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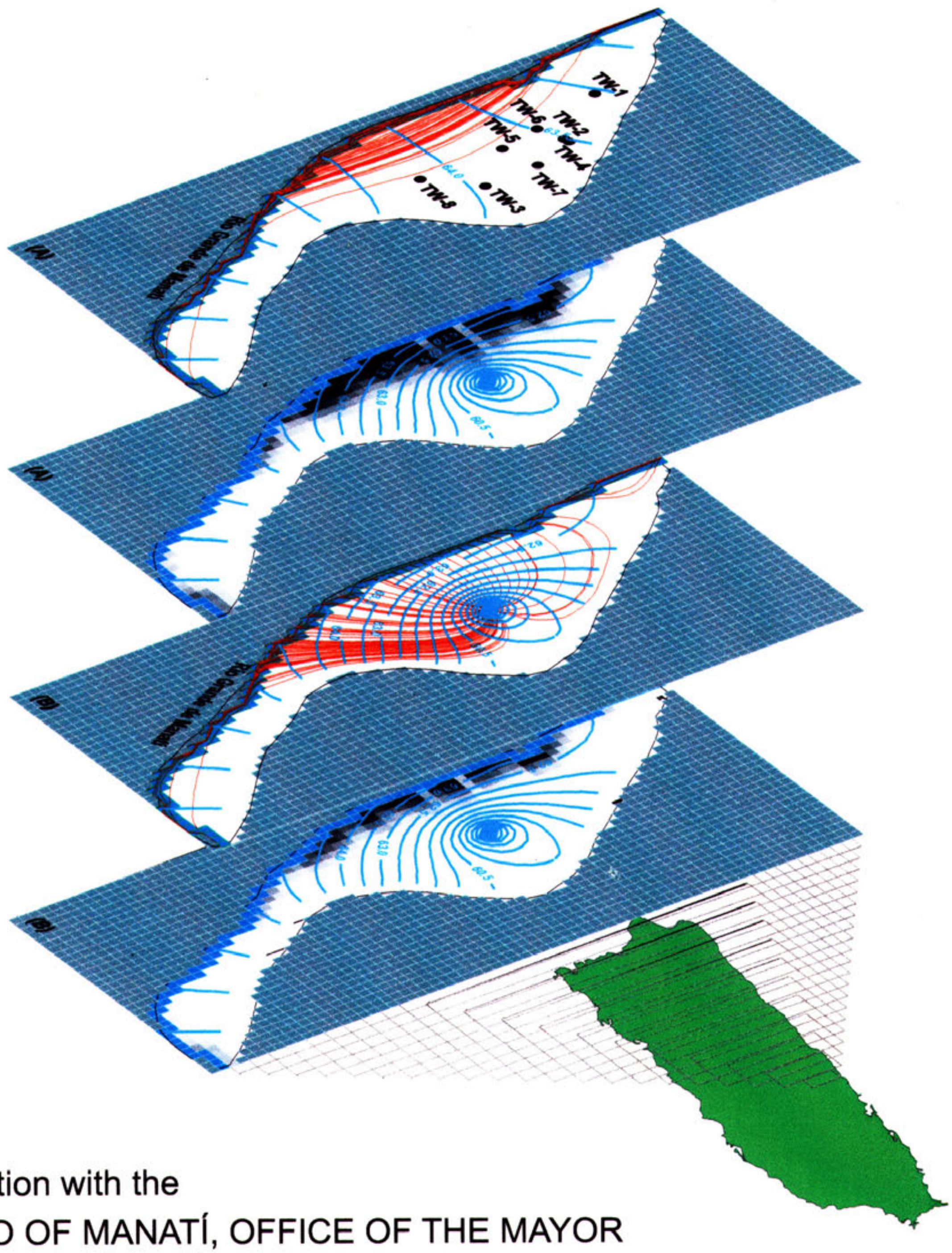
Ground-Water Resource Assessment in the Río Grande de Manatí Alluvial Plain, Río Arriba Saliente Area, Puerto Rico

Water-Resources Investigations Report 02-4132



In cooperation with the
MUNICIPIO OF MANATÍ, OFFICE OF THE MAYOR

U.S. Department of the Interior
U.S. Geological Survey

Ground-Water Resource Assessment in the Río Grande de Manatí Alluvial Plain, Río Arriba Saliente Area, Puerto Rico

By Sigfredo Torres-González, Fernando Gómez-Gómez, and Andrew G. Warne

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San Juan, Puerto Rico: 2002

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CONVERSION FACTORS, DATUMS, WATER-QUALITY UNITS, ACRONYMS, and TRANSLATIONS

Multiply	By	To obtain
acre (acre)	4,047	square meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.003785	cubic meter per day
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

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

$$°F = (°C \times 1.8) + 32$$

Datums

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

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

Abbreviated water-quality units used in this report:

L	liter
mg/L	milligrams per liter
mg	microgram
mL	milliliter
mS/cm	microsiemens per centimeter
mm	micrometer

Acronyms used in this report

NOAA	National Oceanic and Atmospheric Administration
PRASA	Puerto Rico Aqueduct and Sewer Authority
PVC	polyvinyl-chloride
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Translations

Locality names used in this report are in Spanish, whereas the USGS sampling sites are identified as they appear in the National Water Information System data base (most often English translations of the site locality). The following translations of selected common words are provided to facilitate understanding:

Spanish	**English**
Barrio	neighborhood, community
de	of
grande	grand or large
el, los, la, las	the
laguna	lagoon
municipio	generally equivalent to county
norte	north
quebrada	stream or creek
río	river
sur	south

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Abstract

The alluvial aquifer within a 160-acre area of the Río Grande de Manatí alluvial plain was investigated to evaluate its potential as a water-supply source for the Barrios Río Arriba Saliente and Pugnado Afuera, municipio of Manatí, Puerto Rico. Analysis of well boring samples and the results of electric resistivity surveys indicate that the average thickness of the unconsolidated alluvial deposits in the study area is about 100 to 110 feet. The alluvium is a mixture of sand and gravel, which generally has a porosity of 0.2 to 0.35. Short-duration pump tests in small-diameter piezometers indicate that the alluvial aquifer has a hydraulic conductivity of about 200 feet per day and a transmissivity of about 7,900 feet squared per day.

Analyses of water levels in piezometers, combined with stage measurements at a series of surveyed reference points along the Río Grande de Manatí channel, indicate that the water-table gradient in the alluvial aquifer is about 0.001, and that ground-water flow is generally from south to north, in the general direction of river flow. The water-table data indicate that the Río Grande de Manatí is the principal source of ground-water recharge to the alluvial aquifer in the study area. Because base flow for the Río Grande de Manatí is usually greater than 44 cubic feet per second, a continuous withdrawal rate of 0.5 to 1.0 cubic foot per second (225 to 450 gallons per minute) from a production well is possible.

Chemical analysis of a ground-water sample indicates that the alluvial aquifer water meets U.S. Environmental Protection Agency secondary standards for selected constituents. Bacteriological analysis of ground-water samples indicates that the ground water contains little or no fecal coliform or fecal streptococcus bacteria. Although long-term data from upstream of the study area indicate high levels of fecal coliform and fecal streptococcus prior to 1996, bacteriological analyses of Río Grande de Manatí water samples obtained during the present study indicate that fecal coliform and fecal streptococcus concentrations are within the standards for surface water intended for use (or with the potential for use) as a raw source of public water supply in Puerto Rico.

If a production well were constructed in the study area, it would be located close to the river channel (within 500 to 800 feet). Pumping from the porous and permeable alluvial aquifer close to the river channel could substantially enhance recharge from the Río Grande de Manatí channel to the aquifer. Enhanced recharge could shorten travel times for ground water in the aquifer, which might not allow sufficient time to attenuate bacteria and viruses. Travel times for bacteria moving from the river channel to a hypothetical production well were estimated using the numerical transport model MODFLOW/MT3DMS with an uncalibrated model of the alluvial aquifer. The model assumes a well pumping at 1 cubic foot per second. The transport of particles from the river to the well is most sensitive to the porosity of the aquifer and the pumping rate of the well. Sensitivity analysis indicates that a decrease in pumpage will increase the time of travel for particles to move from the river to the pumping well. The model indicates that the leading edge of a plume would reach the production well in about 40 days assuming a porosity of 0.20, 60 days assuming a porosity of

0.275, and about 70 days assuming a porosity of 0.35. If the well were moved 50 feet further from the river, the leading edge of the plume would reach the well in about 50 days assuming a porosity of 0.20 and about 70 days assuming a porosity of 0.275. These estimates are considered worse case estimates because no decay rate was included in the simulation, and because the hypothetical well was located in the center of the alluvial plain rather than further eastward, away from the river channel.

Sumario

El acuífero aluvial en un área de 160 acres en el llano aluvial del Río Grande de Manatí fue investigado para evaluar su potencial como fuente de abasto de agua potable para los Barrios Río Arriba Saliente y Pugnado Afuera, del municipio de Manatí, Puerto Rico. El análisis de muestras de barrenado de pozos y los resultados de los estudios de resistividad eléctrica indican que el promedio de espesor de los depósitos aluviales no consolidados en el área de estudio es de unos 100 a 110 pies. El aluvión es una mezcla de arena y grava, que generalmente tiene una porosidad de 0.2 a 0.35. En él se encuentra una capa de 60 pies de espesor compuesta de grava tosca que se extiende desde unos 15 pies sobre la superficie del nivel freático hasta 45 pies por debajo de ésta. Los exámenes de corta duración de bombeo en piezómetros de diámetro pequeño indican que el acuífero aluvial tiene una conductividad hidráulica de unos 200 pies al día y una transmisividad de unos 7,900 pies cuadrados al día.

Los análisis de los niveles de agua en piezómetros, combinados con los aforos en una serie de puntos de referencia medidos a lo largo del canal del Río Grande de Manatí, indican que el gradiante del nivel freático en el acuífero aluvial es de aproximadamente 0.001, y que el flujo de agua subterránea es, por lo general, de sur a norte, en la dirección general del flujo del río. Los datos sobre el nivel freático indican que el Río Grande de Manatí es la fuente principal de recarga de agua subterránea del acuífero aluvial en el área de estudio. Debido a que el caudal base del Río Grande de Manatí, por lo general, es mayor de 44 pies cúbicos por segundo, es posible una tasa de extracción continua de 0.5 a 1.0 pie cúbico por segundo (225 a 450 galones por minuto) de un pozo de producción.

El análisis químico de una muestra de agua subterránea indica que el agua del acuífero aluvial cumple con los estándares secundarios establecidos por la Agencia de Protección Ambiental de los EE.UU. para constituyentes seleccionados. El análisis bacteriológico de muestras de agua subterránea indica que el agua subterránea contiene poca o ninguna concentración de bacterias de coliformes o estreptococos fecales. Aunque los datos a largo plazo aguas arriba de el área de estudio indican altos niveles de coliformes y estreptococos fecales previo a 1996, los análisis bacteriológicos de las muestras de agua del Río Grande de Manatí obtenidas durante el estudio actual indican que las concentraciones de coliformes y estreptococos fecales se encuentran dentro de los estándares para el agua superficial destinada (o con potencial) a usarse como una fuente de abasto de agua potable en Puerto Rico.

Si se construyera un pozo de producción en el área de estudio, éste se ubicaría cerca del canal del río (a una distancia entre 500 a 800 pies). El bombeo en el acuífero aluvial poroso y permeable cerca del canal del río podría incrementar sustancialmente la recarga desde el cauce del Río Grande de Manatí hasta el acuífero. Una mayor recarga podría acortar el tiempo de traslación del agua subterránea en el acuífero, lo cual no permitiría el tiempo suficiente para atenuar bacterias y viruses. El tiempo de traslación de bacterias desde el cauce del río hasta un pozo de producción hipotético fue estimado utilizando el modelo de transporte numérico MODFLOW/MT3DMS con un modelo no calibrado del acuífero aluvial. El modelo supone un pozo cuya tasa de bombeo es de 450 galones por minuto. El transporte de partículas del río al pozo es mayormente sensible a la porosidad del acuífero y la tasa de bombeo del pozo. El análisis de sensitividad indica que una disminución de bombeo aumentará el tiempo de traslación de las partículas para moverse del río al pozo de bombeo. El modelo indica que el extremo frontal de una pluma llegaría al pozo de producción en unos 40 días, suponiendo una porosidad de 0.20; 60 días, suponiendo una porosidad de 0.275; y unos 70 días, suponiendo una porosidad de 0.35. Si el pozo se moviera 50 pies más alejado del río, el extremo frontal de la pluma llegaría hasta el pozo en unos 50 días,

suponiendo una porosidad de 0.20; y en unos 70 días, suponiendo una porosidad de 0.275. Estos estimados se consideran aplicables en el peor de los casos debido a que no se incluyó una tasa de deterioro en el simulacro, y porque el pozo hipotético fue ubicado más bien en el centro del llano aluvial, y no más hacia el este, alejado del cauce del río.

INTRODUCTION

Essentially all potable water used by the municipio of Manatí is supplied by ground water from limestone and alluvial aquifers underlying the coastal area between the Río Cibuco and the Río Grande de Manatí in the North Coast Limestone Province of Puerto Rico (fig. 1). In recent years, degradation of ground-water quality by agrochemicals and saline-water encroachment has reduced the capacity of these aquifers to meet the public water-supply demands of Manatí (Guzmán-Ríos and Quiñones-Márquez, 1984; Conde-Costas and Gómez-Gómez, 1999). Since 1982, at least eight public water-supply wells in the Manatí area were forced to close because concentrations of agrochemicals, salt water, and bacteria exceeded potable standards recommended by the U.S. Environmental Protection Agency (USEPA, 2000a); closures included several of the most productive wells.

Although a portion of the lost water production was replaced by increasing withdrawals from other wells tapping the limestone aquifers near the coast, the municipio of Manatí communities located farthest inland have experienced chronic water shortages. For example, the community of Barrio Río Arriba Saliente currently receives a large portion of its water supply by tank trucks of commercial water haulers contracted by the municipio of Manatí government and the Compañía de Aguas de Puerto Rico. Barrio Pugnado Afuera has required regular water-truck service to augment ground-water supplies for more than 30 years. Moreover, the availability of public-water supply has become severely limited since about 1992.

The decline in ground-water production caused by gradual deterioration of ground-water quality within shallow aquifers prompted the municipio of Manatí government to find alternative sources of potable water to meet the needs of Barrios Río Arriba Saliente and Pugnado Afuera. Alluvial deposits of the Río Grande de Manatí alluvial plain at Barrio Río Arriba Saliente (fig. 2) are the only nearby ground-water source for these two communities. In 1998, the U.S. Geological Survey (USGS), in cooperation with the Office of the Mayor, municipio of Manatí, initiated a hydrogeologic investigation to evaluate the potential of the alluvial aquifer to supply water for public consumption and use.

Purpose and Scope

This report presents the results of the hydrogeologic analysis of the alluvial aquifer within the Río Grande de Manatí study area to evaluate the potential of the unconsolidated Quaternary deposits to provide sufficient ground water to satisfy the water-use needs of surrounding communities. The results of water-quality investigations are presented to address concerns about the potential for bacterial contamination of ground water. A summary of analyses of ground-water/surface-water interactions within the study area is presented to evaluate the capacity and limitations of the alluvial aquifer to attenuate potentially harmful bacteria and viruses.

