HYDROLOGY AND EFFECTS OF DEVELOPMENT ON THE WATER-TABLE AQUIFER IN THE VEGA ALTA QUADRANGLE, PUERTO RICO

By Fernando Gómez-Gómez and Heriberto Torres-Sierra

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS
REPORT 87-4105

Prepared in cooperation with the
PUERTO RICO INDUSTRIAL DEVELOPMENT COMPANY
PUERTO RICO DEPARTMENT OF NATURAL RESOURCES
PUERTO RICO AQUEDUCT AND SEWER AUTHORITY

San Juan, Puerto Rico
1988

DEPARTMENT OF THE INTERIOR

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CONVERSION TABLE

The following factors may be used to convert inch-pound units of measurement in this report to International systems (SI) units).

Multiply inch-pound unit	By	To obtain SI unit
inch (in.)	2.54	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09294	square meter (m^2)
acre	0.4047	hectare (ha) square
mile (mi^2)	2.590	square kilometer (km^2)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
ton, short	0.907210	megagram (Mg)

U.S. DEPARTMENT OF THE INTERIOR · GEOLOGICAL SURVEY

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ABSTRACT

A finite difference ground-water flow model was developed for the Vega Alta-Dorado area, in northern Puerto Rico. The model was validated by simulating the historical ground-water development trend for 1930 to 1983. Within this time frame, aquifer withdrawals increased from about 1.5 cubic feet per second to about 31 cubic feet per second. This has resulted in: (1) a lowering of the water table in the northern coastal half of the 85 square mile area by as much as 10 feet, (2) a reduction of aquifer flow to regional discharge features of about 23 cubic feet per second, and (3) an increase in streamflow infiltration of about 4.5 cubic feet per second. Under 1983 stress conditions, the principal source of recharge is rainfall infiltration, estimated at 34 cubic feet per second or approximately 85 percent of the total aquifer recharge. The remainder is contributed mostly by seepage from Río Cibuco.

It is anticipated that an additional 1.8 cubic feet per second (1.2 million gallons per day) will be withdrawn between 1983 and 1990 mostly to augment public supply at Vega Alta. This scenario was tested in the model to predict lowering of the water table to the year 2000. The results indicate such stress would lower the potentiometric surface within the eastern half of the coastal plain by as much as 3 feet; and, cause an inland displacement of the 5 feet potentiometric contour by as much as 2.5 miles. At present (1983), various wells located along the coastline and the 5-foot contour already show saltwater encroachment. It can be anticipated that such problems will become critical in the coastal plain if additional ground-water supplies are developed.

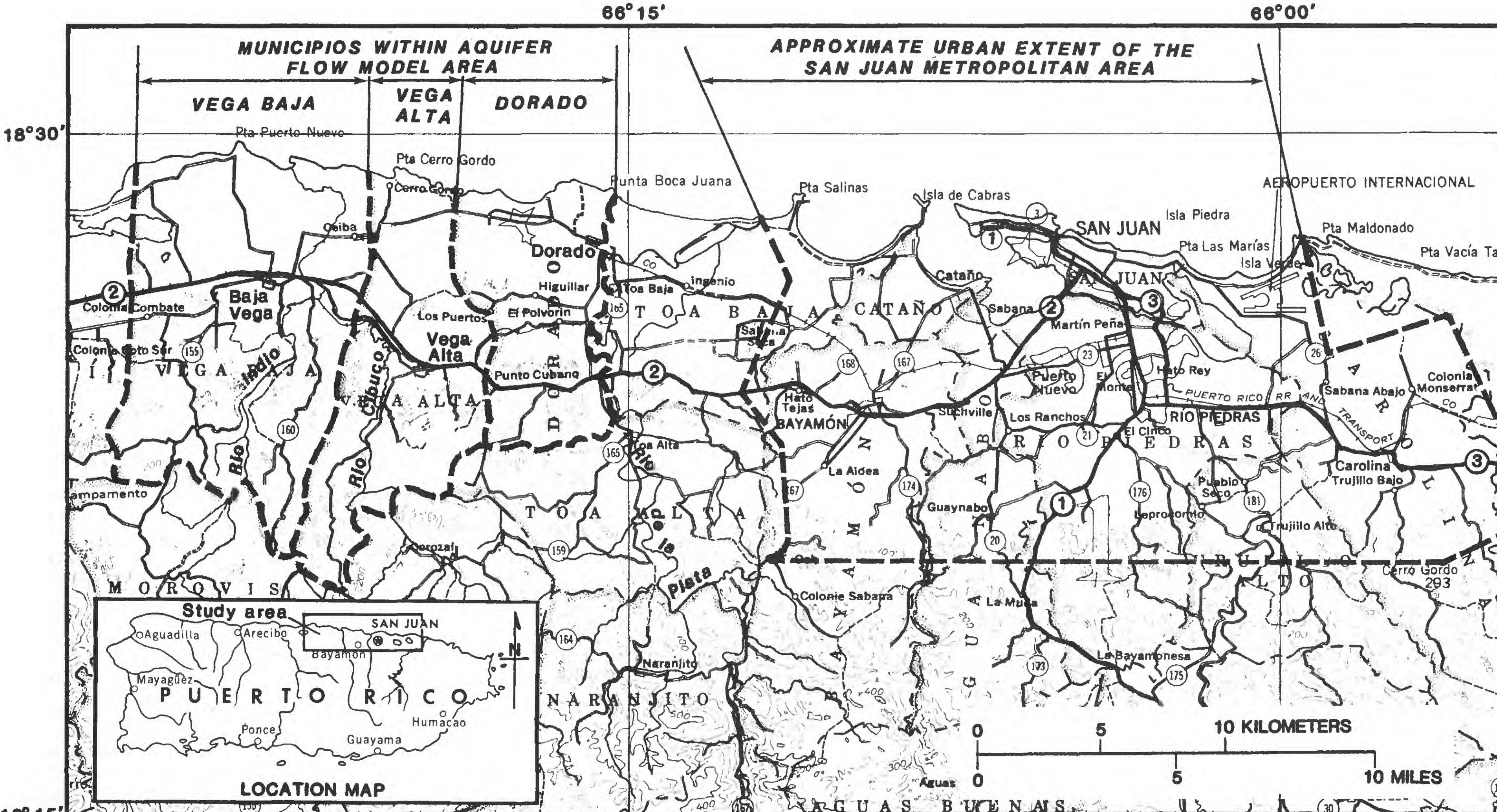
INTRODUCTION

Ground water is the principal source of water for industrial and domestic use in the municipios of Dorado, Vega Alta, and parts of Vega Baja, in north-central Puerto Rico (fig. 1). Withdrawals from the aquifer have increased from about one Mgal/d (one million gallons per day) in 1930 to about 20 Mgal/d in 1982. Most of the ground-water withdrawals are for public-water supply (table 1). Current and planned urban and industrial development in the area will result in additional water demands. There is concern among planners and developers that future urban and industrial development in the area could be affected if additional demands for water cannot be met from local ground-water resources. The area lacks the infrastructure to receive surface water from the nearest source (La Plata filtration plant). Most of the water from the major streams that flow through the region has already been appropriated: Río de la Plata for public-water supply of the San Juan metropolitan area, and the combined flows of Río Cibuco and Río Indio for irrigation of rice crops covering about 1,000 acres within the Río Cibuco flood plain.

In 1983, the U.S. Geological Survey (USGS), in cooperation with the Puerto Rico Industrial Development Company, the Puerto Rico Department of Natural Resources, and the Puerto Rico Aqueduct and Sewer Authority began a 3-year investigation of the ground-water resources in the Dorado-Vega Alta-Vega Baja area.

Purpose and Scope

The purposes of this study were to provide a detailed evaluation of the aquifer system and estimate the effects of increased ground-water withdrawal in the Vega Alta Quadrangle area. The objective was accomplished by reviewing previous literature on the hydrogeology of the study area and collecting additional data necessary for the construction of the ground-water flow model.



Base from USGS topographic map of Puerto Rico, scale: 1:240,000, 1942 edition.

Figure 1.--Location of the municipios of Vega Baja, Vega Alta, and Dorado and the San Juan Metropolitan Area, Puerto Rico.

Table 1. Ground water and surface water withdrawal estimates within the Vega Alta quadrangle area during 1982 and principal use category

Water use category	Withdrawals, in million gallons per day	
	Ground water	Surface water
Public-water supply	12.5	1.4
Irrigation	5.3	8.6
Industrial	1.3	0.0
Commercial	0.4	0.0
Agriculture	0.2	0.0
Domestic	<0.05*	0.0
Mining	0.5	0.0
	20.2	10.0

*1980 census indicates an estimated 255 housing units within municipios of Dorado and Vega Alta are supplied from residential domestic wells. Total withdrawal estimated at less than 50,000 gallons per day.

Field activities included the following:

(1) Conducting a comprehensive well inventory.

(2) Determining estimates of ground-water withdrawals at each well site.

(3) Determining ground-water levels as of February 1983 at selected wells for use in the model calibration.

(4) Surveying selected wells to establish water-level elevations relative to mean sea level datum.

(5) Collecting water samples for chloride analysis to define areas affected by saltwater encroachment.

(6) Conducting surface-resistivity surveys at the coastal plain to estimate the thickness of the freshwater lens.

After the ground-water flow model was calibrated, it was used to:

a) Define the effects of past and future water withdrawals on the water table surface, and on ground water recharge and discharge features.

b) Identify potential well locations for monitoring the effects of future stresses on the aquifer system.

c) Identify additional data required to improve the model's predictive capabilities.

This report describes the data used to develope the ground-water flow model of the aquifer system and the procedures used in its calibration and verification. The report includes figures showing detailed data used in model calibration and verification.

Acknowledgments

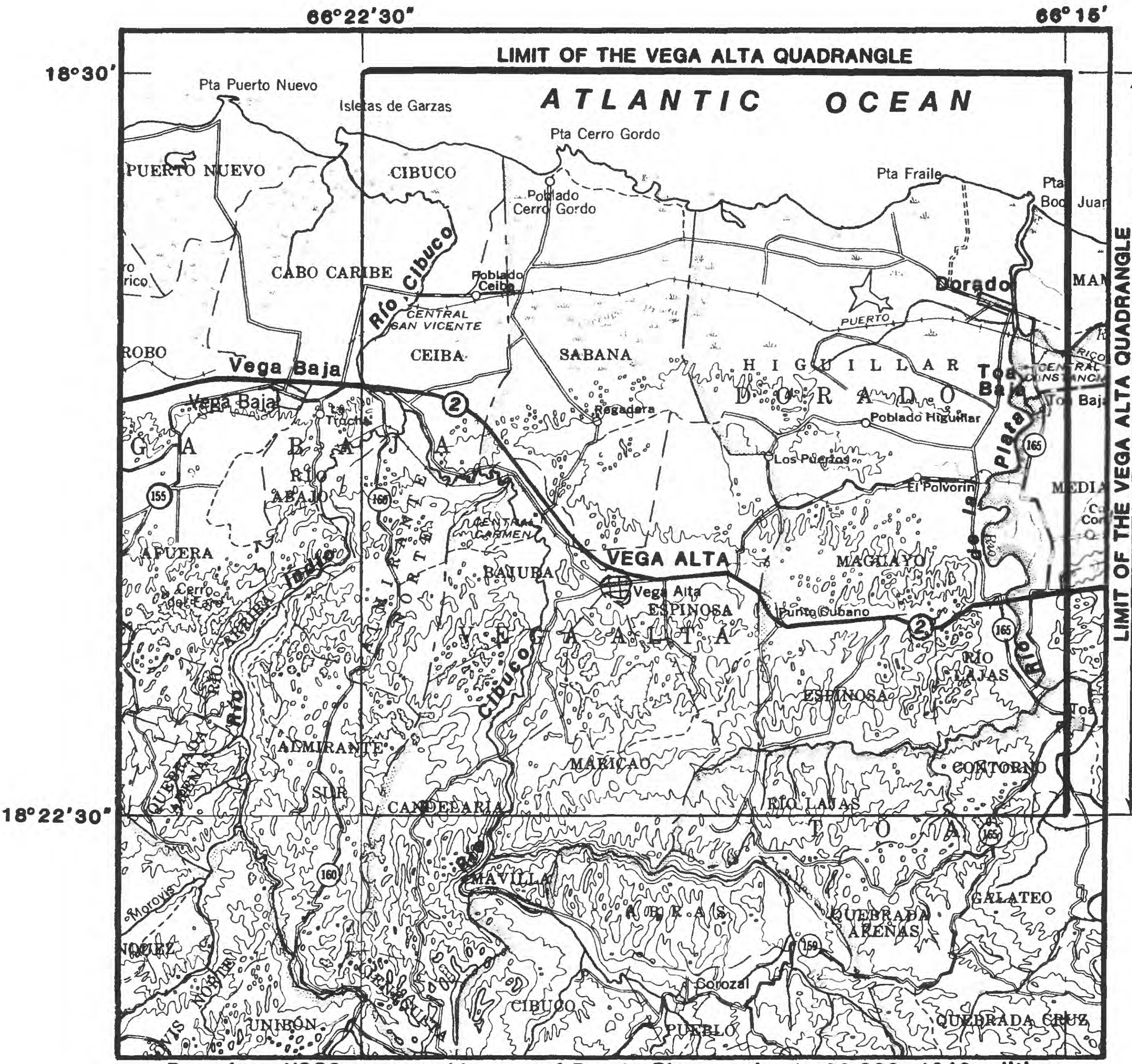
The cooperation provided by landowners in the Dorado-Vega Alta area in granting access to property and wells is appreciated. Wilfredo Freytes, of the Puerto Rico Aqueduct and Sewer Authority, assisted in making available driller's logs for the public supply wells; Michael Dowiak and James Pryor of the NUS, Inc., provided level survey data for numerous wells in the vicinity of Vega Alta. Michael Planert, of the Geological Survey, Alabama District gave support and consultation in the design and verification of the ground-water flow model. Sigfredo Torres and Vicente Quiñones, of the Caribbean District, assisted the authors in managing the numerous computer files necessary for the ground-water model.

DESCRIPTION OF STUDY AREA

Geographic Setting

The area of study lies within the North Coast Limestone Ground-water Province (McGuinness, 1948) between Río de la Plata, Río Cibuco, the Atlantic Ocean, and an imaginary line along latitude 18°22'30" (which is the southern boundary of the Vega Alta Quadrangle, fig. 2). The major geographic features of the area are coastal sand dunes, the coastal plain, and karst uplands.

The coastal sand dunes form an almost continuous ridge between Río de la Plata and Río Cibuco with an elevation of 30 feet, but rise to as much as 65 feet at the town of Dorado. Between the dunes and the inland slopes, which rise to form the karst upland, is the coastal plain. The plain averages slightly more than one mile in width and less than 15 ft in elevation above mean sea level. In the past, most of this plain was inundated, especially during the wetter months of the year (Abbad y Lasierra, 1788). Construction of drainage ditches, during the early 1960's has limited the wetlands to Cienaga Prieta and various other isolated smaller areas (fig. 2).



Base from USGS topographic map of Puerto Rico, scale: 1:120,000, 1942 edition.

0 1 2 3 4 5 KILOMETERS

0 1 2 3 4 5 MILES

Figure 2.--Vega Alta qudrangle showing study area and general geographic features.

The most extensive geographic feature is the karst upland. It is characterized by a generally rugged topography formed by the dissolution and weathering of limestone. In the Vega Alta quadrangle, the karst upland can be divided into two zones: (1) a tableland generally at the 170 ft contour (50 meters on topographic map) bordered by "mogotes" (conical hills), and (2) the area south of Vega Alta (above the 170 ft contour) characterized by a discontinuous belt of mogotes surrounding sinks.

