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

PREPARED IN COOPERATION WITH THE
MUNICIPIO AUTÓNOMO DE CAROLINA, PUERTO RICO, OFFICE OF THE MAYOR

Surface-Water, Water-Quality, and Ground-Water Assessment of the Municipio of Carolina, Puerto Rico, 1997-99

WATER-RESOURCES INVESTIGATIONS REPORT 01-4267

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Cover photograph

View from Cerro San José at municipio de Carolina landfill facility looking southeast. In the foreground are outcrops of the Aguada Limestone within the Río Grande de Loíza coastal plain, and in the background the foothills of Sierra Luquillo rainforest. Photograph taken by Mario L. Oliveras-Feliciano and Jesús Rodríguez-Martínez on January 2002.

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By Jesús Rodríguez-Martínez, Fernando Gómez-Gómez, Luis Santiago-Rivera, and Mario L. Oliveras-Feliciano

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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	1,233.489	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	30.4785	centimeter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3045	meter per day
gallon (gal)	3.785	liter
gallon per day (gal/d)	0.00378	cubic meter per day
gallon per minute (gal/min)	0.00378	cubic meter per minute
inch (in.)	2.540	centimeter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallon per day (Mgal/d)	0.04381	cubic meter per second
square foot per day (ft^2/d)	0.0929	square meter per day
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

µg/L	microgram per liter
µS/L	microsiemen per liter
mL	milliliter

Acronyms used in this report

CAPR	Compañía de Aguas de Puerto Rico
PRASA	Puerto Rico Aqueduct and Sewer Authority
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

Translations

Commonly used Spanish terms and their equivalent in English:

Spanish	English
caño	stream or tributary
lago	lake
municipio	usually equivalent to county
río	river
quebrada	stream or creek
pozo	well

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By Jesús Rodríguez-Martínez, Fernando Gómez-Gómez, Luis Santiago-Rivera, *and* Mario L. Oliveras-Feliciano

Abstract

To meet the increasing need for a safe and adequate supply of water in the municipio of Carolina, an integrated surface-water, water-quality, and ground-water assessment of the area was conducted. The major results of this study and other important hydrologic and water-quality features were compiled in a Geographic Information System and are presented in two 1:30,000-scale map plates to facilitate interpretation and use of the diverse water-resources data.

Because the supply of safe drinking water was a critical issue during recent dry periods, the surface-water assessment portion of this study focused on analysis of low-flow characteristics in local streams and rivers. Low-flow characteristics were evaluated for one continuous-record gaging station, based on graphical curve-fitting techniques and log-Pearson Type III frequency analysis. Estimates of low-flow characteristics for seven partial-record stations were generated using graphical-correlation techniques. Flow-duration characteristics were computed for the one continuous-record gaging station and were estimated for the partial-record stations using the relation curves developed from the low-flow study. Stream low-flow statistics document the general hydrology under current land and water use. Low-flow statistics may substantially change as a result of streamflow diversions for public supply, and an increase in ground-water development, waste-water discharges, and flood-control measures; the current analysis provides baseline information to evaluate these impacts and develop water budgets.

A sanitary quality survey of streams utilized 29 sampling stations to evaluate the sanitary quality of about 87 miles of stream channels. River and stream samples were collected on two occasions during base-flow conditions and were analyzed for fecal coliform and fecal streptococcus. Bacteriological analyses indicate that a significant portion of the stream reaches within the municipio of Carolina may have fecal coliform concentrations above the water-quality goal established by the Puerto Rico Environmental Quality Board (Junta de Calidad Ambiental de Puerto Rico) for inland surface waters. Sources of fecal contamination may include: illegal discharge of sewage to storm-water drains, malfunctioning sanitary sewer ejectors, clogged and leaking sewage pipes, septic tank leakage, unfenced livestock, and runoff from livestock pens. Long-term fecal coliform data at two sampling stations, Quebrada Blasina in Carolina and the Río Grande de Loíza, downstream from the town of Trujillo Alto, indicate that the sanitary quality of Quebrada Blasina is and has generally been poor for more than a decade. The sanitary quality of the Río Grande de Loíza has generally been in compliance with the water-quality goal standard fecal coliform concentrations established in July 1990 by the Puerto Rico Environmental Quality Board.

Geologic, topographic, soil, hydrogeologic, and streamflow data were used to divide the municipio of Carolina into five hydrogeologic terranes. This integrated database was then used to evaluate the ground-water potential of each hydrogeologic terrane. Analysis suggests that areas with slopes greater than 15 degrees have relatively low ground-water development potential. Fractures may be locally important in enhancing the water-bearing properties in the hydrogeologic terranes containing igneous rocks. Potentiometric-surface elevations recorded in

piezometers installed in the coastal area during this study were used to define ground-water flow directions in the hydrogeologic terranes composed of coastal plain clastic and limestone units. The resultant potentiometric map indicates that the coastal plain aquifer and streams in the lowland parts of the municipio of Carolina are hydraulically connected. The potentiometric map also indicates that ground-water discharge to the Río Grande de Loíza, downstream from highway PR-3, has been enhanced by dredging of the streambed for sand and gravel. Dredging the streambed may have reduced the thickness of a locally extensive confining clay unit overlying the upper aquifer in this part of the Río Grande de Loíza. The integrated hydrogeologic approach used in this study can serve as an important tool for regulatory agencies of Puerto Rico and the municipio of Carolina to evaluate the ground-water resource development potential, examine ground- and surface-water interactions, and determine the effect of land-use practices on ground-water quantity and quality in the municipio of Carolina.

Sumario

Para satisfacer la necesidad cada vez mayor de un abasto de agua adecuado y seguro en el municipio de Carolina, se ha llevado a cabo un estudio integrado para evaluar las fuentes de agua superficial, la calidad del agua y las fuentes de agua subterránea en esa área. Los resultados más significativos de este estudio, así como información adicional hidrológica y de calidad de agua, fueron entrados a un sistema de información geográfica y se muestran en dos mapas a escala 1:30,000 para facilitar la interpretación y el uso de información diversa sobre recursos de agua.

Debido a que el abasto seguro de agua potable fue un asunto de suma importancia durante recientes períodos de sequía, la parte correspondiente a la evaluación del recurso de agua superficial en este estudio se concentró en el análisis de características de flujos mínimos en los ríos y arroyos de la localidad. Se evaluaron las características de flujos mínimos en una estación fluviométrica de registro continuo utilizando técnicas para ajustar curvas gráficas y curvas de frecuencia log-Pearson Tipo III. Se generaron estimados de características de flujos mínimos para siete estaciones de registro parcial utilizando técnicas de correlación gráfica. Las características de duración de flujo se computaron para la estación de registro continuo y se estimaron para las estaciones de registro parcial, utilizando las curvas de relación desarrolladas para el estudio de flujos mínimos. Las estadísticas de flujos mínimos documentan la hidrología general bajo los usos actuales de terreno y agua. Las estadísticas de flujos mínimos pueden cambiar significativamente como resultado de desviaciones del caudal para abasto público, y un aumento en el desarrollo del agua subterránea, descargas de aguas residuales y medidas para el control de inundaciones; el presente análisis provee información fundamental para evaluar estos impactos y desarrollar balances de agua.

Se realizó un estudio para medir la calidad sanitaria de unos 140 kilometros de ríos y arroyos de la localidad utilizando 29 estaciones de muestreo. En dos ocasiones se tomaron muestras de agua en ríos y tributarios en condiciones de estiaje para análisis de coliformes del grupo fecales y estreptococos. Los análisis bacteriológicos indican que una porción significativa de tramos de ríos y arroyos dentro del municipio de Carolina pueden tener concentraciones de bacterias de coliformes fecales que superan el límite establecido por la Junta de Calidad Ambiental de Puerto Rico para garantizar la calidad del agua. Entre las fuentes de contaminación fecal pueden encontrarse: la descarga ilegal de aguas residuales en los sistemas de alcantarillado pluvial, operación de eyectores defectuosos de alcantarillas de aguas usadas, alcantarillados sanitarios tapados y con filtraciones, filtraciones en tanques sépticos, ganado libre (sin proteger con cercado de alambre) y escorrentía proveniente de corrales de ganado. Los datos sobre coliformes fecales a largo plazo recogidos en dos estaciones de muestreo, Quebrada Blasina en Carolina y el Río Grande de Loíza aguas abajo del pueblo de Trujillo Alto, indican que la calidad sanitaria de la Quebrada Blasina es generalmente pobre y se ha mantenido así por más de una década. La calidad sanitaria en el Río Grande de Loíza, por lo general, ha estado en cumplimiento con los estandáres de la Junta de Calidad Ambiental para coliformes fecales establecidos en julio de 1990.

Se utilizaron datos geológicos, topográficos, de suelo, hidrogeológicos y fluviométricos para dividir el municipio de Carolina en cinco unidades hidrogeológicas. Luego, se utilizó esta base de datos de forma integrada para evaluar el potencial de desarrollo de agua subterránea en cada unidad

hidrogeológica. El análisis indica que, en general, los terrenos con declive topográfico mayor de 15 grados tienen un potencial bajo de desarrollo de agua subterránea. Además, las fracturas pueden ser importantes localmente para aumentar las propiedades para producción de agua en pozos hincados en regiones hidrogeológicas que contienen rocas ígneas. Las elevaciones de la superficie potenciométrica en piezómetros instalados en el área costera se usaron para definir la dirección del flujo del agua subterránea en las unidades hidrogeológicas constituídas por los depósitos de la llanura costera y unidades de caliza. El mapa potenciométrico resultante indica que el acuífero costero, los ríos y los arroyos en la partes bajas del municipio de Carolina están conectados hidráulicamente. El mapa potenciométrico también indica que la descarga del agua subterránea en el Río Grande de Loíza ha aumentado como resultado del dragado de arena y grava en el lecho del río aguas abajo del puente de la carretera PR-3. El dragado del del lecho del Río Grande de Loíza puede haber reducido la unidad de arcilla que sirve localmente de capa confinante al acuífero en el valle aluvial del Río Grande de Loíza.

INTRODUCTION

The municipio of Carolina (fig. 1), with an estimated population of 189,853 in 1997 (U.S. Department of Commerce, 1998a) and a land area of 45 square miles (mi^2), has among its priorities the investment of public funds to improve the service and reliability of the public water-supply system. Public water consumption in the municipio is estimated to be 24 million gallons per day (Mgal/d), which includes unaccounted-for use that may represent as much as 42 percent of withdrawals (Wanda Molina, U.S. Geological Survey, written commun., 1998). This consumption rate was derived by dividing the daily mean production during 1997 at the Sergio Cuevas filtration plant (87 Mgal/d) by the total estimated population of the municipios of Trujillo Alto, Carolina and San Juan (701,845 persons), which constitute the principal service area supplied from this source.

Chronic water-supply deficits in Carolina have primarily been limited to two upland areas: the rural Barrios of Cedro, Barrazas, Carruzos, Cacao and Santa Cruz (with a population of about 13,000 and an estimated public water-supply demand of about 0.8 Mgal/d), and the highly developed Barrios of Canovanillas, Trujillo Bajo, and Martín González (with a population of about 42,000 and an estimated public water-supply demand of about 3.0 Mgal/d (plate 1)). However, the entire municipio was affected by a deficiency in public water supply during 1994 when the “wet season” months of 1993 (August through November) and 1994 (April and May) failed to produce sufficient runoff within the 200 mi^2 drainage basin of the Lago Loíza reservoir to sustain the public water-supply withdrawal of about 95 Mgal/d by the Sergio Cuevas filtration plant (plate 1).

The rainfall deficiency, which affected northeastern Puerto Rico between August 1993 and September 1994, was about 30 percent below normal. The effect of the rainfall deficit on streamflows within the Lago Loíza drainage basin was of such intensity that between February 20, 1994, and August 17, 1994 (a total of 179 days), the stage in Lago Loíza reservoir continuously declined from 134.24 feet above mean sea level (amsl) to 108.9 feet amsl, even though water-supply withdrawals by the Sergio Cuevas filtration plant were reduced after mid-April. The water-level decline at Lago Loíza reservoir during the 179-day period was equivalent to a storage depletion rate of approximately 19 Mgal/d (Webb and Soler-López, 1997). During this same period, the average streamflow into the reservoir, measured at U.S. Geological Survey (USGS) gaging stations located near the mouth of all major tributaries to the reservoir (USGS gaging stations 50055000, 50055225, 50055390, 50057000, and 50058350; Díaz and others, 1995), was 63 Mgal/d (97 cubic feet per second (ft^3/s)), and the outflow gaged downstream from the Lago Loíza dam averaged 3.3 Mgal/d or 5 ft^3/s (USGS gaging station 50059050; Díaz and others, 1995). The rate of decline in water level at the Lago Loíza reservoir made it necessary to implement water rationing in areas served by the Sergio Cuevas filtration plant for a period of about 136 days commencing about May 7, 1994, and ending September 19, 1994. Water rationing commenced with night-time suspension of water service, and then incrementally increased with service available only during alternate days for periods of less than 12 hours. Communities near the end of distribution pipelines or in the uplands, however, had water service reduced for longer hours during each stage of the water rationing program, and were principally dependent on water-supply trucks during most of the rationing period.