Surface geophysical surveys were used to define the thickness and extent of the alluvial aquifer. A series of piezometers were installed to determine hydrogeologic properties of the alluvial aquifer, including lithology, hydraulic conductivity, potentiometric gradient, and concentration of common dissolved constituents in the ground water. The sanitary quality of water in the study area was evaluated by analyzing a series of ground- and surface-water samples for fecal coliform and fecal streptococcus concentrations.

To evaluate the capacity of the alluvial aquifer system to attenuate bacteria and viruses, the time of travel of ground water moving from Río Grande de Manatí to a potential production well was estimated by developing a numerical model of the site. The computer codes MODFLOW96 (Harbaugh and McDonald, 1996) was used for ground-water flow simulation and MT3DMS (Zheng and Wang, 1999) for transport simulation. The model is based on the hydrogeologic data collected during this study.

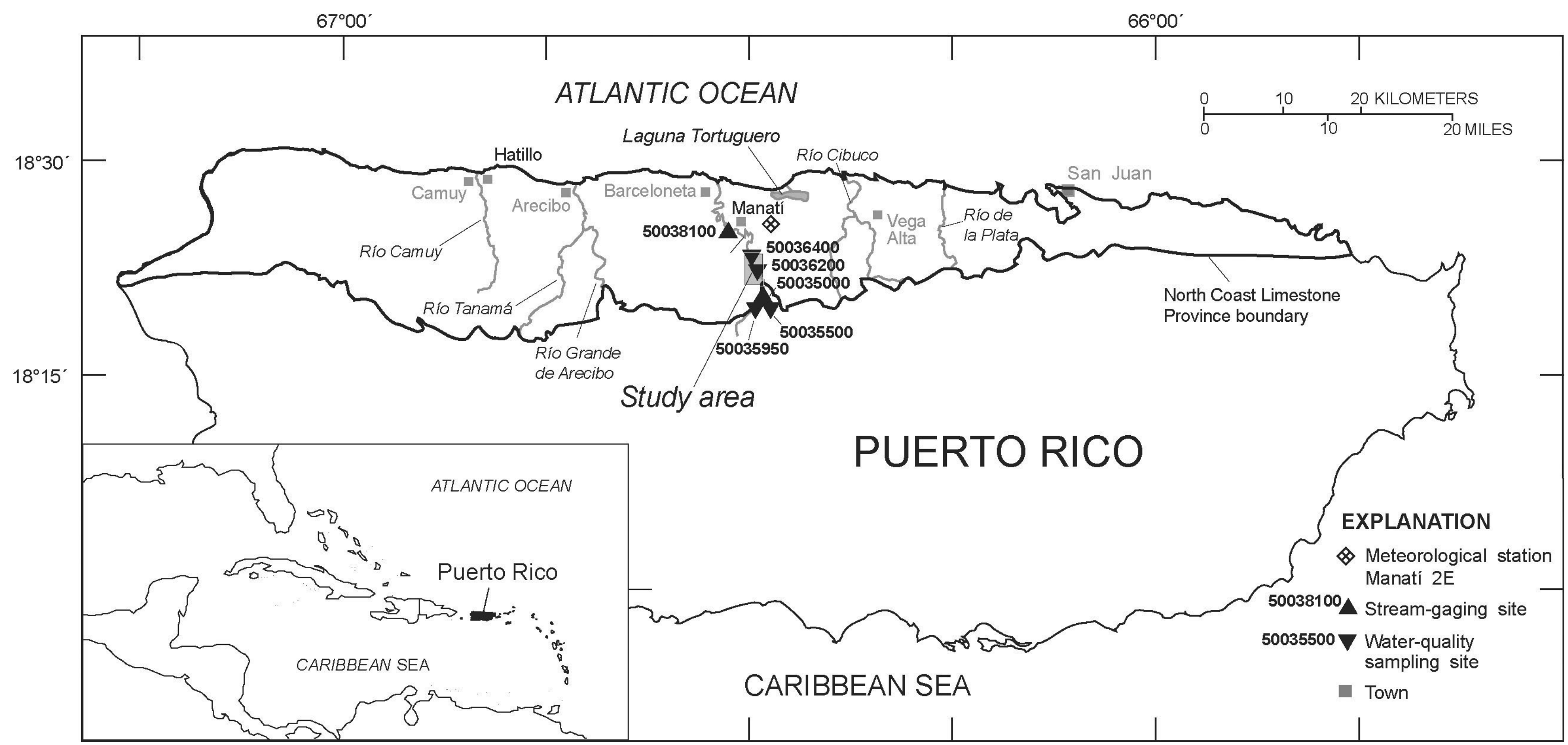

Figure 1. Location of the study area with respect to the Río Grande de Manatí alluvial valley within the North Coast Limestone Province, Puerto Rico.

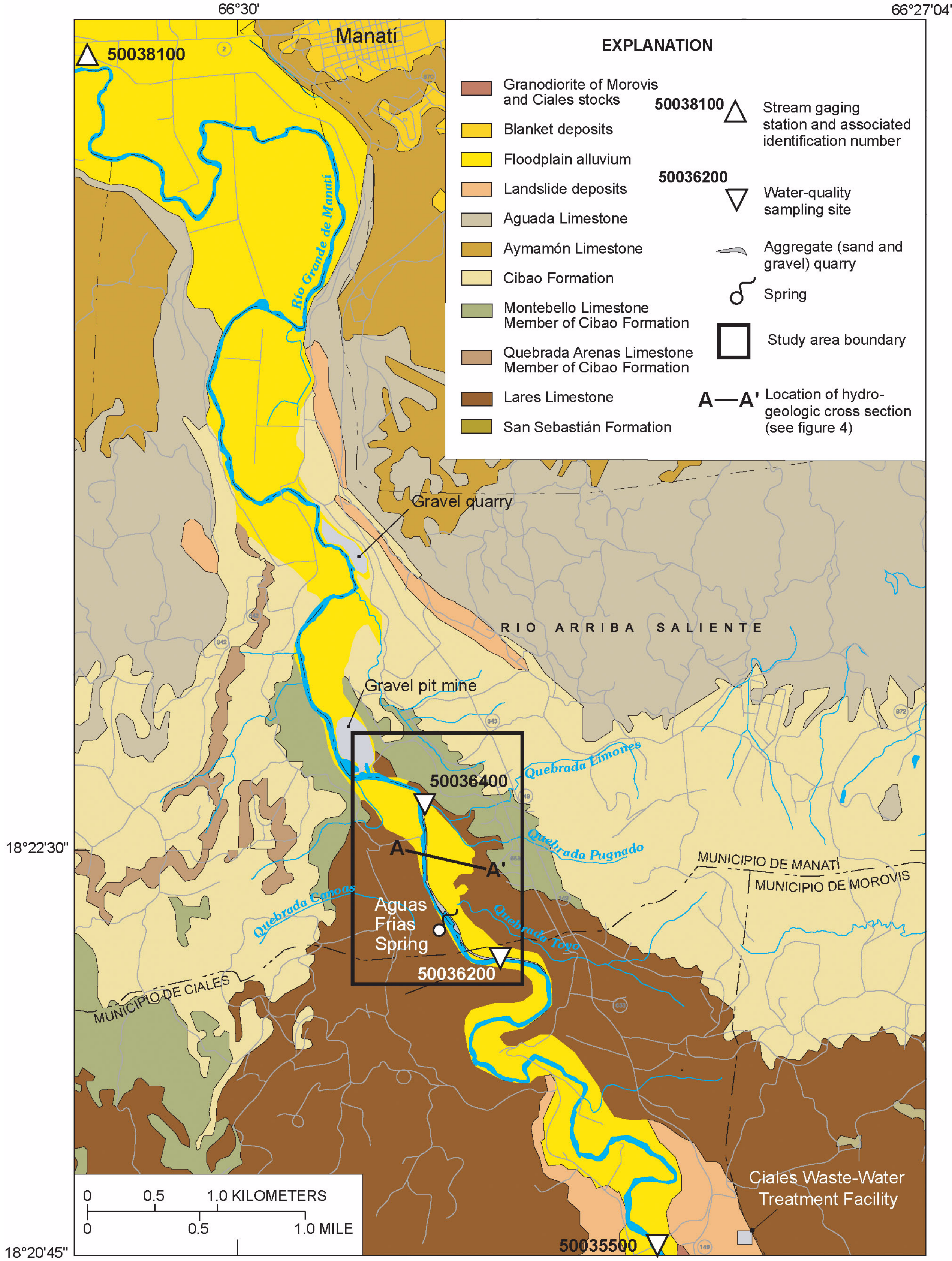

Figure 2. Generalized surficial geology of the Río Arriba Saliente area, municipio of Manatí, Puerto Rico.

Acknowledgments

The collaboration and assistance of personnel from the municipio of Manatí government, especially the Honorable Mayor Juan A. Cruz Manzano, was crucial to the investigation. The cooperation provided by landowners, especially Ms. Esther Larregui, in granting access to her property is appreciated. The assistance of USGS Caribbean District staff in various stages of the investigation was crucial in completing the topographic surveys and the bacteriological and chemical analyses of samples. Heriberto Torres-Sierra, Caribbean District, provided essential information regarding flow characteristics of the Río Grande de Manatí. Eve L. Kuniansky, USGS Regional Ground-Water Specialist, Norcross, Georgia, developed the numerical model for the time of travel estimates.

STUDY AREA

The study area lies within the Río Grande de Manatí valley, about 1.2 miles (mi) west of Barrio Río Arriba Saliente (figs. 1, 2). The study area encompasses about 160 acres or 0.25 square mile (mi^2) of the alluvial plain along a 0.5-mi reach of the east bank of the Río Grande de Manatí (fig. 3). The extent of the alluvial deposits within the study area is about 53 acres.

The climate in the valley is humid-tropical with temperatures ranging from 75 to 80 degrees Fahrenheit (°F). Mean annual rainfall in the study area is about 61 inches (in.), based on historical rainfall data (1931-96) collected at the Manatí 2E National Oceanic and Atmospheric Administration (NOAA) weather station. Periods of diminished rainfall occur from January to April and from June to July. Periods of increased rainfall occur from August to December, and during May.

The area around the study site is drained by the Río Grande de Manatí and, to a lesser degree, by several small ephemeral streams. The Río Encantado, a subterranean stream system that drains karst terrains west of the study area, discharges to the Río Grande de Manatí at Aguas Frías spring (fig. 3). Records from streamflow station 50035000, Río Grande de Manatí at Ciales (upstream of study area, fig. 1) and station 50038100, Río Grande de Manatí at Highway 2 near Manatí (downstream of study area, fig. 1), indicate that flows of the Río Grande de Manatí through the study area are fairly well sustained. Mean-monthly discharge ranges from 14.1 to 2,422 cubic feet per second (ft^3/s) (1946-98 period of record) at gaging station 50035000 and from 49.9 to 3,733 ft^3/s (1970-98 period of record) at gaging station 50038100 (Díaz and others, 2000). During stream low-flow conditions, the daily-mean discharge of the Río Grande de Manatí in the study area may be as low as 31 ft^3/s. Peak discharges of 100,000 ft^3/s may occur during storms.

In the study area, the alluvial-plain surface ranges from about 98 feet (ft) above mean sea level in the central and southernmost parts of the study area to about 93 ft above mean sea level in the northern parts of the study area. During 1997-98, the alluvial-plain surface was about 30 ft higher than the average stream stage and about 35 to 40 ft higher than the base of the river channel (fig. 4).

A variety of human activities in the study area have the potential to impact the quality of surface and ground water. The valley is primarily used for agricultural purposes, especially cultivation of hay for dairy cattle and as pasture. The Ciales waste-water treatment facility discharges secondary-treated waste water into the Río Grande de Manatí, approximately 3 mi upstream of the study area (fig. 2). The reported mean annual waste-water treatment facility effluent discharge during 1995 was 0.38 million gallons per day (Mgal/d) (W. Molina, USGS, written commun., 2001).

Gravel mining is active along the banks and within the channel of the Río Grande de Manatí for the entire length of the stream in the study area (fig. 3). Dredging of the stream channel, associated with gravel mining, has lowered the altitude of the stream surface during base flow conditions by as much as 3 ft, as indicated by eroded banks and exposed vegetation roots upstream of Aguas Frías spring.

The river above the study area is generally unregulated, except by the relatively small Lago de Matrullas. Currently, there are 17 water filtration plants with a total of 43 water intakes in the Río Grande de Manatí drainage basin upstream from the study area. These 17 water filtration plants extract approximately 14.9 Mgal/d (equivalent to 23 ft^3/s) from the river system (W. Molina, USGS, written commun., 2001).

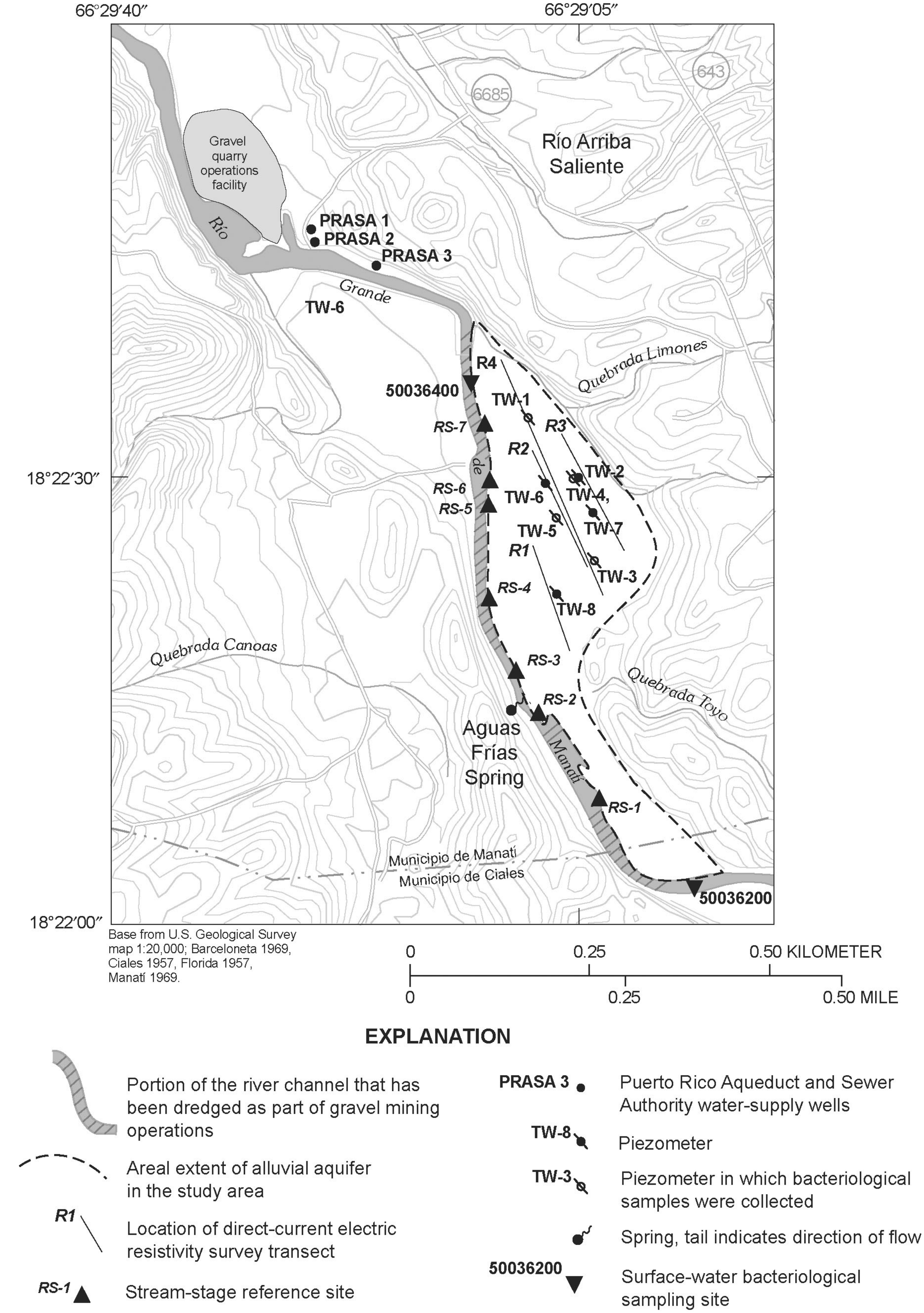

Figure 3. Location of the geophysical survey transects, piezometers, and selected sampling sites within the Río Grande de Manatí valley, Río Arriba Saliente area, Puerto Rico.

