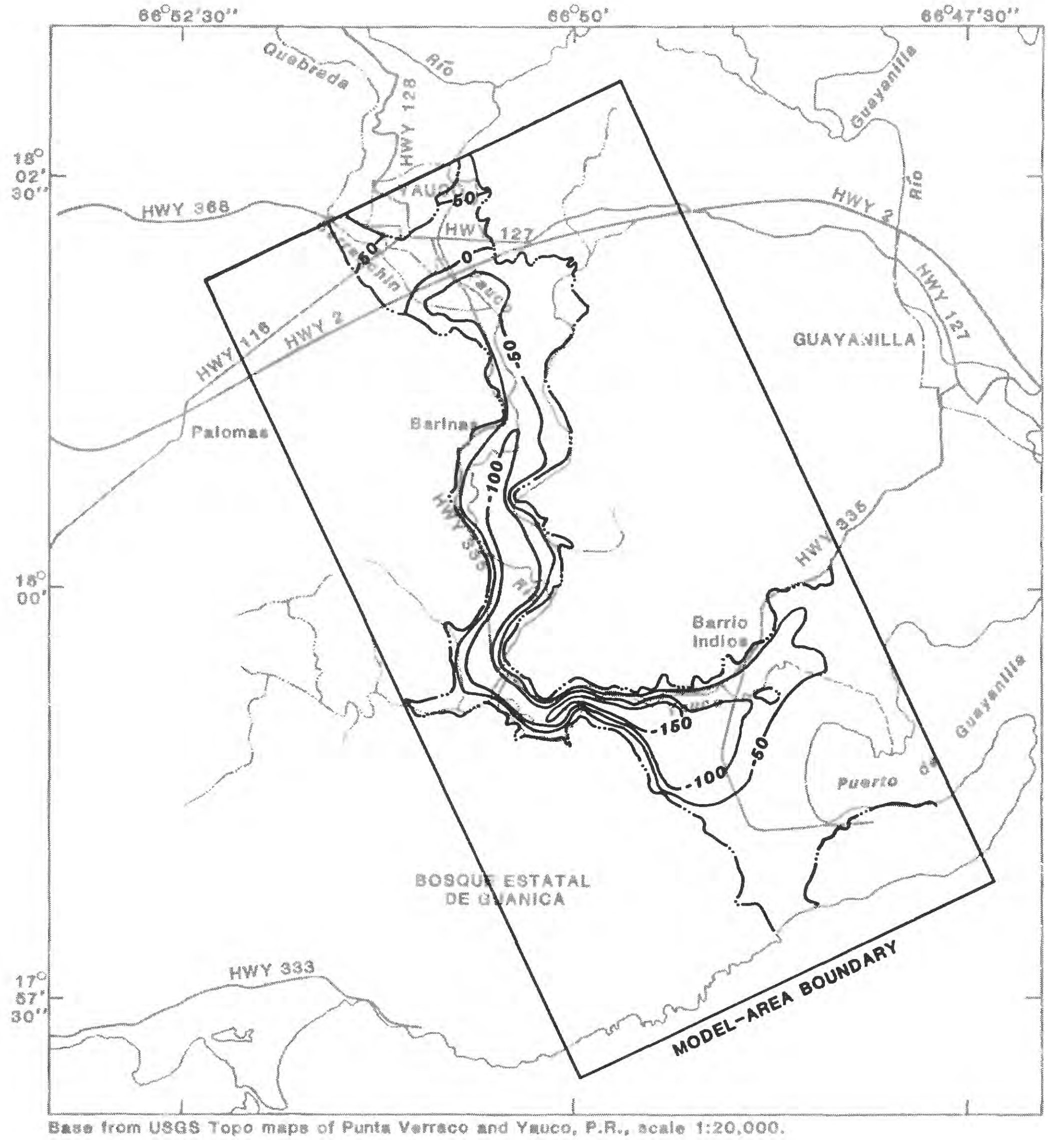


Figure 6.--Altitude of the bottom of the alluvial aquifer.

Model Construction and Conceptualization (Continued)

Hydraulic conductivities and specific yields were initially adapted from Bennett (1976, p.19), and Giusti (1971, p. B249). These parameters vary throughout the valley as follows: hydraulic conductivity from 13 to 200 ft/d, and specific yield from 0.15 to 0.25.

Stream-aquifer leakage in the model is controlled by the altitude of the water surface of the river, the head in the aquifer, the altitude of the riverbed, and the vertical hydraulic conductivity, thickness, and wetted area of the streambed. This stream-aquifer water interchange is represented in the model by an application of Darcy's ground-water flow equation to leakage through the streambed:

$$Qs = k'/b' \ (hs - ha) \ A$$

where,

- Qs = rate of leakage, in cubic feet per second;
- k' = streambed vertical hydraulic conductivity, in feet per day;
- b' = thickness of the streambed, in feet;
- hs = elevation of stream stage, in feet;
- ha = elevation of water table, in feet; and
- A = wetted area of streambed reach, in square feet.

Streambed vertical hydraulic conductivity (k') was determined by a field inspection of streambed materials along the river reach. Values of k' were estimated based on the size of sediments along the streambed. The other parameters were estimated as follows: (b') was assumed to be equal to 1 foot; (hs) were assigned from streamflow data; (ha) is computed by the model; and (A) was determined from field and map computations.

Recharge from irrigation was simulated as an areal distribution of 25 percent of the total water used at the sugarcane field. Leakage from the canals was considered negligible because the canals are constructed of concrete.

Model Calibration

The calibration of a ground-water flow digital model is performed through a iterative process. The hydrologic parameters are adjusted within reasonable limits in an attempt to obtain the best match between computed and observed water levels. Calibration is required to assure that the degree of confidence of the predicted responses, obtained by imposing hypothetical stresses to a ground-water system, is within limits that permits the the utilization of the model for practical purposes.

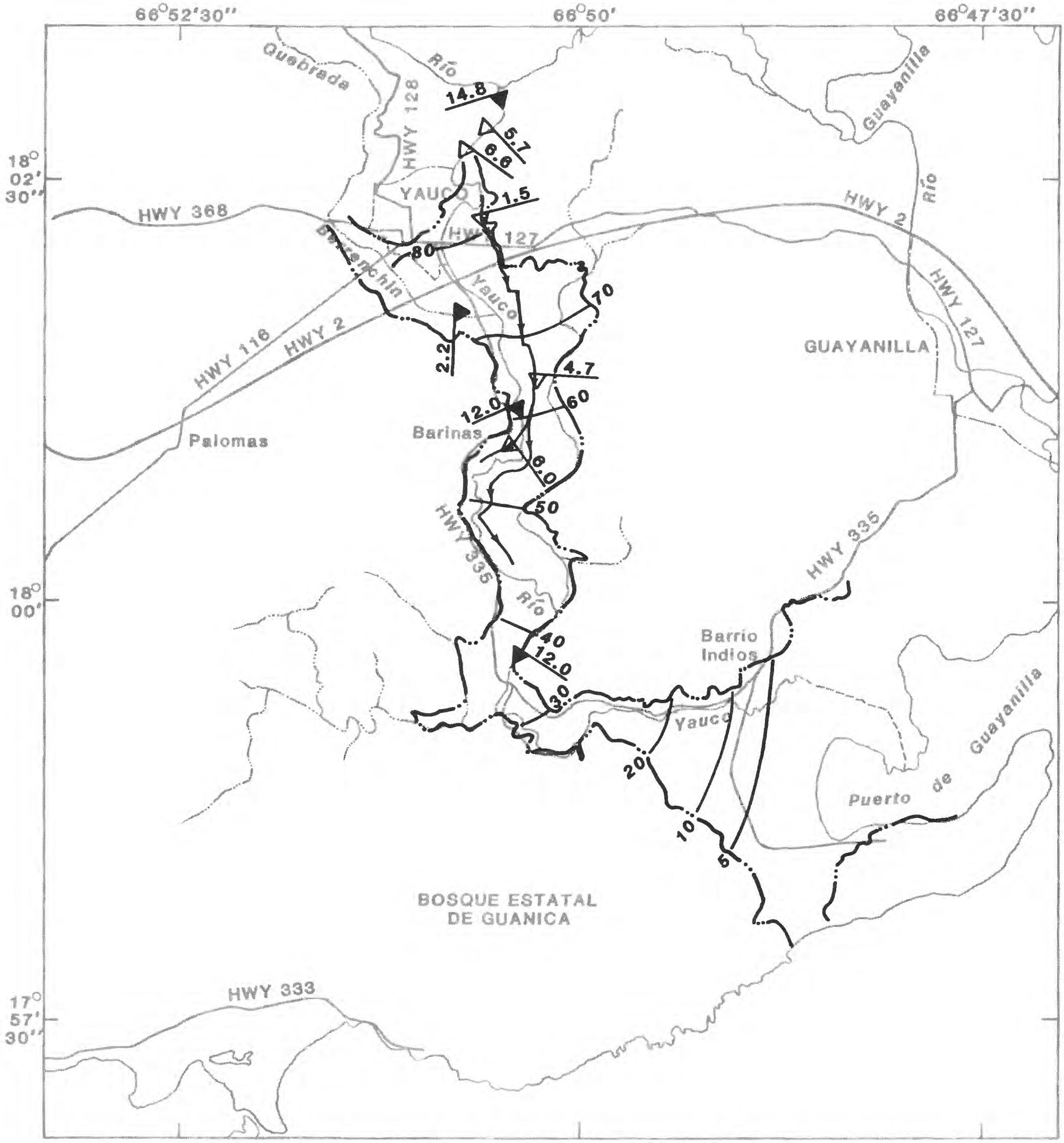
In a calibrated model, differences between computed and observed water levels should be expected. Water levels in a well are measured at a point and the computed water levels represent the average altitude of the potentiometric surface within an entire model cell. Calibration continues until these differences are acceptable within established limits depending on the areal extent covered by the cell.

Steady-State Calibration

Ground-water flow through an aquifer can be considered to be under steady-state conditions when the altitude of the potentiometric surface remains almost constant through time. Ground-water systems constantly tend to approach a new dynamic equilibrium and eventually a steady-state condition. The principal characteristic of the idealized steady-state condition is that quantities of water entering and exiting the aquifer are equal to each other; in other terms, there is no change in storage within the aquifer.