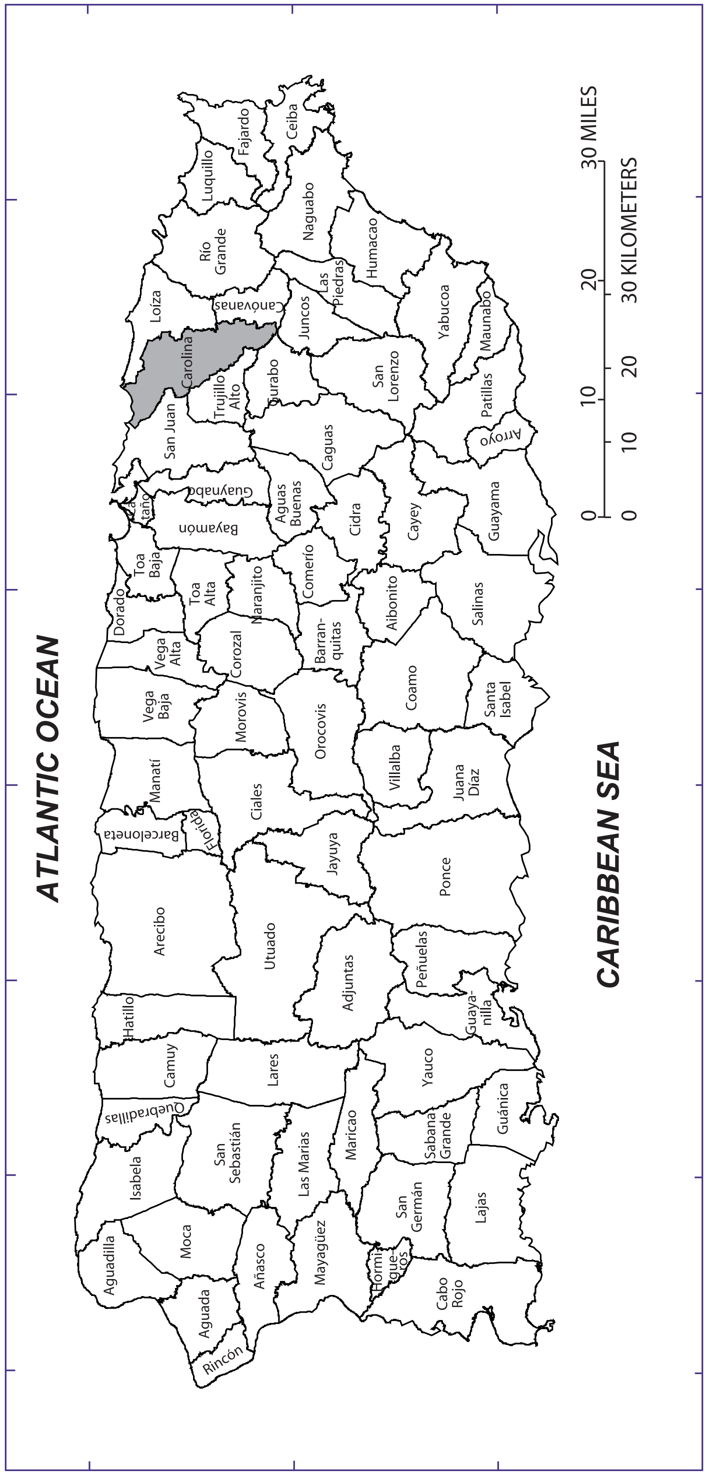

Figure 1. Location of the municipio of Carolina, Puerto Rico.

In May 1994, prior to initiating the water rationing at the Sergio Cuevas filtration plant, the public water-supply production rate was about 90 Mgal/d, which indicates that withdrawal from the Lago Loíza reservoir was about 95 Mgal/d (approximately 5 percent of withdrawals are used in filter backwash) (Wanda Molina, U.S. Geological Survey, written commun., 1998). The reported monthly mean production at the Sergio Cuevas filtration plant was reduced incrementally from about 90 Mgal/d in March, to 75 Mgal/d in April, 69 Mgal/d in May, 65 Mgal/d in June, 57 Mgal/d in July, and 45 Mgal/d in August and September 1994. The water-availability deficit during the rationing period can be estimated as:

Deficit = Required draft rate − Available supply,

where the Required draft rate was 95 Mgal/d; the Available supply for the period May 7 to September 19, 1994, was 66 Mgal/d of stream inflow to the reservoir minus the outflow from the dam of about 3 Mgal/d plus the 19 Mgal/d of reservoir storage depletion. Based on these values, the deficit during the 136-day rationing period was 14 Mgal/d. Alternately, the reservoir would have required an additional storage capacity of 14 Mgal/d X 136 days = 1.9 billion gallons (5,840 acre-feet (acre-ft)) above the available storage capacity of 11,500 acre-ft (Webb and Soler-López, 1997). This estimate assumes that a flow of 3.3 Mgal/d downstream from the Carraízo dam was maintained and that flow from ungaged sources flowing into Lago Loíza, but located downstream from the USGS gaging stations, was equal to the evaporation and transpiration losses. These ungaged sources included discharges from the Caguas and the Gurabo public waste-water treatment facilities, which had an annual mean daily effluent discharge rate of about 7 Mgal/d prior to the drought (Wanda Molina, U.S. Geological Survey, written commun., 1997)

During 1998 and 1999, the Lago Loíza reservoir was dredged to increase storage capacity by about 5,000 acre-ft at a cost of about $60 million (Camacho and Carlson, 1999). However, increased public water-supply withdrawals upstream from the dam and storage losses in the reservoir of about 205 acre-ft per year by sedimentation (Webb and Soler-López, 1997), may have negated the reservoir's capacity to avert a reduction of production at the Sergio Cuevas filtration plant during future droughts.

The experience of the 1994 drought prompted authorities of the municipio of Carolina to develop a strategy to augment local public water-supply sources, to improve the reliability of service to the upland communities, and to augment supply during drought periods. Development of a water-supply strategy required identification of surface- and ground-water sources that can be tapped to augment the supply on a continuous or short-term basis, and characterization of the sanitary quality of surface waters. The sanitary quality of streams is important because most of the upland areas in the municipio lack sewage infrastructure, and any ground-water development would essentially consist of stream-flow capture.

To ensure an adequate supply of safe drinking water, the municipio of Carolina requested that the USGS conduct a comprehensive surface- and ground-water resource assessment, and water-quality analysis of streams. The information from this study will be an integral part of the territorial development plan being developed by the municipio of Carolina, which will take into consideration the sustainable use of water resources.

To facilitate this comprehensive water-resource analysis, thematic maps were developed to delineate the hydrologic and stream bacteriological (sanitary) conditions, and to define the water-bearing properties of potential aquifers. Methods of study and interpretation of results are presented in separate chapters of this report. Chapter A documents the results of the surface-water assessment, Chapter B documents stream bacteriological conditions, and Chapter C documents ground-water availability.

ACKNOWLEDGMENTS

The authors acknowledge the Honorable José Aponte de la Torre, Mayor of the Municipio Autónomo de Carolina, and Engineers Roberto Martínez and Roberto D. Valles-Álvarez, Oficina Acueducto Municipal de Carolina, for their awareness of the need for this assessment to help develop land-use strategies by municipal authorities to promote the sustainable use of water resources. The authors thank Marilyn Santiago and Betzaida Reyes from the USGS Caribbean District's Geographic Information System Unit for the preparation of the spatial databases and maps presented in this report, and Francisco Maldonado, USGS Caribbean District Scientific Illustrator, for the final compilation and editing of the plates.

CHAPTER A:

Surface-Water Resources Assessment of the Municipio of Carolina, Puerto Rico, 1997-99

By **Luis Santiago-Rivera**

PURPOSE AND SCOPE

The USGS in cooperation with the municipio of Carolina conducted an investigation of the surface-water resources from October 1, 1997, to September 30, 1999, in the area primarily within the geographic limits of the municipio of Carolina. A major component of the study consisted of an assessment of the magnitude and frequency of stream low-flow and flow-duration characteristics, which are important for storage-facility design, waste-load allocation, water-supply planning, recreation, and conservation of wildlife. In addition, the current assessment provides reference conditions to assess future changes in flow magnitude, duration, and frequency.

The low-flow and flow-duration monitoring network in Carolina included one long-term continuous-record (index) gaging station and seven partial-record stations (tables 1 and 2, respectively). The continuous-record station (50061800) is located in the adjacent municipio of Canóvanas along Río Canóvanas, which is a second-order tributary of Río Grande de Loíza (plate 1). The seven partial-record stations are distributed among a number of first- to fourth-order streams in the Río Grande de Loíza drainage basin (plate 1). Streamflow was measured concurrently at least eight times at the continuous-record gaging station and partial-record stations at selected base-flow recessions during a 1-year period to obtain the low-flow and flow-duration estimates. The 7-day, 10-year ($7Q_{10}$) and the 7-day, 2-year ($7Q_2$) low-flow frequency characteristics were computed for the continuous-record gaging station, and estimated for the partial-record stations. Flow-duration characteristics for 90-, 95-, and 99-percent probability of exceedance also were computed for the one continuous-record gaging station and estimated for the seven partial-record stations.

Pertinent information regarding surface-water hydrology within the municipio of Carolina is presented on a thematic map (plate 1). The map displays the following information:

- streamflow data-collection sites;
- drainage-basin boundaries for the streamflow sites where low flows were determined;
- the potential public water-supply reservoir sites (Black and Veatch, 1996);
- flood-prone areas as delineated by the Federal Emergency Management Agency (1996);
- points of withdrawal of public water supply;
- water filtration plants; and
- active and closed public waste-water treatment facilities.

METHODOLOGY

A series of eight streamflow measurements were taken concurrently at the one continuous- and the seven partial-record stream-gaging stations to provide a basis for a systematic low-flow and flow-duration analysis. A number of techniques were then applied to compute low-flow characteristics at continuous- and partial-record stations. Analyses of low-flow characteristics for the continuous-record gaging station (index station) were based on frequency analyses of the annual minimum 7-day low flows (table 1). Using the streamflow data generated during this study, the partial-record station base-flow measurements were related to concurrent base-flow measurements or daily mean flows at the nearby index station (Riggs, 1972). The low-flow characteristics at partial-record stations were then estimated using the corresponding characteristics at the index station (table 2). This methodology has been used previously in several areas of Puerto Rico (Santiago-Rivera, 1992, 1996, 1998).

Flow-duration characteristics were computed for the index station using techniques described by Searcy (1959), and flow-duration characteristics were estimated for the partial-record stations using flow-duration characteristics of the index station in conjunction with the relation curve previously developed by correlation methods for the low-flow study. All low-flow and flow-duration characteristics for the index station and partial-record stations were calculated without incorporating the effects of public water-supply withdrawals upstream from stations. Estimated withdrawals, however, were compiled from data furnished by the Puerto Rico Aqueduct and Sewer Authority (PRASA) and reported by Black and Veatch (1996), and are presented in the header of each recording station in tables 1 and 2.

RESULTS AND INTERPRETATION

Low Flow at Continuous-Record Gaging Station

A continuous-record gaging station (index station) is a site where daily flow data are systematically collected over a period of years. A low-flow frequency curve was derived for one index station using the method described by Riggs (1972) and by adapting the log-Pearson Type III flood-frequency program described by the Interagency Advisory Committee on Water Data (1982). Examples of the methodology, as applied to Puerto Rico streams are given in Santiago-Rivera (1992, 1996, 1998). The $7Q_{10}$ and the $7Q_2$ low-flow frequency characteristics computed for the index station used in this report are presented in table 1. The index station used in this analysis is affected by public water-supply withdrawals; low flows may have decreased by 0.9 ft^3/s (Wanda Molina, U.S. Geological Survey, written commun., 2000). Capture of streamflow upstream from this station can result in computational underestimates of low-flow statistics at partial-record sites for which gaging station 50061800 was used as the index station.

Low Flow at Partial-Record Stations

A partial-record station is a site where limited streamflow and/or water-quality data are collected systematically over a period of time for use in hydrologic analysis. At these stations, sufficient base-flow measurements are made to define an adequate relation with concurrent flows at a nearby index station. Low-flow characteristics for partial-record stations were estimated using the graphical correlation technique of Riggs (1972). This technique relates base-flow measurements made at partial-record stations with concurrent flows measured at the index station. This estimating technique transfers low-flow characteristics computed by the log-Pearson Type III frequency distribution for the index station to the graphically determined relation curve to determine the corresponding low-flow characteristics at the partial-record stations. Low-flow characteristics were estimated for seven partial-record stations and are presented in table 2. Partial-record stations are located within the same geographic area of the index station; the partial- and continuous-record stations have similar drainage basin size and geologic setting. At these stations, streamflow was measured concurrently at least eight times at different base-flow recessions from February 1998 to April 1999. Instantaneous streamflow measurements made at partial-record stations are presented in Díaz and others (1998).

Flow-Duration Characteristics

Flow-duration characteristics were computed for the index station using techniques developed by Searcy (1959). The analysis of the index station was based on daily streamflow records for complete water years (October 1 to September 30), and the results are presented in table 1. Flow-duration characteristics were estimated for six partial-record stations within the municipio of Carolina and one partial-record station (Quebrada Grande at Barrio Dos Bocas, 50059210) in the municipio of Trujillo Alto using flow-duration characteristics derived for the index station in conjunction with the relation curve developed for the low-flow study. Index station discharges for the 90-, 95-, and 99-percent flow duration were used as the explanatory variable in the relation curve to estimate the discharges for the corresponding percent-duration points at the seven partial-record stations (table 2).

Discharge/Drainage Basin Area Relation

Using the drainage basin size contributing to each partial-record station and the low-flow statistics, a preliminary analysis of discharge yield per unit-drainage area was conducted. This analysis provides a means to evaluate effective recharge within the study area. The Río Canovanillas at Barrio Canovanillas (station 50061325) and Quebrada Maracuto at Trujillo Bajo (station 50060200) drainage basins have a 99 percentile discharge yield per unit area of 0.05 cubic feet per second per square mile ($ft^3/s\text{-}mi^2$) and 0.03 $ft^3/s\text{-}mi^2$, respectively. Based on the 99-percent discharge exceedance, the surface-water contribution of these two basins is 1.1 ft^3/s, which is equivalent to 0.71 Mgal/d. Discharge yield of Quebrada Grande at Barrio Dos Bocas drainage basin at station 50059210 is 0.12 $ft^3/s\text{-}mi^2$, which is significantly higher than those of the other partial-record stations at drainage basins within the municipio of Carolina (tables 1 and 2, plate 1). Quebrada Grande basin is located outside the municipal boundary of Carolina. The surface-water contribution of this basin at station 50059210 is 1.6 ft^3/s or 1.03 Mgal/d based on the 99-percent discharge exceedance. This discharge (1.6 ft^3/s) is equivalent to approximately 59 percent of the surface water draining to the Río Grande de Loíza downstream of the Lago Loíza dam and upstream from the highway PR-3 bridge based on the 99-percent exceedance, as obtained at partial-record stations 50059210 (Quebrada Grande at Barrio Dos Bocas), 50060200 (Quebrada Maracuto at Trujillo Bajo), and 50061325 (Río Canovanillas at Barrio Canovanillas).