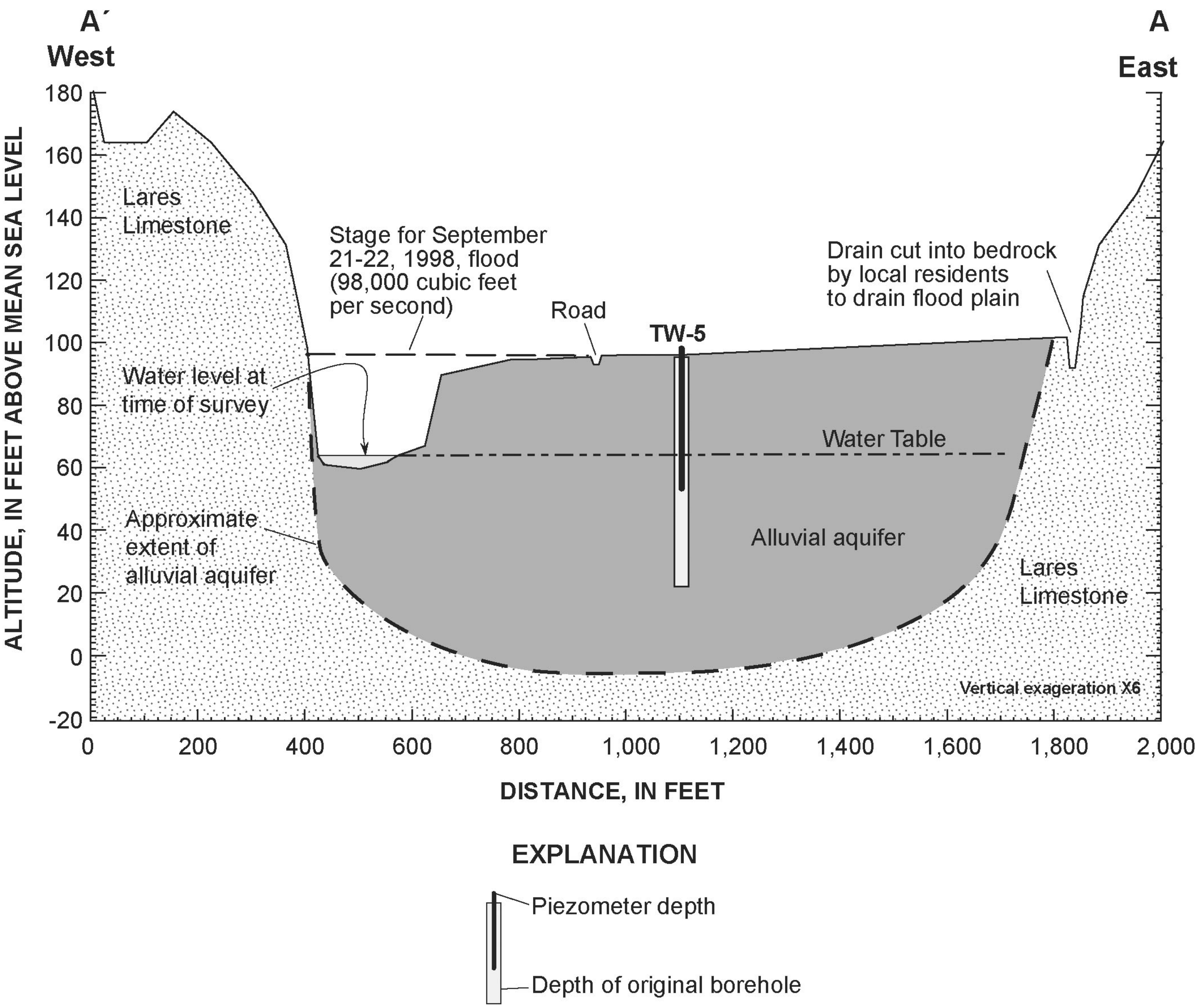

Figure 4. Generalized hydrogeologic cross section across the Río Grande de Manatí valley, Río Arriba Saliente area, Puerto Rico. The location of the cross section is shown in figures 2 and 5. The topographic data used to generate the cross section are from a leveling survey done by the U.S. Geological Survey personnel in June 1997.

APPROACH

Geophysical Surveys

Direct-current (DC) electric resistivity surveys were conducted across the alluvial plain to define the hydrogeologic framework of the study area, particularly the lateral continuity and extent of the water-bearing zones (Zohdy and others, 1974; Dobrin and Savit, 1988). The electric resistivity of subsurface sediments was measured by introducing an electric current into the ground through two current electrodes (AB) and measuring the difference in electric potential between two other electrodes (MN) using the Schlumberger electrode array (Zohdy and others, 1974). The transects produce resistivity measurements at various depth intervals by varying the spacing between electrodes.

In the study area, the DC resistivity survey was conducted along four north-south trending transects (R1 to R4) that ranged from 1,000 to 1,200 ft in length (fig. 3). The four closely spaced, nearly parallel transects were oriented to maximize transect length and to characterize variability of the alluvial aquifer along the floodplain. Resistivity measurements were made using a memory earth-resistivity meter (STING trademark R1, Release 2.5.5, 1997) that has a depth limitation of about 450 ft. The current electrode (AB) spacings used along the transects were 2, 3, 4.5, 7, 10, 14, 20, 30, 45, 70, 100, 140, 300, 450, 700, and 1,000 ft. Potential electrode (MN) spacings were 0.5, 2, 6, 20, and 140 ft.

The resistivity data were tabulated and processed using a Fortran 77 program, Inverse.f77 (Zohdy and others, 1974). The program identifies DC-resistivity inflection points (a marked peak or trough) that result from changes in electric properties with depth. These inflection points typically demarcate a change in subsurface sediment composition or the top of the saturated zone.

Piezometers

Eight piezometers were constructed to evaluate the subsurface stratigraphy, the hydrogeologic properties of the alluvial aquifer, and the direction of ground-water flow in the alluvial aquifer under unstressed (non-pumping) and stressed (pumping) conditions. The eight boreholes were drilled using a 6-in. (outside diameter) hollow-stem auger that retrieved a 3-in.-diameter split-barrel core (for sampling and analysis of sediment). Borehole depths ranged from 40 to 113 ft below the ground surface (table 1). Abundant gravel found during drilling tended to clog the split-barrel corer so that sediment sample recovery in these coarse intervals was poor. When drilling through pebble- and cobble-size (Pettijohn, 1975) gravel layers, the drilling rig would noticeably vibrate. These intervals were recorded on the drillers' logs.

Piezometers were constructed in the eight boreholes following the procedures outlined in Lapham and others (1997). The piezometers were constructed of 2-in. and 4-in. (inside diameter) polyvinyl-chloride (PVC) pipe (table 1). The walls of the boreholes (especially in the gravel intervals) commonly collapsed into the borehole, which prevented installation of the PVC pipe to the full borehole depth. The piezometers were installed to depths between 39 and 63 ft, which included at least 10 to 15 ft of the saturated aquifer. The slotted interval typically extended along the lower 10 ft of the piezometer. A rubber collar was set above the well screen to hydraulically isolate the screened interval from the overlying grout interval. Bentonite grout was emplaced with a pipe from the rubber collar to about 10 ft below the surface. Concrete was emplaced from the top of the grouted interval to the land surface. The piezometers were developed using pressurized air and small yield submersible pumps.

Table 1. Construction data[1] for piezometers in the Río Grande de Manatí alluvial plain, Río Arriba Saliente area, Manatí, Puerto Rico

[ID, inside diameter; PVC, polyvinyl chloride]

Piezometer number [2]	Borehole depth (feet)	Piezometer depth (feet)	Land surface datum [3] (feet)	Casing diameter (inches)	Screened interval below land surface datum (feet)
1	53	43	93.625	4	33 to 43
2	63	51	95.499	4	41 to 51
3	73	43	97.165	4	33 to 43
4	113	63	96.060	4	23 to 63
5	73	39	96.068	4	29 to 39
6	40	40	93.970	2	30 to 40
7	40	40	95.362	2	30 to 40
8	40	40	93.190	2	30 to 40

[1] Total borehole diameter for each piezometer was 6 inches; piezometers were constructed with 4-inch (TW-1 to -5) and 2-inch (TW-6 to -8) ID PVC; slot size 0.02 inch; annular space (2 inches) was grouted with concrete from above the screened interval to the land surface.

[2] See figure 3 for piezometer locations.

[3] Datum elevation was obtained from third-order leveling survey conducted by the USGS during this study.

Aquifer Tests

The hydraulic properties of the alluvial aquifer were estimated from specific capacity tests. A 2-hour aquifer pump test at the fully screened piezometer TW-4 was conducted on April 23, 1998. This piezometer was pumped at a rate ranging from 22.5 to 25 gallons per minute (gal/min). The drawdown at piezometer TW-2, located 50 ft from the pumping well TW-4, was only 0.04 ft. The observed drawdown at the pumping well TW-4 was 0.5 ft. A second 2-hour test was conducted on June 16, 1998. During the second pump test, piezometer TW-4 was pumped at a rate of 37.5 gal/min. The drawdown was 1.35 ft in pumping well TW-4, and only 0.04 ft in piezometer TW-2 after 120 minutes of pumping. Similar pump tests were conducted on piezometers TW-2 and TW-3, which produced small or no drawdown, indicating a high aquifer permeability in the alluvial aquifer.

Water-Level Monitoring and Development of Potentiometric Maps

Two surface-water sampling stations were established along the Río Grande de Manatí channel within the study area and are identified as 50036200 and 50036400 (fig. 3). Station 50036200 is located upstream of the confluence of Aguas Frías spring, and station 50036400 is located downstream of the spring. A Global Positioning System (GPS) was used to obtain coordinates of the right bank locations at both surface-water monitoring sites.

Seven reference sites were established along the Río Grande de Manatí to relate river stage to ground-water levels (fig. 3). A third-order leveling survey (altitudinal accuracy of 0.003 in.) was conducted to determine the altitude of the eight piezometers and the seven reference sites. The piezometer locations and elevations were monumented by chiselling a mark in the cement at the base of each piezometer; the seven channel reference sites were monumented at selected large boulders on the right bank location, at or near the edge of the channel. These reference marks were subsequently used to relate the stream levels to the aquifer heads and construct a potentiometric surface map.

Water levels in the piezometers were measured using a steel tape and are considered to be accurate to within 0.01 ft. River stage was also measured using a steel tape and measurements are accurate to within 0.01 ft. Ground-water and surface-water elevations were measured on March 18, March 26, April 16, May 6, and July 28, 1998, to identify average hydrologic conditions when surface-water/ground-water interactions were relatively stable. Ground- and surface-water elevations were measured under stressed (pumping) conditions on April 23 and June 16, 1998.

The potentiometric map developed for streamflow conditions for March 18, March 26, April 16, April 23, May 6, June 16, and July 28, 1998, represented base-flow conditions on Río Grande de Manatí with mean daily flows ranging from 59 to 130 ft^3/s second; this discharge is equaled or exceeded 70 to 90 percent of the time at USGS gaging station 50038100 (Ramos-Ginés, 1999).

Four topographic sections were surveyed across the valley (fig. 5), and water discharge and stage records from stream gaging stations 50035000 and 50038100 were evaluated to determine the frequency of inundation of the alluvial plain in the study area. USGS stream gaging station 50035000 is located about 0.2 mi upstream from the confluence of the Río Cialitos and Río Grande de Manatí, and about 3.5 river miles upstream of the study area. The drainage area upstream from the Río Cialitos station represents only a small portion of the study area drainage area, and Aguas Frías spring and Ciales waste-water treatment facility discharge into Río Grande de Manatí downstream of station 50035000. Therefore, the lower stream gaging station (50038100) was judged to be the best source of data to estimate discharge frequency and magnitude for the Río Grande de Manatí within the study area, even though the station is located about 8.5 river miles downstream from the study area.

Time of Travel Estimate with a Numerical Model

A numerical model for the alluvial aquifer adjacent to the Río Grande de Manatí was developed to estimate times of travel for water moving from the river to a hypothetical well pumping at a sustainable rate determined from the streamflow frequency analysis. The finite-difference code MODFLOW96 (Harbaugh and McDonald, 1996) was used for simulating flow and the code MT3DMS (Zheng and Wang, 1999) was used to simulate transport. Model parameters (porosity, hydraulic conductivity, aquifer thickness) were based on the information collected during this study. Because of the limited water-level data collected for the study, this model is not considered a calibrated model. Given the irregular geometry of the alluvial aquifer, a simple 1-layer numerical model provides a better estimate of drawdowns and flow paths to a pumping well than using image-wells with an analytical solution of the partial differential equation of ground-water flow that is based on flow to a well in an unconfined aquifer of infinite extent (Eve Kuniansky, USGS, written commun., 2002).

MODFLOW is run under steady-state conditions to generate the ground-water flow field for the transport equation. MT3DMS is then run to solve the transport equation. Advective transport was simulated by setting river water concentrations to 1.0 and observing simulated concentrations versus time at the pumping well. Bacteria concentration in ground water decrease over time (McFetters and others, 1974); however, no decay rate was used in the simulations. The advective transport equation was solved using the total-variation-diminishing solution technique, implemented in MT3DMS (Zheng and Wang, 1999).

Classical sensitivity analysis was performed by changing hydraulic conductivity of the aquifer and river bed conductance within MODFLOW96 simulations, the pumping rate at the hypothetical well, and porosity for MT3DMS and observing the resultant changes in concentration at the pumping well.