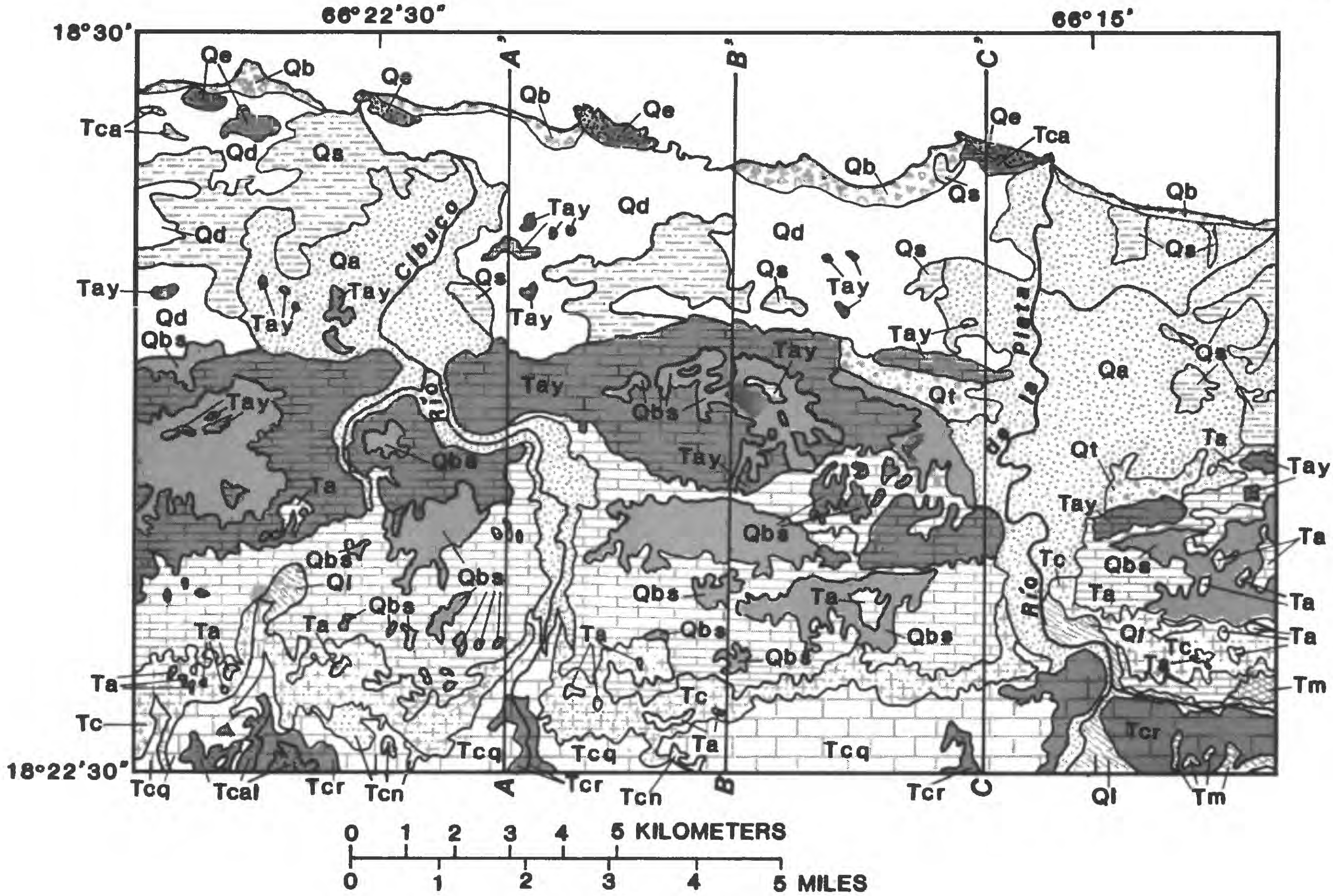
The climate is tropical marine with mean daily temperatures ranging from 23°C in the winter months to 27°C in summer. Rainfall averages 65 inches at the coast and 70 inches at areas greater than 3 miles inland. Although there exists no markedly wet or dry season, long term records at Dorado show that typically the months of February, March and April are dry with an average of 3.4 inches per month, while the average for the other months is 6.1 inches per month. Rainfall statistics at this station indicate an annual rainfall variation from as little as 42.65 inches (1930) to as much as 105 inches (1956), with 90 percent of all years of record (1908-1983) having between 47.1 and 90.2 inches.

Hydrogeologic Setting

Stratigraphy

The principal hydrogeologic units in the study area are: the unconsolidated deposits of Quaternary age in stream valleys, the coastal plain and limestone outcrop areas, and the sedimentary rocks of Tertiary age (fig. 3).

The stream valley alluvial deposits consist predominately of fine sand, silt and clay. Maximum thickness penetrated by water wells has been about 100 ft in the part of the Río de la Plata alluvial valley contained within the study area and 265 ft in the Río Cibuco alluvial valley.



EXPLANATION

QUATERNARY

- Qa STREAM VALLEY ALLUVIUM
- Qt TERRACE DEPOSITS AND UNDIFERENTIATED ALLUVIUM
- Ql LANDSLIDE DEPOSITS
- Qb BEACH DEPOSITS
- Qs SWAMP DEPOSITS
- Qd ANCIENT DELTAIC AND MUD FLAT DEPOSITS
- Qe EOLIANITE
- Qbs BLANKET SAND DEPOSITS

TERTIARY

- Tca CAMUY FORMATION
- Tay AYMAMON LIMESTONE
- Ta AGUADA LIMESTONE
- Tc CIBAO FORMATION (Typical lithology)
- Tcn MIRANDA SAND MEMBER
- Tcq QUEBRADA ARENAS LIMESTONE MEMBER
- Tcal ALMIRANTE SUR SAND LENTIL
- Tcr RIO INDIO LIMESTONE MEMBER
- Tm MUCARABONES SAND

A—A' LOCATION OF CROSS SECTIONS SHOWN IN FIGURE 3

Figure 3.--Generalized surficial geology in the study area.

Unconsolidated sediments, described in this text as "coastal plain deposits" cover most of the coastal area. These are principally ancient deltaic and mud flat deposits of Pleistocene age locally overlain by recent swamp deposits. These deposits consist of carbonaceous sandy clay and muck with localized peat beds. These have a maximum thickness of about 80 ft where they interfinger with the alluvial deposits of Río de la Plata and Río Cibuco.

The blanket sands cover most flat areas between the mogotes and sinkholes of the limestone upland. These deposits generally consist of residual clay and quartz sand, with clay the principal fraction (65:35). Locally sandy deposits occur with a 20:80 ratio (Briggs, 1966). In the study area, the thickness of these deposits seems to be greatest in the vicinity of Vega Alta, where the deposits are as much as 100 ft thick (fig. 4). Elsewhere, these deposits generally are less than 50 ft thick.

The Tertiary sedimentary rocks include five principal hydrogeologic units: the Aymamón and Aguada Limestones of Miocene age; the Cibao Formation and Mucarabones Sand, of Miocene and Oligocene age; and the Lares Limestone, of Late to Middle Oligocene age. The Cibao Formation within the Vega Alta quadrangle is represented by unnamed members of calcareous clay or earthy limestone (referred to as the typical lithology by Monroe, 1980). Also present are the Miranda Sand Member, Quebrada Arenas Limestone Member, Almirante Sur Sand Member, and the Río Indio Limestone Member. This classification is based mainly on the depositional histories of the formations and does not necessarily represent distinct ground water flow systems (Monroe, 1980). In the Vega Alta quadrangle the Mucarabones Sand and the Lares Limestone are not exposed. The Tertiary formations generally dip northward at less than 2.5°. This slight dip of the units is a peculiar feature in the local geology which shows a wide spreading of structure contours in the vicinity of the town of Vega Alta. This may actually be a gentle anticline (Monroe, 1963). To the east of this structure, the strike of the limestone units is north to north-northeast; and to the west, north to north-northwest.

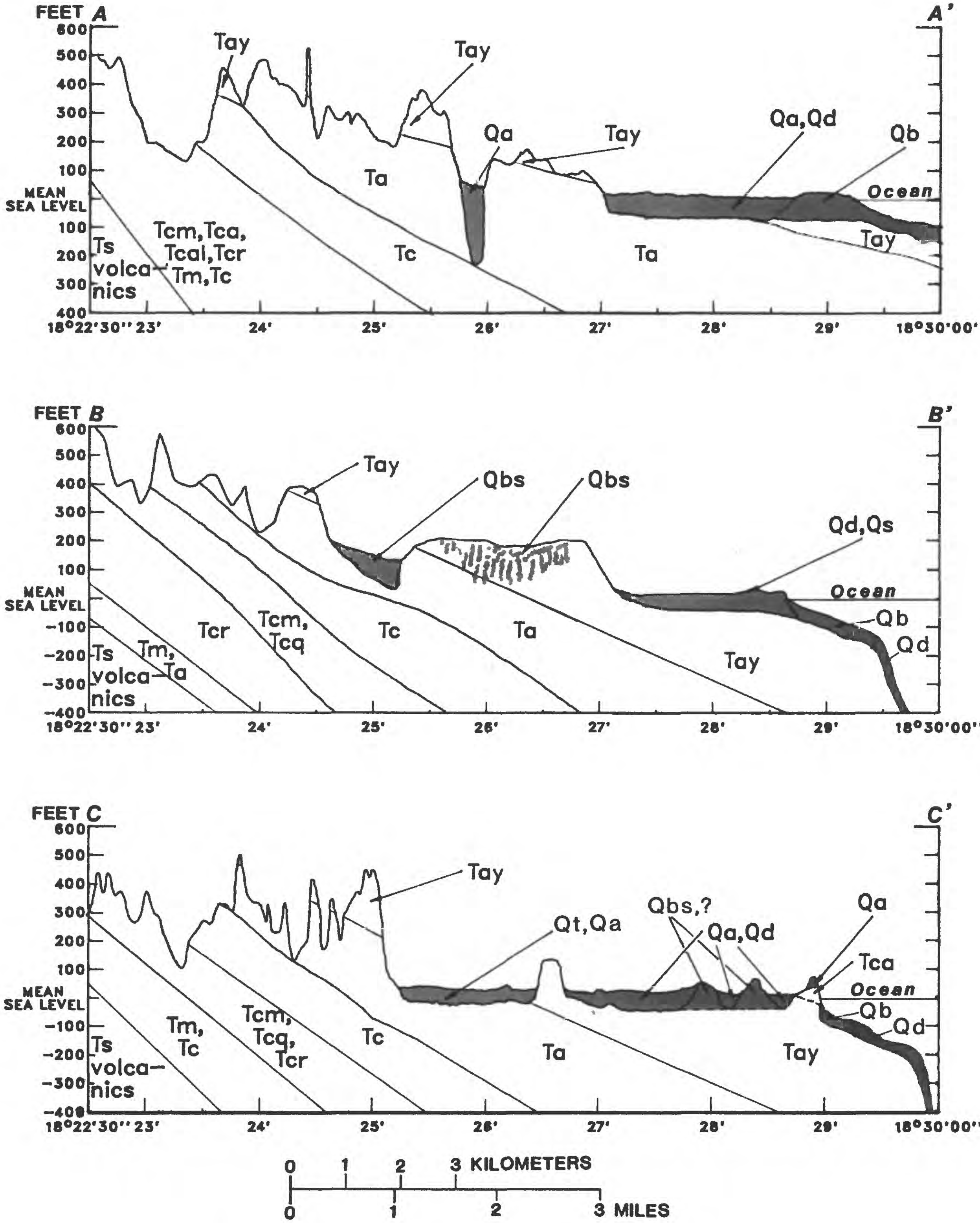


Figure 4.--Generalized cross sections showing the hydrogeologic units within the Vega Alta quadrangle along longitude: a) 66°21'16", b) 66°18'42", and c) 66°16'11". (Refer to figure 3 for location of cross sections and formation names.)

The total thickness of the Tertiary limestone hydrogeologic units varies from about 500 ft at the southeast corner of the Vega Alta quadrangle to about 3,500 ft at the northwest edge (fig.4). These units overlie the San Sebastián Formation of Oligocene age, which consists of sandy and calcareous clay.

Ground water

Ground water occurs in a water-table regional aquifer system extending throughout the unconsolidated deposits of the coastal plain and stream valleys and all the Tertiary limestone hydrogeologic units. Locally, shallow perched aquifers of limited extent are contained within the coastal sand dunes and within the zone of contact beneath the blanket sand deposits and limestone rocks. Only the regional aquifer is of importance as a water supply source. It has been tapped since about 1930, but it was not until 1960 that large scale development began (fig. 5).

Prior to development of the aquifer the coastal plain may have been the principal aquifer discharge area. Driller's logs of wells constructed at Sabana in the early 1960's indicate that the altitude of the potentiometric surface was about equal to the water level at the now almost extinct Cienaga Prieta marsh. In the topographic map version of 1953, the Cienaga Prieta had a water level altitude of 12 ft. At present most of the coastal plain is criss-crossed by drainage ditches and few areas remain as wetlands. Most ditches are less than 3 ft in depth except the principal drainage channel which drains Cienaga Prieta into the Río Cibuco. The principal drainage channel was dredged at about 1960 to or near sea level altitude. The regional impact these drainage works may have had on the ground water flow system is unknown since large scale withdrawals also began in the same period.

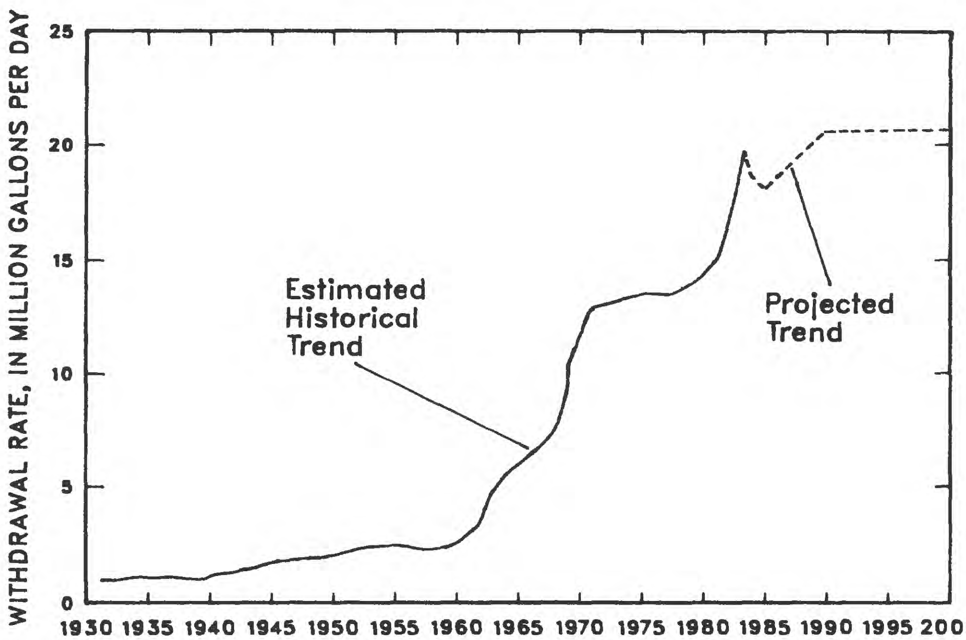


Figure 5.--Historical ground-water development trend within the aquifer flow model area and projection to the year 2000.

MODEL DEVELOPMENT

General Equations and Finite Difference Equivalence

The three dimensional movement of ground water of constant density through porous earth material may be described by the partial differential equation,

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W = S_s\frac{\partial h}{\partial t} \qquad (1)$$

where,

x, y, and z are cartesian coordinates aligned along the major axis of hydraulic conductivity K_{xx}, K_{yy}, K_{zz}

h is the potentiometric head (L)

W is the volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1}),

S_s is the specific storage of the porous material (L^{-1}), and

t is time (t).

In general, S_s, K_{xx}, K_{yy}, K_{zz} may be functions of space ($S_s = S_s$ (x,y,z), and $K_{xx} = K_{xx}$ (x,y,z), and h and W may be functions of space and time (h = h(x,y,z,t), W = W(x,y,z,t)) so that equation 1 describes ground-water flow under nonequilibrium conditions in a heterogenous and anisotropic medium. In many instances it is correct to consider ground-water flow as a two-dimensional flow of a homogenous compressible fluid through a nonhomogenous anisotropic aquifer defined by the following equation (Pinder and Bredehoeft, 1968):

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W(x,y,t) \qquad (2)$$

where T is the transmissivity tensor, L^2/t, and h, W, S and t having the same definitions as in equation (1).

Equation (2) is a reasonable approximation of the real flow system when insufficient data exists on aquifer properties and/or a large uncertainty in estimates of the variables involved to adequately describe a three-dimensional flow system exists. In the above equation, the parameter, W, may represent fluxes of: (a) direct withdrawal or recharge, such as well pumpage, rainfall recharge, or evapotranspiration, and (b) leakage into or out of the aquifer through a streambed or a confining layer. Leakage can be expressed as,

$$W(x,y,t) = K_z(H_s - h)/m \tag{3}$$

where,

W is the rate of withdrawal (positive sign) or recharge (negative sign), L/t,

K_z is the vertical hydraulic conductivity of the streambed or confining layer, L; and

m is the thickness of the confining layer or streambed, L; and

H_s is the hydraulic head in the stream or source bed, L.