MAP FEATURES

A 1:30,000 scale map (plate 1) was developed to show the location of hydrologic data-collection stations, drainage basins, the 100- and 500-year flood-prone areas (Federal Emergency Management Agency, 1996), and existing or potential reservoir sites (Black and Veatch, 1976). The thematic map also summarizes the hydrologic monitoring-station characteristics and stream bacteriological (sanitary) quality during low-flow conditions (see Chapter B for discussion of water quality).

Reservoir Sites

One potential reservoir site was identified by Black and Veatch (1976). The potential reservoir on the Río Canovanillas with a drainage area of approximately 16.5 mi^2, and a storage of about 31,000 acre-ft at a pool elevation of 220 feet (ft) would have a firm yield of approximately 30 Mgal/d (Black and Veatch, 1976). Similarly, a dam at the same location, but with a pool elevation of only 164 ft would have a firm yield of approximately 25 Mgal/d.

Flood-Prone Areas

The earth-filled levee shown on plate 1 along the eastern and northern perimeter of the town of Carolina and urban areas was built during the 1970’s and later modified with a concrete parapet wall throughout most of its north-to-south extent as protection against the 100-year flood (Quiñones, Diez, Silva y Asociados, Ingenieros Consultores, 1986). As of September 2001, however, the Federal Emergency Management Agency had not certified the improved levee as protection against the 100-year flood (Rafael Morales, Puerto Rico Planning Board, oral commun., 2001).

The Federal Emergency Management Agency presents four different types of flood-prone areas for the town of Carolina (Federal Emergency Management Agency, 1996). These areas are shown on plate 1 as (1) Zone VE, an area inundated by a 100-year flood (or the flood that has a 1 in 100 probability of recurrence) with velocity hazard along the Atlantic coast (wave action), for which Base Flood Elevations (BFEs) have been determined; (2) Zone A, an area inundated by a 100-year flood, for which no BFEs have been determined; (3) Zone AE, an area inundated by a 100-year flood, for which BFEs have been determined; and (4) Zone X500, an area inundated by a 500-year flood, equivalent to a 0.2 percent annual chance of flooding; an area inundated by a 100-year flood with average depths of less than 1 ft or with a drainage area less than 1 mi^2; or an area protected by levees from the 100-year flood.

Public Water-Supply Filtration Plants and Waste-Water Treatment Facilities

There are no active water-supply filtration plants within the municipio of Carolina. The municipio relies entirely on public water-supply transfers from the Sergio Cuevas and the Canóvanas urban filtration plants located at the adjacent municipios of Trujillo Alto and Canóvanas (plate 1). A water-supply filtration plant existed previously at Barrio Barrazas and was closed in about 1984. At present (2001), a 2.0-Mgal/d-capacity filtration plant is being constructed in Carolina, and a 10.0-Mgal/d-capacity filtration plant is being built in Canóvanas near the Canóvanas urban filtration plant (plate 1). The municipio of Carolina has no active public waste-water treatment facilities. All public waste-water treatment facilities in Carolina and the adjacent municipios with discharge to first- through third-order streams considered in this study were closed by about 1990 when the Carolina Regional Waste-Water Treatment Facility was put on-line. The location of public water-supply filtration plants, waste-water treatment facilities, and other pertinent data are listed in table 3 and shown on plate 1.

Table 1. Summary of drainage-basin, low-flow, and flow-duration characteristics for a continuous-record gaging station near the municipio of Carolina, Puerto Rico

[lat, latitude; long, longitude; mi, mile; km, kilometer; mi^2, square mile, km^2, square kilometer; ft^3/s, cubic feet per second]

RÍO GRANDE DE LOÍZA BASIN

50061800 Río Canóvanas near Campo Rico, Puerto Rico

LOCATION--Lat 18°19′08", long 65°53′21", Hydrologic Unit 21010005, at upstream side of bridge, on paved secondary road, 0.4 mi (0.6 km) northeast of junction of Highways 185 and 186, 1.5 mi (2.4 km) south of Campo Rico, and 4.4 mi (7.1 km) south of Loíza.

DRAINAGE AREA--9.8 mi^2 (25 km^2).

PERIOD OF RECORD ANALYZED--March 1967 to September 1997.

LOW-FLOW ANALYSIS-- Log-Pearson Type III frequency distribution.

REMARKS--A diversion of 0.9 ft^3/s is made upstream of station 50061800 for public water supply.

LOW-FLOW CHARACTERISTICS
[Based on 1967-97 water years]

Low-flow characteristics	Discharge (ft^3/s)
7-day, 2-year	4.4
7-day, 10-year	2.6

FLOW-DURATION CHARACTERISTICS
[Based on 1967-97 water years]

Discharge (ft^3/s) that was exceeded for indicated percentage of days			
Percent	90	95	99
Discharge	5.2	4.0	2.6

Table 2. Summary of drainage-basin, low-flow, and flow-duration estimates for partial-record stations within the municipio of Carolina, Puerto Rico

[lat, latitude; long, longitude; mi, mile; km, kilometer; mi^2, square mile, km^2, square kilometer; ft^3/s, cubic feet per second; <, less than]

RÍO GRANDE DE LOÍZA BASIN

50059210 Quebrada Grande at Barrio Dos Bocas, Puerto Rico

LOCATION--Lat 18°21′12", long 65°59′23", Hydrologic Unit 21010005, at Barrio Dos Bocas, 0.5 mi (0.8 km) upstream of Río Grande de Loíza, 4.0 mi (6.4 km) northwest of Cerro Gordo, and 1.5 mi (2.4 km) northwest from Canto de Sapo.

DRAINAGE AREA--13 mi^2 (33 km^2).

LOW-FLOW AND FLOW-DURATION ESTIMATES--Based on correlation of 8 base-flow measurements with concurrent base flows at gaging station 50061800.

REMARKS--Quebrada Grande basin is located outside of the municipal boundary of Carolina.

LOW-FLOW CHARACTERISTICS

Low-flow characteristics	Discharge (ft^3/s)
7-day, 2-year	3.2
7-day, 10-year	1.6

FLOW-DURATION CHARACTERISTICS

Discharge (ft^3/s) that was exceeded for indicated percentage of days			
Percent	90	95	99
Discharge	4.0	2.9	1.6

50060160 Quebrada Maracuto at Barrio Santa Cruz, Puerto Rico

LOCATION--Lat 18°21′07", long 65°57′00", Hydrologic Unit 21010005, at Barrio Santa Cruz, 1.6 mi (2.6 km) northwest of Cerro Gordo, 1.2 mi (1.9 km) northeast from Canto de Sapo, and 1.2 mi (1.9 km) northeast from Mariana.

DRAINAGE AREA--6.3 mi^2 (16 km^2).

LOW-FLOW AND FLOW-DURATION ESTIMATES--Based on correlation of 8 base-flow measurements with concurrent base flows at gaging station 50061800.

REMARKS--None.

LOW-FLOW CHARACTERISTICS

Low-flow characteristics	Discharge (ft^3/s)
7-day, 2-year	0.8
7-day, 10-year	0.3

FLOW-DURATION CHARACTERISTICS

Discharge (ft^3/s) that was exceeded for indicated percentage of days			
Percent	90	95	99
Discharge	1.1	0.7	0.3

Table 2. Summary of drainage-basin, low-flow, and flow-duration estimates for partial-record stations within the municipio of Carolina, Puerto Rico—Continued

RÍO GRANDE DE LOÍZA BASIN—Continued

50060190 Quebrada Pastrana near Mariana at Barrio Cacao, Puerto Rico

LOCATION--Lat 18°20′23", long 65°57′35", Hydrologic Unit 21010005, at Barrio Cacao, 1.8 mi (2.9 km) northwest of Cerro Gordo, 0.8 mi (1.3 km) southeast of Canto de Sapo, and 5.7 mi (9.2 km) northeast from Gurabo plaza.

DRAINAGE AREA--0.8 mi^2 (2.0 km^2).

LOW-FLOW AND FLOW-DURATION ESTIMATES--Based on correlation of 8 base-flow measurements with concurrent base flows at gaging station 50061800.

REMARKS--None.

LOW-FLOW CHARACTERISTICS

Low-flow characteristics	Discharge (ft^3/s)
7-day, 2-year	0.2
7-day, 10-year	< 0.1

FLOW-DURATION CHARACTERISTICS

Discharge (ft^3/s) that was exceeded for indicated percentage of days			
Percent	90	95	99
Discharge	0.2	0.2	< 0.1

50060195 Quebrada Pastrana near mouth at Barrio Cacao, Puerto Rico

LOCATION--Lat 18°21′38", long 65°57′40", Hydrologic Unit 21010005, at Barrio Cacao, 2.6 mi (4.2 km) northwest of Cerro Gordo, 0.9 mi (1.4 km) northeast of Canto de Sapo, and 2.6 mi (4.2 km) southwest from Cambute.

DRAINAGE AREA--2.0 mi^2 (5.3 km^2).

LOW-FLOW AND FLOW-DURATION ESTIMATES--Based on correlation of 8 base-flow measurements with concurrent base flows at gaging station 50061800.

REMARKS--None.

LOW-FLOW CHARACTERISTICS

Low-flow characteristics	Discharge (ft^3/s)
7-day, 2-year	0.2
7-day, 10-year	0.1

FLOW-DURATION CHARACTERISTICS

Discharge (ft^3/s) that was exceeded for indicated percentage of days			
Percent	90	95	99
Discharge	0.3	0.2	0.1

Table 2. Summary of drainage-basin, low-flow, and flow-duration estimates for partial-record stations within the municipio of Carolina, Puerto Rico—Continued

RÍO GRANDE DE LOÍZA BASIN—Continued

50060200 Quebrada Maracuto at Trujillo Bajo, Puerto Rico

LOCATION--Lat 18°22′11", long 65°57′28", Hydrologic Unit 21010005, at bridge on Highway 853, and 0.3 mi (0.5 km) above junction with Río Grande de Loíza.

DRAINAGE AREA--10 mi^2 (26 km^2).

LOW-FLOW AND FLOW-DURATION ESTIMATES--Based on correlation of 15 base-flow measurements with concurrent base flows at gaging station 50061800.

REMARKS--Seven base-flow measurements from a previous 1989 low-flow study were added to the flow correlation. The addition of these measurements improved the development of the relation curve and the 7-day, 10-year low-flow characteristic estimated increased from 0.2 to 0.3 cubic feet per second, while the 7-day, 2-year low-flow characteristic remained the same.

LOW-FLOW CHARACTERISTICS

Low-flow characteristics	Discharge (ft^3/s)
7-day, 2-year	0.8
7-day, 10-year	0.3

FLOW-DURATION CHARACTERISTICS

Discharge (ft^3/s) that was exceeded for indicated percentage of days			
Percent	90	95	99
Discharge	1.0	0.6	0.3

50061200 Río Canovanillas at Carruzos, Puerto Rico

LOCATION--Lat 18°19′03", long 65°54′16", Hydrologic Unit 21010005, at bridge on road 500 ft (152 m) off of Highway 185, and 0.7 mi (1.1 km) east of Jesús T. Piñero school.

DRAINAGE AREA--9.1 mi^2 (24 km^2).

LOW-FLOW AND FLOW-DURATION ESTIMATES--Based on correlation of 15 base-flow measurements with concurrent base flows at gaging station 50061800.

REMARKS--Seven base-flow measurements from a 1989 low-flow study were added to the flow correlation. The addition of these measurements improved the development of the relation curve and the 7-day, 10-year low-flow characteristic increased from 0.5 to 0.8 cubic feet per second, while the 7-day, 2-year increased from 1.2 to 1.7 cubic feet per second.

LOW-FLOW CHARACTERISTICS

Low-flow characteristics	Discharge (ft^3/s)
7-day, 2-year	1.7
7-day, 10-year	0.8

FLOW-DURATION CHARACTERISTICS

Discharge (ft^3/s) that was exceeded for indicated percentage of days			
Percent	90	95	99
Discharge	2.2	1.5	0.8

Table 2. Summary of drainage-basin, low-flow, and flow-duration estimates for partial-record stations within the municipio of Carolina, Puerto Rico—Continued

RÍO GRANDE DE LOÍZA BASIN—Continued

50061325 Río Canovanillas at Barrio Canovanillas, Puerto Rico

LOCATION--Lat 18°21′51", long 65°55′09", Hydrologic Unit 21010005, at Barrio Canovanillas, 3.6 mi (5.8 km) northwest of Cerro Pitahaya, 2.2 mi (3.5 km) northeast of Cerro Gordo, and 1.6 mi (2.8 km) southwest from Canóvanas plaza.

DRAINAGE AREA--15 mi^2 (39 km^2).

LOW-FLOW AND FLOW-DURATION ESTIMATES--Based on correlation of 8 base-flow measurements with concurrent base flows at gaging station 50061800.

REMARKS--Minor diversion is made above the station for public-water supply.

REMARKS--None.