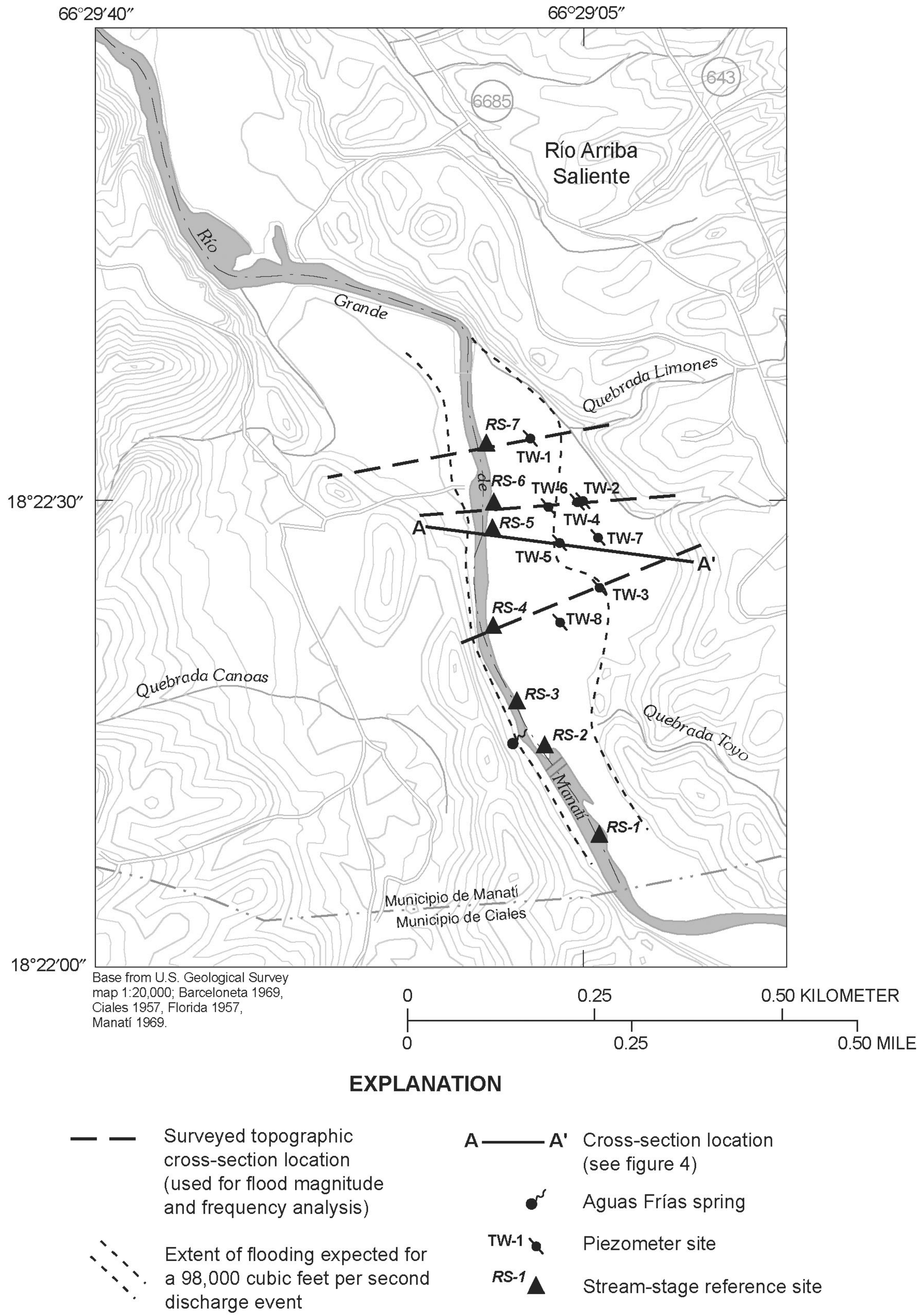

Figure 5. Extent of significant flooding event, location of piezometers, and location of selected sampling sites within the Río Grande de Manatí valley, Río Arriba Saliente area, Puerto Rico.

Water-Quality Analysis

An important component of the investigation was to determine if ground-water quality meets drinking-water standards. In addition, analysis of indicator bacteria concentrations of surface and ground water provide a basis for evaluating the potential for bacterial contamination of water obtained from a potential water-supply well located in the study area.

Sampling Procedures

Bacteriological and chemical conditions in the ground- and surface-water systems were collected using procedures described in the U.S. Geological Survey, National field manual for the collection of water-quality data (U.S. Geological Survey, 1997-1999).

Ground Water

Ground-water samples for chemical analysis were collected on two occasions: (1) during the first aquifer test (April 23, 1998), samples were collected at TW-1, TW-3, TW-4, and TW-5 using a submersible pump discharging at a rate of 25 gal/min; and (2) during the second aquifer test (June 16, 1998), samples were collected at the same piezometers using a submersible pump discharging at a rate of 37.5 gal/min. Six 250-milliliter (mL) polyethylene bottles were filled at each piezometer (three originals and three duplicates). Two of the three original samples were filtered using a 1.5-ft-diameter cellulose nitrate membrane filter. One of the two filtered samples was treated with 1 mL of nitric acid (HNO_3) to lower the pH of the sample below 2.

The procedure for collecting ground-water samples for nutrient analysis followed the same procedure used for collecting samples for water-quality analysis with a few minor differences. Smaller (125 mL), brown polyethylene bottles were used, and only two sets of samples (and duplicates) were collected, because filtered samples treated with nitric acid were not needed. Prior to analysis, all collected samples were stored in a refrigerator that was maintained at 4 degrees Celsius (°C).

Ground-water bacteriological samples were collected for analysis at piezometers TW-1, TW-3, TW- 4, and TW-5 on July 28, 1999. The samplers and sample line were autoclaved to sterilize followed by flushing with ground water for 15 to 20 minutes at rates ranging from 22.5 to 37.5 gal/min, before the ground water was pumped into sterile bottles. A total of twelve 100-mL polyethylene bottles were collected at each of the four piezometers.

Surface Water

To evaluate sanitary water conditions, surface-water samples were collected at sampling stations (50035500, 50036200, and 50036400) along the Río Grande de Manatí (figs. 2, 3). The surface-water samples were collected using the “hand-dip” method (Britton and Greeson, 1989). This sampling method consists of dipping a sterile narrow-mouth borosilicate 99-mL bottle 2.5 to 5.0 centimeters below the water surface with the bottle opening pointed slightly upward towards the current and with the hand and arm on the downstream side of the bottle.

Surface-water samples were analyzed only for fecal coliform and fecal streptococcus indicator bacteria (and not for chemical constituents). Surface-water samples were collected on March 18 and 26, April 16 and 23, May 6, June 16, and July 28, 1998. Although most samples were collected following storms that produced substantial rainfall, river discharge during each sampling event was below the long-term mean for that date (table 2).

Analytical Procedures

Samples from piezometer TW-4 were analyzed in the field for temperature, specific conductivity, pH, and calcium carbonate alkalinity. Analyses of major chemical constituents (Ca, Mg, Na, K, SO_4, F, SiO_2, Fe, and Mn), nutrients (total nitrogen and NO_3-N) and dissolved solid concentration were conducted at the USGS Water Quality and Research Laboratory in Ocala, Florida, following standard USGS water chemistry analytical procedures (Hem, 1970).

Table 2. Summary of Río Grande de Manatí discharge characteristics associated with dates of bacteriological sampling

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

Sample date	Discharge [1] (ft^3/s)	Long-term mean monthly discharge (ft^3/s) [1]	Percent of time that discharge is equaled or exceeded [2]
03/18/98	62	181	98
03/26/98	49	181	99
04/16/98	251	347	30
04/23/98	243	347	30
05/06/98	94	649	90
06/16/98	146	248	60
07/28/98	142	156	60

[1] As determined from USGS stream-gaging station 50038100 (fig. 2) (Díaz and others, 2000)
[2] Flow exceedance calculated by Ramos-Ginés (1999).

The analytical procedures used to evaluate fecal coliform and fecal streptococcus bacteria concentrations consisted of the membrane-filter method immediate incubation test following standard USGS procedures (Britton and Greeson, 1989; Myers and Sylvester, 1997). Sterile buffered water, culture media and other culture-specific reagents (including rosolic acid crystals, 0.2 N sodium hydroxide for fecal coliform tests, and triphenyltetrazolium crystals for fecal streptococcus tests) were provided by the USGS Water Quality and Research Laboratory in Ocala, Florida. Petri dishes were prepared with the hydrated incubation media and sample bottles were sterilized at the USGS Caribbean District laboratory. Sample volumes used in dilution ratios for membrane filtration analyses at each site were prepared to maximize the probability of obtaining colony counts in the range of 20 to 60 colonies per filter for fecal coliform bacteria and 20 to 100 colonies per filter for fecal streptococcus bacteria. The appropriate size of sample volumes were determined based on the experience of USGS personnel who routinely collect samples at long-term water-quality stations upstream at USGS stations 50035500 and 50035950 (fig. 1), and at other water-quality sampling sites in Puerto Rico. Samples were kept at 1 to 4 °C (in ice water) and processed at the Caribbean District laboratory within 6 hours of sample collection.

The quality assurance and quality control (QA/QC) protocols for bacteriological analyses included: (a) incubation of sterile buffered water in culture media at the Caribbean District laboratory to verify the sterile conditions of buffer, media, and filters; and (b) field procedure blanks to verify field equipment aseptic conditions. The number of QA/QC samples consisted of one in the laboratory and one field blank for protocol parts a and b. The results for part a should be negative (no development of fecal coliforms or of fecal streptococcus colonies); if positive, the media sample petri dishes and buffered-water dilution bottles are not acceptable for use. The results for part b should also be negative; if not, the analytical results of samples obtained between negative QA/QC blanks (before and after the positive blank) are reviewed for suspect data results.

RESULTS

Surface Hydrology

Hydrologic conditions in the study area are largely controlled by the Río Grande de Manatí. The river is the principal source of recharge to the alluvial aquifer, although local rainfall is a contributor during the wet months (May, September through December). Ground water also discharges locally from the alluvial aquifer to the Río Grande de Manatí. Aguas Frías spring is the discharge point for the Río Encantado, a subterranean stream that drains the karst upland to the west of the study area (figs. 2, 3). Discharge of Aguas Frías spring is in the range of 6.1 to 10 ft^3/s (Guzmán-Ríos, 1988) (table 3).

Streamflow in the Río Grande de Manatí valley fluctuates on a seasonal and yearly basis. Streamflow typically decreases from January to March and from June to August. Streamflow typically increases during April and May and from September to December. Long-term streamflow records (1946-98) from station 50035000, Río Grande de Manatí at Ciales, located about 3.5 mi upstream from the study area, indicate that the mean monthly discharge ranges from 104 ft^3/s during July to 421 ft^3/s in October (fig. 6) (Díaz and others, 2000). At station 50038100, Río Grande de Manatí at Highway 2 near Manatí, located 8.5 mi downstream from the study area, the long-term mean monthly flow (1970-98) ranges from 153 ft^3/s during July to 708 ft^3/s in October (fig. 6) (Díaz and others, 2000).

Mean daily discharge records of station 50035000, Río Grande de Manatí at Ciales (drainage area 128 mi^2), indicate that discharge equals or exceeds 29 ft^3/s 99 percent of the time (Atkins and others, 1999). At station 50038100, Río Grande de Manatí at Highway 2 (drainage area 197 mi^2), a mean daily discharge of 59 ft^3/s is equaled or exceeded 99 percent of the time (Atkins and others, 1999). The discharge per unit area was determined for the Ciales gaging station (50035000) by dividing the low-flow discharge (29 ft^3/s) by the drainage area (128 mi^2) to obtain 0.226 $ft^3/s/mi^2$. This value was extrapolated to estimate the 99-percent discharge at the study site (drainage area 158 mi^2), which was 36 ft^3/s.

A streamflow-discharge value commonly used in assessing a stream's potential to supply a required flow is the 7-day, 10-year minimum flow (7Q10). This statistical value is defined as the minimum-flow rate for 7 consecutive days with a recurrence interval of 10 years. In the study area, data are inadequate for the computation of the 7Q10 minimum flow. At the Río Grande de Manatí at Ciales gaging station (50035000) the 7Q10 is 25 ft^3/s, and at the Río Grande de Manatí at Highway 2 gaging station (50038100) the 7Q10 is 47 ft^3/s (Santiago-Rivera, 1998). An estimate of the 7Q10 through the study area of about 31 ft^3/s was determined utilizing the data from the Ciales gaging station (1960-97) in combination with drainage area information. Possible ground-water discharge from the alluvial aquifer to the stream or possible recharge from the stream to the alluvial aquifer is not considered. However, the stream channel may discharge as much as 7 ft^3/s to the upper limestone aquifer in downstream reaches of the study area near the Highway PR-2 bridge (Cherry, 2001).

Table 3. Physical, chemical, and bacteriological characteristics of Aguas Frías spring, Puerto Rico, 1982-83 (modified from Guzmán-Ríos, 1988)

[ft^3/s, cubic feet per second; µm/mf, micrometer membrane filter; mg/L, milligrams per liter; mL, milliliter; $CaCO_3$, calcium carbonate]

Sampling date	Spring discharge (ft^3/s)	Hardness (mg/L as $CaCO_3$)	Fecal coliform, 0.7 µm/mf (colonies per 100 mL)	Fecal streptococcus, KF Agar (colonies per 100 mL)
12/16/82	10	160	1,800	830
08/11/83	6.1	190	340	360

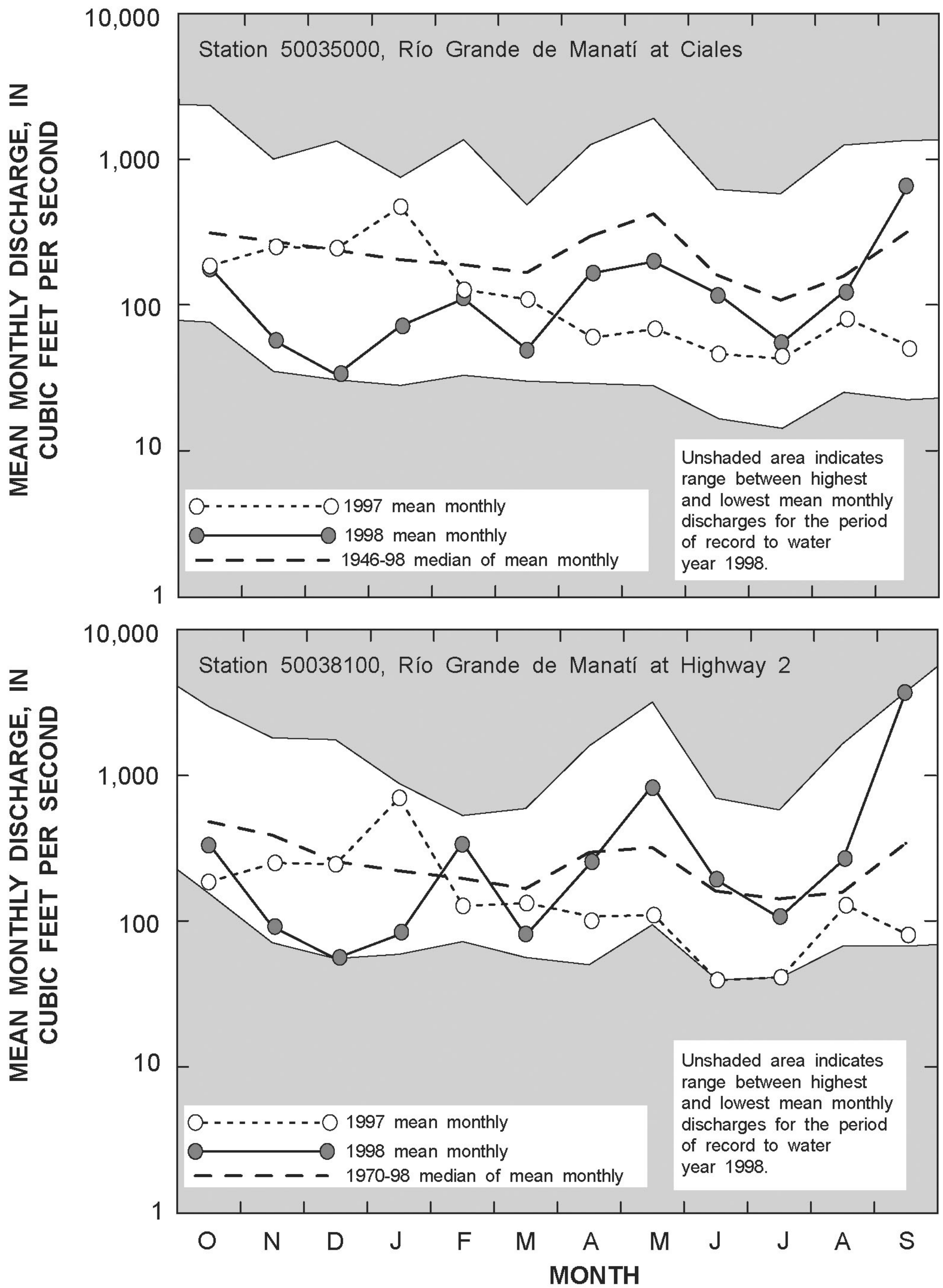

Figure 6. Mean monthly discharge at U.S. Geological Survey stream-gaging stations 50035000 and 50038100 for 1997 and 1998 water years. Also shown are the highest and lowest mean monthly discharge, as well as the long-term mean. The approximate locations of gaging stations 50035000 and 50038100 are shown in figure 2. Most of the 1997 and the first half of the 1998 water year were drier than normal.