Altitudes of ground-water levels during October 19, 1960, were used as a base to match the model results (fig. 7). The location of pumping wells during October 19, 1960, was obtained from Crooks and others (1968, fig. 8). Pumping rates for the wells were estimated by a weighted distribution of the total withdrawal (5 Mgal/d) reported by Crooks and others (1968, p. 37), based on areas having more or less water production (fig. 8).

For the Río Yauco alluvial valley aquifer model, the steady-state calibration produced a good match on the lower and central parts of the valley and a fairly good match



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000.

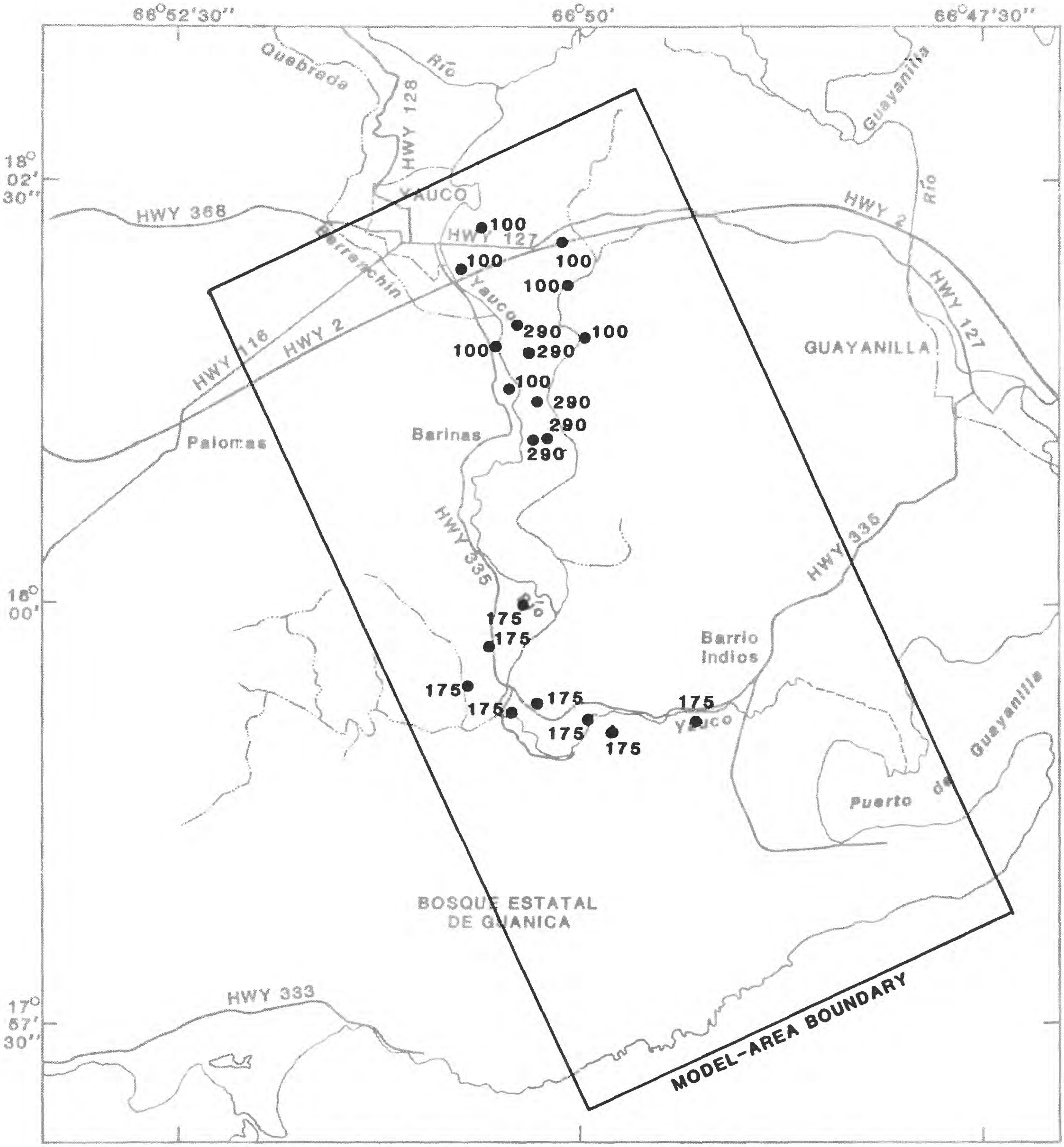
EXPLANATION

——*50*—— **WATER-TABLE CONTOUR** – Shows altitude of water table in alluvium. Contour interval 5 and 10 feet. Datum is mean sea level.

12.0 ▼ **STREAMFLOW** – Number denotes flow in cubic feet per second. Arrow indicates direction of flow.

6.0 ▽ **FLOW THROUGH IRRIGATION CANAL** – Number denotes flow in cubic feet per second. Arrow indicates direction of flow.

Figure 7.—Streamflow, flow through irrigation canals, and ground-water levels during October 19, 1960. (From Crooks and others, 1968).



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000.

EXPLANATION

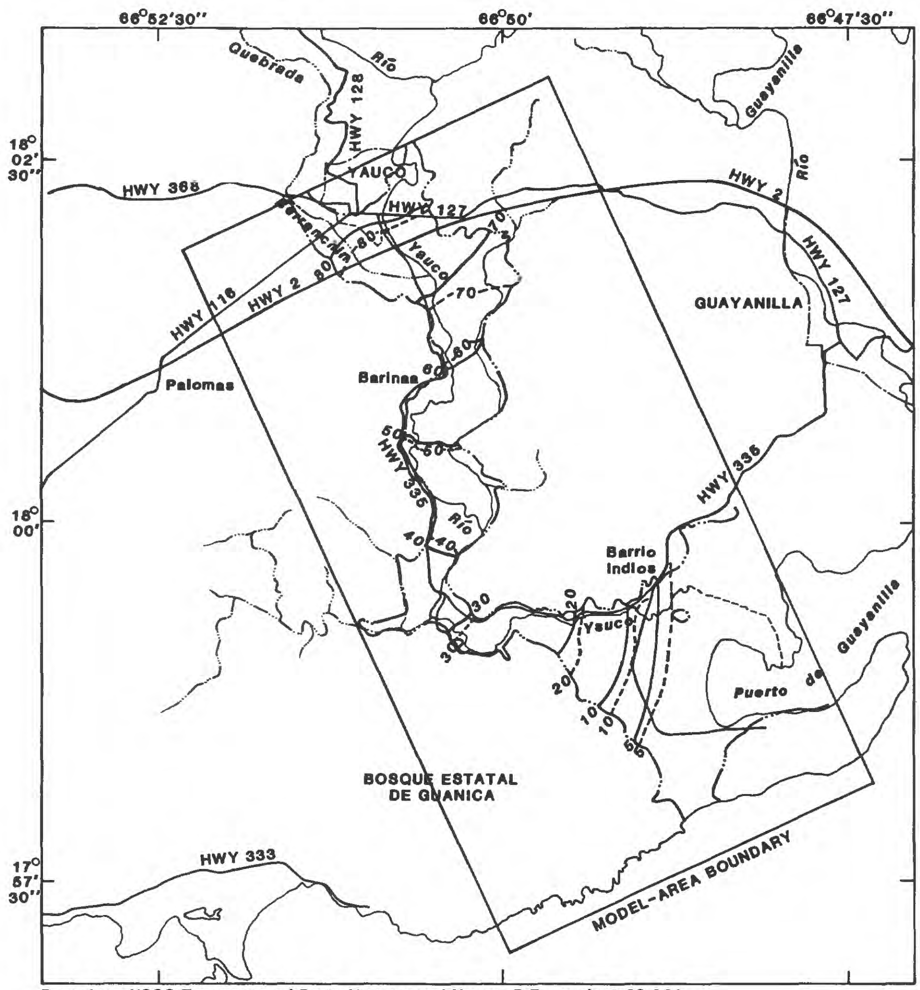
● WELL LOCATION

175 PUMPING RATE IN GALLONS PER MINUTE (VALUES REPRESENT EQUIVALENT 24 HOURS PUMPING RATE).

Figure 8.--Location of wells pumping during October 19, 1960.

at the upper part (fig. 9). The first step in the steady-state calibration process was to match the altitude of the water table at the stream cells to the October 19, 1960 condition by adjusting the streambed vertical hydraulic conductivity to thickness ratio (k'/b'). The second step was to adjust the hydraulic conductivity values at all active cells throughout the model. The initial hydraulic conductivity values used in the steady-state calibration were: 200 ft/d in the upper part of the valley, 67 ft/d in the central part, and 13 ft/d in the lower part.

No changes were required in the upper area of the model. However, in order to calibrate the model on the central and lower parts of the valley, the hydraulic conductivity values were modified from 67 to 150, and 13 to 5 ft/d respectively (fig. 10). Using these hydraulic conductivity values and the aquifer thickness throughout the valley, a transmissivity map (fig. 11) was prepared showing values ranging from 15,000 to 30,000 ft^2/d in the upper and central parts of the valley, and from 100 to 700 ft^2/d in the lower part of the valley (alluvial fan).