LOW-FLOW CHARACTERISTICS

Low-flow characteristics	Discharge (ft^3/s)
7-day, 2-year	1.9
7-day, 10-year	0.8

FLOW-DURATION CHARACTERISTICS

Discharge (ft^3/s) that was exceeded for indicated percentage of days			
Percent	90	95	99
Discharge	2.5	1.6	0.8

Table 3. Principal features of public water-supply filtration plants, surface-water intakes, and public waste-water treatment facilities within the municipio of Carolina, Puerto Rico

[Mgal/d, million gallons per day; --, no data; *, under construction; NA, not applicable/not available; (a) Q-99 flow estimate in this study (refer to chapter A, table 2); (b) value includes upstream public water-supply diversion of 0.6 Mgal/d; ~ 80, approximate value estimated using the 1994 drought condition for the Sergio Cuevas filtration plant intake; ~2.5, approximate value estimated as part of the study and flow-duration data at station 50059050, October 1, 1987, to September 30, 1998; (c) value is total for Río Canovanillas at partial-record station 50061325 and Río Canóvanas gaging station 50161800 used in this report, assuming an intake on Río Canovanillas, and that new filtration plant replaces old Canóvanas filtration plant; (d) value is total for Quebrada Grande at partial-record station 50061325 and Quebrada Maracuto at partial-record station 50060200 estimated in this study; (e), value is the production reported by Puerto Rico Aqueduct and Sewer Authority or 1998 plus 5 percent; (f) value is plant design capacity; (g) mean daily discharge in 1995]

Public water-supply filtration plants and surface-water intakes	Latitude [1]	Longitude [1]	Safe-yield [2] (Mgal/d)	Water available (Mgal/d)	Mean daily withdrawal	Source stream
Sergio Cuevas	18°22′23"	66°01′23"	NA	NA	100	--
Sergio Cuevas intake	18°19′49"	66°01′00"	54	~ 80	105	Lago Loíza
Canóvanas urban filtration plant	18°22′48"	65°53′34"	NA	NA	4.2	
Canóvanas filtration plant pump intake	18°22′46"	65°53′35"	2.1	1.7 (a, b)	4.4 (e)	Río Canóvanas
Canóvanas (new) *	18°22′47"	65°52′50"	NA	NA	10.0 (f)	
Canóvanas (new) filtration plant pump intake	--	--	--	2.2 (c)	NA	Río Canóvanas and Río Canovanillas
Cubuy filtration plant	18°16′14"	65°52′04"	NA	NA	NA	--
Cubuy filtration plant pump intake	18°15′51"	65°52′05"			0.6	Río Cubuy
Acueducto Municipal de Carolina *	18°22′33"	65°56′59"	NA	~2.5	2.0 (f)	--
Acueducto Municipal de Carolina pump intake	18°22′33"	65°57′05"	--	1.2 (d)	NA	Río Grande de Loíza
Barrazas rural aqueduct	18°19′21"	65°56′08"	0.07	--	abandoned	unnamed stream

Public waste-water treatment facility	Latitude [1]	Longitude [1]	Discharge capacity (Mgal/d)	Mean daily discharge rate (Mgal/d)	Receiving stream
Carolina regional waste-water treatment facility	18°26′30"	65°53′22"	--	16.7 (g)	Atlantic Ocean
Rolling Hills (closed by 1990)	18°23′08"	65°58′50"	NA	0	Quebrada Blasina
Round Hills (closed by 1990)	18°22′32"	66°00′45"	NA	0	Quebrada Blasina
Villa Carolina (closed by 1990)	18°24′54"	65°57′53"	NA	0	Quebrada Blasina
Vistamar (closed by 1990)	18°25′49"	65°58′08"	NA	0	Quebrada Blasina
Lomas de Carolina (closed by 1990)	18°22′32"	65°56′47"	NA	0	unnamed stream
Loíza Valley (closed by 1990)	18°22′25"	65°55′07"	NA	0	Río Canovanillas
Loíza (closed by 1990)	18°25′28"	65°53′24"	NA	0	Caño Gallardo
Trujillo Alto (closed by 1990)	18°21′24"	66°00′36"	NA	0	Río Grande de Loíza

[1] Datum for latitude and longitude is NAD 27 in degrees (°), minutes (′), and seconds (").

[2] Safe yield from Black and Veatch (1996).

CHAPTER B:

Sanitary Quality of Surface Water during Base-Flow Conditions in the Municipio of Carolina, Puerto Rico, 1998-99

By **Fernando Gómez-Gómez** *and* **Mario L. Oliveras-Feliciano**

BACKGROUND

Water-quality standards for surface waters in Puerto Rico have been established by the Puerto Rico Environmental Quality Board (Junta de Calidad Ambiental de Puerto Rico, 1990) on the basis of the designated use (for example, fishing, source of raw water for public supply, and secondary contact recreation, among others). All perennial fresh surface waters in Puerto Rico inland of their estuary segments have been classified as Class SD waters. This classification includes surface waters intended for use (or with the potential for use) as a raw source of public water supply, for propagation and preservation of desirable aquatic species, and for primary (swimming) and secondary (boating and fishing) contact recreation. All coastal lagoons within the territorial limits of the municipio of Carolina (Lagunas San José, La Torrecilla and Piñones), estuary segments of streams and along the Atlantic coastline for a distance up to 500 meters (1,650 ft) offshore are designated as Class SB surface waters. Class SB-designated use waters are intended for use in primary and secondary recreation and for the propagation and preservation of desirable aquatic species.

With the exception of surface waters to be used for primary contact recreation, the sanitary quality standard of Class SD-designated use surface waters is based on total coliform and fecal coliform bacteria concentrations as follows: the geometric mean concentration of at least five samples obtained in sequential order should not exceed 10,000 colonies per 100 milliliters (mL) for total coliform bacteria, or 2,000 colonies per 100 mL for fecal coliform bacteria, and not more than 20 percent of the samples (one in a set of five) should exceed 4,000 colonies per 100 mL of fecal coliform bacteria (Junta de Calidad Ambiental de Puerto Rico, 1990, Article 3, Section 2.4, as amended July 20, 1990). Unlike other regions in the United States, the Puerto Rico regulations do not constrain the time period during which the sequential samples must be obtained. In Puerto Rico, however, these standards are applicable only to samples taken when streamflows are greater than the 7-day, 2-year ($7Q_2$) discharge (Junta de Calidad Ambiental de Puerto Rico, 1990). The $7Q_2$ discharge corresponds to the discharge at the 2-year recurrence interval taken from a frequency curve of annual values of the lowest mean discharge for 7 consecutive days (the 7-day low flow).

The sanitary quality standard for Class SB-designated use surface waters, with the exception of primary use contact recreation, is based on the fecal coliform bacteria concentrations as follows: the geometric mean concentration of at least five samples obtained in sequential order should not exceed 200 colonies per 100 mL for fecal coliform bacteria, and not more than 20 percent of the samples (one in a set of five) should exceed 400 colonies per 100 mL of fecal coliform bacteria (Junta de Calidad Ambiental de Puerto Rico, 1990, Article 3, Section 2.2, as amended July 20, 1990). For Class SB surface waters used intensively for primary contact recreation, such as the Isla Verde public beach, the sanitary quality constraints are more stringent. In addition to the above requirements for fecal coliform concentrations, Class SB waters used for primary contact recreation must have for five representative samples obtained sequentially a geometric mean concentration of enterococcus indicator bacteria of less than 35 colonies per 100 mL, and also must meet other statistical analysis constraints. The reader should refer to the “Reglamento de Estándares de Calidad de Agua de Puerto Rico” (Puerto Rico Environmental Quality Standards Regulations) by the Junta de Calidad Ambiental de Puerto Rico (1990) for details on the sanitary quality requirements for primary contact recreation in SB-designated use waters.

Typical ranges of concentrations for the two most common indicator bacteria in contaminated water are given in table 4. Fecal coliform and fecal streptococcus bacteria are not pathogenic, but have been correlated to the presence of several waterborne, infectious disease-causing organisms present in wastes from warm-blooded animals (including humans). Thus, the concentration of these indicator bacteria is a measure of water safety for consumption or for body contact.

Table 4. Ranges of fecal indicator bacteria concentrations typically found in contaminated surface water (modified from Myers and Sylvester, 1997)

Bacteriological group	Fecal-contaminated surface water, colonies per 100 milliliters
Fecal coliform	200 to greater than 2 million
Fecal streptococcus	400 to greater than 1 million

Contamination sources that affect stream sanitary quality during base-flow conditions are distinct for urbanized and rural areas of the municipio of Carolina. In urbanized areas, probable major sources of fecal contamination are illegal discharge of sewage to storm-water drains, especially within the older sectors of the city of Carolina, overflows from sewer mains into the storm-water drains as a result of malfunctioning sanitary sewer ejectors or clogged mains, ruptured sewer mains, and seepage from sewer mains into the local aquifer. In rural areas, major sources of fecal contamination include gray-water discharges (gray water includes waste water except sanitary wastes) from residential and commercial establishments along stream channels, septic tank seepage or overflows, feces contamination directly into streams from unfenced livestock, and runoff from restrained livestock pens near stream courses.

Baseline data on the sanitary quality of surface waters within or with flow into the municipio of Carolina are primarily from the long-term (1978 to present) monitoring stations at the Quebrada Blasina near Carolina and the Río Grande de Loíza below Trujillo Alto (USGS stations 50050300 and 50059100, respectively, shown in plate 1) and at selected estuary stations in Laguna de Piñones, Laguna La Torrecilla and Laguna San José (stations 50050335, 50050350, 50050355, 50049720, 50049760 and 50049820 respectively, shown in plate 1) for the period 1990-92 and 1994-95. Systematic sampling for selected physical, chemical, and bacteriological properties has been done at these stations by the USGS in cooperation with the Puerto Rico Environmental Quality Board, and data are available in the USGS annual Water Data Report series or in the National Water Information System database. The trend of geometric mean concentrations for fecal coliform bacteria of five sequential samples at the stream stations for the period 1984 to 1998 is shown in figures 2a and 2b; the trend for the six estuary stations sampled between 1990-92 and 1994-95 is shown in figures 3a-3f.

Using this historical database to initially assess the sanitary quality of streams and estuaries in the Carolina area, the following was determined: (1) at the Quebrada Blasina long-term sampling station, there has been no substantial improvement towards achieving the Puerto Rico sanitary water-quality goals established for Class SD fresh surface waters, since the amended regulations were enacted in July 1990 (Junta de Calidad Ambiental de Puerto Rico, 1990) even though the Round Hills and Rolling Hills public waste-water treatment facilities were closed (plate 1); (2) the estuary portion of Quebrada Blasina does not appear to meet the sanitary quality goals established for Class SB surface waters at least at its junction with Laguna La Torrecilla, even though the Villa Carolina, Vistamar, and Jardines de Country Club public waste-water treatment facilities were closed (plate 1); (3) Laguna La Torrecilla and Laguna San José do not meet the Class SB goal for estuarine waters; (4) Laguna de Piñones does meet the Class SB goal at least in its northern portion; (5) during rainfall runoff events, the sanitary quality in the lagoons deteriorates significantly with concentrations of fecal coliform increasing from 2 to 100 times that found during dry season conditions (Webb and Gómez-Gómez, 1998); and (6) these baseline fecal coliform data are insufficient to identify sources of fecal contamination within the municipio of Carolina. The data also indicate that the geometric mean concentration of fecal coliform indicator bacteria for five sequential samples has consistently ranged from 20,000 to 200,000 colonies per 100 mL at the Quebrada Blasina sampling station (station 50050300) and from 100 to more than 10,000 colonies per 100 mL at the Río Grande de Loíza sampling station (station 50059100) since the amended regulations were enacted in July 1990 (figs. 2a, 2b). At the Quebrada Blasina sampling station, the geometric mean fecal coliform concentrations consistently remain above 20,000 colonies per 100 mL, although 90 percent of the samples collected were obtained at baseflow rates ranging between 4 and 13 ft^3/s. These data indicate that raw sewage is being discharged from the highly urbanized drainage basin upstream of the sampling station. At the Río Grande de Loíza sampling station, however, the geometric mean concentration of fecal coliform was within the Class SD sanitary quality goal of 2,000 colonies per 100 mL except during 1996 (fig. 2b). Because each plotted geometric mean value takes into consideration the fecal coliform concentration of the four previous sample dates, the high geometric mean concentrations during 1996 reflected fecal coliform concentrations in all samples obtained between February and October 1996. The fecal coliform concentrations ranged from 2,200 to 110,000 colonies per 100 mL with no relation to instantaneous flow rates, which may indicate an intermittent source, and most likely from the town of Trujillo Alto.

The systematic sampling of fecal coliform indicator bacteria within the lagoons during 1990-92 and 1994-95 (figs. 3a-3f) clearly shows the effect of fecal contamination in the estuary from the unsewered communities along the western perimeter of Laguna San José and the Caño de Martín Peña (Webb and Gómez-Gómez, 1998), and the effect of fecal-contaminated discharges into Quebrada Blasina, which flows into the lagoon (fig. 2a). In the estuary, the geometric mean concentration of fecal coliform indicator bacteria for the most recent of five sequential samples is highest within Laguna San José, ranging from 2,000 to 25,000 colonies per 100 mL near the mouth of the Caño de Martín Peña (station 50049820, plate 1) and from less than 200 to 2,000 colonies per 100 mL at the northern-most part of the estuary (station 50049720, plate 1). During 1995, the geometric mean fecal coliform concentrations in Laguna San José near the mouth of Quebrada San Antón (station 50049760, plate 1) ranged between 300 and 3,000 colonies per 100 mL. The geometric means at the other estuary stations decrease from an average of about 3,000 colonies per 100 mL in Laguna La Torrecilla (stations 50050355 and 50050350, plate 1) to an average of about 70 colonies per 100 mL at Laguna de Piñones (station 50050335, plate 1). It is probable that the southern part of Laguna de Piñones has fecal coliform concentrations substantially greater than at the sampling station near its northern shoreline as a result of the deteriorated sanitary quality of Quebrada Blasina and its estuary segment Canal Blasina, and also because of the large population of snowy egrets that roost within the small island in the lagoon.