The study area is periodically subject to intense floods. Floods can occur anytime during the year, but are most common from May through December. The magnitude and frequency of floods affecting the alluvial plain in the study area were estimated using four topographic cross sections surveyed across the Río Grande de Manatí valley and annual peak discharge data from gaging stations 50035000 and 50038100. Based on analysis of the annual peak discharge data from gaging stations 50035000 and 50038100 (table 4), the alluvial plain in the study area is inundated by peak discharges greater than 70,000 ft^3/s; flood peaks of this magnitude occur at a frequency of about 10 years (H. Torres-Sierra, USGS, written commun., 2001). During the September 21-22, 1998 (Hurricane Georges) flood, the piezometer casings at TW-1, TW-3, TW-6, and TW-8 were inundated by about 1 foot of water (fig. 5). Evidence indicates that the remaining piezometers in the study area were not inundated; however, the September 21-22, 1998, flood inundated public-water supply wells constructed during 1997 by the Puerto Rico Aqueduct and Sewer Authority (PRASA), downstream of the study area (fig. 3) such that surface water entered into the piezometer casings. The magnitude of the September 21-22, 1998, flood in the study area was computed to be 98,000 ft^3/s with an estimated frequency of 25 years (H. Torres-Sierra, USGS, written commun., 2001).

Table 4. Major annual peak discharges since 1960 for USGS gaging stations 50035000 and 50038100, Manatí, Puerto Rico

[ft^3/s, cubic feet per second; >, more than]

Water year	Date	Peak discharge (ft^3/s)
	50035000	
1960	09/06/60	77,300
1970	11/09/69	56,500
1971	10/09/70	125,000
1975	09/16/75	72,100
1985	05/18/85	74,300
1986	10/07/85	75,400
1996	09/10/96	128,000
1998	09/21/98	78,900
	50038100	
1960	09/06/60	62,000
1970	11/09/69	68,110
1971	10/09/70	81,760
1985	05/18/85	90,000
1986	10/07/85	97,250
1996	09/10/96	>140,000
1998	09/22/98	136,000

Hydrogeology

The alluvial aquifer is underlain and surrounded by the upper Oligocene Lares Limestone in the study area (figs. 2, 4). The Lares Limestone is about 550 ft thick and composed primarily of fine-grained packstone and wackestone (Rodríguez-Martínez, 1995). Ground-water recharge from the Lares Limestone to the alluvial aquifer may occur; however, the Lares Limestone is characterized by low transmissivities of about 150 to 500 square feet per day (ft^2/d) (Giusti, 1978; Rodríguez-Martínez, 1995; Torres-González and others, 1996) and by the lack of production wells, particularly in areas east and west of the study area. Ground-water flow rates in the Lares Limestone are small in comparison with the alluvial aquifer. This limestone unit probably contributes less than 15 percent to alluvial aquifer recharge; the remainder of the ground-water recharge is from the Río Grande de Manatí.

Physical Characteristics of the Alluvial Aquifer

The alluvial aquifer is composed of unconsolidated clay, silt, sand, pebbles, and cobbles that were deposited during the Quaternary Period, apparently by river systems similar to the modern Río Grande de Manatí (Monroe, 1980; Krushensky, 2000). The thickness of the alluvial deposits along the Río Grande de Manatí varies, but in general, the deposits are about 100 ft thick where they overlie the Lares Limestone in the part of the valley north of Ciales, and as much as 300 ft thick north (downstream) of the study area where the floodplain widens near Highway PR-2 (Gómez-Gómez, 1984). Drilling logs and DC electric resistivity surveys indicate that the alluvial aquifer is about 100 to 110-ft in the study area.

Lithologic data compiled during the drilling phase of the investigation and by observations made at local sand and gravel quarries indicate that a 60-ft-thick coarse gravel layer extends from about 15 ft above the phreatic surface to depths exceeding 45 ft below the phreatic surface. The drillers' logs from the study indicate that the thickness of the gravel layer varies (logs are vague because recovery of samples from the gravel intervals was poor). Inspection of local quarries along the river channel revealed a gravel layer at least 15-ft thick, containing cobbles and boulders 2.5 to 36 in. in diameter. The elevation of the top of this gravel layer along the river channel ranges between 63 and 68 ft above mean sea level.

The DC electric resistivity survey results for the four transects were consistent in that the field values in all four transects steadily increased with depth from about 30 to 60 ohm-meters at 2 ft to about 200 to 500 ohm-meters at 100 ft, and then declined below 100 ohm-meters below 100 ft. The computer-calibrated resistivity curves in the four transects are also similar, showing a peak at about the 10- to 20-ft depth, a pronounced low at about the 80- to 100-ft depth, and a peak at about 110 ft. The results of the four DC electric resistivity surveys agreed well with piezometer borehole drilling records, especially with regard to depth to saturated zone and the depth to the underlying limestone (fig. 7). The DC electric resistivity survey results and other subsurface studies in the Río Grande de Manatí alluvial plain suggest that the high resistivity (100 ohm-meter) layer at depths greater than 90 ft (fig. 7) may be the top of the Lares Limestone (Gómez-Gómez, 1984). Those sections within the unsaturated alluvium between depths of about 10 and 70 ft that register electric resistivity values near 100 ohm-meters are assumed to represent the coarse-grained deposits of gravel layers documented during drilling and observed in the nearby sand and gravel quarries. The zones of lower resistivity between 1 and 10 ft, and between about 60 and 90 ft are interpreted to represent relatively fine-grained alluvial deposits (Gómez-Gómez, 1984).

Hydraulic Characteristics of the Alluvial Aquifer

Water-level readings were taken on March 18 and 26, April 16 and 23, May 6, June 16, and July 28, 1998, under generally dry but variable meteorologic conditions. Hydraulic head measurements in the piezometers indicate that the water table is about 30 to 35 ft below the ground surface, which is equivalent to an altitude of about 63 to 64 ft above mean sea level (table 5; fig. 4). Water-table levels at TW-4 did not fluctuate more than 1 ft from April to July, 1998.

Table 5. Altitude of water level obtained in tightly cased piezometers in the Río Grande de Manatí alluvial aquifer, Río Arriba Saliente area, Puerto Rico, May 14, 1998

Piezometer identifier	Latitude [1]	Longitude [1]	Surface elevation [2]	Water table elevation [2]	Horizontal distance to TW-4 (ft)
TW-1	18°22′34"	66°29′08"	93.625	63.43	614.86
TW-2	18°22′30"	66°29′04"	95.499	63.56	34.02
TW-3	18°22′23"	66°29′04"	97.165	63.58	569.81
TW-4	18°22′30"	66°29′05"	96.060	63.64	0
TW-5	18°22′26"	66°29′06"	96.068	63.59	375.18
TW-6	18°22′29"	66°29′07"	93.970	63.52	312.48
TW-7	18°22′27"	66°29′04"	95.362	63.71	275.21
TW-8	18°22′22"	66°29′05"	93.190	63.86	762.93

[1] See figure 3 for general location of piezometer sites. Latitude and longitude cited here were determined with a non-differential GPS and the accuracy is within about 60 feet.

[2] Elevation, in feet above mean sea level.

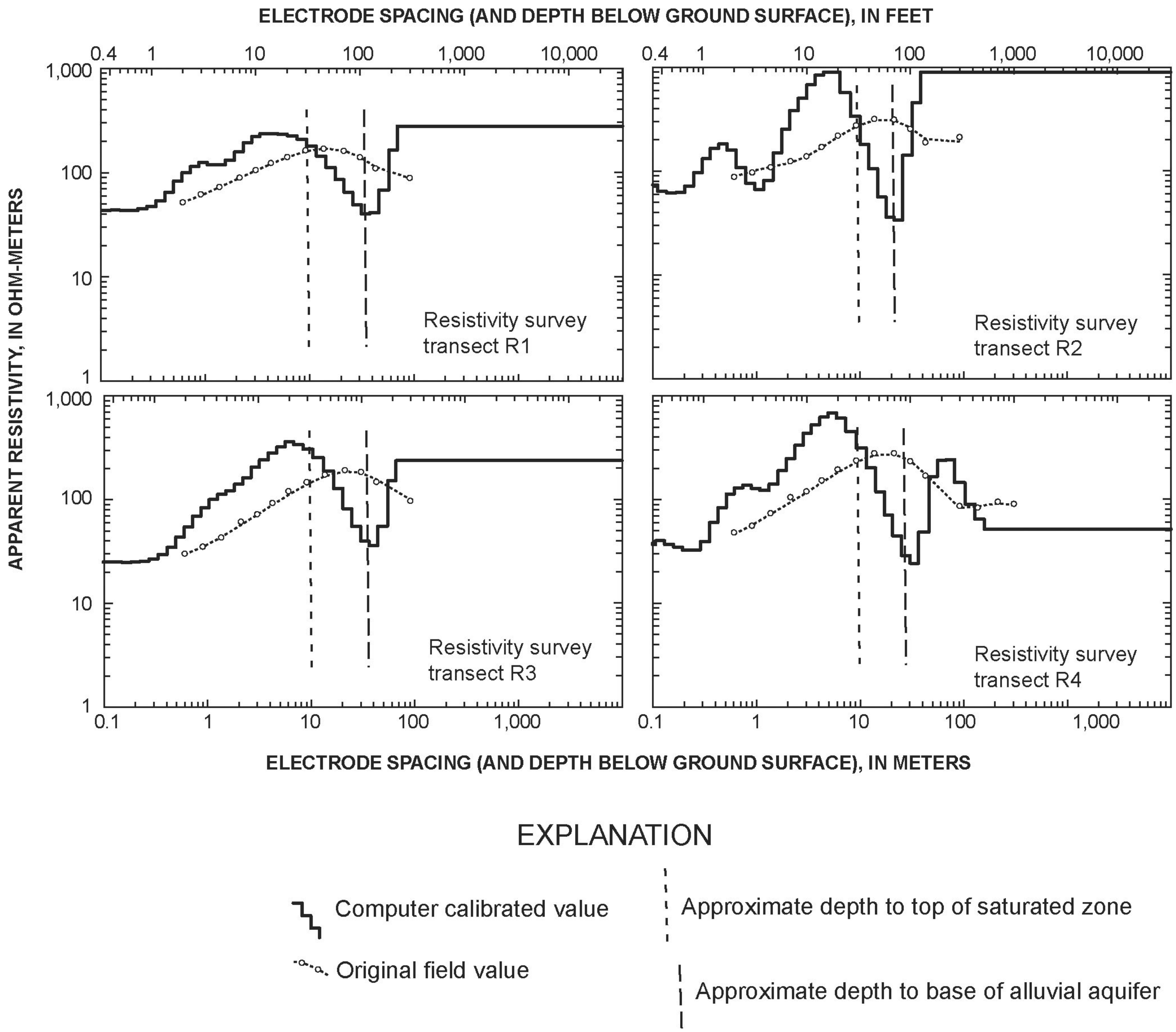

Figure 7. Surface direct-current electric resistivity survey results of four Schlumberger arrays in the Río Grande de Manatí alluvial plain, Río Arriba Saliente area, Puerto Rico. Refer to figure 3 for survey transect locations. The horizontal spacing of the electrodes is generally equivalent to the depth of direct-current electric resistivity measurement.

Aquifer-test results, borehole logs and DC electric resistivity surveys, in conjunction with the potentiometric surface map of the study area, indicate that local variations in horizontal hydraulic conductivity are relatively small. Based on the aquifer pump tests at piezometer TW-4, a specific-capacity of 27.8 gallons per minute per foot (gal/min/ft) of drawdown was estimated (Wenzel, 1942; Ferris and others, 1962; Theis and others, 1963; Prickett, 1965). An average hydraulic conductivity of about 200 feet per day (ft/d) was calculated using the specific-capacity method described in Theis and others (1963) and assuming a screened interval saturated thickness of 40 ft. Razack and Huntley (1991) utilized a different approach in evaluating the relation between transmissivity and specific capacity (Fetter, 1994). The Razack and Huntley (1991) method, contrary to Theis and others (1963), does not consider well losses. The hydraulic conductivity derived from this method was about 210 ft/d, which compares well with the value derived from the Theis and others (1963) method. Using the equations of Theis and others (1963) and data generated during the June 16, 1998 pump test, a transmissivity of 7,900 ft^2/d was estimated for the alluvial aquifer in the vicinity of TW-4.

A potentiometric map of the alluvial aquifer in the study area for May 14, 1998 (fig. 8), indicates a ground-water gradient of about 0.001, generally in the direction of river flow. Ground-water and stream gradients are similar. The potentiometric map indicates that, under natural conditions, the Río Grande de Manatí recharges the alluvial aquifer perimeter along the southern half of the aquifer's perimeter and the alluvial aquifer discharges to the Río Grande de Manatí along the northern part of the river.

Simulation of the Alluvial Aquifer and Time of Travel Estimates

A 1-layer model was developed for the alluvial aquifer using the data collected during the study. The area is relatively small and an equal-spaced finite-difference grid with a spacing of 50 ft for cell sides was used, resulting in a model grid of 69 rows (north to south) and 32 columns (west to east). The Río Grande de Manatí forms the eastern boundary of the alluvial model and is simulated as a head dependent flux. Average river stage was linearly interpolated along the stream reach from the upstream and downstream stage data. All other lateral boundaries were placed along the eastern edge of the alluvial plain (fig. 3), and simulated as no flow boundaries. The base of the aquifer was assumed to be no-flow and set to an elevation of sea level (fig. 4).

Steady-state simulations were used for the time of travel estimates, based on the river stage data collected. The alluvial aquifer is simulated as unconfined and simulated average river stage ranged from 67 to 62 ft above sea level from south to north. Thus, the average thickness of the simulated model layer is about 64 ft. In order for the transmissivity of the alluvial aquifer to remain about 8,000 ft^2/d as estimated from the specific capacity tests, the hydraulic conductivity of the alluvial aquifer was set as a constant of 133 ft/d. Because the river has been dredged, it was assumed that the river bed materials would be thin and have a conductance similar to the aquifer. Thus, the riverbed conductance was set at 100 day^{-1} to represent a hydraulic conductivity of 100 ft/d divided by a thickness of 1 ft.