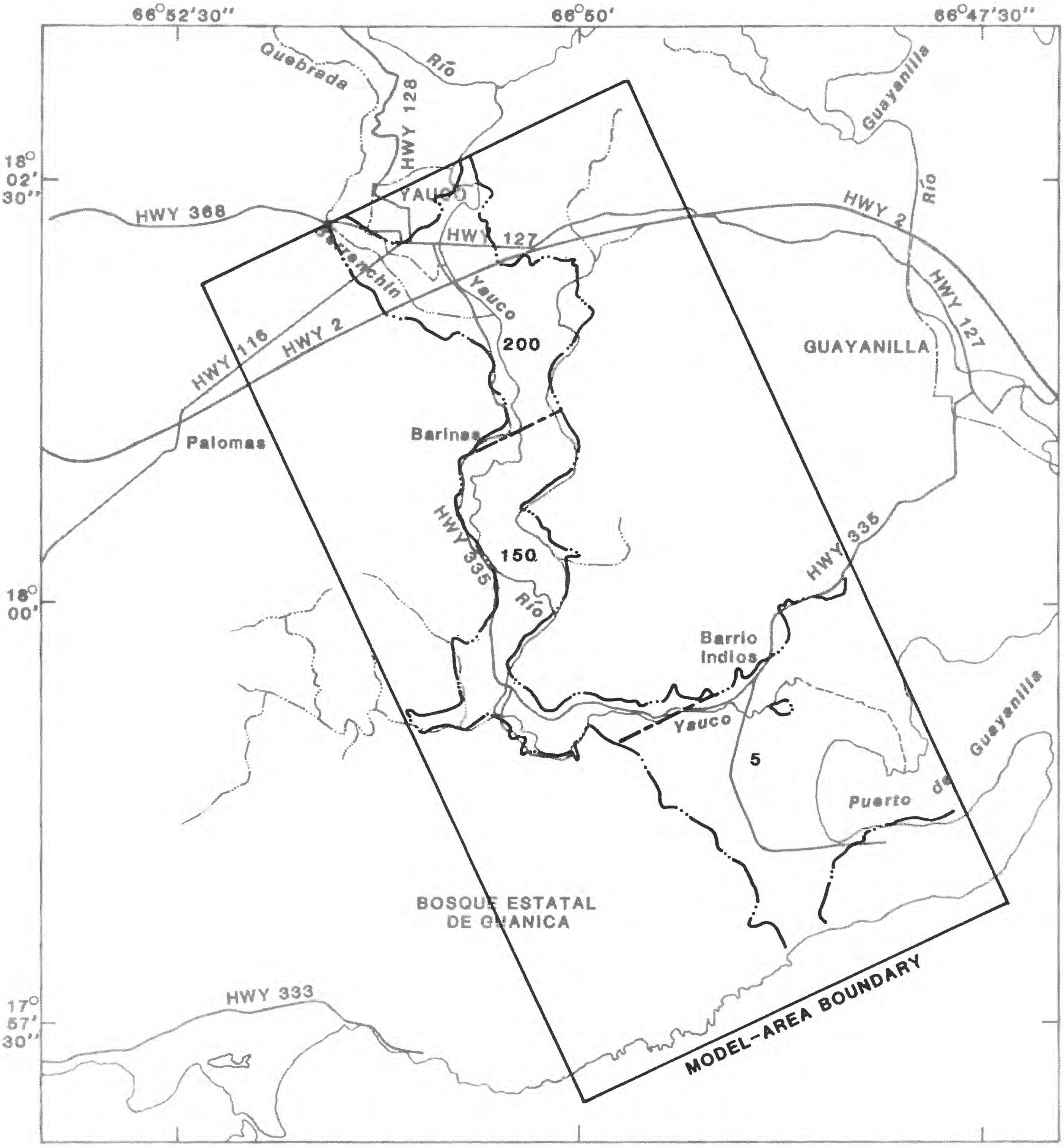
EXPLANATION

—5— MEASURED WATER-TABLE CONTOUR – Shows altitude of water table based on water levels measured during October 19, 1960. Contour interval 5 and 10 feet. Datum is mean sea level.

—5— SIMULATED WATER-TABLE CONTOUR – Shows simulated altitude of the water table after 1 day pumping period, steady-state condition. Contour interval 5 and 10 feet. Datum is mean sea level.

—·—·— AQUIFER BOUNDARY (BEDROCK)

Figure 9.--Observed and simulated altitude of the water table during October 19, 1960, steady-state condition.



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000.

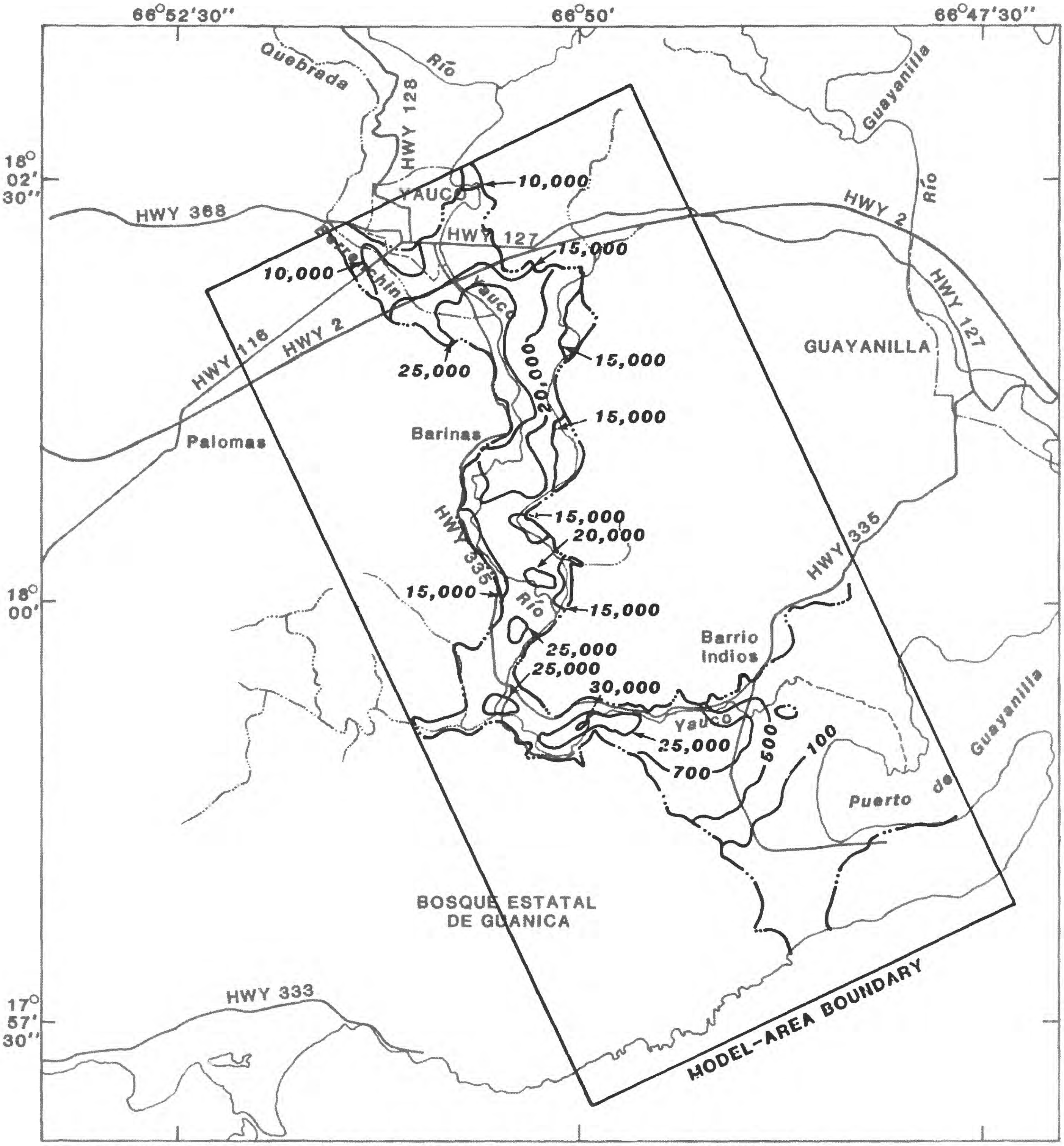
EXPLANATION

— — — BOUNDARY BETWEEN AREAS OF DIFFERENT HYDRAULIC CONDUCTIVITY

5 HYDRAULIC CONDUCTIVITY (FEET PER DAY)

—··— AQUIFER BOUNDARY (BEDROCK)

Figure 10.--Areas of equal calibrated hydraulic conductivity in the alluvial aquifer.



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000.

EXPLANATION

— 100 — LINES OF EQUAL TRANSMISSIVITY (FEET SQUARED PER DAY)

—··—·— AQUIFER BOUNDARY (BEDROCK)

Figure 11.--Lines of equal transmissivity generated from the calibrated model.

The steady-state calibration of the model requires an accurate water budget of the aquifer system so that the hydrologic parameters obtained from the calibration fall within limits of confidence acceptable for practical purposes. An estimated aquifer water budget for the study area was prepared based on information from Crooks and others (1968, table 1). The aquifer water budget and measurements of streamflow, ground-water levels, and streamflow diversions to irrigation canals as of October 1960 (fig. 7), were utilized as a base for the steady-state calibration of the model. Values shown on table 1 were estimated as follows: recharge from irrigation -- 30 percent of the water applied for irrigation at different localities within the valley (areal recharge), river leakage -- differences between streamflow measurements (fig. 7), constant head -- applying Darcy's equation across the northern boundary (where the alluvium pinches out), pumpage -- reported by Crooks and others (1968, p. 37), ET -- 6 percent of recharge.

The water budget simulated by the model compares favorably for most of the flow parameters with the estimated aquifer water budget (table 1). The greatest difference between items of the two budgets was 0.6 ft^3/s of stream leakage (table 1).

Table 1.--Estimated and simulated steady-state aquifer water budgets.

ESTIMATED				SIMULATED			
INFLOW (ft^3 per second)		OUTFLOW (ft^3 per second)		INFLOW (ft^3 per second)		OUTFLOW (ft^3 per second)	
Recharge		Pumpage	7.8	Recharge		Pumpage	7.85
Irrigation	3.5	ET	0.2	Irrigation	3.8	ET	1.11
River leakance	6.7	River leakance	2.5	River leakance	6.98	River leakance	1.92
Constant head	0.1	Constant head	0.0	Constant head	0.1	Constant head	0.002
TOTALS	10.5		10.5	TOTALS	10.88		10.88

Transient Calibration

Ground-water flow is considered to be under transient conditions when water is being withdrawn from aquifer storage or when recharge increases the aquifer storage. In other words, transient conditions occur during increases or decreases of aquifer storage.

In the transient condition, stresses to the aquifer usually change during different time intervals. This is represented in the model by different stress periods. A single stress period is a time interval during which stresses to the aquifer remain constant. A combination of different stress periods are used to represent changes in pumpage, recharge, stream leakage and other stresses to the ground-water system.

Five years of information on ground-water levels, ground-water withdrawals, and streamflow data at USGS stations 50126150 and 50128000 were used for the transient calibration of the model. The duration of stress periods was determined according to time variation in ground-water withdrawals and streamflow (fig. 12).