Since aquifer properties and boundary conditions vary with location, an exact solution to the partial differential equations of flow (equation 1 or 2) cannot be obtained directly. Instead an approximate numerical solution can be obtained through the use of a digital computer. In this study, the partial differential equation for ground-water flow (equation 2) is solved numerically using a finite-difference method. To solve the flow equation using the finite-difference method, the aquifer is divided into a grid of rectangular cells with a special point called a node located at the center of each cell. The partial differential equation is approximated at each cell by a linear algebraic equation expressed in terms of the hydraulic head at the node in that cell and the hydraulic head at the nodes in the four adjacent cells. The result is a system of linear algebraic equations that can be solved to obtain the hydraulic head at all of the nodes. The computer code used in this study is the

Survey finite-difference ground-water flow model. Detailed descriptions of the finite-difference equations and documentation of the computer code are presented by McDonald and Harbaugh (1984).

Conceptual Model

The aquifer system as considered in the flow model is that part of the saturated zone containing freshwater. It includes an area of about 85 square miles (mi^2) which was subdivided into a variable finite difference grid of 1,692 cells consisting of 36 rows and 47 columns (fig. 6).

Conceptualization of the ground water flow system for this model is based on the analyses of a potentiometric surface map of February 1983 (fig. 7). Cross sectional diagrams showing the altitude of water levels at wells along a south to north profile and its relation to hydrogeologic units (fig. 8) were also used. Analyses of these diagrams indicated the following aquifer flow conditions:

(1) Recharge occurring within the outcrop of the Cibao Formation flows radially from a high located in the area of the headwaters of Río Lajas.

(2) Río Lajas forms a divide, controlling the maximum altitude of the potentiometric surface along the southern perimeter of the Vega Alta quadrangle area.

(3) Both Río Cibuco and Río de la Plata are gaining streams at least to the latitude at which they cross the top of the Cibao Formation. Northward of this line it seems Río Cibuco could be loosing flow to the part of the aquifer located beneath the tableland north of Vega Alta.

(4) At the coastal plain the altitude of the potentiometric surface is below that which previously existed at marshes and shallow drainage ditches.

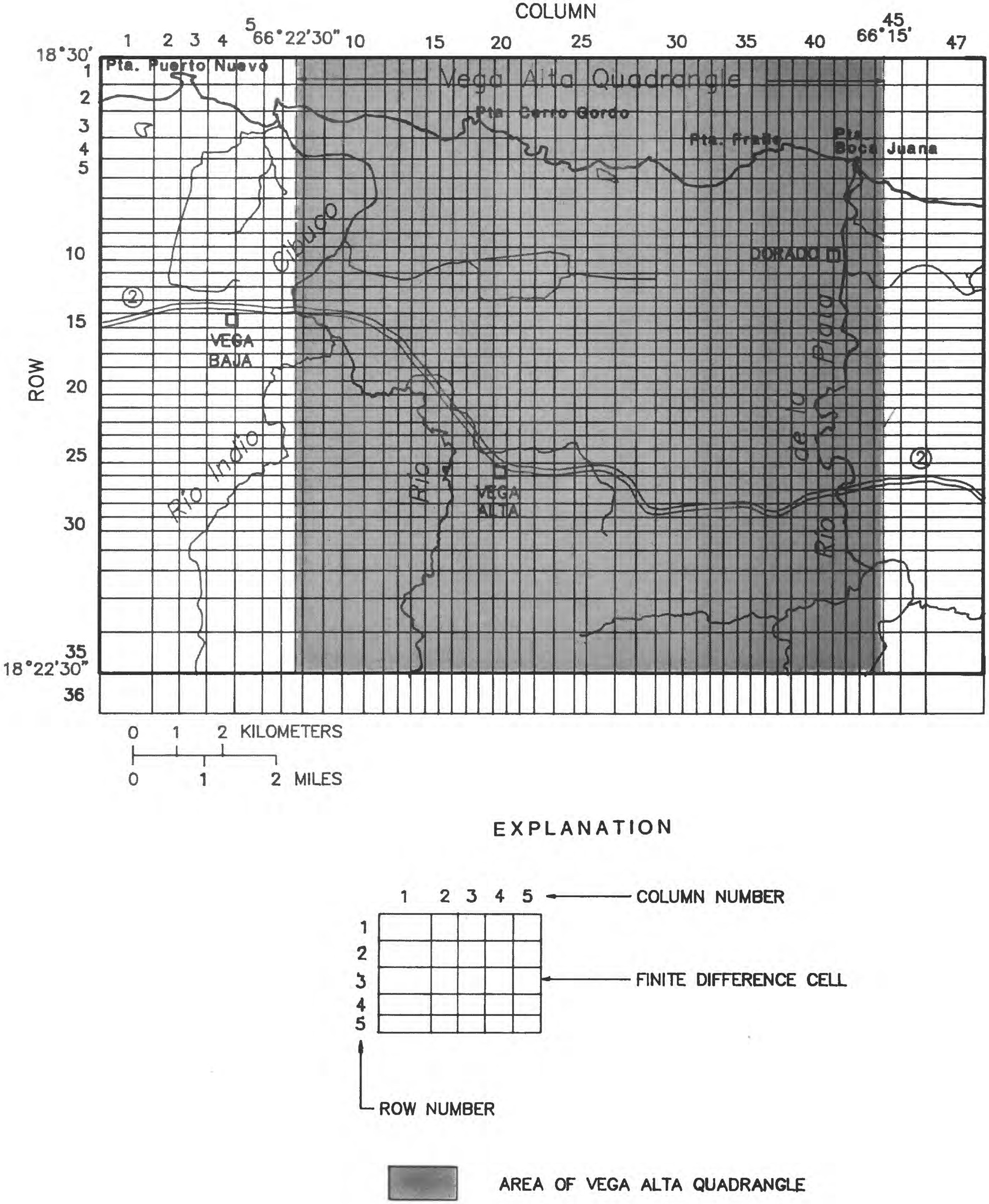
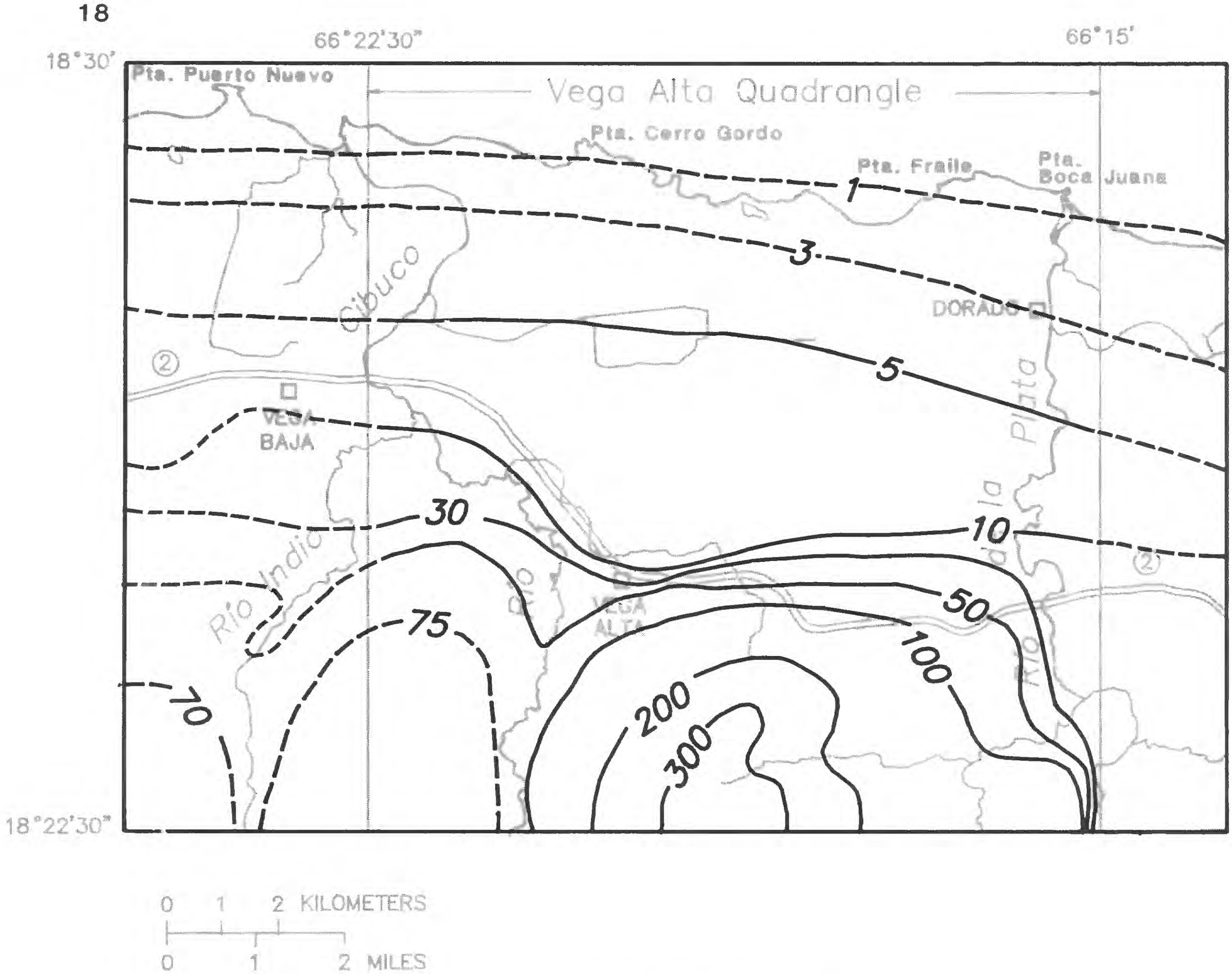


Figure 6.--Finite difference mesh used in aquifer flow model.



EXPLANATION

——— *300* — — — POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval, in feet, is variable. Datum is mean sea level.

Figure 7.--Potentiometric surface of the regional aquifer within the Vega Alta quadrangle, February 1983.

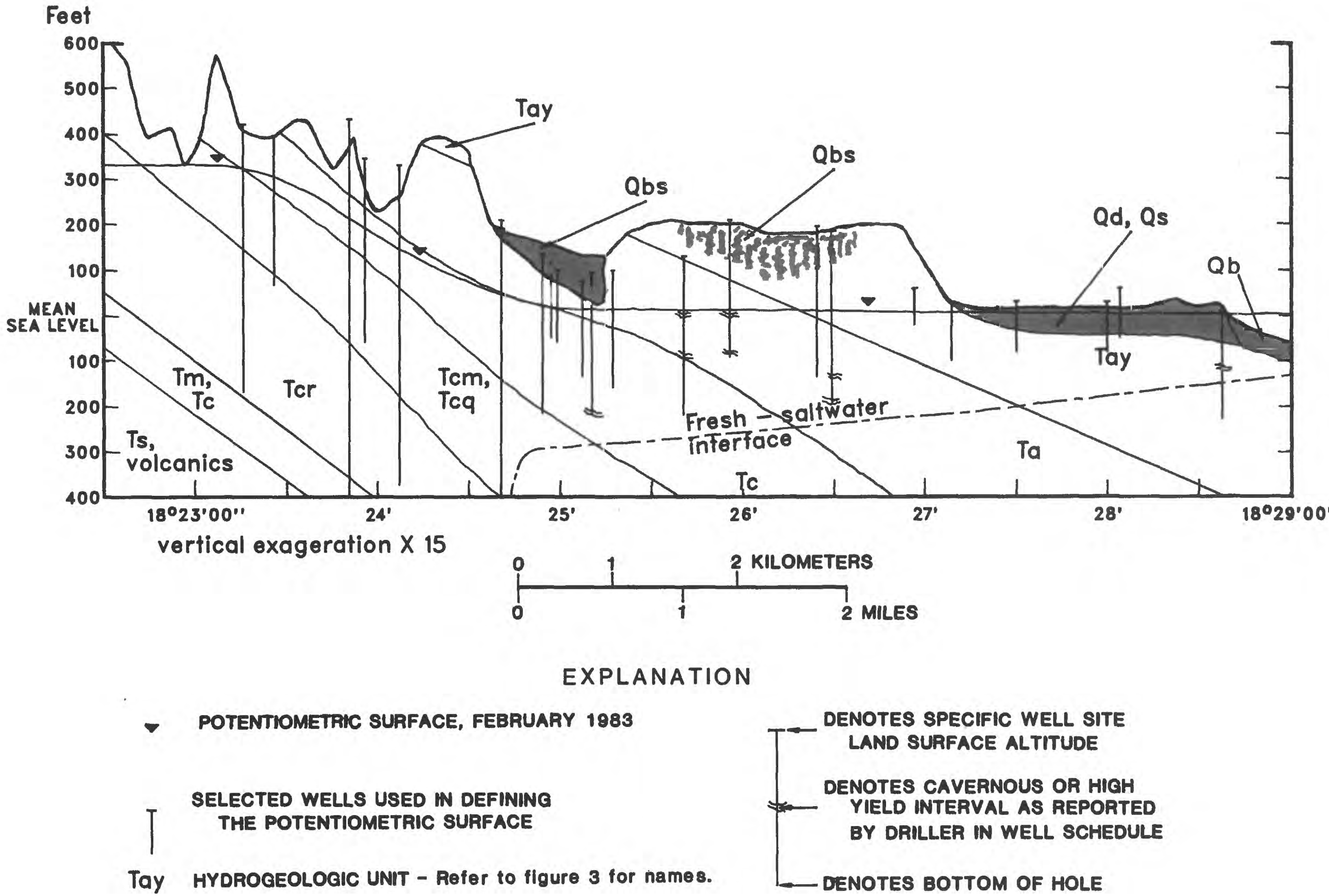


Figure 8.--Generalized section along longitude 66°18'52" showing the relation of the potentiometric surface to the hydrogeologic units.

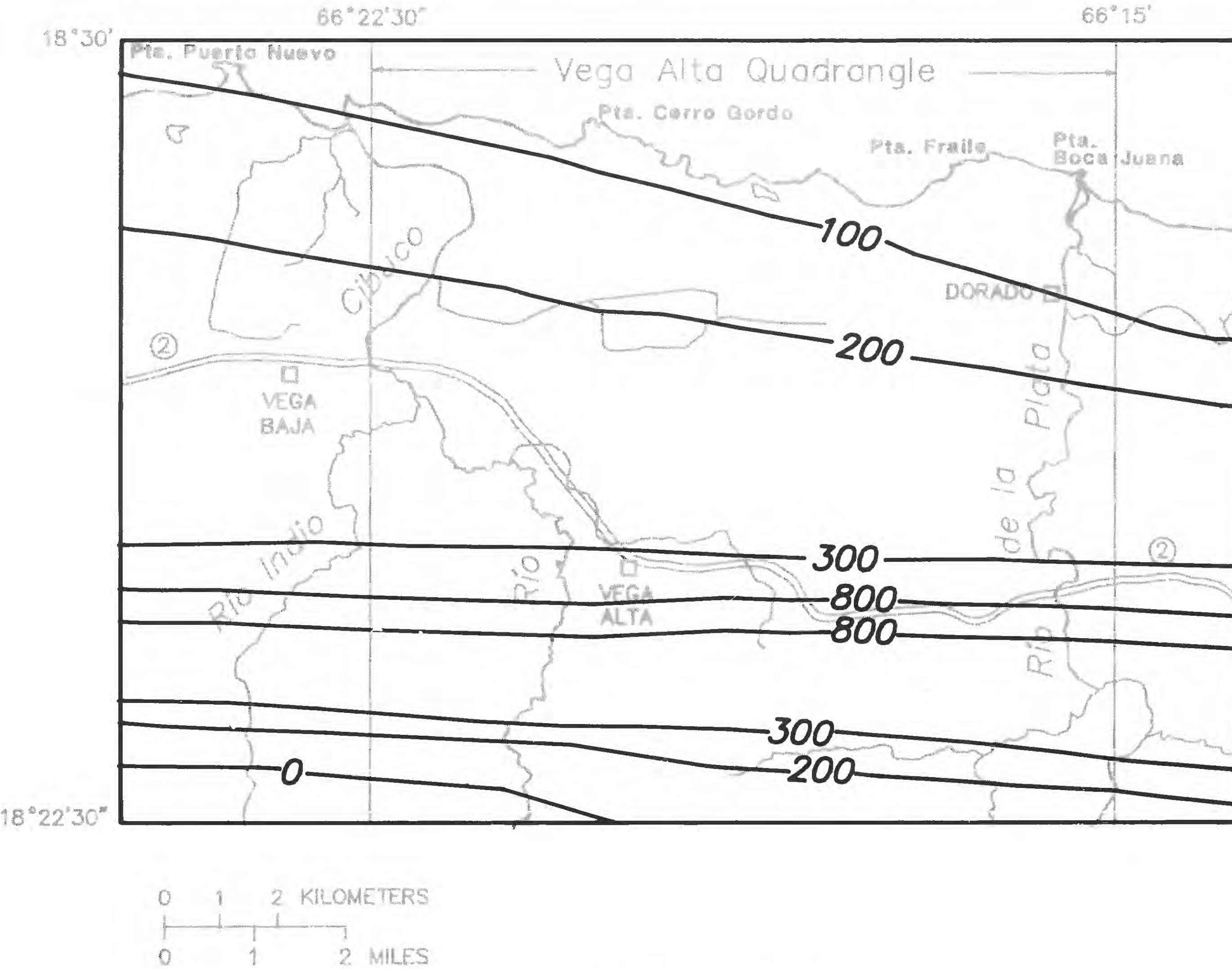
(5) There is no indication of a regionally extensive confined aquifer system as indicated by water levels in wells. In general, wells penetrating into parts of the aquifer previously defined as confined within the Cibao Formation, show a lowering in the potentiometric surface. This can be directly related to the regional anisotropy caused by a general reduction of hydraulic conductivity with stratigraphic depth (Giusti, and Bennett, 1976, p. 21). In transient simulations a water table storage coefficient should be considered.