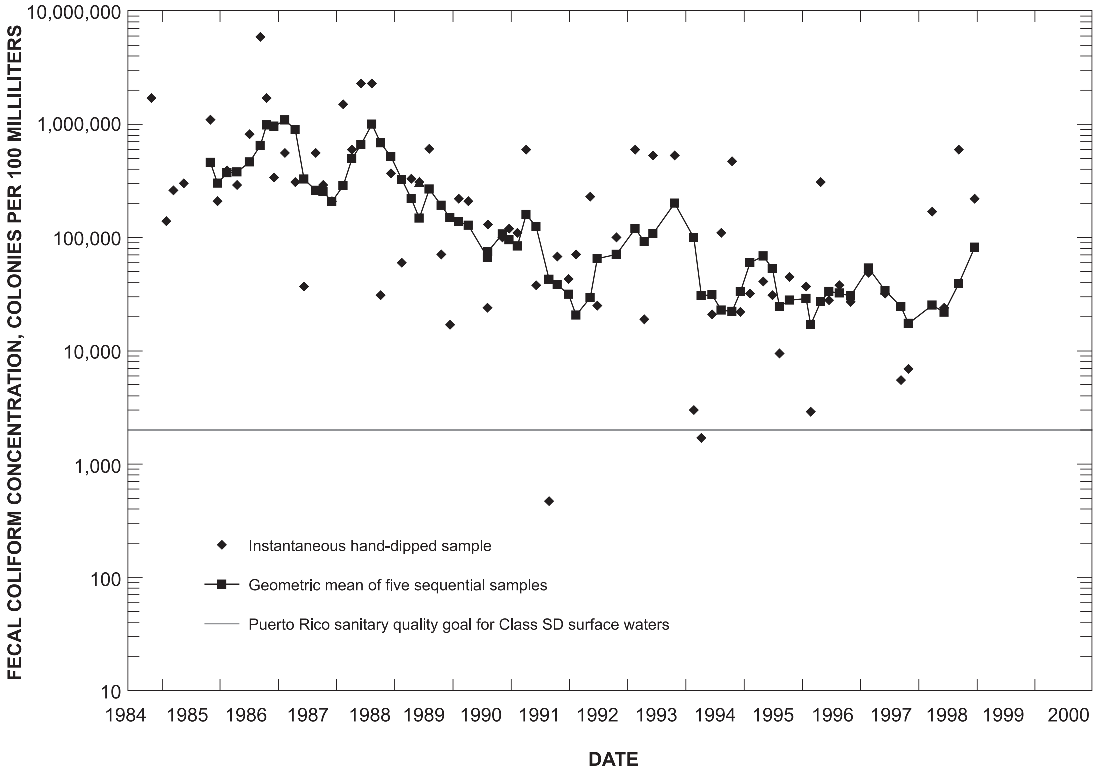

Figure 2a. Long-term geometric mean concentration of fecal coliform bacteria at Quebrada Blasina near Carolina (USGS station 50050300), October 1984 to September 1998.

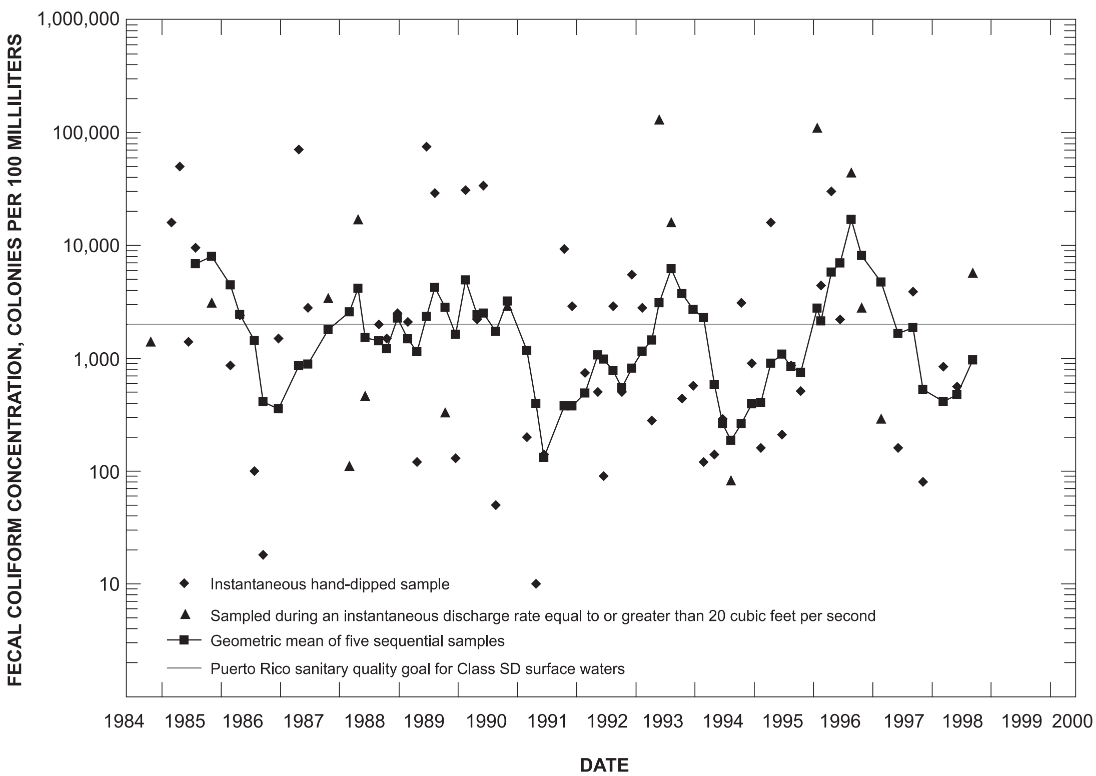

Figure 2b. Long-term geometric mean concentration of fecal coliform bacteria at Río Grande de Loíza below Trujillo Alto (USGS station 50059100), October 1984 to September 1998.

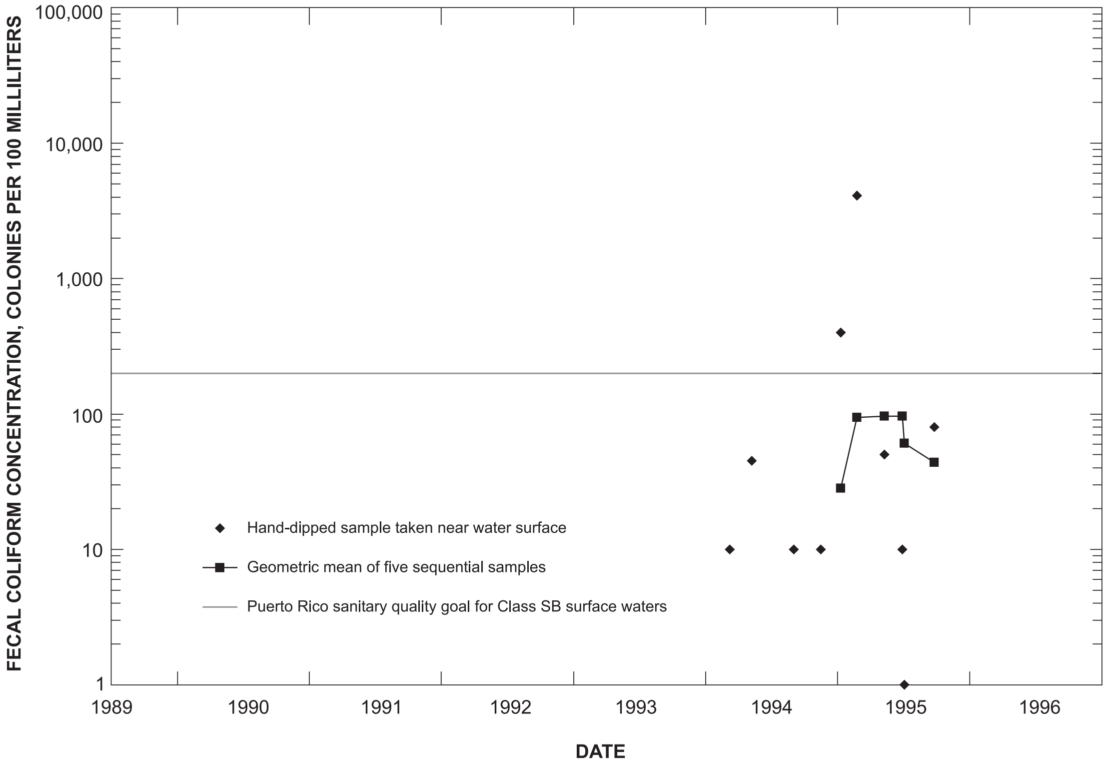

Figure 3a. Geometric mean concentration of fecal coliform bacteria at Laguna de Piñones near Carolina (USGS station 50050335), 1994-95.

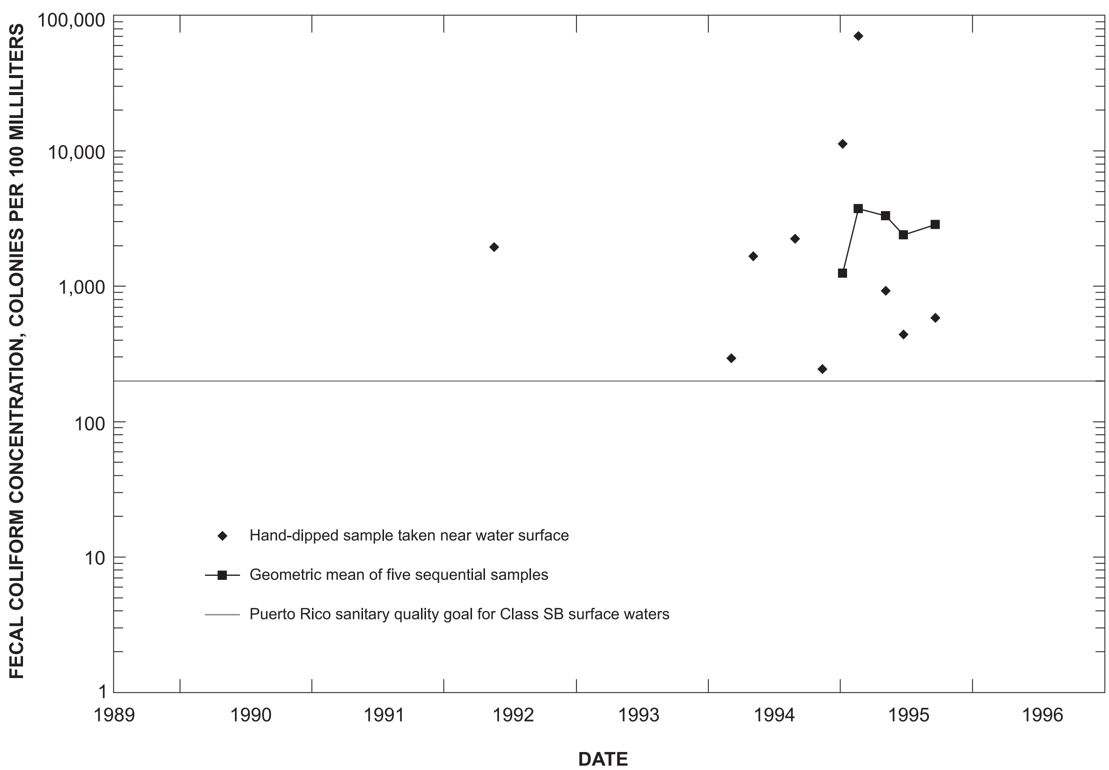

Figure 3b. Geometric mean concentration of fecal coliform bacteria at Laguna La Torrecilla near Carolina (USGS station 50050350), 1994-95.

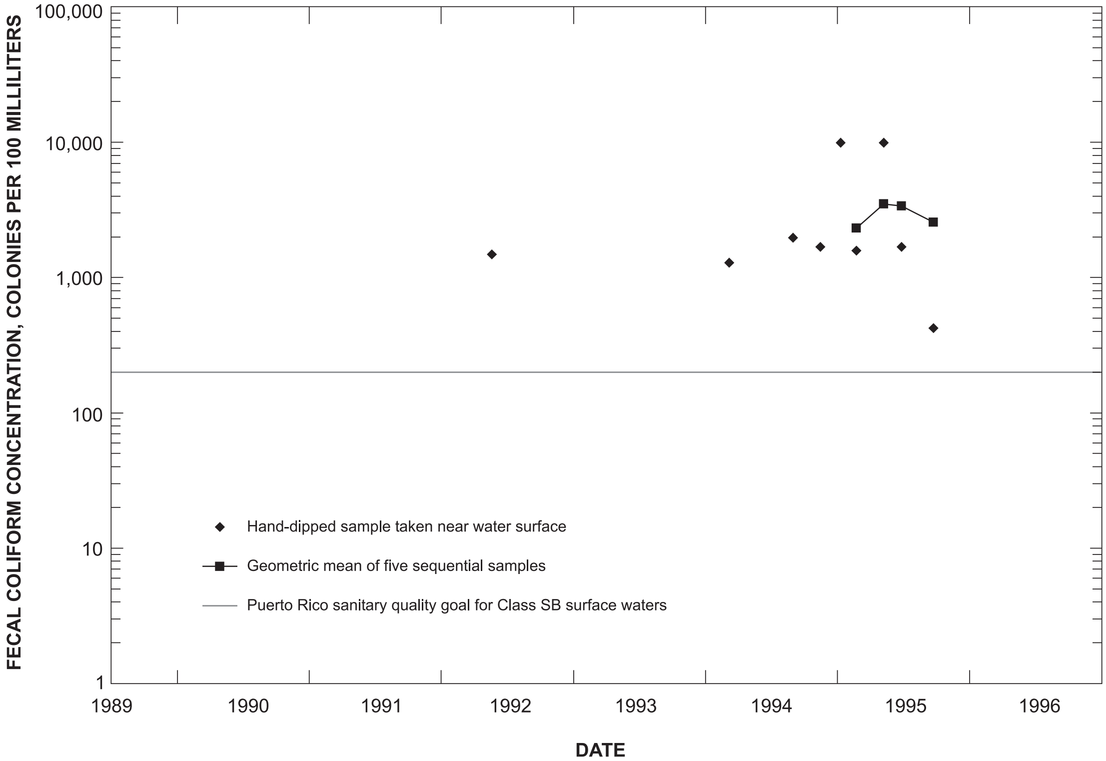

Figure 3c. Geometric mean concentration of fecal coliform bacteria at Laguna La Torrecilla near Carolina (USGS station 50050355), 1994-95.