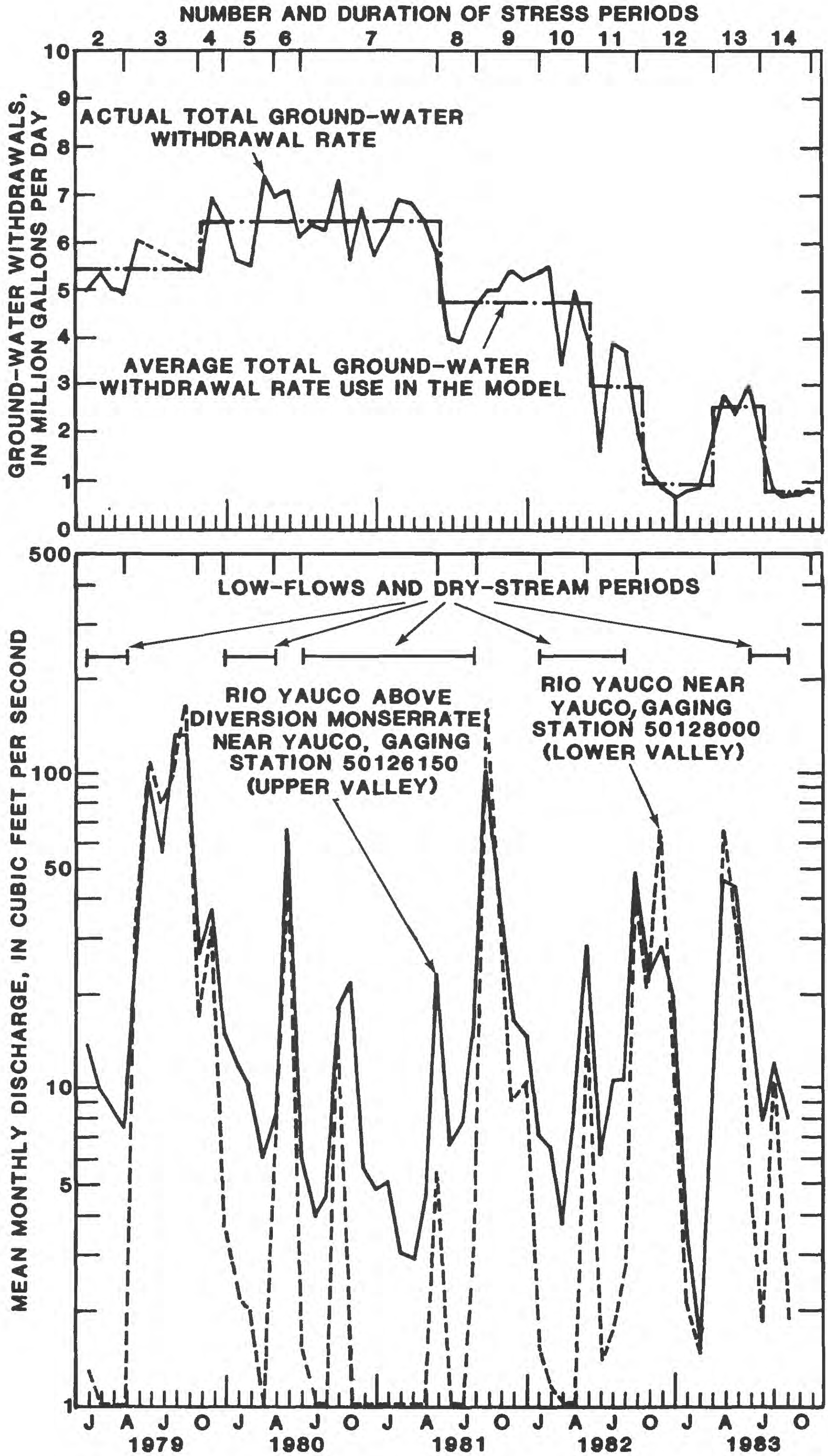
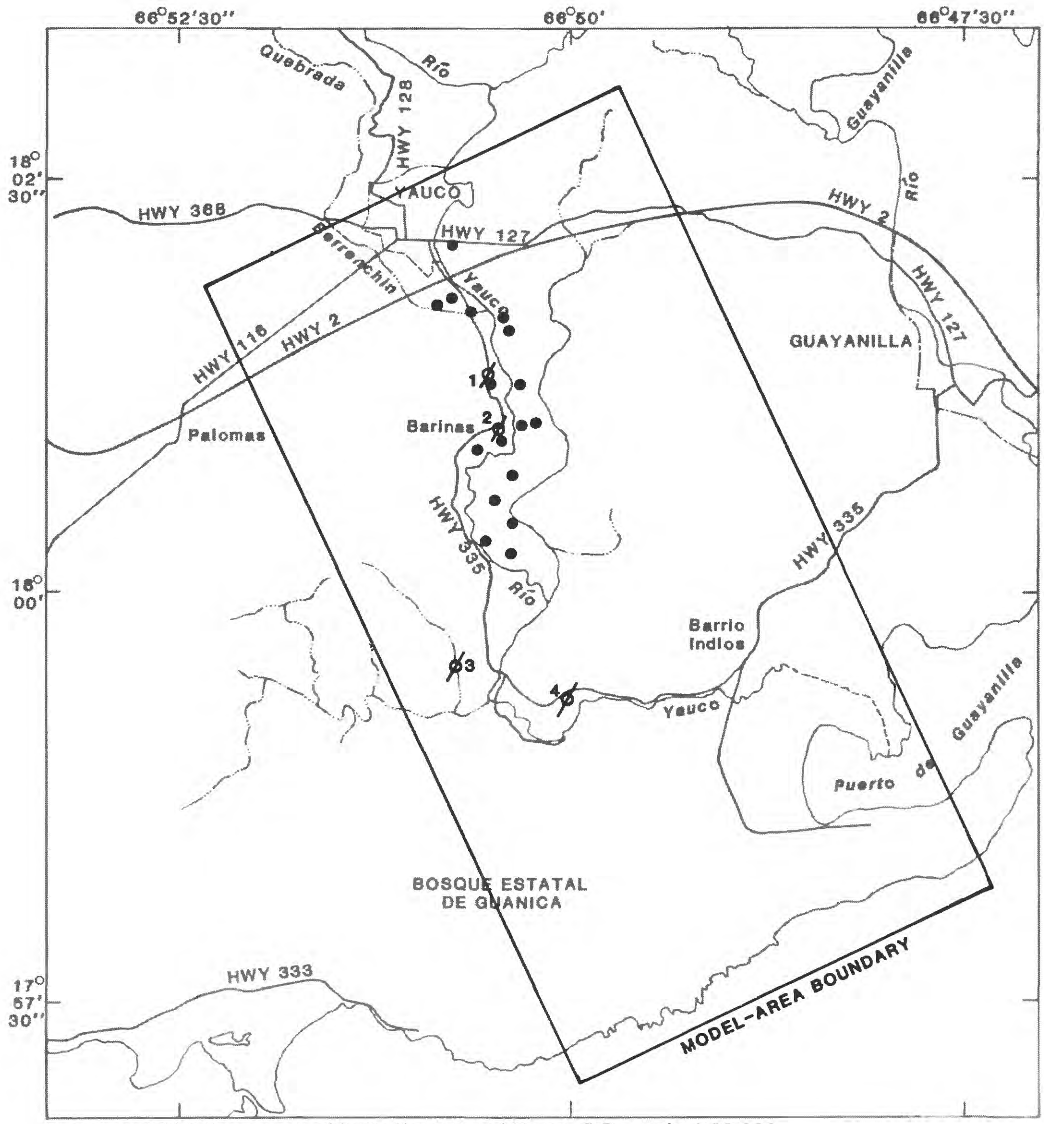


Figure 12.--Changes in ground-water withdrawals and variation in river discharge, during 1979-83, within the Río Yauco alluvial valley.

The average total ground-water withdrawn and lowflow or dry-stream periods were used as criteria in selecting time periods (stress periods) for which stresses can be assumed constant (fig. 12). Location of observation wells and production wells during the transient calibration are shown in figure 13. Total pumping rates during transient conditions ranged from 1 to 6.5 Mgal/d.



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000

EXPLANATION

● PUMPING WELLS

OBSERVATION WELL AND NUMBER

Figure 13.--Location of observation wells and pumping wells, January 1979 to December 1983, transient condition.

The transient calibration of the Río Yauco alluvial valley aquifer model was initiated using a specific yield value of 0.25. This value did not provide satisfactory results, particularly in the upper part of the valley. Simulated water levels were, in general, too high and the predicted trend departed significantly from the observed. A further attempt was made using a different specific yield value (0.15). Model results improved significantly with this value, particularly in simulating the observed water level trends in the valley (fig. 14).