(6) Ground water discharges as seepage to the seabed, streams and the principal drainage ditch at Cienaga Prieta, in addition to being withdrawn at wells. Aquifer loss to evapotranspiration at the coastal plain may be insignificant at present (1982) due to depth of water beneath land surface.

Aquifer Properties

Transmissivity values for each cell were estimated from specific capacity values reported by well drillers for the larger production wells and analyzed by techniques described by Theis and others (1963) for water-table conditions. Values obtained in this manner were assumed to represent the transmissivity for only that part of the aquifer open to the well. These were adjusted to account for the entire aquifer thickness containing freshwater (fig. 9). The lower limit of freshwater was estimated on the basis of surface resistivity surveys in the coastal plain and from wells known to be salty. Beneath the limestone tableland north of the town of Vega Alta the thickness of the freshwater lens was estimated on the basis of data from wells in the stream valleys and several wells which tap almost the full thickness of the Cibao Formation. The following criteria were used in adjusting the transmissivity (T') for each well site:

1. If lithology beneath the maximum penetration depth open to the well is similar, as based on regional hydrogeology, then the assumed value for the cell was a multiple of T' by the number



EXPLANATION

——300—— SUBSURFACE CONTOUR—Shows estimated altitude of bottom of freshwater aquifer in feet below sea level. Contour interval in feet, is variable. Datum is mean sea level.

Figure 9.--Estimated altitude of the bottom of the aquifer.

of well lengths untapped by the well.

2. If the well was selectively screened at water producing zones, and penetrated at least 80 percent of the estimated aquifer thickness, no adjustment was made.

3. If upward coning of saltwater was evident (increase in chlorides concentration with rate of pumpage), no adjustment of T' was made. Areas where saltwater upconing seems to occur, based on chloride ion concentrations, are within the coastal plain and lower Río Cibuco alluvial valley (fig. 10).

The equation used in estimating T' was,

$$T' = (Q/s)[K - 264\log 5S + 264\log t]$$

where,

T' is the estimated transmissivity as previously defined, in gallons per day per feet. To obtain modern units, in feet squared per day divide by 7.48,

Q is the well pumpage rate expressed in gallons per minute,

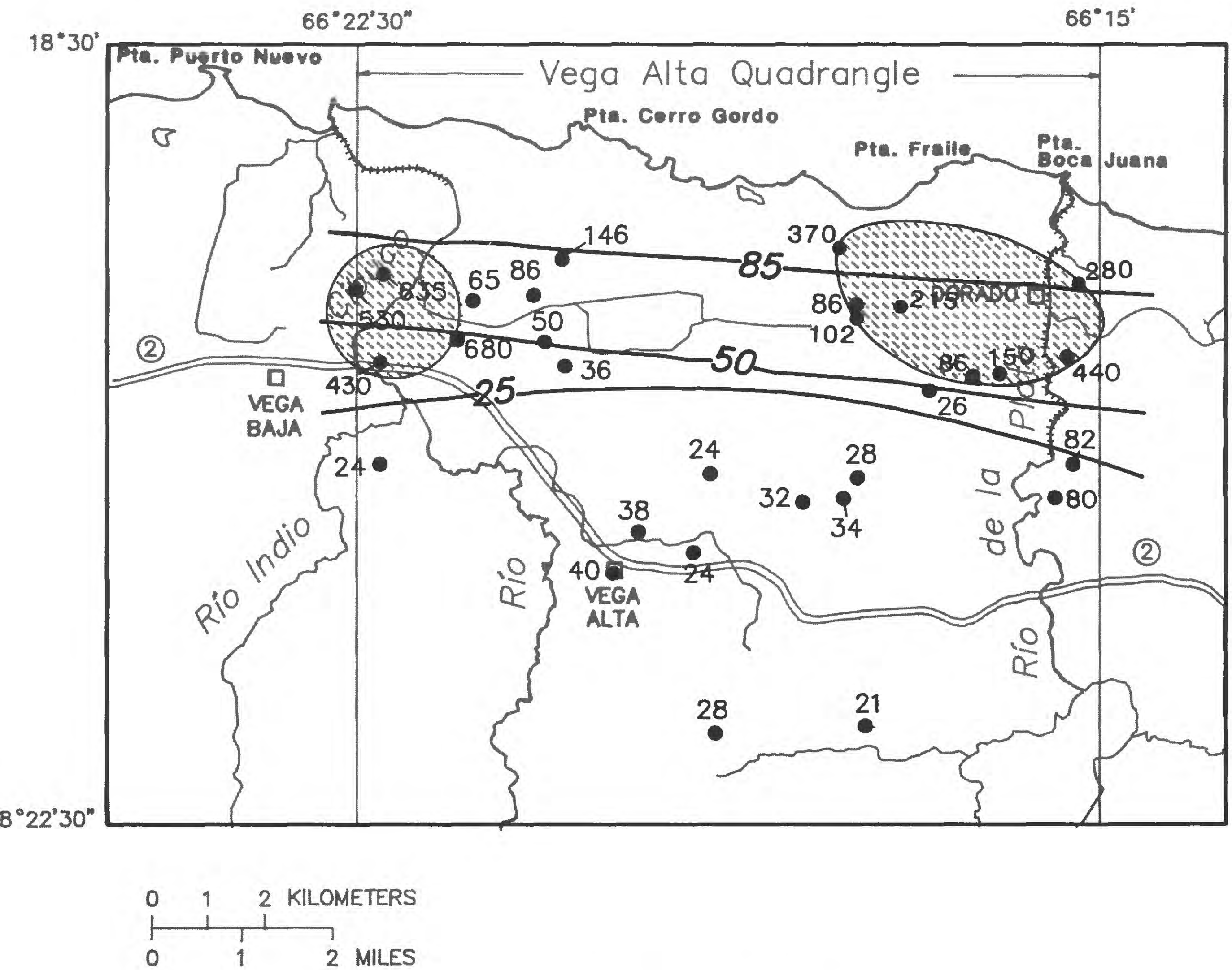
s is the drawdown in the well at time, t, in feet,

K is a coefficient dependent on the effective radial distance at which s is valid. A value of 1,367 was used, corresponding to an effective radius of 1.0 feet. This value seems appropriate given the rock units tapped, if no cavernous conditions exist. For wells penetrating cavernous zones the effective radial distance was assumed as 5.0 feet; at such wells a value for K of 996 was used,

S is the storage coefficient, which was assumed as 0.1,

t is the duration of the test, in days.

The estimated transmissivity values obtained indicate a significant local variation which can be related to the degree of secondary porosity development of limestone rocks. Wells completed in the Aymamón Limestone



EXPLANATION

AREA WHERE UPWARD CONING OF SALTWATER IS EVIDENT.

25 — LINE OF EQUAL ESTIMATED BASELINE CONCENTRATION OF CHLORIDE IN FRESHWATER PART OF AQUIFER--Interval, in milligrams per liter, is variable.

ESTUARY SEGMENT OF STREAM AFFECTED BY SALTWATER WEDGE.

28 ● WELL--Number is maximum chloride concentration at selected well sites during 1983, in milligrams per liter.

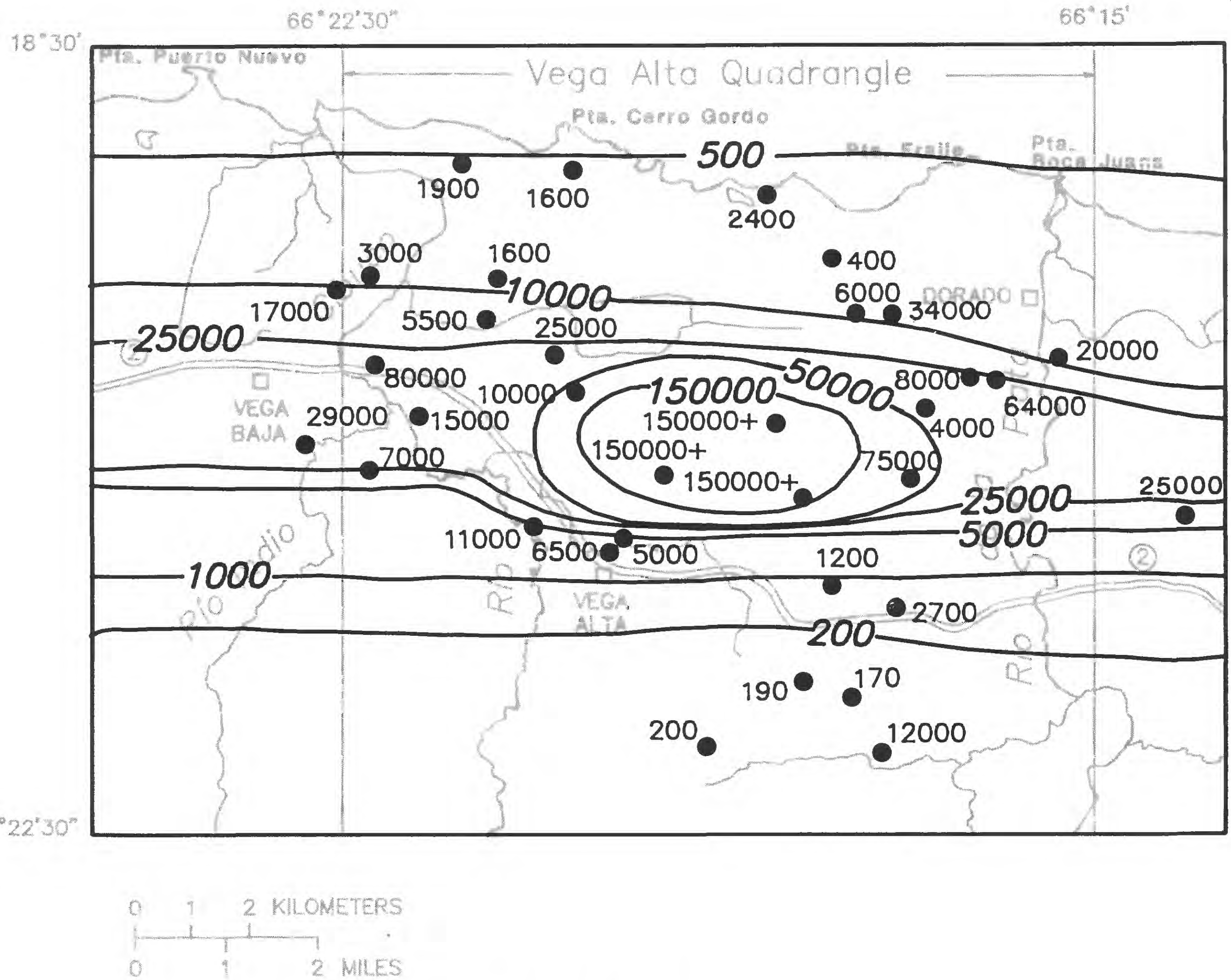
Figure 10.--Areas where wells are affected by saltwater upconing.

showed the greatest variation. Therefore, in defining the preliminary regional estimates of transmissivity, smoothed contour lines were drawn varying from as low as 100 ft^2/d within the southern limit of the aquifer system (consisting of the Cibao Formation and the Mucarabones Sand and Lares Limestone hydrogeologic units which do not crop out within the Vega Alta Quadrangle) to as high as 150,000 ft^2/d in the tableland area north of Vega Alta (representing the Aymamón and Aguada Limestone hydrogeologic units). Seaward, the transmissivity estimates decreased from an estimated 25,000 ft^2/d on the southern fringe of the coastal plain to about 2,000 ft^2/d at the coast line. In general, these first areal estimates of transmissivity required minor adjustment during the model calibration process. The final areal transmissivity values obtained through the calibration process are shown in figure 11.

The other important aquifer property which needed definition in order to complete transient simulations was the specific yield. Based on the previous analyses, (potentiometric surface map and relation to hydrogeologic units) it can be assumed that on a regional basis the aquifer can be considered to be under water-table conditions. Therefore, for transient simulations, a storage coefficient of 0.10 was assigned to all cells. This value is probably representative of most areas except possibly in that part of the aquifer underlying the coastal dunes. Confined conditions are evident in this zone as shown from driller's logs and analyses of well and tidal records of water level fluctuations at the Dorado airfield and the nearby coast.

Boundary Conditions

The following discussion refers to the boundary conditions used in the analysis of the aquifer as a two dimensional (2-D) flow system. A 2-D approach was used because of the unavailability of regional potentiometric surface data prior to modification of the aquifer flow system through drainage works and large scale ground-water withdrawals. Without such information, the regional vertical anisotropy cannot be defined without additional field testing. The results obtained through a 2-D



EXPLANATION

——200—— LINE OF EQUAL TRANSMISSIVITY ESTIMATED FOR FRESHWATER FLOW ZONE OF AQUIFER——Interval in, feet squared per day, is variable.

150000+ ● WELL——Number is estimated transmissivity, in feet squared per day. Plus sign after value indicates estimate is presumed as conservative.

Figure 11.--Transmissivity estimates at selected wells and the regionalized transmissivity distribution as obtained through model calibration for the freshwater part of the aquifer.

modeling approach, nevertheless, serve to indicate what specific data needs seem more pertinent and should be obtained before construction of a 3-D flow model which would more closely resemble the real flow system.

Prior to defining the boundary conditions for the model, the following general assumptions were made:

1. Aquifer transmissivity values assigned are independent of water table changes in transient simulations. This is justified on the basis of driller's logs which indicate the probable existence of preferential horizontal flow planes in the part of the aquifer within the Aguada and Aymamón Limestones at water-table depth and within approximately 70 to 120 feet below sea level. The same justification may not apply within the less permeable Cibao Formation, but ground-water withdrawals and long-term variation of the water table in this area have been minimal.

2. Areal rainfall recharge rates are constant.

3. Stream water level altitudes are constant.

4. The fresh-saltwater interface is static beneath the freshwater part of the aquifer; the interface was assumed to be the lower boundary of the flow system where it underlies the freshwater zone.

5. Ground-water withdrawal rates reported by owners or estimated in this study are constant for the given period of simulation.