Figure 9 shows the model grid, boundary conditions, and simulated potentiometric surfaces and flow paths of particles placed at each river cell. Two conditions were simulated: (a) the natural flow system and (b) with a well pumping 1 ft^3/s in the middle of the alluvial aquifer. For the natural system, both the observed and simulated water-table maps (figs. 8, 9a) indicate flow from south to north paralleling the river. In the model simulation 0.16 ft^3/s enters the alluvial aquifer along the southern river boundary and exits the alluvial aquifer to the river in the along the northern part of the river boundary. Most of the particles stay fairly close to the river or travel in cells beneath the river. After adding a 1 ft^3/s pumping well in the southern part of the modeled area, particles move from the river channel towards the well (fig. 9b). In the northern part of the modeled area some particles completely reverse their natural path (fig 9b). With the pumping well there is an increase to 1.06 ft^3/s of water entering the alluvial aquifer from the river along most of the river boundary and a decrease to 0.06 ft^3/s of water discharge from the alluvial aquifer to the river channel along part of the northern boundary.

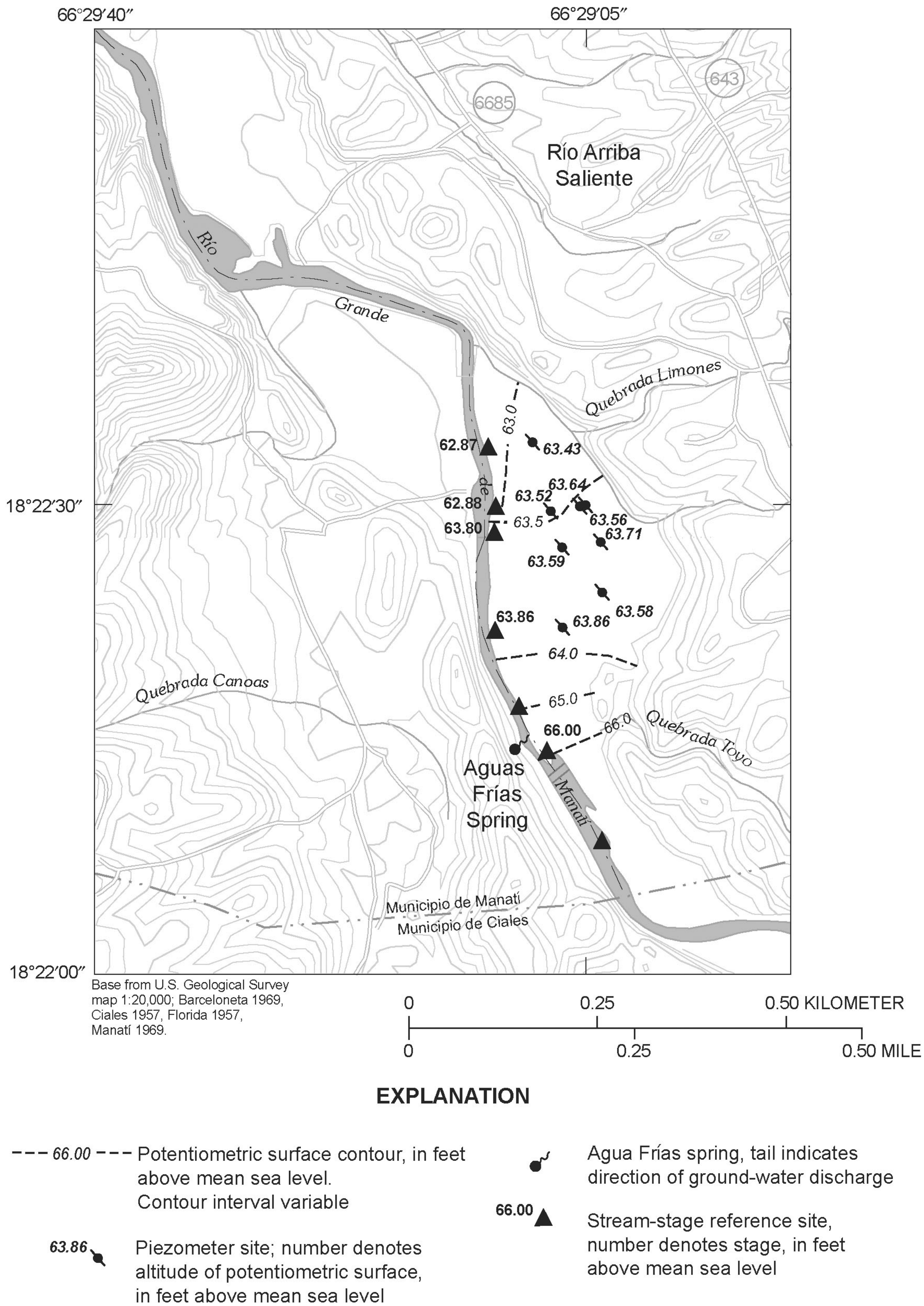

Figure 8. Potentiometric-surface elevation in the Río Grande de Manatí alluvial plain, Río Arriba Saliente area, Puerto Rico, May 14, 1998.

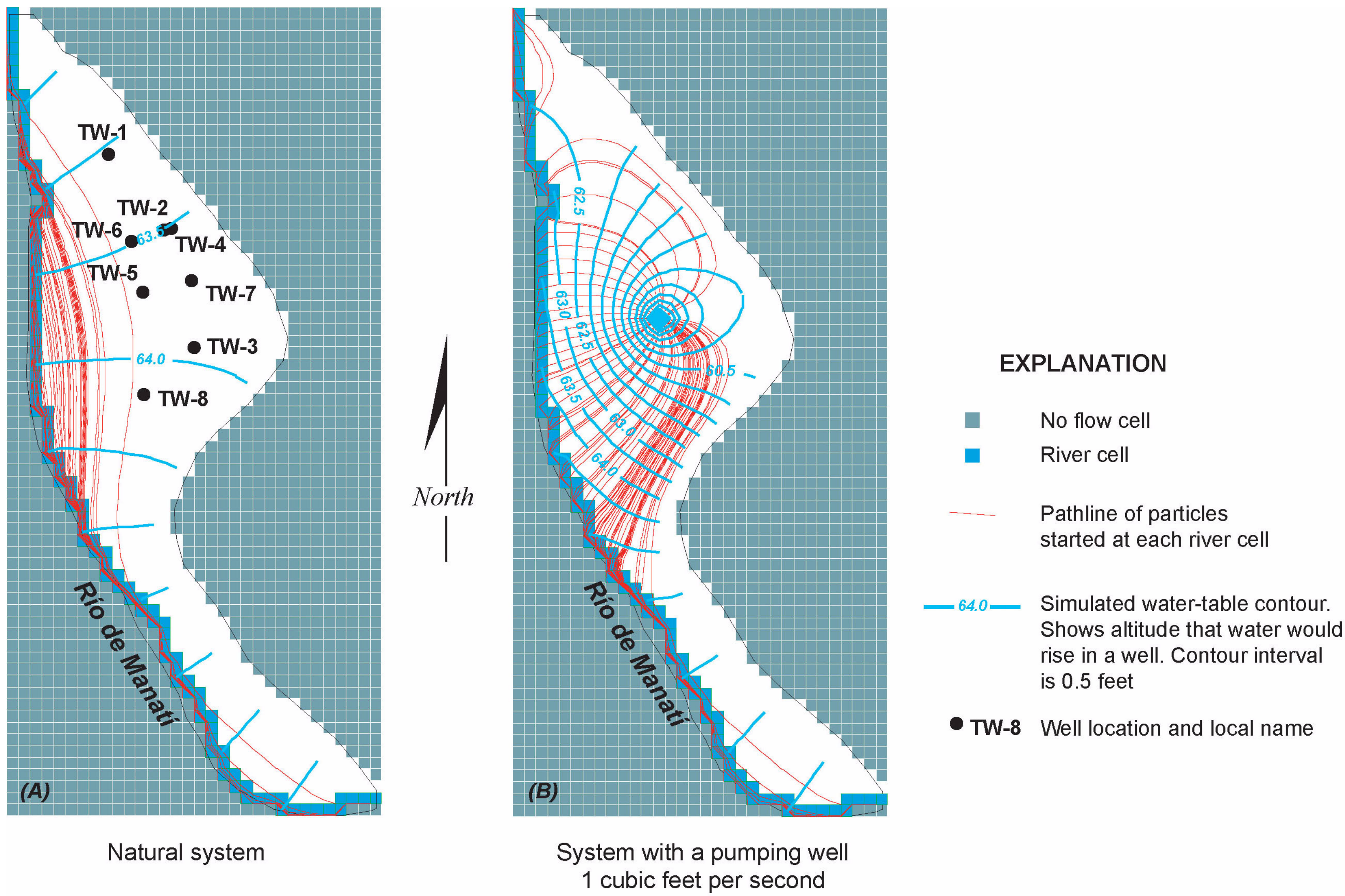

Figure 9. Ground-water flow model of the alluvial aquifer, simulated water levels, and flowpaths of particles placed at each simulated river cell.

Times of travel from the river to the 1 ft^3/s pumping well were estimated by setting the concentration of the river water to 1.0, the initial concentration in the aquifer to 0.0, and using the steady-state flow model fluxes in the transport equation. To simulate transport, one must specify the porosity of the aquifer (the percent of void spaces in the alluvium). No field tests were done to estimate porosity. According to Fetter (1994), the porosity of mixed sand and gravels range from 20 to 35 percent, with an average of 27.5 percent.

Because the main objective of the model is to estimate times of travel for potential contaminants, specifically bacteria, traveling from the river to a well pumping at the rate of 1 ft^3/s, sensitivity analysis was performed by changing hydraulic conductivity of the aquifer, river bed conductance, the average porosity and the pumping rate, then comparing the simulated concentration at the well after 100 days. Only one parameter was changed at a time by doubling and cutting in half each value. The simulated concentration is most sensitive to porosity and the pumping rate (fig. 10). The ground-water flow equation computes the "Darcy" velocity, which was based on the flow though the aquifer divided by the total area. The pore velocity is the average velocity of the water moving through the connected void spaces in the aquifer. It is computed by dividing the "Darcy" velocity by the porosity. Thus, the smaller the porosity, the faster the pore velocity, which is why porosity has such a large effect on transport velocities. Additionally, since all of the water moving towards the well comes from the river, if the pumping rate is increased or decreased, this greatly effects the mass balance of water moving from the river to the pumping well. Thus, increasing the pumping rate increases the volume of water moving from the river to the well, just as decreasing the pumping rate will decrease the volume of river water moving towards the well.

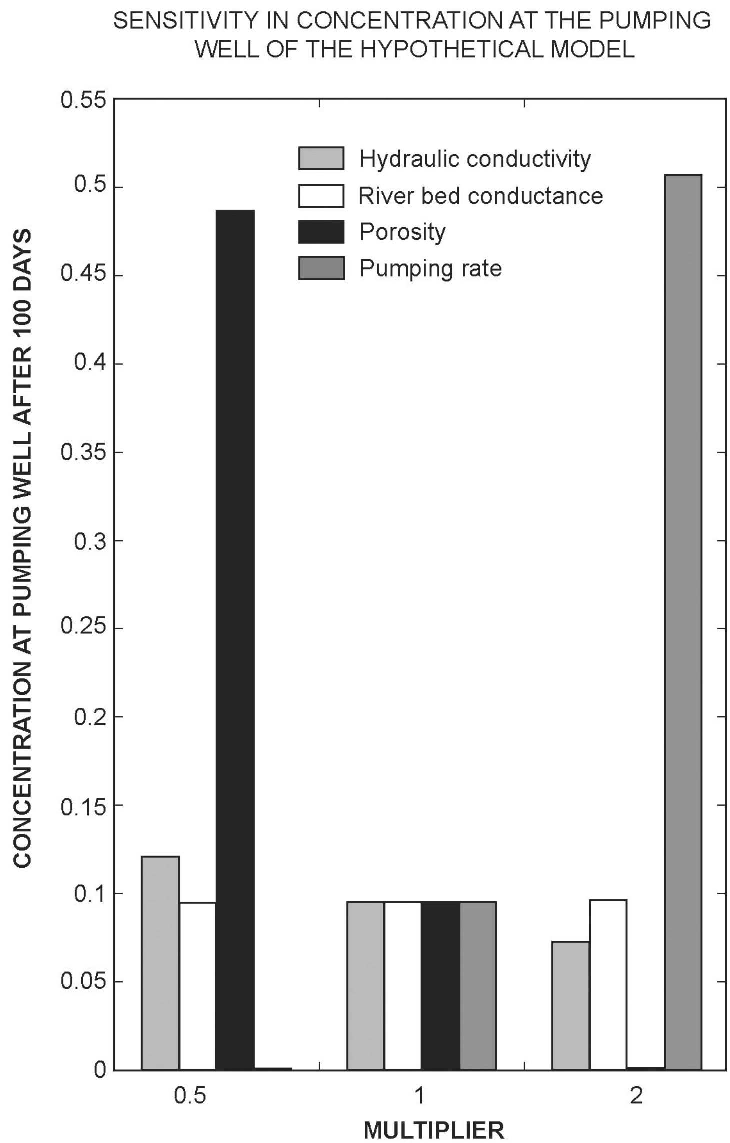

Figure 10. Sensitivity of simulated concentration at the pumping well to changes in model parameters.

Figure 11 shows the simulated concentration distribution at about 60 days in the aquifer with lower and upper porosity range. With either porosity value, much of the aquifer remains free of the hypothetical contaminant, although higher concentrations spread to more area in 60 days with the lower porosity value. Figure 12 shows the concentration breakthrough curves at the well. The leading edge of a plume would reach the production well in about 40 days assuming a porosity of 0.20, 60 days assuming a porosity of 0.275, and in about 70 days assuming a porosity of 0.35. These estimates are considered a worse case estimate because no decay rate was included in the simulation. Moreover, if the pumping well were positioned eastward, further from the river channel, travel times would be longer. Also shown on figure 12 is the breakthrough curve when the well is moved 50 ft east ward, further from the river, for the lowest porosity and the average porosity. If the well is 50 ft further from the location shown on figure 9b, the leading edge of the plume reaches the well in 50 days with a porosity of 0.20 and 70 days with a porosity of 0.275.

Water Quality

As indicated previously, an important aspect of this investigation was to determine if ground water in the area is suitable as a source of potable water. Suitability includes water quality; therefore, concentrations of major dissolved chemicals, nitrate, fecal coliform, and fecal streptococcus were determined for selected surface- and ground-water samples.

Ground-Water Chemistry

The quality of ground water in the study area is similar to that of surface water in Río Grande de Manatí, except for higher alkalinity, which is likely caused by carbon dioxide saturation (table 6a). An alkalinity value of 321 mg/L as $CaCO_3$ classifies this ground water as very hard (Hem, 1970). Drinking water in many areas of the United States, however, has a hardness value of 300 mg/L or higher, and these concentrations pose no threat to human health (Hem, 1970).

Analysis of nitrate-nitrogen (NO_3-N) in ground water at TW-4 indicates concentrations of 2.6 mg/L (table 6b). The source of nitrate is probably from fertilizer applications to enhance pasture growth (Hem, 1970). Waters are considered unsafe for human consumption at nitrate concentrations of 10 mg/L (U.S. Environmental Protection Agency, 2000b). Nitrate concentrations of 2.6 mg/L are well below the 10-mg/L limit. Table 7 shows selected secondary drinking water standards established by USEPA. Comparison of tables 6a and 7 indicates that the surface- and ground-water samples collected in the Río Grande de Manatí, Río Arriba Saliente area, were within the secondary drinking water standards for the constituents listed. Secondary standards are non-enforceable guidelines for constituents that have cosmetic and aesthetic effects on drinking water.