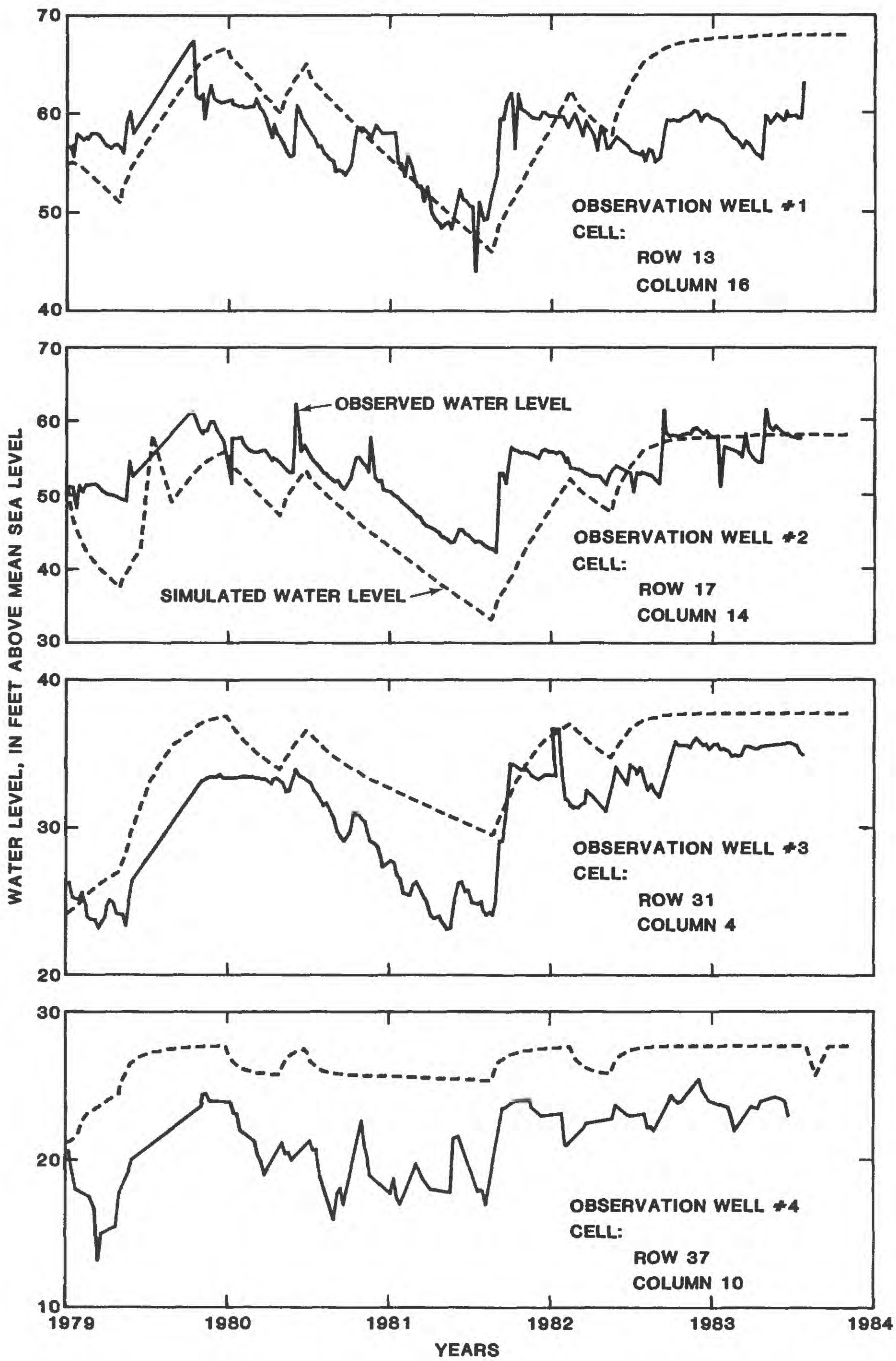


Figure 14.—Observed and simulated water levels at different areas within the valley during the January 1979 to December 1983 transient condition. (See figure 13 for well location).

Sensitivity Analyses

In order to test the sensitivity of the model to possible errors in calibration, the modeled hydrologic parameters were varied over a range of values. The resulting water levels were compared to water levels generated utilizing the calibrated hydrologic parameters. Hydraulic conductivity (K), specific yield (Sy), and the streambed vertical hydraulic conductivity/thickness ratio (k'/b') were varied by 50 percent, greater and less, than their respective calibrated values. Sensitivity analysis was also preformed for areal recharge (RCH) and evapotranspiration (ET) values, which are flow terms empirically estimated and could be subject to large errors.

A transient simulation of 16 days at a pumping rate of 2.54 Mgal/d from different wells throughout the valley (fig. 13) was used for purposes of the sensitivity analyses.

The effects of the sensitivity analysis on the aquifer water levels were observed along two cross sections located at the upper and central parts of the valley (fig. 15). At section A-A' (on the upper

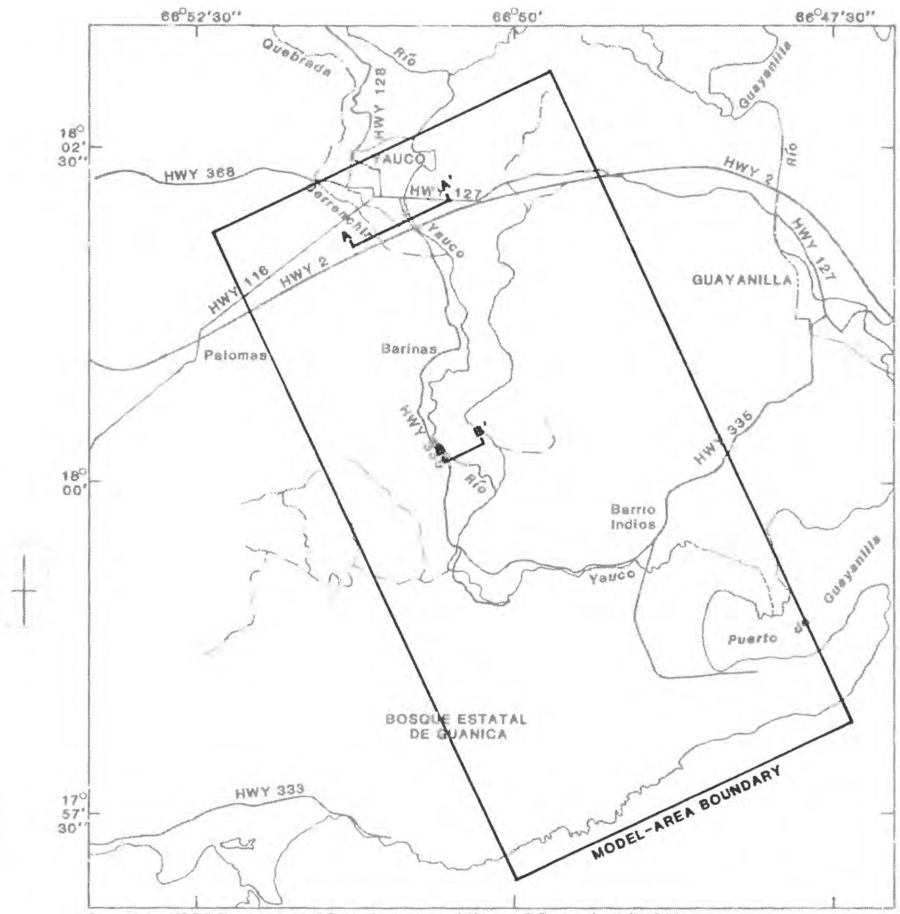


Figure 15.--Location of sections A-A' (ROW 5) and B-B' (ROW 26) utilized for the sensitivity analyses.

part of the valley) the model was most sensitive to changes in the streambed K'/b' ratio, with water-level fluctuations of as much as 2 feet (fig. 16). The other parameter which produced significant changes in water levels at this section was "Sy", particularly when its value was lowered (fig. 16). Hydraulic conductivity (K) was the parameter for which the model was less sensitive at section A-A'.

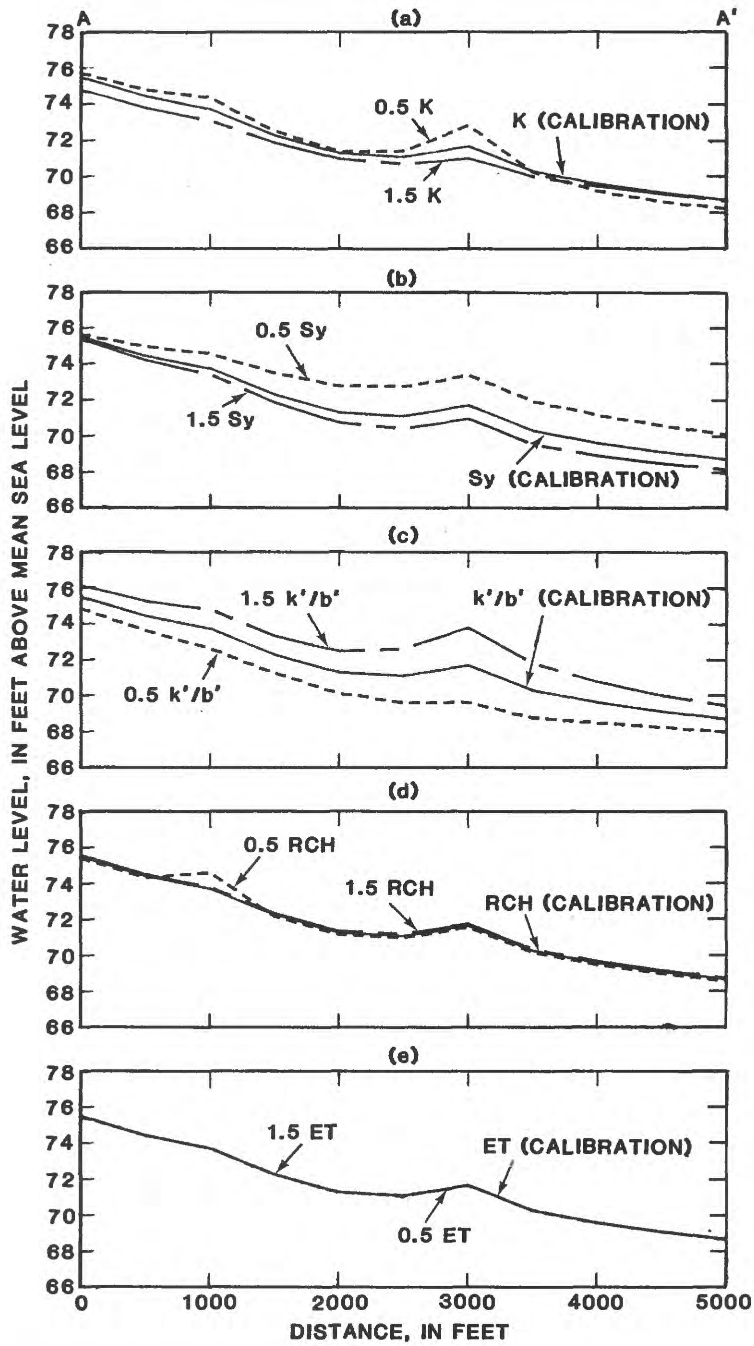


Figure 16.--Changes in water levels along section A-A' (ROW 5) resulting from varying the hydraulic conductivity (K), specific yield (Sy), streambed vertical conductivity to thickness ratio (k'/b'), recharge (RCH), and evapotranspiration (ET). (See figure 15 for location of section).

At section B-B' (across the central part of the valley) the model was most sensitive when Sy was decreased (fig. 17). However, at this section the model was more sensitive to changes in values of all the hydrologic parameters than at section A-A' (figs. 16 and 17).

Changes of 50 percent in the calibrated values of areal recharge (RCH), and evapotranspiration (ET) caused the least significant effects on the simulated water levels (figs. 16 and 17). However, it is expected that torrential rains over the valley would produce significant changes in water levels in the aquifer. A cell by cell camparison of the sensitivity of RCH and ET show the RCH is more sensitive than ET with differences in water levels in the order of 0.6 feet or less. The sensitivity of ET produce changes in the water levels of about 0.1 feet.