6. The aquifer is at equilibrium under the stress conditions used in calibrating the model (February 1983).

Constant head boundaries were assigned along the cells delineating the coastline and the east and west limits of the modeled area. A no-flow boundary was assigned along the cells delineating the southern part of the modeled area (fig. 12). The head values assigned at cells along the coastline vary from 1.0 to 2.0 ft. Such values were estimated to be greater than zero because wells drilled through the dune deposits

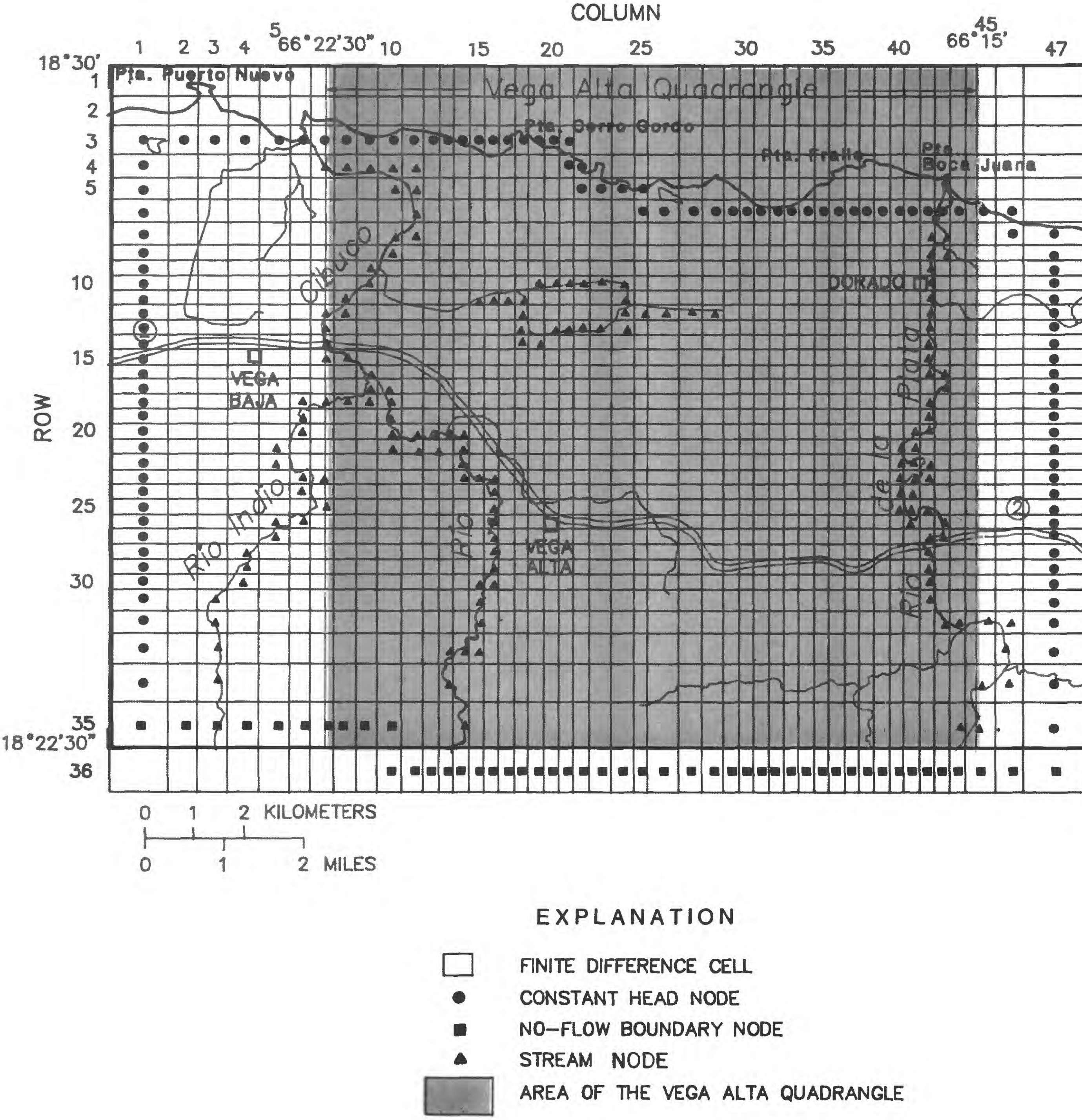


Figure 12.--Boundary conditions specified in steady-state model.

indicate confined conditions. The values assigned for individual cells correspond to the estimated potentiometric surface of February 1983 (Torres-Sierra, 1985). Along the lateral boundaries outside the Vega Alta quadrangle area the head values assigned were estimated by extrapolating contours obtained in the February 1983 survey.

Initial Conditions

Well and spring discharge rates were represented by specifying the estimated flux for each node in cubic feet per second (ft^3/s). The rates assigned correspond to that which existed during 1982 for the individual wells and springs. In general the flow rates of most wells are maintained constant throughout the year with the only exception being the irrigation wells located at the northwest part of the modeled area. Discharge rates estimated for the springs correspond to base flow rates.

Stream-bed leakage, is computed for each cell for which vertical leakage has been assigned. A sub-routine for river leakage in the computer code was used for the solution (McDonald and Harbaugh, 1984, p. 18). The input requirements in the subroutine are streambed altitude and the water head in the stream. An initial value for the conductance of the river bed, C, (the ratio of the streambed hydraulic conductivity, K_z, to the thickness of the riverbed, m, times the length, l, and width, w, of the stream segment within the finite difference cell [$C = (K_z/m) \times (l) \times (w)$]) also needs to be specified. Since for most conditions, K_z/m, is unknown, C is determined indirectly through calibration procedures. The assigned values of streambed altitude were estimated from 1:20,000 topographic maps, visual inspections and previous field surveys (Torres-González and Díaz, 1985). Head values were estimated from field observations of stream depth during base flow conditions. Cells activated for stream-aquifer flux mass balance included the entire length of Río Cibuco, Río Indio, Río de la Plata, and parts of the principal drainage ditch at Ciénaga Prieta (fig. 12). Río Lajas was not incorporated in the model because its effect on the conceptualized regional flow system for the given conditions can be assumed as negligible; the stream can be considered a water table divide in 2-D ground-water flow asumptions.

Initial estimates of aquifer recharge rates were obtained from a correlation of rainfall versus evapotranspiration developed by Giusti (1978, p. 21) for watersheds at which ground-water discharge to streams is negligible in Puerto Rico. From this correlation an approximation of the maximum amount of rainfall which could be available for infiltration beneath the ground surface on an annual rate can be obtained. This correlation is especially useful in obtaining preliminary estimates of rainfall rates in enclosed basins within the karst areas where runoff is known to be minimal. The maximum amount of recharge for such locations (cells) was estimated at 33 inches per year. This rainfall recharge is for a mean annual precipitation of 79 inches (the average for records at a National Weather Service site at the Dorado airfield and data at Media Luna and Poblado Higuillar (fig. 2) for the years 1979-82). For the upper part of the aquifer where runoff drains to Río Lajas, an average of about 10 inches per year of rainfall could result in ground-water recharge since 13 inches per year is accounted for as runoff. This is based on 8 years of record at the discontinued USGS gage 50457000 at Río Lajas. Other locations within the limestone upland were assigned preliminary recharge rates according to geologic features: areas known to have thick blanket deposits were assigned recharge rates of approximately 1/2 the maximum (a recharge rate of 16 inches per year) except at enclosed topographic lows which receive runoff; limestone outcrop areas were assigned recharge rates equal to or slightly below maximum. Cells within the coastal plain were assigned recharge rates about equal to 5 percent of the mean annual rainfall (a recharge rate of 4 inches per year) or lower at sites where soils are mostly derived from deposits of clay and muck.

Evapotranspiration from the aquifer at the coastal plain was not modeled because the potentiometric surface in this area lies at more than 6 ft below land surface. This depth was found to be the approximate lower limit for direct evapotranspiration from aquifers (Gardner, 1958).

Calibration

The procedure used in calibrating the model began with areal adjustments in recharge rates, followed by adjustments in streambed conductance values. These two parameters were treated as "variables" since their initial estimates in the input arrays are the least certain. Recharge rates specified for individual cells were modified areally during the calibration process only to a minor degree. Most changes were made to the entire recharge matrix at once by changing the value of the conversion factor. As a result the end values obtained after the calibration process show recharge rates to the nearest tenth of an inch. After calibration no effort was made to round the values to the nearest integer (table 2). Rainfall recharge rates obtained through the model calibration procedures were generally lower than the preliminary estimates. This is to be expected since the preliminary estimates, based on Giusti's rainfall versus evapotranspiration correlation, assume all water not accounted for as evapotranspiration results in aquifer recharge with no runoff.

After a general agreement was achieved between the water level contours simulated and those of February 1983 (Torres-Sierra, 1985), areal adjustments of transmissivity values were made. Most of the transmissivity changes were required in the part of the aquifer extending southward of the Aguada Limestone-Cibao Formation contact. At about this hydrogeologic contact, it is estimated that the fresh-water aquifer reaches its maximum thickness (fig. 9) and hydraulic conductivity is much lower resulting in a change of nearly two orders of magnitude in transmissivity between the Aguada Limestone and Cibao Formation across a distance of less than one mile (figs. 4 and 11). Transmissivity values south of row 27 initially varied from a maximum of 1,000 ft^2/d to a minimum of 100 ft^2/d along row 35. Final calibration resulted with values of 200 ft^2/d at all rows past 30. Another area where transmissivity values were reduced to achieve a better match of the simulated potentiometric surface with the calibration data set was near the coastline. Transmissivity values were lowered from 1,000 ft^2/d to 500 ft^2/d.

Table 2. Areal rainfall reacharge rate by finite difference cell in inches per year resulting from model calibration

ROW NUMBER	COLUMN NUMBER 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
7	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
8	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
10	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
11	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	9.7	9.7	9.7	9.7	3.9	3.9	3.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
12	3.9	3.9	3.9	3.9	3.9	3.9	3.9	9.7	9.7	9.7	9.7	3.9	3.9	3.9	3.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
13	3.9	3.9	3.9	3.9	3.9	3.9	3.9	9.7	9.7	9.7	9.7	3.9	3.9	3.9	3.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
14	3.9	3.9	3.9	3.9	3.9	3.9	3.9	9.7	9.7	9.7	9.7	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
15	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	9.7	9.7	9.7	9.7	9.7	9.7	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6
16	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.9	3.9	19.5	19.5	19.5	19.5	19.5	19.5	14.6	14.6	14.6	19.5	17.0	14.6	14.6	14.6
17	9.7	9.7	9.7	9.7	3.7	3.7	3.7	3.9	3.9	19.5	19.5	19.5	19.5	19.5	19.5	14.6	14.6	14.6	17.0	17.0	14.6	14.6	14.6
18	9.7	9.7	9.7	9.7	9.7	3.9	3.9	3.9	3.9	19.5	19.5	19.5	19.5	19.5	19.5	14.6	14.6	17.0	17.0	17.0	17.0	17.0	17.0
19	9.7	9.7	9.7	9.7	9.7	3.9	3.9	3.9	3.9	19.5	19.5	19.5	19.5	19.5	19.5	17.0	17.0	14.6	14.6	14.6	14.6	14.6	14.6
20	9.7	9.7	9.7	9.7	4.9	2.4	9.7	9.7	4.9	2.4	14.6	14.6	14.6	19.5	19.5	19.5	14.6	14.6	14.6	14.6	14.6	14.6	14.6
21	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	2.4	2.4	2.4	2.4	2.4	2.4	3.9	14.6	14.6	18.3	18.3	18.3	18.3	18.3
22	19.5	19.5	19.5	14.6	14.6	14.6	19.5	19.5	19.5	19.5	14.6	14.6	14.6	3.9	3.9	3.9	3.9	14.6	14.6	14.6	19.5	19.5	19.5
23	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	3.9	3.9	3.9	3.9	3.9	14.6	14.6	17.0	17.0	17.0
24	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	3.9	3.9	3.9	3.9	14.6	14.6	14.6	17.0	17.0	17.0
25	14.6	14.6	14.6	14.6	9.7	9.7	14.6	14.6	14.6	14.6	14.6	14.6	14.6	9.7	9.7	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
26	14.6	14.6	14.6	14.6	9.7	9.7	14.6	19.5	17.0	17.0	17.0	17.0	17.0	17.0	14.6	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
27	3.9	3.9	3.9	3.9	3.9	3.9	9.7	17.0	17.0	17.0	17.0	17.0	17.0	17.0	3.9	3.9	9.7	17.0	3.9	3.9	3.9	3.9	3.9
28	3.9	3.9	3.9	3.9	3.9	19.5	19.5	17.0	17.0	17.0	17.0	17.0	17.0	11.2	3.9	3.9	3.9	17.0	17.0	17.0	17.0	17.0	17.0
29	3.9	3.9	3.9	3.9	19.5	19.5	19.5	9.7	9.7	9.7	9.7	9.7	19.5	3.9	3.9	3.9	3.9	15.8	15.8	15.8	15.8	15.8	15.8
30	1.0	1.0	1.0	1.0	1.0	1.0	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	9.7	9.7	9.7	9.7	9.7	9.7	9.7
31	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.7	3.7	3.7	3.7	3.7	3.7	7.3
32	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.7	3.7	3.7	3.7	3.7	7.3
33	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.7	3.7	4.9	4.9	4.9	4.9
34	1.0	1.0	1.0	1.0	1.0	1.0	2.4	2.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.7	3.7	3.7	4.9	4.9	4.9	6.1	6.1
35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	3.7	3.7	3.7	4.9	6.1	6.1	6.1	7.3
36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER	COLUMN NUMBER 24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	3.9	3.9	3.9	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	0.0	0.0
8	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	1.9	1.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
15	14.6	14.6	14.6	14.6	14.6	14.6	14.6	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
16	14.6	14.6	14.6	14.6	17.0	14.6	14.6	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
17	14.6	14.6	14.6	14.6	17.0	12.2	12.2	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	3.9	3.9	3.9	3.9	3.9	3.9	3.9
18	17.0	17.0	17.0	17.0	12.2	12.2	12.2	17.0	17.0	14.6	14.6	14.6	14.6	12.2	12.2	12.2	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
19	14.6	14.6	14.6	14.6	14.6	14.6	17.0	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	3.9	3.9	3.9	3.9	3.9	2.4	2.4
20	14.6	14.6	14.6	14.6	14.6	14.6	14.6	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
21	18.3	18.3	18.3	18.3	18.3	18.3	18.3	14.6	14.6	12.2	12.2	12.2	12.2	12.2	12.2	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
22	19.5	19.5	19.5	19.5	14.6	14.6	14.6	14.6	14.6	12.2	12.2	12.2	12.2	12.2	12.2	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
23	17.0	17.0	17.0	17.0	17.0	17.0	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
24	17.0	17.0	17.0	17.0	17.0	17.0	14.6	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	3.9	3.9	3.9	3.9	3.9	3.9	3.9	9.7	9.7
25	3.9	3.9	3.9	15.8	15.8	15.8	15.8	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	3.9	3.9	3.9	3.9	3.9	3.9	3.9	9.7	9.7
26	3.9	3.9	3.9	17.0	17.0	17.0	17.0	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	3.9	3.9	3.9	3.9	3.9	3.9	3.9	14.6	14.6
27	3.9	3.9	3.9	19.5	19.5	19.5	19.5	12.2	12.2	12.2	12.2	12.2	12.2	9.7	9.7	9.7	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
28	17.0	19.5	19.5	19.5	19.5	19.5	19.5	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
30	15.8	15.8	15.8	15.8	15.8	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
31	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	2.4	2.4	2.4	2.4	2.4	2.4	2.4
32	7.3	7.3	9.7	7.3	7.3	7.3	7.3	7.3	7.3	7.3	3.7	3.7	3.7	3.7	3.7	2.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
33	7.3	7.3	9.7	9.7	7.3	7.3	7.3	7.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
34	6.1	13.4	6.1	3.7	3.7	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
35	6.1	6.1	6.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
36	7.3	7.3	6.1	6.1	6.1	6.1	6.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Comparison of the model generated potentiometric surface contours at the end of the calibration process with those of February 1983 (Torres-Sierra, 1985) were generally good (fig. 13). The only significant discrepancies were for the northwest part of the modeled area and at the vicinity of the river mouths. Since contours outside the Vega Alta quadrangle were extrapolated beyond the data, this discrepancy may only be apparent. The landward displacement of the 3.0 ft contour could be caused by an overestimation of pumpage at wells. This was determined through the sensitivity analyses process discussed in a separate section.