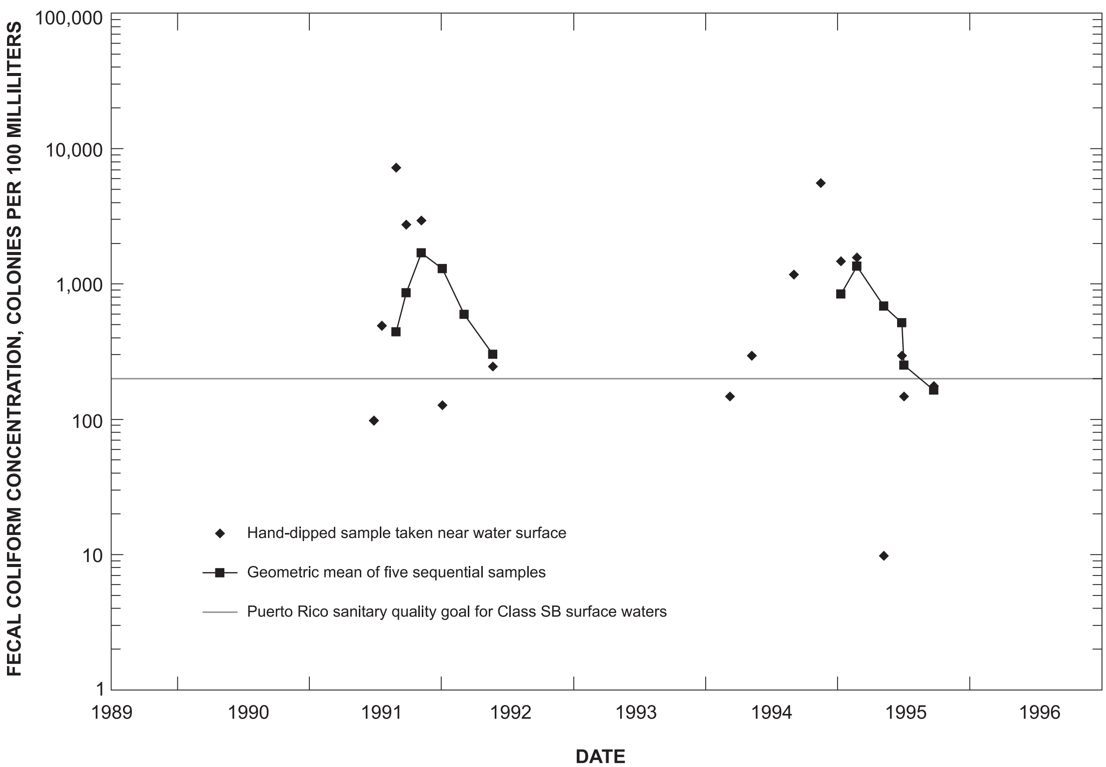

Figure 3d. Geometric mean concentration of fecal coliform bacteria at Laguna San José at San Juan (USGS station 50049720), 1991-92 and 1994-95.

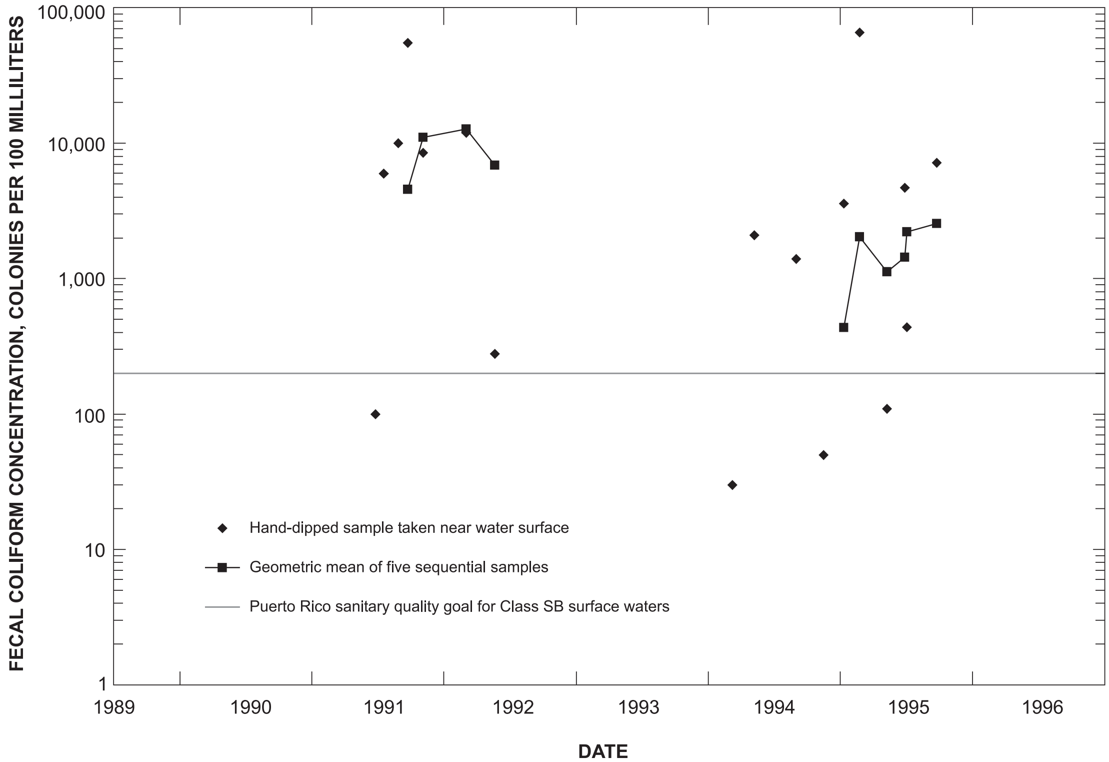

Figure 3e. Geometric mean concentration of fecal coliform bacteria at Laguna La Torrecilla near Carolina (USGS Laguna San José at San Juan (USGS station 50049760), 1991-92 and 1994-95.

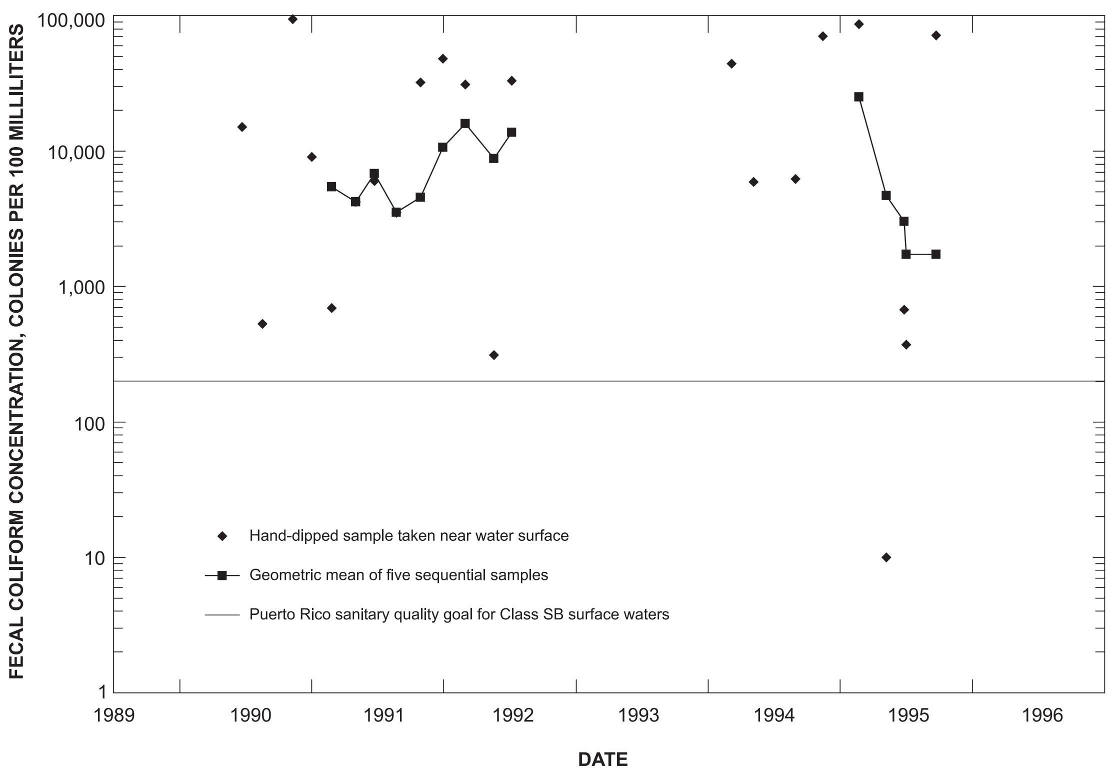

Figure 3f. Geometric mean concentration of fecal coliform bacteria at Laguna San José at San Juan (USGS station 50049720), 1991-92 and 1994-95.

PURPOSE AND SCOPE

A survey of stream sanitary quality was conducted by the USGS in cooperation with the municipio of Carolina primarily to define the extent of fecal contamination in streams within the upland area to the south of highway PR-3. The assessment was made by obtaining and analyzing samples for fecal coliform and fecal streptococcus bacteria from 29 stream locations during base-flow conditions between March 1998 and July 1999. Although the synoptic surveys were conducted in streams that have headwaters outside the municipal boundary, the sampling was conducted within the territorial limits of the municipio of Carolina. The sampling stations are representative of drainage from approximately 33 mi^2 of land south of highway PR-3 (plate 1). The streams used in the synoptic survey consist primarily of second order streams with drainage to the Río Grande de Loíza, Laguna La Torrecilla, and Laguna San José.

This chapter describes the methods and techniques used in conducting the sanitary quality synoptic survey, and provides interpretations of the fecal coliform and fecal streptococcus indicator bacteria concentrations by developing a classification procedure to rank the sanitary quality of stream courses. The data were incorporated into a thematic map (plate 1) that also includes the results of the bacteriological sampling conducted within the estuary by the USGS during 1990-92 and 1994-95. Also included in the thematic map are other important hydrologic features to (a) serve as an initial source of information to guide future efforts by municipal and Commonwealth authorities in implementing measures to enhance the sanitary quality of contaminated streams and estuaries, and conserve those with an acceptable quality; (b) provide reliable scientific information to planners and managers of the water and biological resources; and (c) encourage local citizens to serve as stewards of water resources within their municipio.

METHODOLOGY

Field-Data Collection

Water samples for fecal coliform and fecal streptococcus analyses were obtained from 29 locations at streams with drainage to or within the municipio of Carolina. Sampling was conducted at all stream stations using the “hand-dip” method (Britton and Greeson, 1989). This method is applicable to the stream low-flow conditions in this study. This sampling method consists of dipping a sterile narrow-mouth borosilicate 99-mL bottle 1 to 2 inches below the water surface with the bottle opening pointed slightly upward towards the current and the hand and arm on the downstream side of the bottle.

Most samples were obtained during stream base-flow periods between March and August 1998 and a subset obtained in July 1999 for two hydrologic conditions (1) near the annual stream low flow, and (2) during base-flow conditions after a rainfall event. Samples obtained during these flow regimes were used in developing a classification methodology to rank approximately 87 mi of stream courses within the municipio of Carolina or with drainage into Carolina. During stream base-flow conditions, fecal contamination in streams is principally from sources that discharge directly to stream channels (especially during the period of annual low flow), or are washed into stream channels from sources adjacent (hundreds of feet) to stream banks. To conduct the assessment, 29 stream sampling stations were established; however, only 27 stations were sampled on both occasions at base-flow conditions during March and August 1998, and only 4 stations were sampled during July 1999. The sample results for the station Río Canovanillas at Carruzos (station 50061200) for August 14, 1998, were discarded because the plate counts for fecal coliform and fecal streptococcus were negative indicating an analytical error (analysis was possibly run for buffer solution instead of sample dilutions). Results for fecal streptococcus for the station Río Canovanillas at Barrio Canovanillas (station 50061325) for August 12, 1998, also were discarded because plate counts for sample dilutions were inconsistent.

Instantaneous streamflow measurements were made during sample collection using the current meter method (Carter and Davidian, 1968) except at the sampling station on the Río Grande de Loíza upstream of the highway PR-3 bridge crossing (station 50060001), where discharge was estimated on the basis of the streamflow measurements at stations Río Grande de Loíza below damsite (station 50059050) and at Quebrada Grande at Dos Bocas (station 50059210). Six of the bacteriological sampling stations correspond with stations also used in the surface-water low-flow statistics assessment (Chapter A). Among the low-flow statistics estimated at these sampling stations is the 7-day, 2-year flow. This statistical flow value is shown along with the instantaneous streamflow measurements made at the times of sampling (table 5) to indicate the minimum discharge at which the fecal coliform concentration standards are applicable in Puerto Rico (Junta de Calidad Ambiental de Puerto Rico, 1990).

Analytical Techniques

The analytical procedure used to measure 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 (among these, 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. Hydrated incubation media in petri dishes and sterile sample bottles were prepared at the Caribbean District laboratory in Guaynabo, Puerto Rico.

Based on previous sampling experience, dilution ratios for membrane filtration analyses at each station were prepared to maximize the probability of obtaining about 20 to 60 colonies per filter for fecal coliform bacteria and 20 to 100 colonies per filter for fecal streptococcus bacteria. If colony counts were not in the ideal range, concentrations were reported as non-ideal. With few exceptions, most samples were processed and incubated immediately after collection using the field laboratory. Where the field laboratory was not used, samples were preserved in an ice chest (ice water) at 1° to 4° C and processed at the USGS Caribbean District laboratory within 6 hours of sample collection.

The quality-assurance and quality-control (QA/QC) protocols for bacteriological analyses included (a) laboratory blanks, which consist of incubation of sterile buffered water in culture media as a check primarily on the sterile conditions of buffer, media, and filters; (b) field blanks to check sterile conditions of field equipment; and (c) processing of sequential replicate samples as a check on dilution procedures and variability of bacteriological concentrations resulting from dip sampling. Most QA/QC samples (on average 94 percent) consisted of laboratory or field blanks for parts (a) and (b). One replicate sample dilution was made per sample run. Overall, the results for part (a) should be negative (no development of colonies; if positive, the media sample petri dishes and buffered-water dilution bottles are not acceptable for use). Results for (b) should also be negative; if not, analytical results of samples obtained between negative QA/QC blanks (before and after the positive blank) are reviewed for suspect data results (for example, high counts or significant discrepancy between the number of colonies developed for sample dilutions with ideal and non-ideal counts). Anomalous data are not reported. For this study, three bacteriological results were discarded. Replicate samples obtained as part of this survey were within 15 percent of the original sample, which is typical for replicate samples having fecal coliform and fecal streptococcus concentrations in the range of 100 to low thousand colonies per 100 mL. Relative percent difference (RPD) of primary and replicate samples are calculated as:

$$RPD = S1\text{-}S2 \,/\, [(S1+S2)/2] \times 100,$$

where S1 is the primary sample count and S2 is the replicate sample count, with the number of colonies in the ideal range of 20 to 60 for fecal coliform and 20 to 100 for fecal streptococcus.