The sensitivity analyses revealed the importance of the stream-aquifer relation as a mechanism of water transfer between the river and the alluvial aquifer.

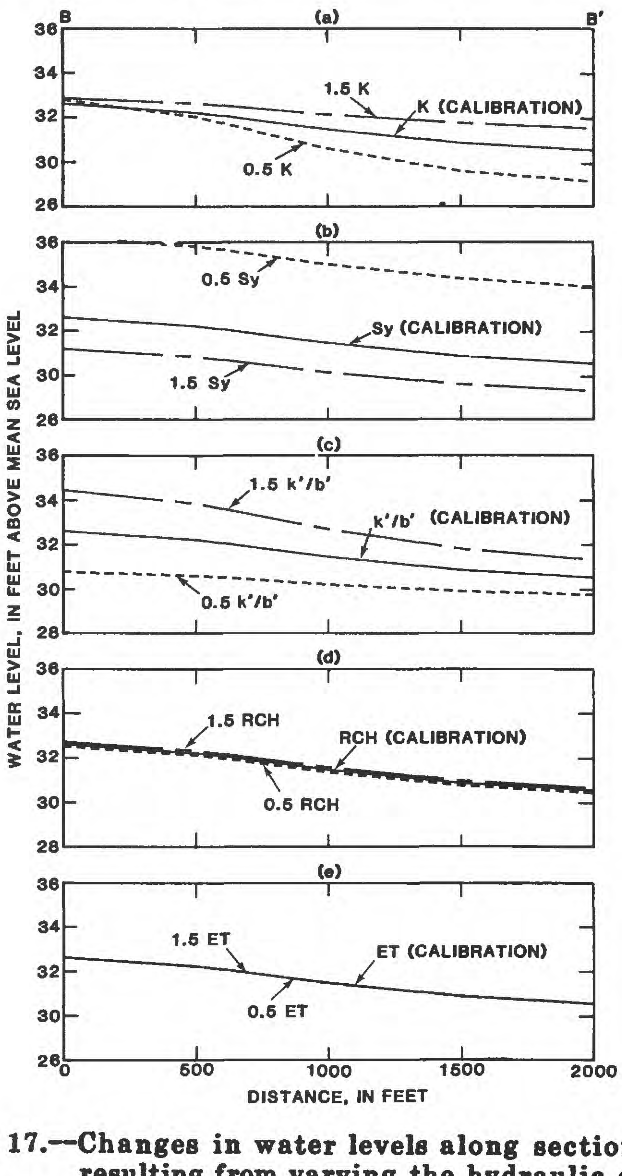


Figure 17.--Changes in water levels along section B-B' (ROW 26) resulting from varying the hydraulic conductivity (K), specific yield (Sy), streambed vertical hydraulic conductivity to thickness ratio (k'/b'),recharge (RCH), and evapotranspiration (ET). (See figure 15 for location of section).

DIGITAL EVALUATION OF THE RIO YAUCO ALLUVIAL VALLEY AQUIFER

The principal objective of the alluvial aquifer flow model was to evaluate the effect of different stresses upon water levels in the aquifer. A series of simulations were conducted for streamflow conditions of 20, 3.5, and 1.2 ft^3/s under total ground-water withdrawals of 2, 4, 6, and 8 Mgal/d. The streamflow conditions were simulated assuming a constant streamflow along the valley. This assumption is unrealistic, but allows the determination of quantities of water from the river required to maintain favorable water-level conditions in the aquifer. A length of time of 1 year was used for the simulations because, within this time frame, dynamic equilibrium would be reached by all of the evaluated scenarios. The location of pumping wells for these simulations are shown on figure 14.

Curves showing how water is delivered from storage or induced from the stream at different time intervals were developed for these streamflow and pumping conditions (fig. 18, 19, and 20). The curves suggest that within the first 20 days of pumpage, water is mostly delivered from storage. After this period of time induced recharge from the stream started replacing the aquifer water that was previously taken out of storage. The results also suggest that the lower the stream discharge, the longer it takes the ground-water system to reach a dynamic equilibrium condition (figs. 18-20).

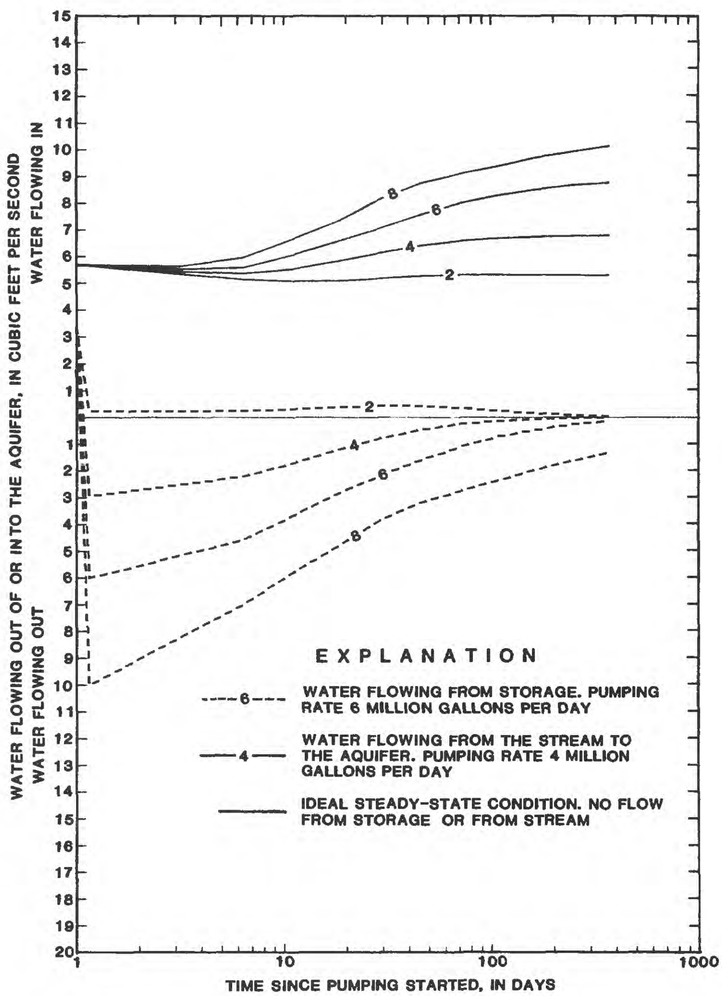


Figure 18.--Rates of water from induced stream recharge and storage for various pumping scenarios predicted by the model for an initial streamflow condition of 20 cubic feet per second exiting the valley, one year of simulation.

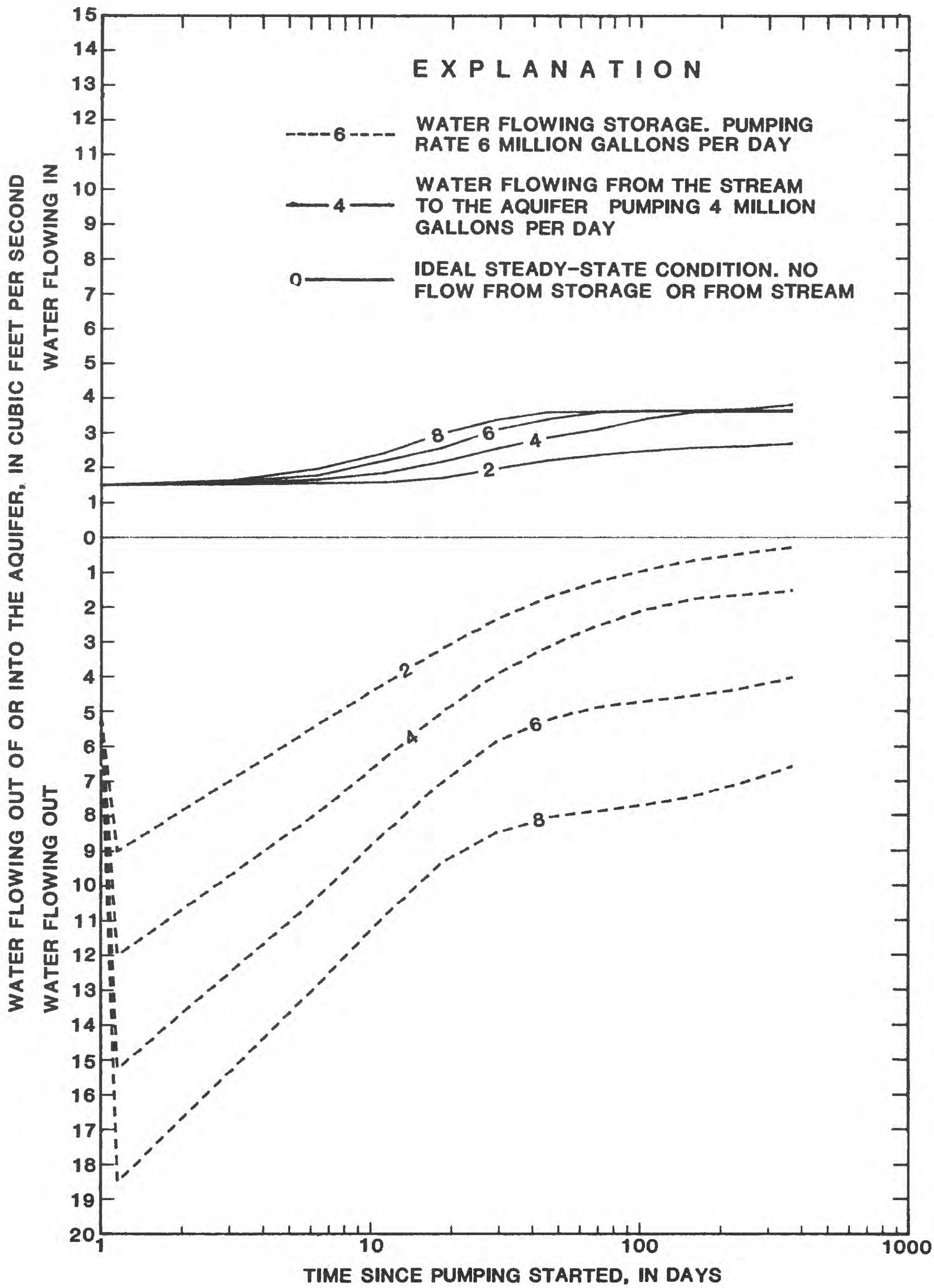


Figure 19.—Rates of water from induced stream recharge and storage for various pumping scenarios predicted by the model for an initial stream-flow condition of 3.5 cubic feet per second exiting the valley, one year of simulation.