Various conclusions obtained from the model calibration effort are:

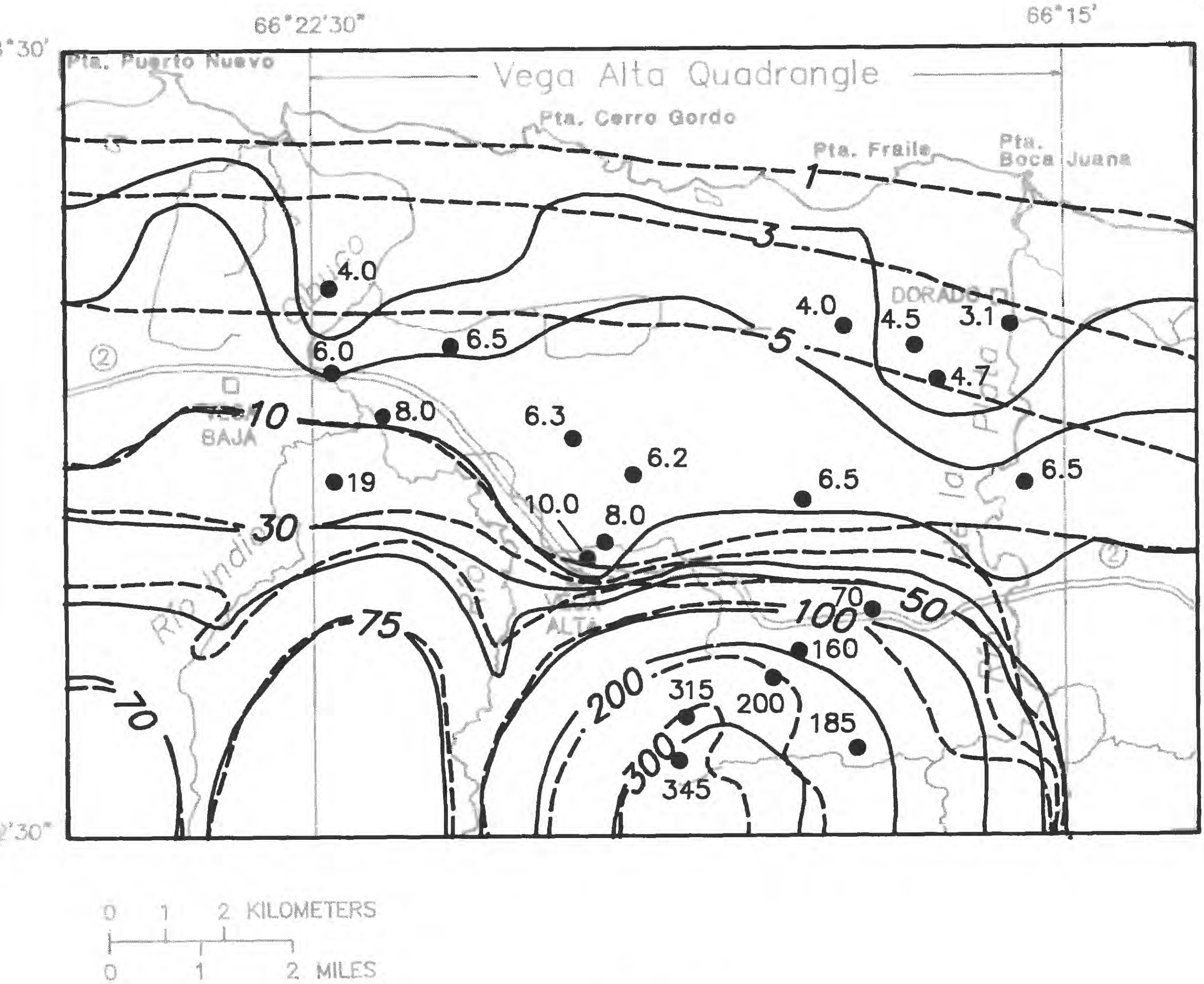
1. Areal rainfall infiltration is the principal source of recharge to the aquifer, estimated at 34 ft^3/s, or about 85 percent of the total recharge rate under existing aquifer withdrawal rates.

2. Río Cibuco could be contributing approximately 6 ft^3/s (15 percent of the total aquifer recharge under existing pumping conditions).

3. Aquifer discharge at present occurs as follows:

Sink	Flow rate, ft^3/s	Percent
Ground-water withdrawals	31.0	76.0
Coastline outflow	.6	1.5
Cienaga Prieta drainage	2.8	6.9
Río Cibuco and Río Indio	2.1	5.1
Río de la Plata	1.2	2.9
Spring outflow	0.7	1.7
Outflow across lateral boundaries	2.4	5.9

4. The tableland north of the town of Vega Alta is the "core" of the aquifer both as the major source of recharge and best yield to wells (highest transmissivity).



EXPLANATION

——300—— MODEL GENERATED 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.

– – – 100 – – – ACTUAL POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contours from map prepared by Torres-Sierra(1985) for the Vega Alta quadrangle and model boundaries. Contour interval, in feet, is variable. Datum is mean sea level.

6.5 ● WELL--Number is altitude of water level for well sites used by Torres-Sierra(1985), in feet above mean sea level.

Figure 13.--Model generated potentiometric surface and actual potentiometric surface for reference conditions of February 1983.

5. Stream-aquifer interrelationship along the coastal segment of Río de la Plata seems to be insignificant. This could be caused by the combination of low conductance of streambed deposits, thickness of the alluvium, and high transmissivity of the Tertiary units which underlie the alluvium. As a result, ground-water flow is preferentially northward through the limestone units.

6. Rainfall recharge rates are highest at outcrop areas of the Aymamón and Aguada Limestones, varying areally from 10 to as much as 20 inches per year.

Model Validation

Validation of the ground water flow model was accomplished by simulating the historical ground water development trend as occurring in six stress periods beginning in 1930 and ending in 1983 (fig. 14). The ground water withdrawal rates used for each stress period were estimated by assuming the wells were put into operation on the date of their construction and pumped at the rate reported in well schedules. Wells which were abandoned or not pumped within given stress periods were not included in that specific time interval of the simulation. Initial values of the potentiometric surface prior to development were assumed to correspond to those obtained by the calibrated model under no pumpage conditions. Other parameters and aquifer boundary conditions were maintained constant throughout the entire transient simulation period. No effort was made to modify the coastal plain aquifer discharge feature from the streambed-aquifer interrelationship used at Cienaga Prieta to a more realistic areal representation of seepage or evapotranspiration for the stress periods prior to construction of the principal drainage ditch.

Changes in the potentiometric surface predicted by the model were compared with water level measurements at the Sabana Hoyos monitoring well (node 17,15, fig. 6) and the Higuillar well (node 35,16, fig. 6). These are the only sites for which scheduled measurements in the study area have been made by the USGS for a significant length of time.

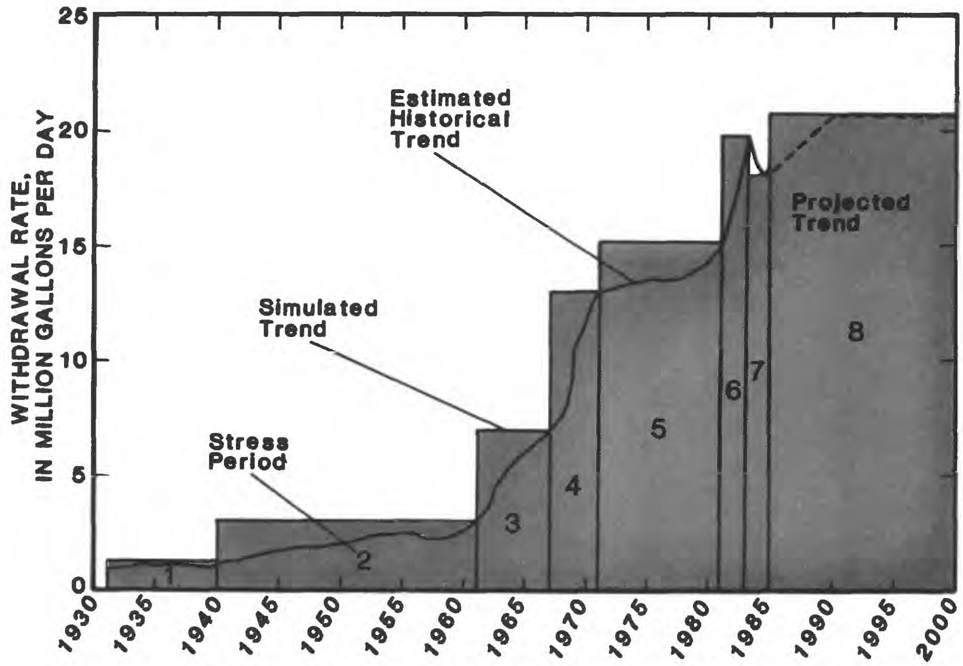


Figure 14.--Stress periods used in simulating the ground-water development trend between 1930 and 1983 and projected trend and stress periods for the period 1984 to 2000.

A second set of data used in verifying the aquifer flow model consisted of the water levels reported by drillers upon completion of wells and unscheduled measurements at abandoned wells (table 3).

The water level trend predicted for both long-term monitoring sites very closely matched the actual recorded data until the mid 1960's (fig. 15). At first it seemed that the model predicted water levels were in good agreement with actual data for the early stress periods, but predicted greater aquifer drawdown in the latter stress periods. However, on analysis it was confirmed that the water levels being measured at both monitored wells are affected by oil within the casings. At Sabana Hoyos crankcase oil was possibly disposed of in the well casing after the pump was removed in 1960 and the well house abandoned (USGS Hydrologic Technicians R. Dacosta and F. Hernández, written commun., 1985). This does not include lube oil left in the casing. Onsite inspection made September 1985, indicated the presence of an oil lenş within the immediate vicinity of the well casing with a thickness of about 3 to 5 ft. At the Dorado public water supply well (Higuillar well), lube oil was found within the annulus of the well casing and pump column with a thickness greater than 30 ft (onsite inspection Oct 1985). Its source is most likely leakage from pump bearings. Confirmation that the model-simulated water levels at these two sites better represents the true potentiometric surface was obtained from data used in the development of the potentiometric surface map of February 1983. The map was based on wells which were leveled to mean sea level datum (Torres-Sierra, 1985). The two long-term observation wells have not been referenced to sea level datum. That would indicate altitudes of the water surface under static conditions of about 6.5 ft at Sabana Hoyos and about 5.0 ft at the Dorado public water supply well.

The data in table 3 indicate that in general for the early time periods of simulation the potentiometric surface values at nodes 20,23; 20,27, and 27,20 are higher than actual measurements. This error could be due to departure from the two major assumptions used in developing the flow model:

Table 3. Recorded water-level measurements at selected well locations used in model verification analysis

[Water levels shown to one decimal point are for well sites tied to mean sea level datum by NUS, Inc. Data at other sites are referenced to local land surface altitude from 1:20,000 topographic map. All field measurements reported are for static (no pumpage) conditions.]

Node row, column	Date, year	Water level altitude, feet above mean sea level: Reported	Simulated
27,20	1940	20	47
14,16	1956	10	14
27,20	1958	16	17
20,23	1961	9	19
15,38	1961	16	13
20,27	1964	7	17
25,20	1967	10	12
28,30	1970	105	47
27,8	1971	35	55
34,24	1977	336	324
15,39	1978	5	1
34,24	1982	317	319
20,27	1983	7.6	7.4
24,21	1983	8.8	6
20,23	1983	8	6.5
27,23	1984	35.7	33.3
32,28	1984	210	235

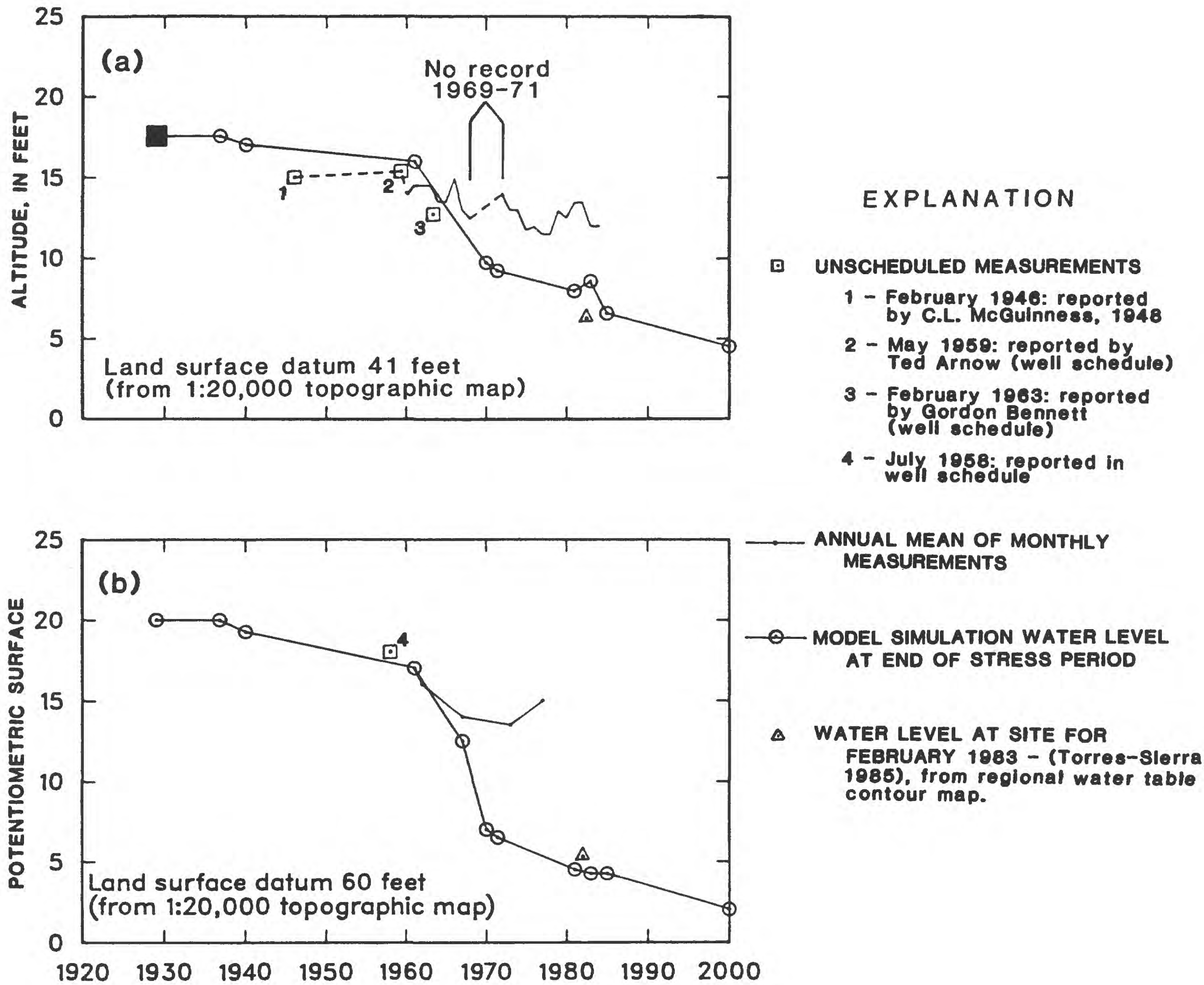


Figure 15.--Historical water-level measurements at long-term ground-water monitoring sites: (a) Sabana Hoyos and (b) Higuillar and model predicted water levels.

1) that the fresh-saltwater interface is static and serves as the lower boundary of the aquifer, and

2) aquifer recharge by rainfall infiltration is constant and equal to the model calibration rate of 34.2 ft^3/s.

It is possible that upward displacement of the interface has occurred particularly in the high transmissive part of the aquifer where cavernous limestone occurs. In such areas the ratio of vertical to horizontal anisotropy could be near unity. Since only the freshwater flow zone was considered in estimating transmissivity, this would result in an underestimation of transmissivity for predevelopment conditions and early time periods in the historical simulation. Concerning the second assumption, it is most probable that aquifer recharge from rainfall infiltration has been augmented through increased withdrawals in the vicinity of pumping wells.

Sensitivity Analysis

Sensitivity analyses were made on the calibrated aquifer model for each of the parameters while maintaining the others constant. Each parameter was varied in value within a range considered to be within the uncertainty of its estimated value as obtained from actual field data (as pumpage and transmissivity estimates) or through the calibration process (as streambed conductance and rainfall recharge).