Bacteria Concentrations in Surface and Ground Water

Water-quality standards for surface water in Puerto Rico were established by the Puerto Rico Environmental Quality Board (Junta de Calidad Ambiental de Puerto Rico, 1990, p. 30) on the basis of the designated use. All perennial, fresh surface water in Puerto Rico, inland of their estuary segments, have been classified as Class SD waters. This classification applies to surface water intended for use (or with the potential for use) as a raw source of public water supply, propagation and preservation of desirable aquatic species, and primary and secondary contact recreation. The Río Grande de Manatí is classified as Class SD waters upstream of its estuary. The maximum concentration of fecal coliform and fecal streptococcus established for class SD waters is 2,000 colonies per 100 mL (Junta de Calidad Ambiental de Puerto Rico, 1990). Fecal coliform and fecal streptococcus bacteria are not pathogenic, but have been correlated to the presence of several waterborne disease-causing organisms present in wastes of warm-blooded animals, including humans. Thus, the concentration of these indicator bacteria is a measure of the safety of water for human contact and consumption. However, in tropical climates, fecal coliforms may not be a good measure of risk to human health. The USEPA (1998) recommended water-quality standard for fecal coliform in recreational fresh waters is 200 colonies per 100 mL and 2000 colonies per 100 mL for marine waters.

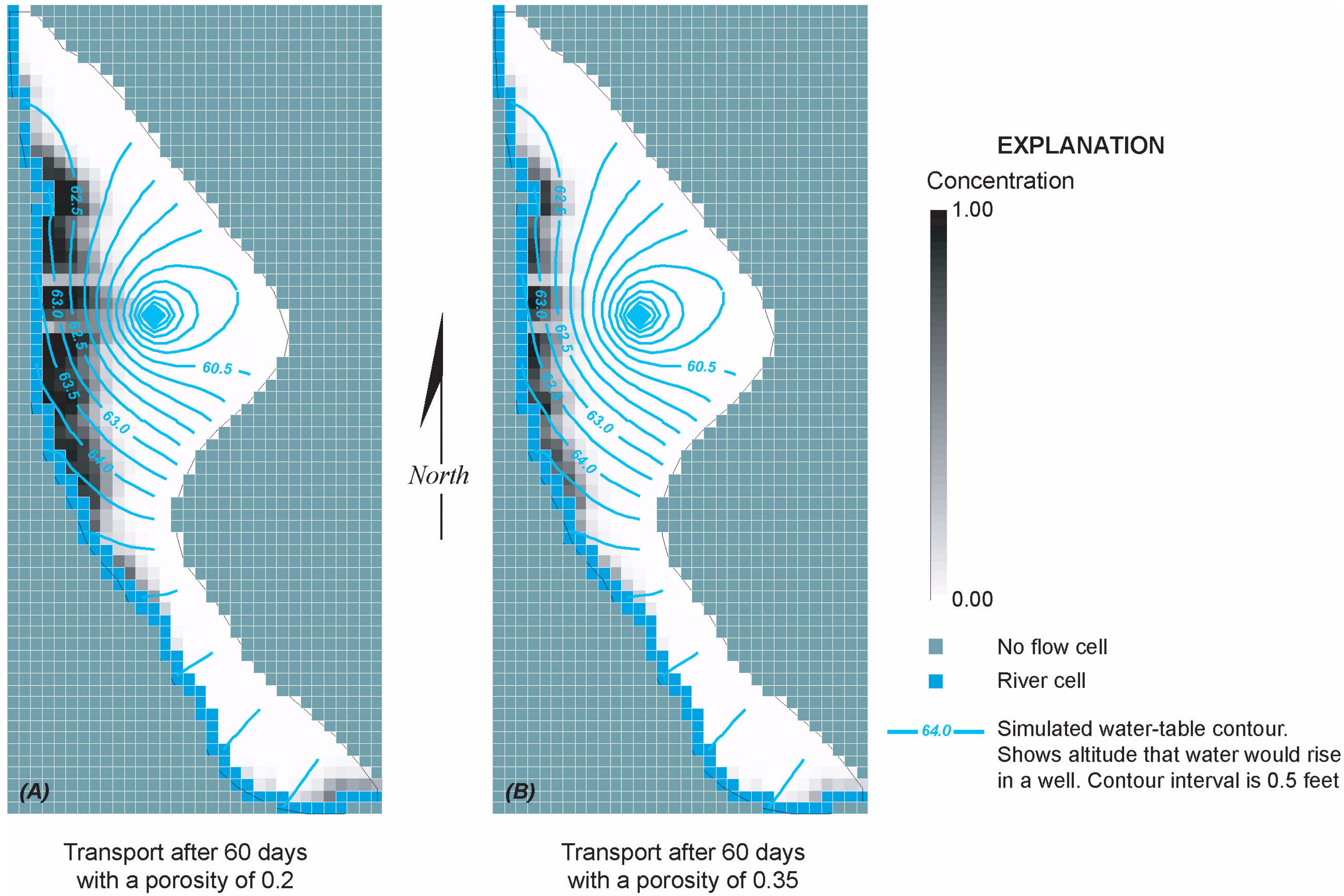

Figure 11. Simulated concentrations in the alluvial aquifer after 60 days of simulation with (A) a porosity of 0.2 and (B) a porosity of 0.35.

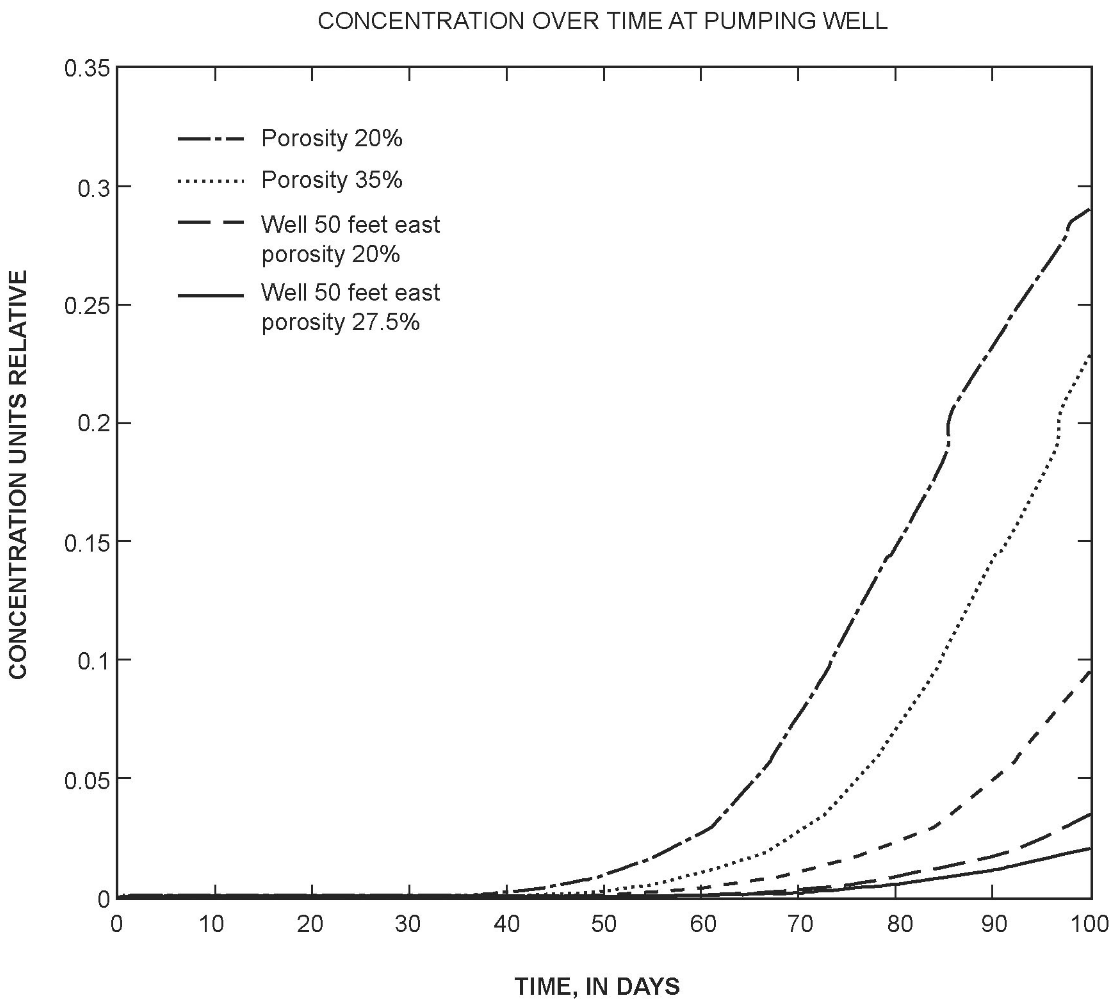

Figure 12. Simulated concentration breakthrough curves for the range of possible porosities of a mixed sand and gravel alluvial aquifer.

Table 6a. Water-quality characteristics in a ground-water sample collected on April 23, 1998, from piezometer TW-4, Río Grande de Manatí alluvial plain, Río Arriba Saliente area, Puerto Rico

[µS/cm, microsiemens per centimeter; mg/L, milligram per liter; µg/L, microgram per liter; °C, degrees Celsius; $CaCO_3$, calcium carbonate; NO_3, nitrate]

Specific conductance µS/cm at 25 °C	pH, standard units	Hardness total mg/L as $CaCO_3$	Calcium, dissolved mg/L as Ca	Magnesium, dissolved mg/L as Mg	Sodium, dissolved mg/L as Na	Potassium, dissolved mg/L as K	Chloride, dissolved mg/L as Cl
644	7.03	330	112	11.8	12.1	2.0	16.2

Sulfate, dissolved mg/L as SO_4	Fluoride, dissolved mg/L as F	Silica, dissolved mg/L as SiO_2	Iron, dissolved µg/L as Fe	Manganese, dissolved µg/L as Mn	Dissolved solids, sum mg/L	Alkalinity, mg/L as $CaCO_3$	
						Field	Laboratory
13.4	0.1	20.3	11.8	72.5	375	321	313

Table 6b. Nitrogen concentration in a ground-water sample collected on May 14, 1998, from TW-4, Río Grande de Manatí alluvial plain, Río Arriba Saliente area, Puerto Rico

Specific conductance µS/cm at 25 °C	Alkalinity mg/L as $CaCO_3$	Nitrate-Nitrogen, in mg/L as NO_3-N
634	321	2.6

Table 7. Chemical and constituent concentration limits for selected constituents of the secondary drinking water standards, as established by the U.S. Environmental Protection Agency (2000a)

Constituents	USEPA Secondary drinking water regulations (concentrations in milligrams per liter)
Chloride	250.0
Fluoride	2.0
Iron	0.3
Manganese	0.05
Sulfate	250.0
Total dissolved solids	500.0

Fecal coliform and fecal streptococcus samples were collected by the USGS about every other month at two stream sampling stations upstream of the study area for the period from 1989 to 1998 (total of 55 samples); station 50035500 on the Río Grande de Manatí, and station 50035950 on the Río Ciales. The fecal coliform data are shown on figure 13 for both sites. For the Río de Manatí sampling station 50035500, fecal coliform exceeded 2,000 colonies per 100 mL for 17 of the 55 samples (31 percent of the samples) and fecal streptococci exceeded 2,000 colonies per 100 mL for 8 of the 55 samples (15 percent of the samples). For the Río Ciales sampling station, 50035950, both fecal coliform and fecal streptococci exceeded 2,000 colonies per 100 mL for 18 of the 55 samples (33 percent of the samples). The Ciales waste-water treatment facility and the Aguas Frías spring discharge water to the Río Grande de Manatí downstream of station 50035500, but upstream of the study area. Treated effluent from the Ciales waste-water treatment facility is chlorinated and the reported discharge volume ranged from 0.30 to 0.42 Mgal/d for January and March 1995, respectively (W. Molina, USGS, written commun., 2000). Samples taken in 1982-83 at Aguas Frías spring indicated fecal coliform bacteria concentrations (colonies per 100 mL) that ranged from 340 to 1,800 for fecal coliform, and 360 to 830 for fecal streptococcus (Guzmán-Ríos, 1988) (table 3). These samples may not reflect the current bacterial concentrations at Aquas Frías springs.

A summary of the surface-water bacteriological analyses collected at stations 50036400, 50036200, and 50035500 (fig. 2) is presented in table 8. During 1998, the minimum and maximum counts of fecal coliform were 20 and 750 colonies, respectively, per 100 mL of water sampled. The minimum and maximum counts of fecal streptococcus in 1998 were less than 1 and 490 colonies, respectively, per 100 mL of water sampled.

Samples were collected for ground-water bacteriological analysis on July 28, 1998, at piezometers TW-1, TW-3, TW-4, and TW-5. Analytical results (table 9) demonstrate that indicator bacteria were not present in the aquifer system in the vicinity of the piezometers. Within the study area, under natural conditions, ground-water flow paths between the river channel and the alluvial aquifer do not extend landward as far as TW-4 (fig. 9a).

Potential and Limitations of Ground-Water Development of the Alluvial Aquifer

The availability of ground water in the Río Grande de Manatí valley, Río Arriba Saliente area, is largely controlled by the rate of aquifer recharge from the Río Grande de Manatí. For steady-state (non-pumping) conditions, surface-water recharge from the Río Grande de Manatí into the alluvial aquifer was estimated to be 0.16 ft^3/s. If the aquifer is developed as a source of public water supply, infiltration from the stream would increase by the same amount of withdrawal at a well field after withdrawal derived from aquifer storage becomes insignificant. Induced recharge from the Río Grande de Manatí necessary to maintain a withdrawal rate of 449 gal/min (1 ft^3/s) is possible because the estimated river discharge at station 50038100 is equal to or greater than 44 ft^3/s, 98 percent of the time (Ramos-Ginés, 1999), and the aquifer is sufficiently permeable to maintain this rate of ground-water flow to a pumping well.

McFeters and others (1974) conducted several experiments to determine the capacity of pathogenic and indicator organisms to survive in ground water. They determined that the populations of several strains of bacteria were reduced by an order of magnitude, 1 to 6 days after the bacteria-bearing waters entered the ground-water system. Martin and Noonan (1977) reported an order-of-magnitude reduction in the concentration of fecal coliform bacteria after 6.2 days in a ground-water system. However, information about the survival capacity of bacteria and viruses in the ground-water environment is not conclusive (Britton and others, 1983; Keswick and Gerba, 1980). For example, Wellings and others (1975) reported that some bacteria may survive in ground water more than 28 days, and viruses may survive in ground water for up to 60 days. Additionally, survival of bacteria and viruses might be different from the above studies given the tropical climate of Puerto Rico.