RESULTS AND INTERPRETATION

Two major assumptions in the interpretation are that streamflow during base-flow conditions is derived from ground-water discharge, and that fecal contamination during stream base-flow conditions is primarily derived from sources discharging directly into stream courses or near the riparian zone. Another assumption is that, with an average of two samples obtained at least several months apart during stream low-flow recession periods at numerous locations throughout a watershed, it is possible to define, on a qualitative basis, the relative sanitary quality at a site with respect to other sampling locations.

Table 5. Fecal coliform and fecal streptococcus bacteria concentrations at selected stations in the municipio of Carolina, and areas with drainage into the municipio of Carolina, Puerto Rico

[*, indicates number of bacteria colony developed at end of incubation period less than ideal; †, sample not used in station ranking, only two with lowest discharge; ND, statistic not determined for site; e, discharge estimated; low-flow stations given are for comparison of $7Q_2$ (7-day, 2-year recurrence frequency low flow) at station with instantaneous discharge measured at adjacent quality of water station; (a), drainage area below dam; instant, instantaneous; mL, milliliters; ft^3/s, cubic feet per second; mi^2, square mile; m/d/y, month/day/year; --, no data; Pre-, presumed]

Sampling station USGS identification number (plate 1)	Station name	Sample date (m/d/y)	Time	Fecal coliform colonies per 100 mL	Fecal streptococcus colonies per 100 mL	Instant. discharge (ft^3/s)	$7Q_2$ mean daily discharge (ft^3/s)	Drainage area (mi^2)	Station sanitary quality ranking
50050100	Quebrada San Antón at Barrio San Antón	04/07/98	1000	15,000	460	4.28	ND	2.73	Poor
		08/07/98	1300	82,000*	35,000	16.50			
50050290	Quebrada Blasina at Saint Just	07/13/99	1000	33,000	52,000	0.63	ND		Pre-poor
50050300	Quebrada Blasina near Carolina	03/25/98	1030	170,000*	22,000	3.80	ND	2.96	Poor
		06/09/98	1105	24,000	45,000	5.50			
50059100	Río Grande de Loíza below Trujillo Alto	03/10/98	1130	840*	2,100	9.30	ND	213	Acceptable
		06/02/98	1115	560	30	9.50			
50060001	Río Grande de Loíza at Trujillo Bajo	04/22/98	1400	300	50*	60 e	ND	22.1 (a)	Acceptable
		08/05/98	1230	20*	40*	30 e			
50060050	Quebrada Maracuto at Highway PR-852	04/08/98	930	10,000	680	0.75	ND	2.03	Fair
		08/04/98	1920	450	440	0.29			
50060060	Tributary to Quebrada Maracuto at	04/08/98	1930	4,700	4,000	0.11	ND	0.36	Fair
	Highway PR-852	08/04/98	1030	330	800	0.06			
50060100	Quebrada Maracuto at Barrio Barrazas	04/08/98	1230	12,000	4,500	1.46	ND	3.19	Fair
		08/04/98	1140	470	430	0.42			
50060105	Tributary to Quebrada Maracuto at	04/08/98	1200	13,000	4,500	0.16	ND	0.43	Fair
	Barrio Barrazas	08/04/98	1300	750*	550	0.10			
50060160	Quebrada Maracuto at Barrio Santa Cruz	Not sampled; only a low-flow station			--	--	0.8	6.31	
50060170	Quebrada Maracuto at Highway PR-853	04/08/98	1400	2,700	430	5.45	ND	7.52	Fair
		08/04/98	1400	680*	260	0.82	--		
50060175	Quebrada Hoya Fría at mouth	04/07/98	1240	530	300	0.18	ND	0.32	Acceptable
		08/05/98	1030	40*	360*	0.13	--		

Table 5. Fecal coliform and fecal streptococcus bacteria concentrations at selected stations in the municipio of Carolina, and areas with drainage into the municipio of Carolina, Puerto Rico—Continued

Sampling station USGS identification number (plate 1)	Station name	Sample date (m/d/y)	Time	Fecal coliform colonies per 100 mL	Fecal streptococcus colonies per 100 mL	Instant. discharge (ft^3/s)	$7Q_2$ mean daily discharge (ft^3/s)	Drainage area (mi^2)	Station sanitary quality ranking
50060190	Quebrada Pastrana near Mariana at Cacaos	04/07/98	1400	22,000	35,000	0.35	0.2	0.79	Poor
		08/07/98	1030	15,000	40,000	0.58	--		
50060195	Quebrada Pastrana near mouth at Cacaos	04/07/98	1130	580	360	0.27	0.2	2.04	Acceptable
		08/05/98	1130	590	550	1.90			
50060200	Quebrada Maracuto at Trujillo Bajo	Not sampled; only a low-flow station	--	--	--	--	0.8	10.2	
50061100	Río Canovanillas at Highway PR-953	04/15/98	1130	720*	250	0.56	ND	1.51	Fair
		08/07/98	1200	5,800	3900	0.50	--		
50061120	Tributary to Río Canovanillas at Highway PR-185	04/15/98	1200	490	160*	0.01	ND	0.23	Fair
		08/13/98	1100	3000	600	0.02	--		
		07/13/99	1100	420	800	0.52†	--		
		07/14/99	1140	12,000	24,000	0.50†	--		
50061130	Quebrada González at Barrio Cedros	08/13/98	1200	450	520	0.18	ND	0.50	Acceptable
		04/45/98	1230	460	300	0.28	--		
50061135	Río Canovanillas near Highway PR-185	04/17/98	1100	10,000	3,700	2.41	ND	4.30	Fair
		08/13/98	1030	400*	300*	1.48	--		
50061140	Tributary to Río Canovanillas at Barrio Cedros	07/13/99	1200	5,000	4,600	0.51	ND	0.46	Pre-poor
50061150	Tributary to Río Canovanillas near Highway PR-853	04/17/98	1030	4,000	600	0.76	ND	0.94	Poor
		08/7/98	1130	5,800	3,900		--		
50061180	Tributary to Río Canovanillas near Barrio Carruzos	04/17/98	1230	2,500	750	0.41	ND	0.63	Fair
		08/14/98	1050	1,100*	800	0.08	--		
50061200	Río Canovanillas at Carruzos	04/17/98	1330	24,000	3,200	7.46	1.7	9.10	Pre-poor
		08/14/98	1130	discarded	discarded	2.45	--		
50061210	Tributary to Río Canovanillas	04/20/98	1130	800	420	0.30	ND	0.37	Acceptable
		08/11/98	950	550	500	0.23	--		

Table 5. Fecal coliform and fecal streptococcus bacteria concentrations at selected stations in the municipio of Carolina, and areas with drainage into the municipio of Carolina, Puerto Rico—Continued

Sampling station USGS identification number (plate 1)	Station name	Sample date (m/d/y)	Time	Fecal coliform colonies per 100 mL	Fecal streptococcus colonies per 100 mL	Instant. discharge (ft^3/s)	$7Q_2$ mean daily discharge (ft^3/s)	Drainage area (mi^2)	Station sanitary quality ranking
50061220	Tributary to Río Canovanillas on Highway PR-857	04/20/98	1400	330	690	0.26	ND	0.41	Acceptable
		08/11/98	1030	450	680	0.09	--		
50061225	Tributary to Río Canovanillas at mouth	04/20/98	1230	200	300	0.29	ND	0.67	Acceptable
		08/12/98	1030	420	450	0.25	--		
50061265	Quebrada Las Lajas at Highway PR-857	04/13/98	1000	10,000	5,300	0.58	ND	0.65	Poor
50061265	Quebrada Las Lajas at Highway PR-857	08/11/98	1100	3,500	1,700*	0.36	--		
50061270	Río Canovanillas below Quebrada Las Lajas at Barrio Cacaos	Not sampled, only a low-flow station	--	--	--	--	ND	13.2	
50061285	Quebrada Limones at Highway PR-857	04/13/98	1030	11,000	6,800	0.48	ND		Fair
		08/11/98	1130	900*	1,200*	0.17	--		
50061295	Tributary to Quebrada Limones at Barrio Canovanillas	04/13/98	1130	5,500	6,700	0.27	ND	0.47	Fair
		08/12/98	1130	500*	1,500*	0.15	--		
50061325	Río Canovanillas at Barrio Canovanillas	04/13/98	1300	3,000	5,400	15.70	1.9	15.00	Fair
		08/12/98	1230	1,500*	discarded	4.92			
50061450	Quebrada Cambute at Barrio Canovanillas	04/13/98	1330	10,000	4,500	1.28	ND		Fair
		08/14/98	1300	1,400*	500*	0.82	--		
50061800	Río Canóvanas near Campo Rico	Not sampled; only a low-flow station	--	--	--	--	4.4	9.8	

Based on these assumptions, the analytical results for fecal coliform and fecal streptococcus bacteria concentrations from the stream sampling stations were used to characterize the sanitary quality of about 80 mi of perennial stream channels within the municipio of Carolina and about 7 miles (mi) of stream channels outside the municipal boundaries but draining into the Río Grande de Loíza and the municipio of Carolina (table 5). Bacteriological data were insufficient to adequately assess the sanitary quality of approximately 3 mi of the Río Grande de Loíza downstream of the highway PR-3 bridge to its junction with the Río Canovanillas.

Based on the results, a relative ranking of the stream sanitary quality was established to delimit stream channels as being either **poor**, **fair**, **acceptable**, or **good** (table 6). This relative ranking was established using the Puerto Rico Water Quality Standards for fecal coliform of 2,000 colonies per 100 mL, and the following rationale.

Sampling stations where fecal coliform bacteria concentrations were greater than 2,000 colonies per 100 mL for both base-flow sample dates were considered **poor**. The stream segment given the same classification was extended upstream and downstream as follows:

If another sampling station was established upstream and/or downstream within the same order stream and the results were comparable, the same classification was given for the entire stream segment between both sampling stations; if the upstream station and/or downstream station was classified differently, the classification was extended to mid-point; and if no other sampling station was located upstream, the same classification was extended upstream not more than 0.6 mi along the main trunk of the stream. For stream segments, an upstream distance greater than 0.6 mi of the sampling station and for its tributaries, the same classification was assigned but using the terminology of **presumed poor**. If no other sampling station was established downstream, the same classification was used up to a distance of 0.6 mi along the main channel of the stream (same stream order), with the **presumed poor** classification assigned downstream of the 0.6-mi distance.

Sampling stations where fecal coliform bacteria concentrations were equal to or greater than 2,000 colonies per 100 mL on one sample occasion, but below 2,000 colonies per 100 mL in the second sample run were classified as **fair**. The classification of **presumed fair** was extended upstream and downstream of the sampling station following the same rationale as stated previously for **poor** and **presumed poor**.

Within the developed areas of Carolina south of highway PR-3 an exception was made where the stream classification of **presumed fair** was extended upstream to the urban limits. This was justified on the basis of the bacteriological data results at Quebrada Cambute at Barrio Canovanillas (sampling station 50061450), which is considered as representative of the land use in the adjacent drainage areas.

Sampling stations where fecal coliform bacteria concentrations were equal to or less than 2,000 colonies per 100 mL on both sample occasions were classified as **acceptable**. The classification of **presumed acceptable** was assigned for stream segments upstream and downstream of the sampling station using the same rationale described previously.

If both samples had fecal coliform bacteria concentrations below 200 colonies per 100 mL and fecal streptococcus concentrations below 400 colonies per 100 mL, the **good** and **presumed good** classifications were assigned in the same manner as the other rankings. The **presumed** ranking was not assigned to any stream (or tributary) in which no fecal coliform and fecal streptococcus analyses were obtained, given the low probability of bacteriological concentrations being within the classification of **good** or **presumed good** (only 2 of 56 samples (4 percent) used in the rankings met the requirements for the **good** classification, however, no station met the requirements on 2 sample occasions in order to be ranked as **good**). Only two sampling stations had at least one of the sample results with fecal coliform concentrations below 200 colonies per 100 mL and fecal streptococcus concentrations below 400 colonies per 100 mL: Río Grande de Loíza at Trujillo Bajo (station 50060001) and Quebrada Hoya Fría at mouth (station 50060175).

Table 6. Classification rationale used in ranking the sanitary quality of streams in the municipio of Carolina, Puerto Rico

[>, greater than; <, less than; ≥, greater or equal to; ≤, less or equal to; mL, milliliters; *, number of colonies estimated from non-ideal plate count; NA, not applicable (no station met conditions (rationale) on either sample occasion)]

Ranking	Fecal coliform concentration for stream reach during base-flow conditions, in colonies per 100 mL	Rationale	Summary of the concentrations found during synoptic surveys		
				Fecal coliform concentration, in colonies per 100 mL	Fecal streptococcus concentration, in colonies per 100 mL
Poor	> 2,000	Samples obtained within 0.6 mile upstream or downstream from delimited reach.	**Maximum**	170,000*	52,000
Presumed poor	> 2,000	Samples obtained at a distance greater than 0.6 mile upstream or downstream from delimited stream reach were used to infer that similar concentrations are probable within delimited stream reach.	**Minimum**	3,500	460
			Geometric mean	16,208	7,744
			Number of samples	13	13
Fair	Equal probability for < or ≥ 2,000	Samples obtained within 0.6 mile upstream or downstream from delimited reach.	**Maximum**	13,000	6,800
			Minimum	330	160*
Presumed fair	Equal probability for < or ≥ 2,000	Samples obtained at a distance greater than 0.6 mile upstream or downstream were used to infer same conditions are probable within the delimited stream reach.	**Geometric mean**	2,015	1,148
			Number of samples	26	25
Acceptable	≤ 2,000	Samples obtained within 0.6 mile upstream or downstream of delimited reach.	**Maximum**	840	2,100
			Minimum	20*	30
Presumed acceptable	≤ 2,000	Samples obtained at a distance greater than 0.6 mile upstream or downstream were used to infer that equal concentrations are probable within the delimited stream reach.	**Geometric mean**	333	305
			Number of samples	16	16
Good	< 200	Samples obtained at station also had fecal streptococcus concentrations less than 400 colonies per 100 mL; ranking was applied to entire stream upstream from sampling station.	**Maximum**	NA	NA
			Minimum	NA	NA
Presumed good	< 200	Samples obtained at a distance greater than 0.6 mile upstream or downstream were used to infer that equal concentrations are probable within the delimited stream reach.	**Geometric mean**	NA	NA
			Number of samples	NA	NA

The **presumed** prefix was used in the ranking of several streams having drainage areas of less than 3 mi^2. At these streams, the classification was based on sampling results obtained at streams draining adjacent watersheds with similar land-use conditions as determined from field inspections and 1994 aerial photographs. The **presumed** prefix also was used at stations sampled only once during base-flow conditions.