The sensitivity analysis is only intended for demonstrating the relative effect of variation of one of these parameters on the potentiometric surface since locally some parameters are more important than others. The results of the analyses are shown for a cross section of the area along column 25 (fig. 16). Generally, along this transect, the model is most sensitive to recharge and least sensitive to streambed conductance. It also can be observed that transmissivity estimates are not critical in the northern part of the aquifer. With regard to the streambed conductance, this parameter should have the least effect along

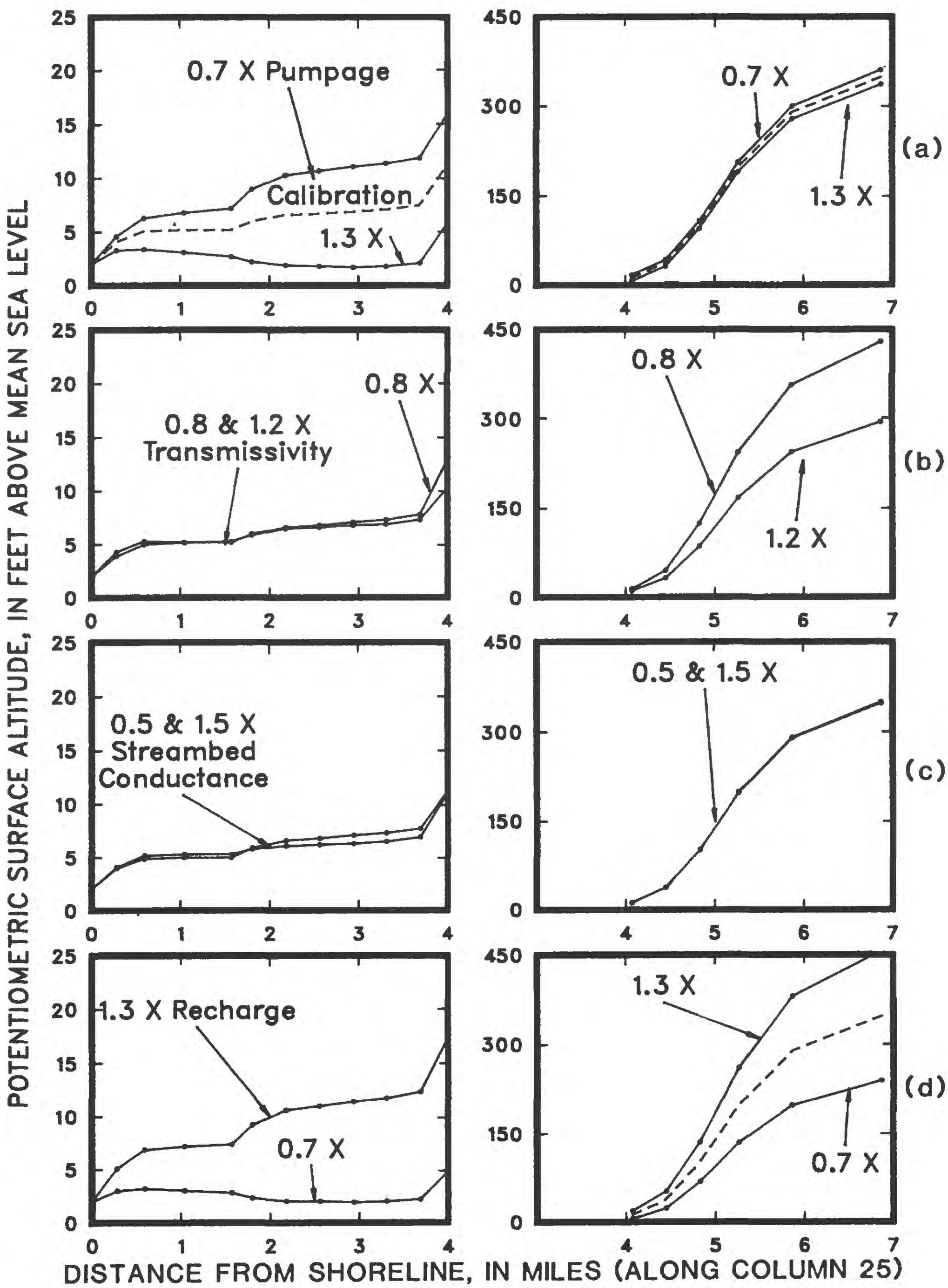


Figure 16.--Model sensitivity to areal variations in: (a) pumpage, (b) transmisivity, (c) streambed conductance, and (d) recharge.

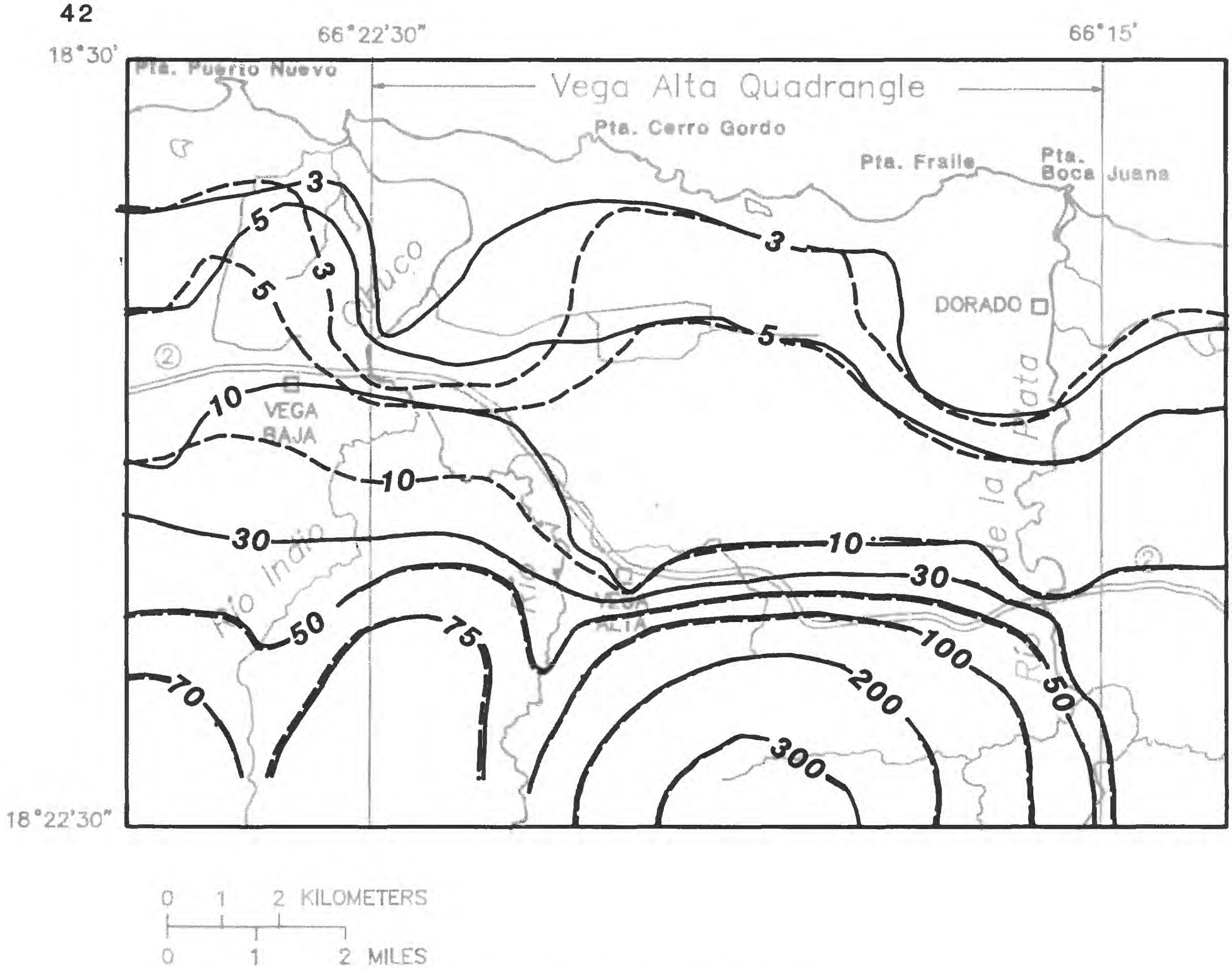
the central part of the aquifer. However, when a regional view of the potentiometric surface is considered (fig. 17), the aquifer model is most sensitive to streambed conductance along Río Cibuco.

A sensitivity analysis was also conducted for the storage coefficient, S_c. Model output of the potentiometric surface at the two long term monitoring sites were compared for values of $S_c = 0.15$ and 0.05. Simulations with these values for S_c for the period 1930 to 1983 produced identical results to the simulation with $S_c = 0.10$. The apparent insensivity of the model to S_c can be attributed to the long-term simulation and relatively rapid rate at which the aquifer system establishes equilibrium. This is evident along the northern part of the modeled area where recharge rates and aquifer transmissivity values are high. Within the southern region of the aquifer, transmissivities are low, and the model is more sensitive to S_c. This is inferred from the decline in the water level in the vicinity of the public water supply well at node 34,24. At this site water level declined at a rate of 4 ft/yr between 1977 (when the well was constructed) to 1982 (when the pump was dismantled for repair). This rate of drawdown was simulated using a $S_c = 0.05$. A drawdown rate of 2.4 ft/yr was obtained with a $S_c = 0.15$ and 2.6 ft/yr with a $S_c = 0.10$. Data from driller's well logs suggest that S_c values of 0.05 could be representative of zones in the aquifer within the Cibao Formation and older units, while an $S_c = 0.10$ could be a good estimate of zones of the aquifer in the Aymamón and Aguada Limestones.

EFFECTS OF DEVELOPMENT

Effect of Withdrawals on Hydrologic System

The digital flow model was used to assess the effects of ground-water withdrawals on streamflow infiltration and natural discharge features, and to simulate the effects of future withdrawals. In essence, an increase of ground-water withdrawals resulted in reducing aquifer



EXPLANATION

——300—— MODEL GENERATED POTENTIOMETRIC CONTOUR WITH STREAMBED CONDUCTANCE VALUES. A FACTOR OF 1.5 TIMES THE MODEL CALIBRATION VALUE--Shows altitude at which water level would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is mean sea level.

- - -10- - - MODEL GENERATED POTENTIOMETRIC CONTOUR WITH STREAMBED CONDUCTANCE VALUES. A FACTOR OF 0.5 TIMES THE MODEL CALIBRATION VALUE--Shows altitude at which water level would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is mean sea level.

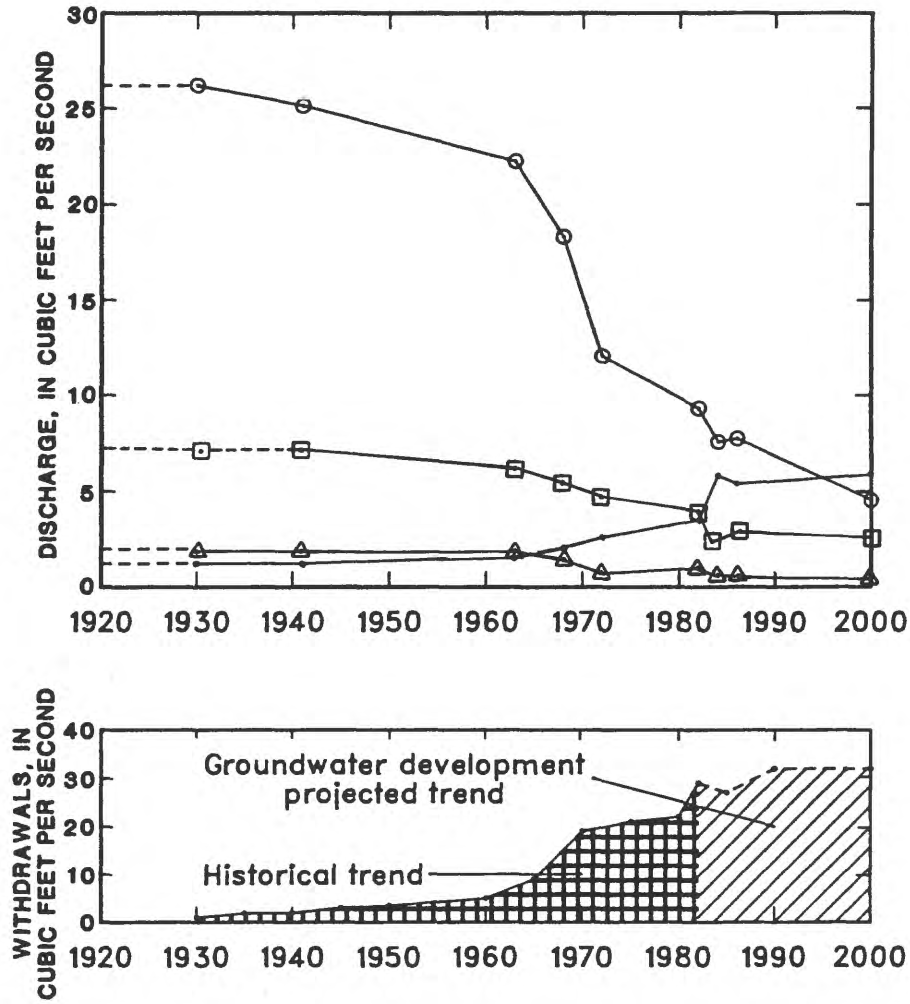
Note: Refer to figure 13 for potentiometric surface contour map of calibrated aquifer flow model. Above the 10 foot contour the variation of streambed conductance had nagligible effects on potentiometric surface.

Figure 17.--Model sensitivity to streambed conductance.

discharge to natural sinks--coastal marshes, seabed and streambed seepage--and an increase in seepage to the aquifer from streamflow (fig. 18). Prior to aquifer development, the only streams recharging the aquifer were Río Cibuco and Río Indio along the stream segments contained between the 5000 and 25,000 ft^2/d transmissivity contours. The model-estimated seepage at both sites was about 1.2 ft^3/s. Under 1985 conditions, streamflow infiltration to the aquifer is predicted by the digital model to occur at Río Cibuco along stream segments contained from node 7,12 to node 16,28, and at Río Indio from its junction with Río Cibuco to node 7,23. The total infiltration was estimated as about 5.4 ft^3/s, mostly from Río Cibuco. A summary of the overall predicted hydrologic effects of ground-water development on the principal streams and Cienaga Prieta is summarized on table 4. Whether such reduction in streamflow has occurred is unknown since no historical data is available. As a check on the model-predicted stream losses, discharge measurements were conducted for a 2.5 mile segment of Río Cibuco (from node 20,13 to node 30,16) during low flow conditions with the following results:

Date	Discharge, in ft^3/s		Streamflow gain (+) in ft^3/s or loss (-)
	upstream	downstream	
Feb. 4, 1983	21.34	22.87	+1.53
Feb. 9, 1984	13.86	17.76	+3.90
Jan. 24, 1985	46.90	42.06	-4.84

The transient simulation predicts a streamflow loss of 1.25 ft^3/s throughout this time period for the same stream segment. Although the model predicted streamflow loss is within the range of the above results (+3.90 to -4.84) this is neither a confirmation or rejection of the model predicted value. Such confirmation of model predicted streamflow loss or gain is probably not possible due to the annual variation of rainfall recharge, problems in obtaining discharge measurements of better than 5 percent accuracy, difficulty in estimating discharge in near stagnant water (such as estuary portions of streams and the drainage ditch at Cienaga Prieta), and streamflow irrigation diversions in the lower Río Cibuco valley. The only approach would be annual surveys of streamflows along a "control" segment during low flow periods and analyses of trends through statistical techniques.



EXPLANATION

GROUND-WATER FLOW TO STREAMS AND CIENAGA PRIETA MARSH

GROUND-WATER FLOW TO LATERAL CONSTANT HEAD BOUNDARY - (Inflow remainded insignificant)

STREAMFLOW INFILTRATION TO AQUIFER

GROUND-WATER FLOW TO SEABED

Figure 18.--Model predicted effects of ground-water development on hydrologic recharge and discharge features--streams, Ciénaga Prieta, and coastal seabed.

Table 4. Predicted effects of ground-water development on aquifer flux to streams and Ciénaga Prieta

Flow from aquifer to:	Discharge, in cubic feet per second		
	1930	1985	2000
Ciénaga Prieta	15.2	3.8	3.0
Río Cibuco	5.5	1.6	1.6
Río Indio	1.5	1.1	1.1
Río de la Plata	2.9	1.2	1.3
Streambed infiltration to aquifer from:			
Río Cibuco	1.0	5.0	5.2
Río Indio	0.2	0.4	0.4
Río de la Plata	0.0	0.0	0.0

Proposed Changes in Ground-Water Withdrawals

The model was used to anticipate the effects on the aquifer resulting from the following changes expected to occur between 1983 and the year 2000.