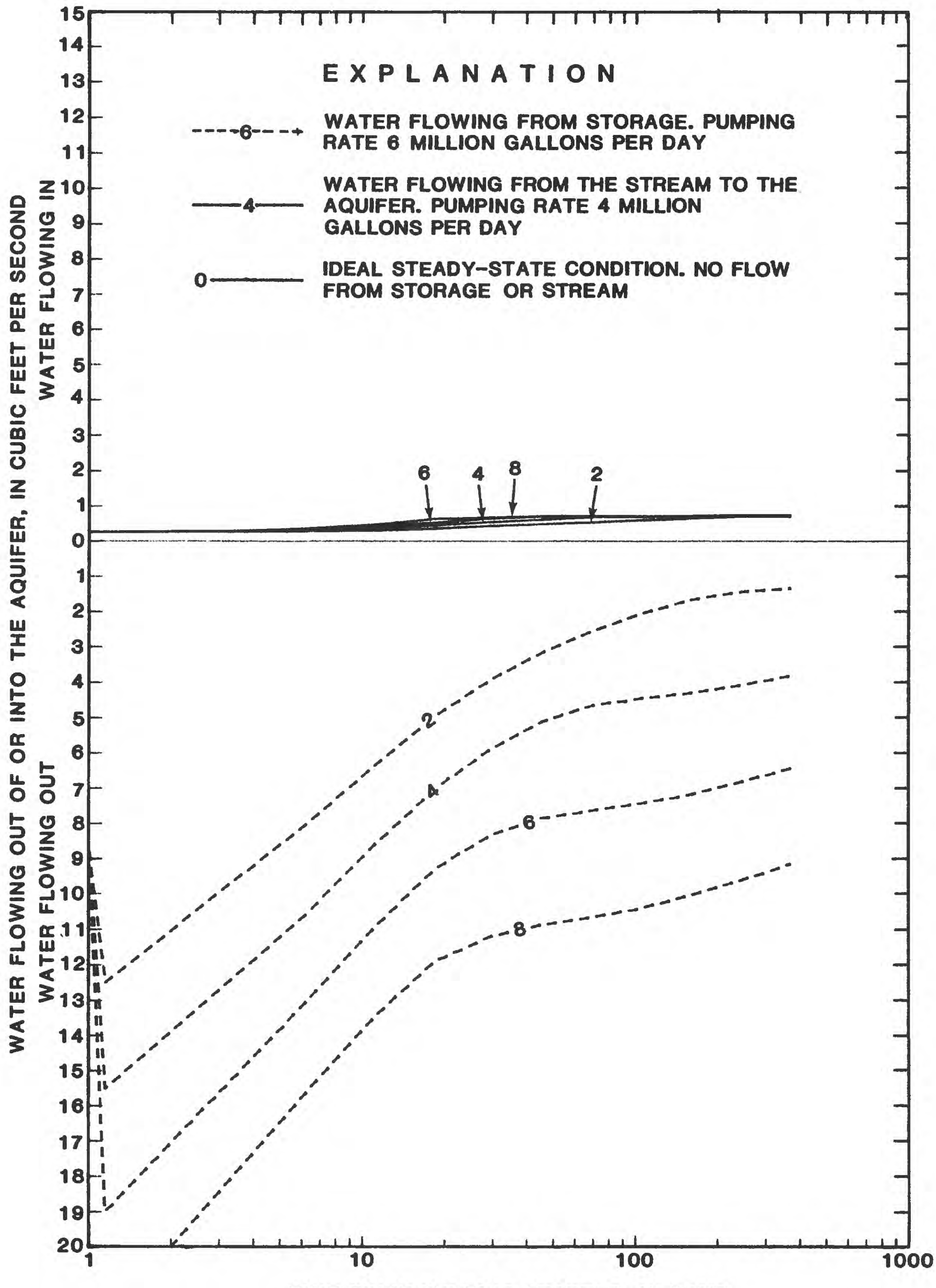
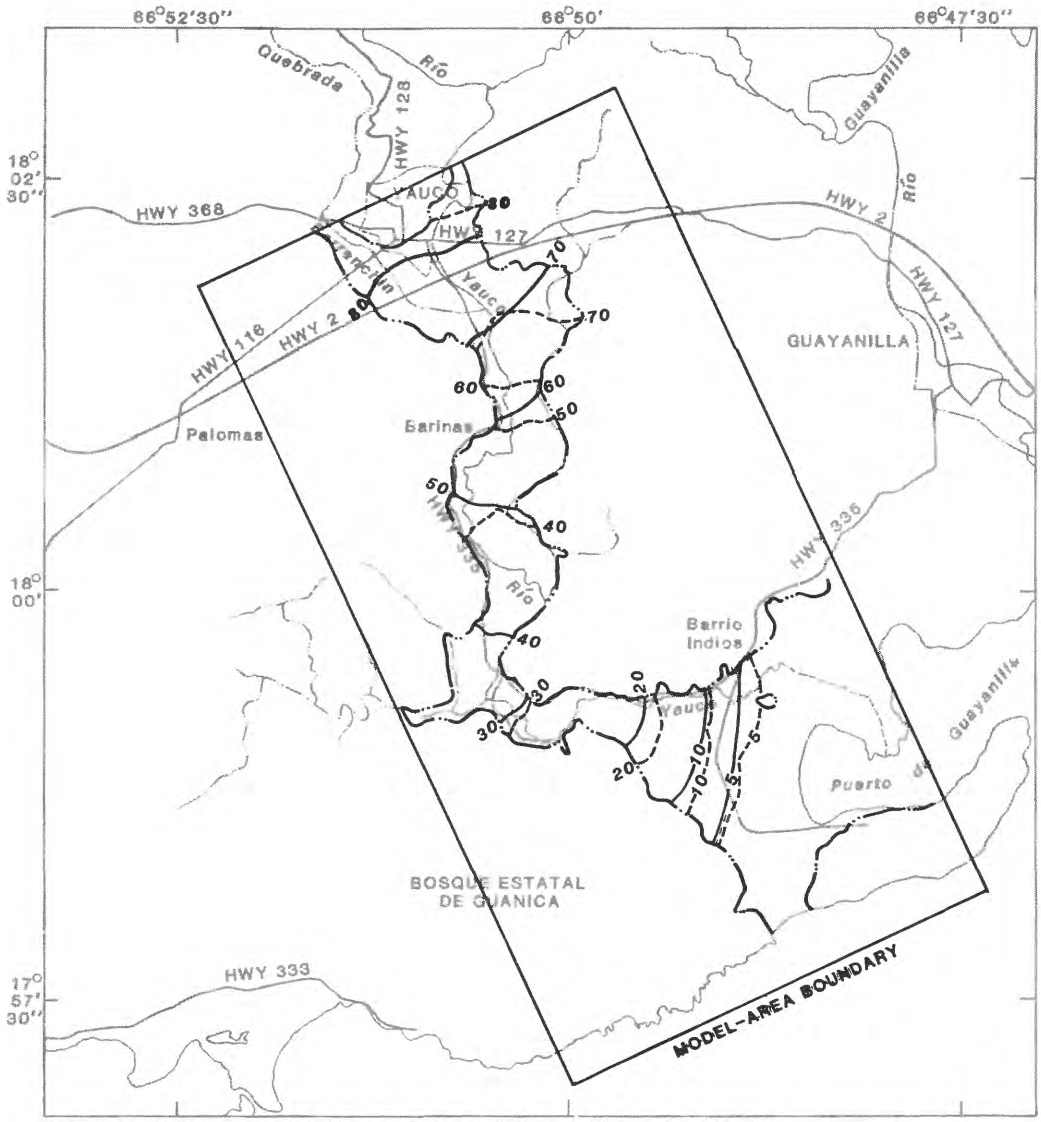


Figure 20.--Rates of water from induced stream recharge and storage for various pumping scenarios predicted by the model for an initial stream-flow condition of 1.2 cubic feet per second exiting the valley, one year of simulation.

Simulation of a streamflow of 20 ft^3/s (at station 1280, fig. 18), indicates that dynamic equilibrium was reached, for the four pumping scenarios, after 40 to 100 days. The pumping rates (2, 4, 6, and 8 Mgal/d) did not produce large drawdowns (fig. 21). However, it should be considered, that a constant streamflow of 20 ft^3/s leaving the valley requires a release of 26 to 30 ft^3/s from Lucchetti reservoir at the headwaters.