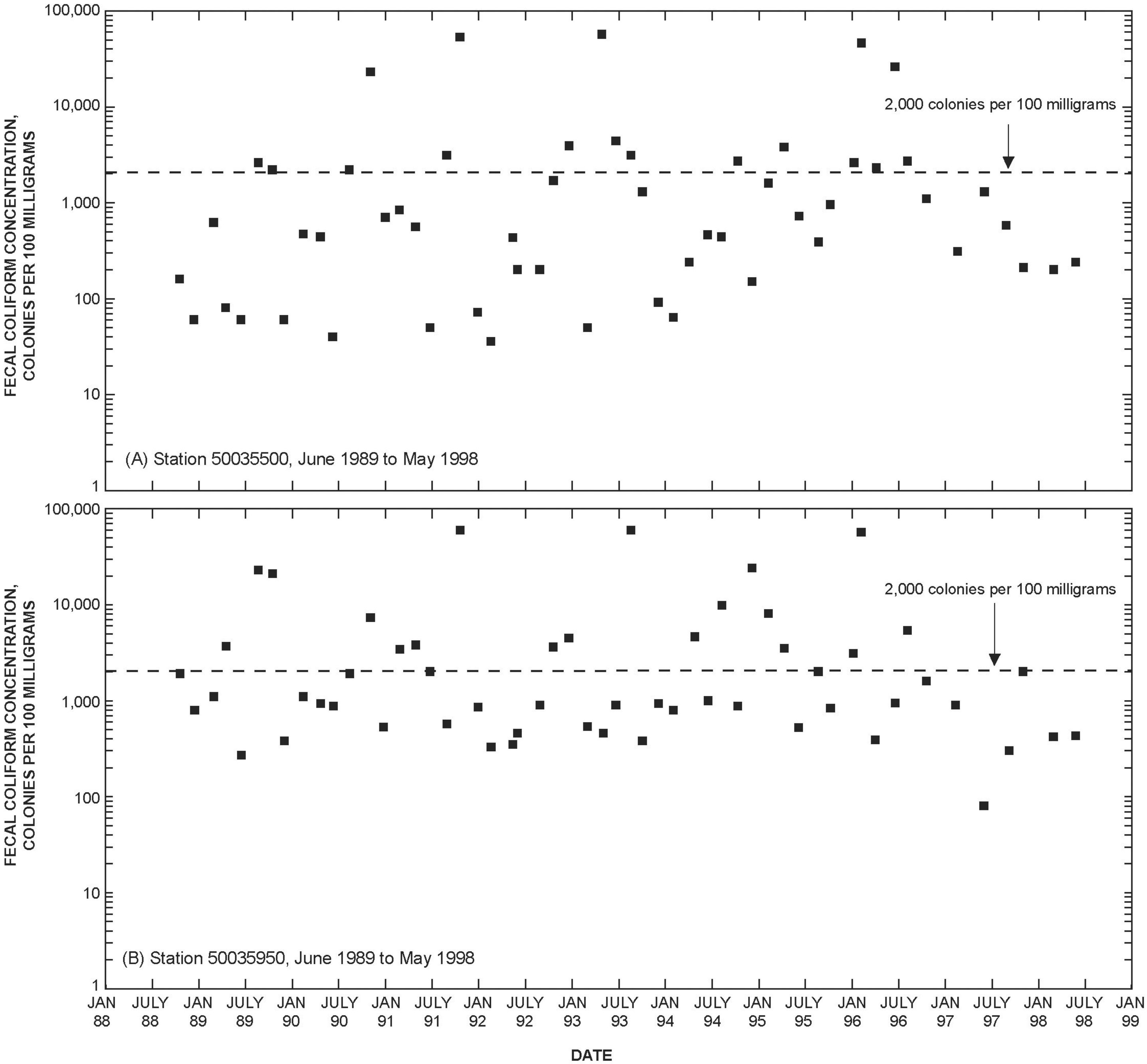

Figure 13. Concentration of fecal coliform bacteria at station 50035500 along the Río Grande de Manatí at Highway 149, about 5 miles upstream of the study area; and station 50035950 along the Río Cialitos at Highway 649, about 4 miles upstream of the study area.

Table 8. Results of bacteriological analyses of surface-water samples from the Río Grande de Manatí, Río Arriba Saliente area, Puerto Rico

[FC, fecal coliform; FS, fecal streptococcus; --, colony counts not recorded; <, less than; mL, milliliter]

Site location [1]	Sampling date and time	Type of analysis	Colonies per 100 mL
Upstream of PR-149 Ciales bridge, station 50035500 [not sampled on March 26, 1998]	March 18, 1998, 10:30AM	FC	90
		FC	50
	April 16, 1998, 10:20AM	FC	710
		FS	150
	May 6, 1998, 10:15AM	FC	420
		FS	400
	July 28, 1998, 11:55AM	FC	200
		FS	50
Upstream of Aguas Frías spring, station 50036200	March 18, 1998, 12:15PM	FC	20
		FS	40
	March 26, 1998, 10:55AM	FC	20
		FS	30
	April 16, 1998, 10:45AM	FC	610
		FS	250
	May 6, 1998, 10:50AM	FC	80
		FS	490
	July 28, 1998, 11:30AM	FC	280
		FS	<1
Downstream of Aguas Frías spring, station 50036400	March 18, 1998 12:16PM	FC	40
		FS	--
	March 26, 1998, 10:56AM	FC	40
		FS	10
	April 16, 1998, 10:46AM	FC	750
		FS	340
	May 6, 1998, 10:51AM	FC	100
		FS	450
	July 28, 1998, 11:35AM	FC	330
		FS	6

[1] Locations shown in figure 2.

Table 9. Results of bacteriological analyses of ground-water samples from the Río Grande de Manatí alluvial plain, Río Arriba Saliente area, Puerto Rico

[FC, fecal coliform; FS, fecal streptococcus; TC, total coliforms; mL, milliliter; <, less than]

Site location	Sampling date	Type of analysis	Colonies per 100 mL
TW-1	July 28, 1998	FC	<1
		FS	<1
		TC	<1
TW-3	July 28, 1998	FC	<1
		FS	<1
		TC	<1
TW-4	July 28, 1998	FC	<1
		FS	<1
		TC	<1
TW-5	July 28, 1998	FC	<1
		FS	<1
		TC	<1

The following combination of factors have raised concern about the potential for bacterial contamination of ground water in the study area: (1) recharge of the alluvial aquifer is primarily by infiltration from the Río Grande de Manatí channel; (2) water-quality records from stations upstream from the study area indicate elevated concentrations of fecal coliform and fecal streptococcus in the river water; (3) the hydraulic conductivity of the alluvial aquifer is relatively high; and (4) the distance between the river channel and the proposed water-supply well is only about 500 ft (fig. 4). Therefore, ground-water residence times in the ground-water system may not be sufficient to attenuate potentially harmful microorganisms. Because of possible microbiological contamination from the Río Grande de Manatí, the time of travel for water moving from the river channel to a pumping well is a major limiting condition on the rate at which uncontaminated water can be pumped from the aquifer. Analysis indicates that withdrawals of 224 gal/min would result in a time of travel of more than 60 days. At a pumping rate of 449 gal/min (1 ft^3/s), the time of travel may be as little as 40 days for water moving from the river channel to a pumping well. Available studies indicate that a time of travel of 40 days would result in about a 95 percent reduction in fecal streptococcus, total coliform, and fecal coliform concentrations (fig. 14). Fecal streptococcus, total coliform, and fecal coliform may not be indicators of the presence of viral pathogens. Even if a 95 percent attenuation of these bacteria did occur after 40 days, this may not be relevant to the attenuation of other pathogenic organisms.

Fecal coliform and fecal streptococcus concentrations in the waters of the Río Grande de Manatí may be influenced (reduced) by chlorinated water discharged from the Ciales waste-water treatment facility (fig. 2). Additional analysis of chlorine content in the river water is required to determine if bacteria concentrations in the Río Grande de Manatí are reduced by Ciales waste-water treatment facility effluent. A change in microbiological characteristics in the surface water may also be caused by discharge of Aguas Frías spring, which is located directly across the channel from reference site 3 (fig. 3).

In this report, bacteria were assumed to move through the subsurface by advection, such that the rate of movement of bacteria through the system is equal to the rate of ground-water flow. Therefore, transport through the saturated porous material was calculated using Darcy's equation. Other possible processes that may accelerate or retard the movement of contaminants through an aquifer are diffusion, dispersion, and retardation. In porous media, diffusion does not proceed as fast as in open water because the ions must follow longer pathways as they travel around mineral grains. Dispersion occurs as mixing of contaminated water causes dilution along the flow pathway, and by lateral expansion. Although dispersion may accelerate the spreading of contaminants through the ground-water system, dispersion also increases dilution; consequently, dispersion generally means a reduction in potential toxicity. Retardation is the process in which the solute transport is slower than that of water. Retardation can result from physicochemical or biochemical processes, including chemical reactions (ion exchange, hydrophoric exclusion, authigenic

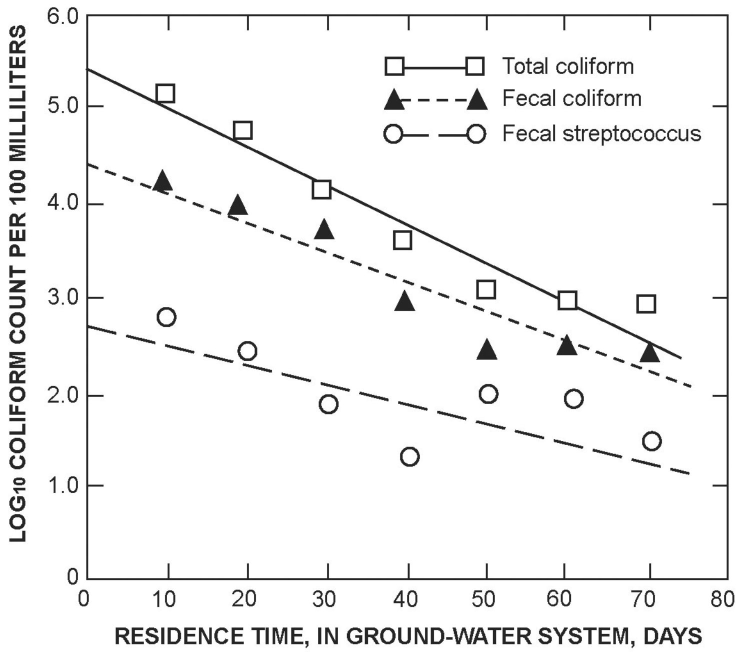

Figure 14. Attenuation over time of indicator bacteria in a natural ground-water system, Walton, Florida (modified from Britton and others, 1983).

mineral precipitation), exolution (degassing), and biological processes (including uptake and decomposition). In the retardation process, reaction kinetics may play an important role in the determination of abiotic or biotic fate of organic contaminants. Evidence indicates that the processes of diffusion, dispersion, and retardation, if active in the ground-water system, would reduce the concentration of contaminants relative to the movement of ground water, or result in substantial dilution of bacteria and viruses. Hence, the time of travel calculations used in this report may under estimate residence times and over estimate concentrations of bacteria moving through the alluvial aquifer.

SUMMARY AND CONCLUSIONS

The USGS, in cooperation with the Mayor's Office of the municipio of Manatí, conducted a hydrogeologic study of the alluvial aquifer of the Río Grande de Manatí, Río Arriba Saliente area to evaluate its potential as a ground-water source. To define the stratigraphic and hydrogeologic properties of the alluvial aquifer, eight piezometers were installed at depths ranging from 39 to 63 ft, and four DC electric resistivity survey transects were conducted. Analysis of well-boring samples and electric resistivity survey results indicate that within the study area, the average thickness of the alluvial aquifer is about 100 to 110 ft, and that there is a 60-ft-thick coarse-gravel layer that extends from about 15 ft above to 45 ft below the top of the phreatic zone.

Preliminary estimates of hydraulic conductivity (200 ft/d) and transmissivity (7,900 ft^2/d) were generated, based on short-duration pump tests in small diameter piezometers. A larger (12-in. inside) diameter test well constructed to a depth of 100 to 110 ft, in which an extended aquifer test (4 to 5 days) with a ground-water withdrawal rate of about 250 gal/min would verify and perhaps improve the hydraulic conductivity and transmissivity estimates. A larger diameter test well located 50 ft northeast of piezometer TW-4 would maximize the use of all available piezometers during aquifer tests.

Analysis of water levels in the piezometers combined with stage measurements at a series of surveyed reference points along Río Grande de Manatí channel indicate that the ground-water gradient in the alluvial aquifer is about 0.001, and that ground-water flow is generally from south to north, in the general direction of river flow. The potentiometric map indicates that Río Grande de Manatí is the principal source of ground-water recharge to the alluvial aquifer in the study area.

To address concerns about possible contamination by agrochemicals and fecal bacteria, selected ground-water samples were analyzed for the chemical and biological content. Nitrate concentrations in the local ground water at piezometer TW-4 are 2.6 mg/L; these concentrations are considered safe for drinking water (U.S. Environmental Protection Agency, 2000b). At piezometer TW-4, field-measured alkalinity of 321 mg/L indicates that the ground water is very hard though potable, and a laboratory pH of 7.03, indicates that waters are neutral. Bacteriological analysis of samples from piezometers TW-1, TW-3, TW-4, and TW-5 indicate that the ground water contains little or no fecal coliform bacteria.

To address concerns of possible surface-water contamination by discharge from the nearby Ciales waste-water treatment facility and other sources of fecal contamination, selected surface-water samples were analyzed to determine indicator bacteria concentrations. Preliminary analyses show that minimum and maximum counts of fecal coliforms in the Río Grande de Manatí channel were 20 and 750 colonies, respectively, per 100 mL of water sampled; the minimum and maximum counts of fecal streptococcus were less than 1 and 490 colonies, respectively, per 100 mL. These concentrations are below the limits established by Puerto Rico Environmental Quality Board for raw water (Junta de Calidad Ambiental de Puerto Rico, 1990) for Class SD waters.

Because the alluvial aquifer is porous and permeable and because a public-supply well would be close (500 to 800 ft) to the river, there is concern that pumping from the alluvial aquifer will greatly enhance recharge from the Río Grande de Manatí channel to the aquifer. Enhanced recharge would result in short residence times for ground water in the aquifer, which might not allow sufficient time for attenuation of bacteria and viruses. To address these concerns, the time of travel of ground water moving from the river channel to a hypothetical production well at the center of the aquifer was estimated for non-pumping (steady-state) and pumping (stressed steady-state) conditions. Travel times for bacteria moving from the river channel to a production well were estimated using the numerical transport model MODFLOW96/MT3DMS with an uncalibrated model of the alluvial aquifer at the site with a well pumping at 1 ft^3/s. The leading edge of a plume would reach the production well in about 40 days assuming a porosity of 0.20, 60 days assuming a porosity of 0.275, and in about 70 days assuming a porosity of 0.35. If the simulated well were moved 50 ft further from the river, the leading edge of the plume would reach the well in about 50 days assuming a porosity of 0.20 and in about 70 days assuming a porosity of 0.275. The transport of particles from the river to the well is most sensitive to the porosity of the aquifer and the pumping rate of the well. Sensitivity analysis indicates that a decrease in pumpage will increase the time of travel for particles to move from the river to the pumping well. These estimates are considered a worse case estimate, because no decay rate was included in the simulation and because the hypothetical well was located in the center of the alluvial plain rather than further eastward, away from the channel.

The study methodologies and baseline data presented in this report provide government agencies and resource managers a means to safeguard ground-water quality by evaluating minimal ground-water residence time and distance requirements needed between a stream and a public-supply well constructed in a narrow alluvial plain. Further evaluations of diffusion, dispersion, and retardation may be required to better understand attenuation capacity of bacteriological contamination of unconsolidated deposits. Further studies are needed to determine the survival capacities of bacteria and viruses in ground-water systems.

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