1984 and 1985

- Discontinued pumpage of irrigation wells at nodes 9,8 and 10,7 due to saltwater upward coning. This represents a decrease in pumpage of 2.0 Mgal/d.

- Discontinued use of public water supply wells at nodes 24,21 and 25,20 due to contamination with organic solvents. Wells previously supplied 1.8 Mgal/d.

- Pumpage rates of public water supply wells increased: at node 14,17 from 0.4 to 0.89 Mgal/d; at node 15,17 from 0.0 to 0.40 Mgal/d and at node 23,16 from 0.21 to 1.15 Mgal/d. Overall increase in pumpage of 1.83 Mgal/d.

1986-1990

- New public water supply well at node 20,14 with a pumpage rate of 1.15 Mgal/d.

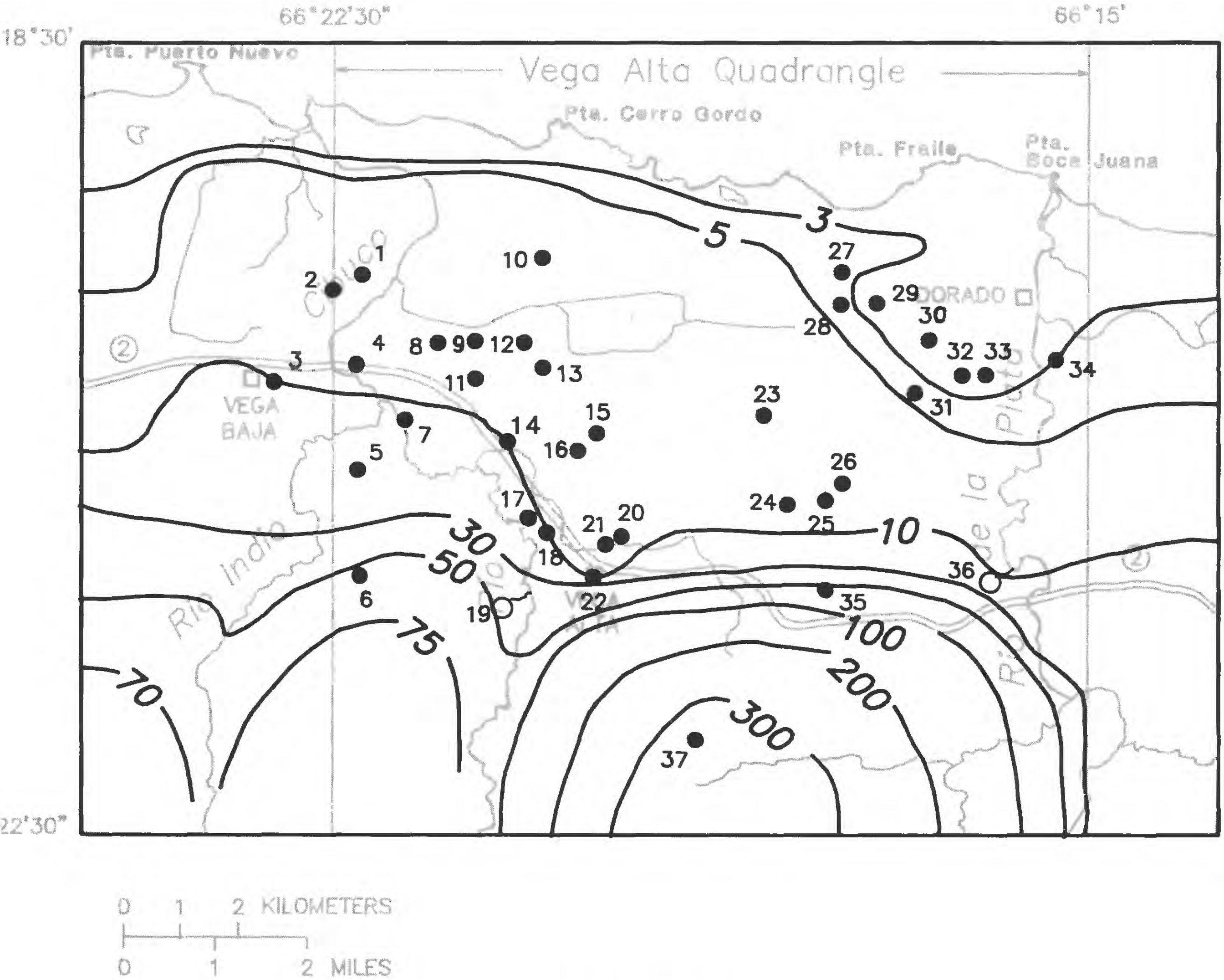
- New well at node 9,27 with a pumpage rate of 0.20 Mgal/d.

- New well field to meet public supply needs at Vega Alta located between nodes 23,33 and 23,27 with pumpage rate of 1.78 Mgal/d.

The proposed change in pumpage was simulated with the validated model under transient conditions. In order to compare model outputs for the year 2000 with 1983 (the potentiometric surface data base) the transient run began at the year 1930 and ended for the year 2000 with a total of 8 pumpage stress periods (refer to fig. 14). The model transient output of predicted water levels for 1983 was compared with the calibration potentiometric surface map (fig. 19 and table 5). The predicted water levels are almost identical with the steady-state simulation (refer to fig. 13) for contours above the 10 ft altitude and satisfactory for the 3 and 5 ft contour intervals.

If the potentiometric surface line denoting the 3 ft contour is deleted, both plots (the steady state calibration model output given in figure 13 and the transient prediction given figure 19) can be considered a reasonable representation of the potentiometric surface with the control data points used. As such, the potentiometric surface contour map obtained for 1983 by the transient simulation was used as the reference from which to anticipate the effects of future pumpage to the year 2000. The model run indicates that a net pumpage increase of only 1.2 million gallons per day (Mgal/d), mostly in the vicinity of the town of Vega Alta may result in a large scale inland displacement of the 5 ft contour (fig. 20 and table 6). In addition it can be expected that most wells in the vicinity of the town of Dorado will become salty or have an increase in salinity.

To ascertain if such anticipated trends in aquifer water levels and water quality result will require a monitoring network. Consideration should be given to the replacement of the two long-term water-level monitoring sites at Sabana Hoyos and Higuillar with new wells in the same vicinity and scheduled water quality sampling of wells within the coastal plain.



EXPLANATION

——— 100 ——— TRANSIENT MODEL--Predicted potentiometric surface contour in feet above mean sea level. Contour interval variable.

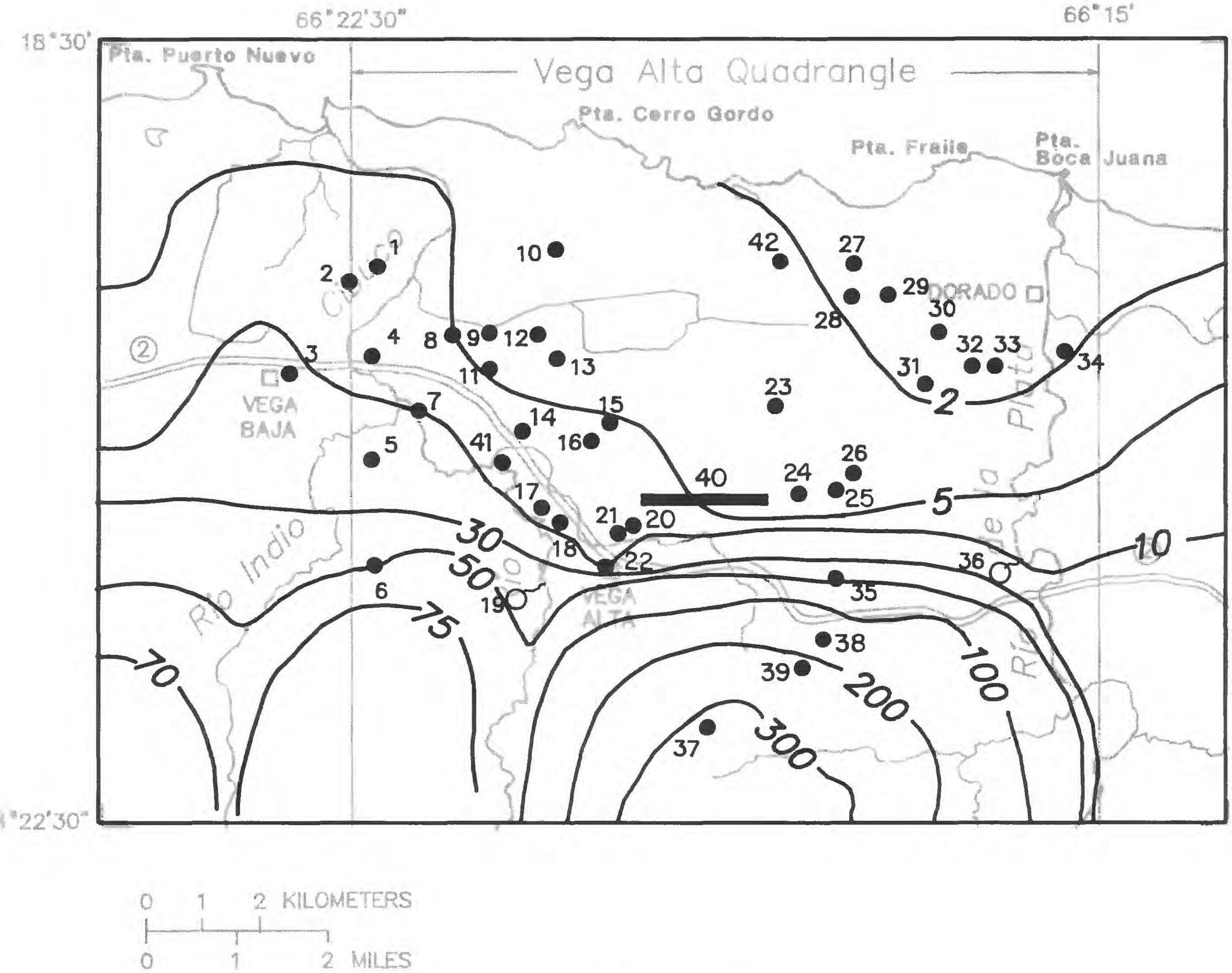
37● PUMPAGE CENTER AND SITE NUMBER--Simulated withdrawal rates are given for stress period 6.

SPRINGFLOW--Simulated discharge rates are given for stress period 6 in table

Figure 19.--Potentiometric surface condition for February 1983 as predicted by transient simulation.

Table 5. Withdrawal rate simulated during stress period 6 (Refer to figure 19.)

Site number	Withdrawal, million gallons per day	Site number	Withdrawal, million gallons per day
1	1.00	19	0.07
2	1.00	20	0.92
3	0.36	21	0.90
4	1.94	22	0.43
5	0.25	23	0.50
6	0.13	24	1.02
7	0.71	25	1.12
8	1.00	26	1.29
9	0.70	27	0.13
10	0.03	28	0.13
11	0.14	29	0.13
12	0.40	30	1.36
13	0.00	31	0.26
14	0.63	32	0.70
15	0.26	33	0.67
16	0.26	34	0.32
17	0.21	35	0.26
18	0.45	36	0.26
–		37	0.10
		Others	0.07
		Total	20.11



EXPLANATION

100	TRANSIENT MODEL--Predicted potentiometric surface contour, in feet above mean sea level. Contour interval variable.
37	PUMPAGE CENTER AND SITE NUMBER--Simulated withdrawal rates are given for stress period 8 in table 6.
40	PUMPAGE CENTER AND SITE NUMBER--Symbol indicates battery of wells along given line. Simulated withdrwal rate are given for stress period 8 in table 6.
	SPRINGFLOW--Simulated discharge rates are given for stress period 8 in table 6.

Figure 20.--Model predicted potentiometric surface condition for the year 2000 as predicted by transient simulation.

Table 6. Withdrawal rate simulated during stress period 8
(Refer to figure 20.)

Site number	Withdrawal, million gallons per day	Site number	Withdrawal, million gallons per day
1	0.00	22	0.43
2	0.00	23	0.50
3	0.36	24	1.02
4	1.94	25	1.12
5	0.25	26	1.29
6	0.13	27	0.13
7	0.71	28	0.13
8	1.00	29	0.13
9	0.70	30	1.36
10	0.03	31	0.26
11	0.14	32	0.70
12	0.89	33	0.67
13	0.40	34	0.32
14	0.63	35	0.26
15	0.26	36	0.26
16	0.26	37	0.10
17	1.15	38	0.10
18	0.45	39	0.10
19	0.07	40	1.78
20	0.00	41	1.15
21	0.00	42	0.13
		Total	21.31

DATA REQUIREMENTS TO IMPROVE MODEL

...or limitation of the 2-D aquifer flow model is the assumption th... ...d-water movement occurs only in the horizontal plane and the a... homogeneous and isotropic in the vertical plane. These c... are not met in the modeled area where ground-water flow occurs t... ...rious hydrogeologic units with distinct hydraulic conductivity v... within limestone which has developed preferential high porosity ...es. The hydraulic properties of these units need to be more ...defined to improve the flow model. Specific efforts should be ...towards:

... Conducting field tests to define the hydraulic conductivity of ...am valley alluvial deposits and coastal plain deposits.

...) Test drilling to determine if a high porosity zone exists ...the 70 to 120 ft below sea level depth throughout the Tertiary ...n the northern half of the study area. This interval was ...fied in several driller's well logs as being highly productive ...).

3) In the same test drilling effort, definition of the hydraulic ...tivity of the Tertiary units beneath the coastal plain through the ...-to-saltwater zone. Driller's logs indicate that the Aymamón ...tone beneath the coastal plain deposits does not have the same high ...ulic conductivity as found farther inland.

In addition to the above, efforts should be made to improve the accuracy of the estimated aquifer water budget of 40 ft^3/s. Since ground-water withdrawals may account for almost 80 percent of this flow (31 ft^3/s), significant gains in improving the water budget can be obtained by a better accounting of pumpage. Likewise the source of aquifer recharge--stream seepage and rainfall infiltration--can be more accurately defined by concentrating efforts in obtaining data regarding stream losses or gains at specific segments during base flow conditions.

SUMMARY

A 2-dimensional finite difference aquifer flow model was developed for the freshwater part of the ground-water system in the Vega Alta quadrangle. The model was calibrated with data obtained during 1982-83 and verified with the estimated historical ground-water development trend and water level measurements for the period 1930-1983. Results obtained through the model validation process indicate that the increase in withdrawals from 1.0 Mgal/d in 1930 to an estimated 20 Mgal/d in 1982 has: (1) resulted in a lowering of the potentiometric surface within the part of the aquifer contained north of Highway 2 by as much as 10 ft, (2) reduced aquifer discharge to regional discharge features by about 23 ft^3/s (15 Mgal/d), and (3) increased streamflow infiltration into the aquifer by about 4 ft^3/s (2.6 Mgal/d) essentially from Río Cibuco.

A simulation was made to anticipate the effect of withdrawing an additional 1.2 Mgal/d (above the 1983 pumpage rate of 20.1 Mgal/d) between 1984 and 1990 mostly for public water supply augmentation of the town of Vega Alta and adjacent communities. The model results indicate that this would cause a lowering of the potentiometric surface within the eastern half of the coastal plain of as much as 3 ft, and a regional inland displacement of the 5 ft potentiometric surface contour by as much as 2.5 mi. This lowering of the potentiometric surface at the coastal plain would most probably induce salt-water encroachment, making ground water in the vicinity of the town of Dorado unfit for potable use (1983 estimated withdrawal of 3.7 Mgal/d). Wells within this general area are already (1983) affected by upward coning of saltwater, as evidenced by increase in chloride concentrations with pumpage rate. Whether such anticipated changes will have the predicted effects can only be ascertained by establishing a monitoring network, especially within the coastal plain, for water level measurements and quality of water sampling.

Although the flow model developed was able to reasonably duplicate the historical trend of the potentiometric surface, it should be used with discretion for localized or short-term prediction of changes. This

limitation is imposed principally by the assumptions used in the conceptual model and lack of data to more properly quantify the hydraulic properties of an anisotropic flow system.

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