EXPLANATION

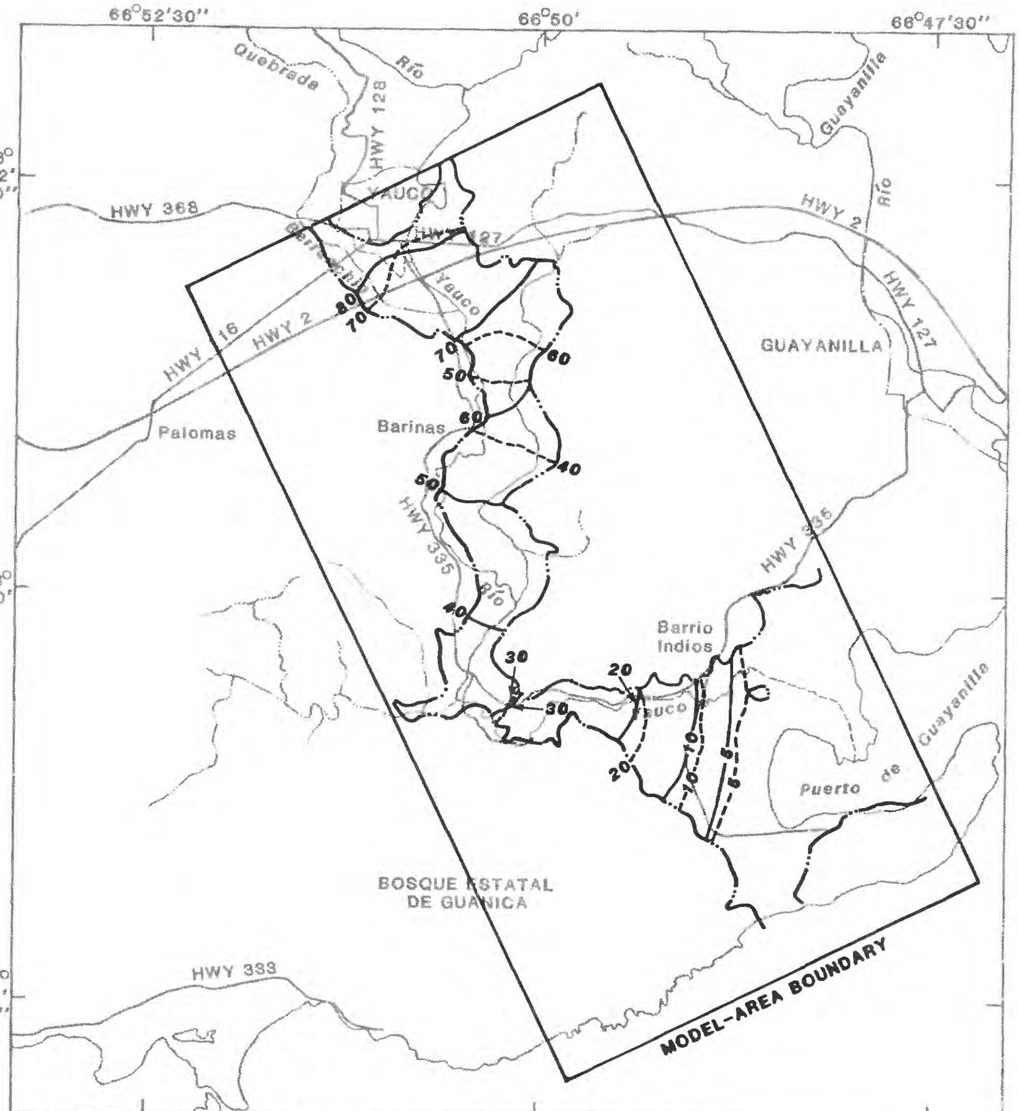
—10— INITIAL WATER-TABLE CONTOUR -- Shows altitud of an albritrary water-table, assuming no pumping. Contour interval 5 and 10 feet. Datum is mean sea level.

--10-- SIMULATED WATER-TABLE CONTOUR -- After 160 days at total pumping rate of 8 million gallons per day from different wells, (see fig. 13 for wells location). Contour interval 5 and 10 feet. Datum is mean sea level.

—··— AQUIFER BOUNDARY (BEDROCK)

Figure 21.--Initial water-table contour and water-table contour after 160 days of simulation at a total pumping rate of 8 million gallons per day and a constant streamflow of 20 cubic feet per second.

For the second streamflow scenario (3.5 ft^3/s) the dynamic equilibrium was approached before 1,000 days only at pumping rates of 2 and 4 Mgal/d (fig. 19). This required a streamflow of 6.5 to 8 ft^3/s entering into the valley. At pumping rates of 6 and 8 Mgal/d the aquifer delivered from storage 4 and 6.5 ft^3/s respectively near dynamic equilibrium (fig. 19). This indicates that the quantity of water leaving the aquifer is greater than that entering it, resulting in large drawdowns (fig. 22).



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000

EXPLANATION

—10— INITIAL WATER-TABLE CONTOUR -- Shows altitude of an arbritary water-table, assuming no pumping. Contour interval 5 and 10 feet. Datum is mean sea level.

---10--- SIMULATED WATER-TABLE CONTOUR -- After 160 days at total pumping rate of 8 million gallons per day from different wells, (see fig 13 for wells location). Contour interval 5 and 10 feet. Datum is mean sea level.

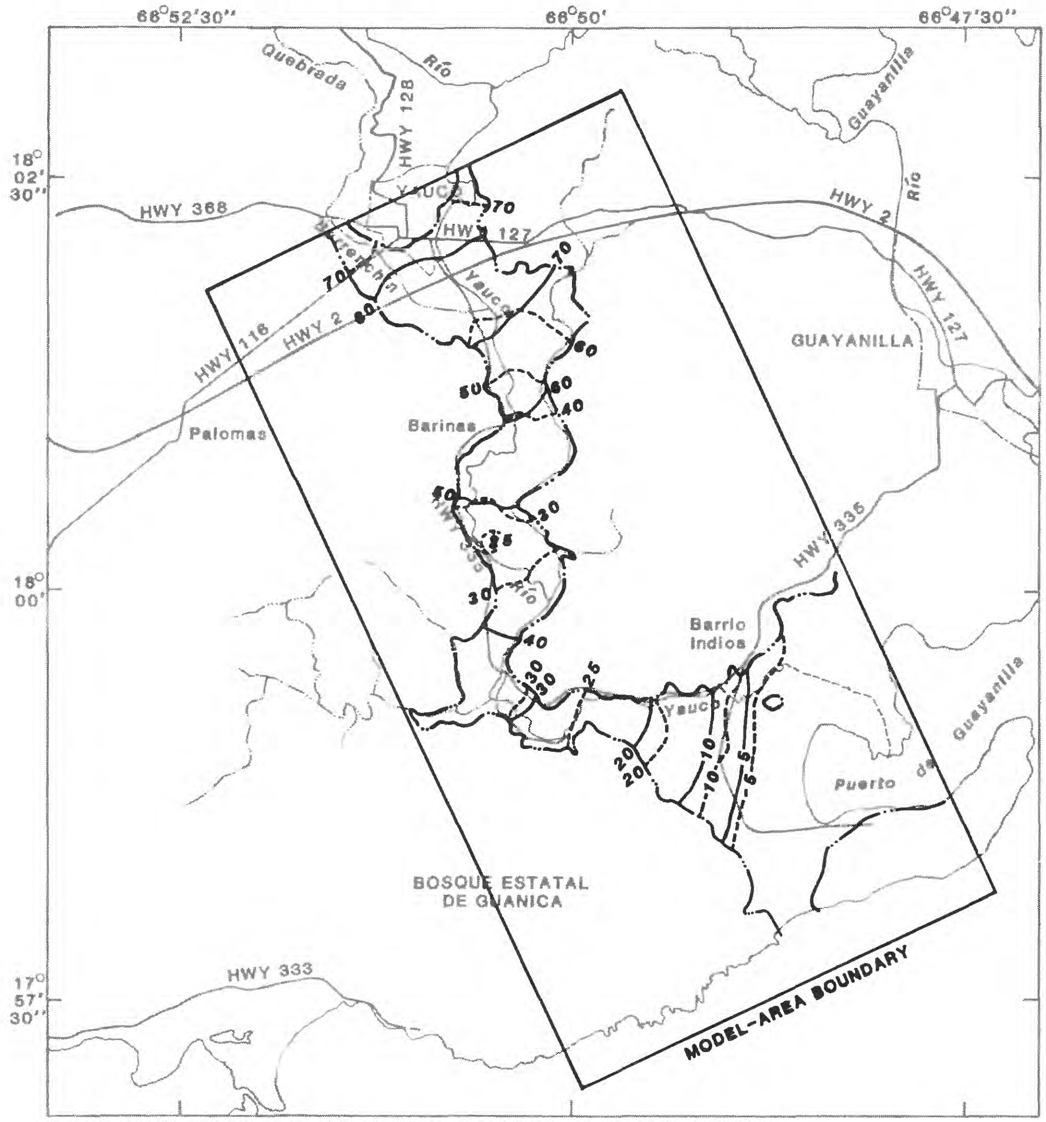
—··— AQUIFER BOUNDARY (BEDROCK)

Figure 22.--Initial water-table contour and water-table contour after 160 days of simulation at a total pumping rate of 8 million gallons per day and a constant streamflow of 3.5 cubic feet per second.

For a streamflow of 1.2 ft^3/s, dynamic equilibrium was approached only at a pumping rate of 2 Mgal/d, resulting in small drawdowns (fig. 20). This required 2 to 3 ft^3/s flowing into the valley. Pumping rates larger than 2 Mgal/d produced large drawdown (fig. 23).

Large drawdowns could probably result in seawater intrusion in the Río Yauco alluvial valley aquifer. Water quality data from some wells in the valley already suggests such a possibility.

Changes in the location and pumping rates of wells could change the results obtained from this model evaluation.



Base from USGS Topo maps of Punta Verraco and Yauco, P.R., scale 1:20,000.

EXPLANATION

—10— INITIAL WATER-TABLE CONTOUR -- Shows altitude of an arbritary water-table, assuming no pumping. Contour interval 5 and 10 feet. Datum is mean sea level.

--10--- SIMULATED WATER-TABLE CONTOUR -- After 160 days at total pumping rate of 8 million gallons per day from different wells, (see fig 13 for wells location). Contour interval 5 and 10 feet. Datum is mean sea level.

—··— AQUIFER BOUNDARY (BEDROCK)

Figure 23.—Initial water-table contour and water-table contour after 160 days of simulation at a total pumping rate of 8 million gallons per day and a constant streamflow of 1.2 cubic feet per second.

SUMMARY AND CONCLUSIONS

The Río Yauco alluvial valley aquifer model, as calibrated, can be used to evaluate the effects of different artificial or natural hydrologic stresses on the ground-water levels.

The sensitivity analyses showed that the streambed vertical hydraulic conductivity to thickness ratio (k'/b') is the most sensitive hydrologic parameter of the aquifer. These analyses also reflects the limited areal extent of the aquifer when changing to a lower value the specific yield (Sy). The model was almost insensitive to changes in recharge (RCH) and evapotranspiration (ET).

Curves for rates of induced stream leakage and storage were generated utilizing the model. The curves were used for a general evaluation of the most important water budget items of the Río Yauco alluvial valley aquifer.

The following conditions were found during the calibration and sensitivity analyses:

1) The stream (Río Yauco) is the principal source of recharge to the alluvial aquifer and reductions in streamflow will necessarily reduce recharge to the aquifer (leakage).

2) The limited geometrical dimensions of the aquifer did not allow storage of large quantities of water. Drawdowns were accelarated by depleting water from storage at certain pumping rates.

3) Almost all the streamflow entering the alluvial valley during base-flow or low-flow conditions is rapidly recharged into the aquifer.

4) The present streamflow conditions throughout the valley can possibly be improved by releasing more water from Lago Lucchetti (when available) so that recharge to the aquifer (leakage) increases.

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