No classification was made for the part of the Río Grande de Loíza downstream of the bridge on highway PR-3 or in the abandoned meanders in the floodplain. The Río Grande de Loíza is affected by tides as far inland as the highway PR-3 bridge as documented in river stage records obtained between October 1990 and September 1997 by the USGS (station 50061000, plate 1), thus, this part of the stream would need to meet the lower fecal coliform concentrations of Class SB surface waters to meet the Puerto Rico sanitary quality goals.

Classification of the surface waters in the estuary areas of the municipio of Carolina was based on the Class SB sanitary quality goal, which is based on a geometric mean of not greater than 200 fecal coliform bacteria per 100 mL. The data used to rank the lagoons were obtained by the USGS during 1994-95, and are displayed in figures 3a-3f. The ranking rationale applied in the lagoons was based on the geometric mean of five sequential samples (except at station 50050355 in Laguna La Torrecilla, for which only four sequential samples were available). For estuary surface waters, the classification used in this study was as follows.

Sampling stations where fecal coliform bacteria geometric mean concentrations were greater than 200 colonies per 100 mL were considered **poor**. Sampling stations where fecal coliform bacteria geometric mean concentrations varied from less than or equal to 200 to greater than 200 colonies per 100 mL were considered **fair,** and sampling stations where fecal coliform bacteria geometric mean concentrations were less than 200 colonies per 100 mL were considered **acceptable.**

For estuary parts of streams, the fecal coliform results obtained at the downstream-most sampling station used in ranking the Class SD surface waters were used to classify the estuary segment. The estuary segment of Río Grande de Loíza could not be classified since it is subject to the ebb and flow of tides. The downstream-most sampling station on the Río Grande de Loíza was ranked as **acceptable**, but the downstream-most sampling station on the Río Canovanillas was ranked as **fair**. Thus, the water mass in this part of the Río Grande de Loíza is affected by the quality of flow contributed by both sources. The downstream-most stations along Quebrada Blasina and Quebrada San Antón were classified as **poor,** because the fecal coliform concentrations were greater than 200 colonies per 100 mL on both sampling occasions.

A summary of the bacteriological results, the classification assigned at sampling stations, and stream miles classified under each ranking is presented in table 7. Results from the 29 stream-sampling stations were interpolated and extrapolated to classify a total of about 87 mi of stream courses inland of their estuary segments including the Río Grande de Loíza from highway PR-3 to the Lago Loíza dam (plate 1). Approximately 4 mi of Río Canovanillas tributaries outside the municipio boundary, but with drainage to Carolina and a Río Grande de Loíza tributary upstream of the Carolina-Trujillo municipio boundary were not classified.

It is possible that indicator bacteria become stressed by household waste-water discharges, rendering them incapable of growth and colony formation because of structure or metabolic changes associated with discharge of untreated (gray water) wastes (American Public Health Association, 1998). Hence, an additional symbol was added to plate 1 to show potential sources of household waste-water discharges that were evident within the municipio boundary during the field surveys. Stream reaches that may be affected by these potential sources were mapped using 1994 aerial photographs, and are identified as "riparian zone with potential as a source of contamination from household waste-water discharges" on plate 1. The approximately 3 mi of delimited stream reaches may be affected by "gray-water" discharges and septic tank effluent from housing communities bordering the riparian zones of streams or from relatively dense housing developments (generally, with five or more housing units per acre) that are located within 300 ft of the stream courses. The adequacy of the 300-ft setback distance between houses with septic tanks and stream courses that was used to delimit potential sources of contamination to streams from unsewered

Table 7. Summary of bacteriological analyses, water-quality ranking determined for sampling stations, and stream miles classified under each ranking

[Total miles do not include the estuary segments of streams draining to Laguna San José and Laguna La Torrecilla; Rio Grande de Loíza was ranked as far downstream as the Highway PR-3 bridge crossing; --, no data; NA, not applicable]

Classification	Number of sampling stations ranked within the classification	Percent of total sampling stations ranked	Stream miles with same classification	Percent of total stream miles[1]	Percent of total stream miles classified
Poor	5	27.6	4.4	29.4	30.6
Presumed poor	3		22.4		
Fair	13	44.8	22.5	50.0	52.0
Presumed fair	0		23.0		
Acceptable	8	27.6	9.1	16.6	17.4
Presumed acceptable	0		6.1		
Good	0	0.0	0.0	0.0	0.0
Presumed good	0		0.0		
Not classified	--	NA	3.7	4.1	--

[1] Total does not equal 100 due to rounding.

communities is unknown. Determination of adequate setback distance must consider rainfall recharge, hydrogeology, and housing density, in addition to the soil percolation rate typically used in designing septic tank systems. The 300-ft distance, however, can be used as an initial estimate of stream contamination by unsewered communities because viruses from a septic tank can move as far as 215 ft in sandy soils (Vaughn and others, 1983) and persist up to 131 days in ground water (Stramer, 1984).

Grazing dairy and beef cattle also may be a major source of fecal contamination in several streams, because cattle are not restricted from wandering into stream courses. According to the 1997 agricultural census (U.S. Department of Commerce, 1998b), there were an estimated 551 head of dairy cattle and 2,840 head of beef cattle in the municipio of Carolina. The number of dairy cattle has declined substantially since the agricultural census of 1992 when 1,592 head of dairy cattle were counted (U.S. Department of Commerce, 1994). As observed during the study, dairy cattle are primarily limited to the coastal plain part of the municipio at Barrio Hoyo Mulas. Beef cattle were observed pasturing in the eastern side of Río Canovanillas (upstream of sampling station 50061200 within the municipio of Canóvanas) and in the drainage basins of an unnamed tributary of the Río Canovanillas (upstream of sampling station 50061150). Similarly, there has been a decline in the number of hogs and pigs and also possibly in poultry. In the 1997 agricultural census, there were an estimated 1,938 hogs and pigs as compared to 5,171 in the 1992 agricultural census. Poultry agro-enterprises may be on a decline; poultry operations were observed only in the upland Barrios of Cacao and Santa Cruz. The total number of poultry in the municipio was not reported in the agricultural census of 1997 because of the limited number of farms (15) dedicated to this agro-business. In comparison, the 1992 agricultural census reported 121 poultry farms with a total estimate of 43,618 chickens. Hence, livestock and poultry, as a source of fecal contamination to streams, has declined during the past 10 years.

CHAPTER C:

Hydrogeologic Terranes and Ground-Water Resources in the Municipio of Carolina, Puerto Rico, 1997-99

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PURPOSE AND SCOPE

As part of the surface- and ground-water resource study of the municipio of Carolina, the area was differentiated into sections with similar hydrogeologic characteristics, which are referred to as hydrogeologic terranes. Geologic, topographic, soil, hydrogeologic, and streamflow data were used to delineate the various hydrogeologic terranes. These data were obtained from field reconnaissance, USGS topographic and geologic maps, streamflow data, and available published information. Some of the hydrogeologic terranes extend beyond the municipio of Carolina boundaries; however, only those parts of the hydrogeologic terranes within the municipio are described in this report.

The concept of a hydrogeologic terrane was first used by Berg and others (1984) to regionally evaluate ground- and surface-water interactions, and to subdivide the State of Illinois into geographic areas having similar hydrogeologic properties. Hydrogeologic terranes were identified, characterized, and delineated in water-resources assessments of Caguas and Comerío (Gómez-Gómez and others, 2001; Rodríguez-Martínez and others, 2001, respectively). Five hydrogeologic terranes were delineated in the municipio of Carolina and are denoted by the acronym CarHT. For example, CarHT1 refers to the Carolina hydrogeologic terrane number 1.

METHODOLOGY

The factors considered to differentiate the municipio of Carolina into hydrogeologic terranes were, in order of importance, (a) the underlying rock and sediment type, (b) the soil thickness and infiltration capacity, (c) the ground-water flow rate, (d) the general depth to water table, and (e) the land-surface slope. The geologic substrata and associated attributes, such as the presence of fractures, joints, and stratification, were determined from USGS geologic maps, lineament-trace analyses, core and well-cutting descriptions, surface geophysical surveys, and a field reconnaissance (Pease and Briggs, 1960; Seiders, 1971). The soil thickness and infiltration capacity were obtained from soil maps published by the Natural Resources Conservation Service, formerly the Soil Conservation Service (U.S. Department of Agriculture, 1973). The ground-water flow rate was estimated from stream low-flow measurements and using the Q-98 and Q-90 flows (streamflows equaled or exceeded 98 and 90 percent of the time, respectively). The general depth to ground water was obtained from USGS data files and field surveys. The land-surface slope was obtained using a computer to process a digitized topographic map of the municipio of Carolina. The hydrogeologic terranes are delineated on a 1:30,000 map of the municipio of Carolina, which also includes drainage sub-basins (plate 2).

Some of the factors mentioned above, although considered separately in this report, are generally interrelated, the nature of a particular factor being dependent on the nature of one or more other factors. For example, the geology of an area greatly influences the type and thickness of soil cover present. Similarly, geologic control may highly influence the depth to the water table and the rate of ground-water flow. Stream low flows, an indirect measure of the ground-water flow or equivalent effective recharge in the aquifer(s) within a drainage basin, are highly dependent on geologic factors such as the type of lithology, stratification, and the presence of fractures and fissures.

Exploratory drilling and the installation of 17 piezometers and collection of water-level data from 13 private and public water-supply wells and non-USGS test wells in the lower Río Grande de Loíza alluvial valley (table 8; plate 2), was conducted to map the configuration of the potentiometric surface and to delineate the direction of ground-water flow. Well cuttings were examined and described to evaluate the hydraulic characteristics of the alluvial aquifer and to identify the principal water-bearing units. Ground-water samples were collected at 12 sites to determine the concentration of the major chemical constituents present in ground water from the lower Río Grande de Loíza alluvial aquifer (table 9).

The surface-resistivity geophysical surveys were conducted to detect and delineate the areal extent of the saline ground-water zone and, in conjunction with lithologic data obtained from the exploratory drilling, define the main lithologic units in the study area. Direct current resistivity (DC) data were collected along 12 transects using a Schlumberger array method (Zohdy and others, 1974). Test-well data and surface-resistivity data were used to construct cross sections (fig. 4 on plate 2) showing the subsurface variation in lithology and thickness of the alluvial units.

Lineament-trace analysis was used to identify topographic and drainage features, geologic contacts, and tonal differences in soil colors that might be related to subsurface fractures that are zones of enhanced ground-water flow in an otherwise low-permeability formation (Lattman, 1958). For this study, the lineament traces were identified on aerial photos and corroborated in the field. Lineament-trace analysis was limited to the interior uplands of the municipio of Carolina. The trace, type, and identification number of the lineaments are shown in plate 2 and presented in table 10.

Stream low-flow values can be used to approximate the ground-water flow rate in a corresponding drainage basin, and therefore, can be used to infer the ground-water development potential of an area (Ineson and Downing, 1964; Farvolden and Nunan, 1970; Berg and others, 1984). The correlation of low flows to ground-water flow rate assumes that (a) ground water in a particular ground-water basin discharges entirely into the stream and its tributaries, and (b) ground-water discharge into the stream and tributaries is restricted to aquifer(s) in the corresponding drainage basin. This correlation also assumes that the contributing ground-water catchment does not vary seasonally in extent because of fluctuating ground-water levels. Low-flow measurements were preferentially made at stream junctions and, wherever possible, at stream sections coinciding with the boundaries of different geologic units, as delineated on the 1:30,000 scale geologic quadrangle maps. This discharge-measurement strategy provided the low-flow values required to calculate the contribution of ground-water flow from the drainage area. The low-flow values were divided by the drainage area to remove the effect of drainage-basin area, and thus are expressed as gallons per day per square mile (gal/d/mi^2) and in the equivalent effective recharge, in inches per year (in/yr). The low-flow measurements were adjusted for the effects of stream diversion, ground-water withdrawals, and domestic springs present in the corresponding drainage subbasin.

Pérez-Blair (1997) used the Q-98 (streamflow value equaled or exceeded 98 percent of the time) as an indicator of ground-water discharge into a stream to provide a good approximation of the ground-water flow in the corresponding drainage basin. Berg and others (1997) used the Q-90 (streamflow equaled or exceeded 90 percent of the time) determined from 30 years of streamflow data. For this study, the range between Q-98 and Q-90 was used to approximate ground-water flow in the aquifer(s) within the corresponding drainage basin. The Q-98 and Q-90 flows were obtained using the graphical correlation method described in Chapter A. By calculating the Q-98 and Q-90 flows for various drainage subbasins, as shown in table 10, it was possible to obtain a reasonable approximation of the ground-water flow rate in the various hydrogeologic terranes delineated in the municipio of Carolina.

Stream low-flow contributions from outside the municipio of Carolina were not considered in the analysis. That fraction of low flow from ground-water discharge originating outside the municipio of Carolina and from regional ground-water flow is not known, and consequently, cannot be accounted for in the analysis. Given the limited extent of the water-bearing units and their generally low permeability, it is assumed that local ground-water flow systems predominate.

Table 8. Description of wells and piezometers used to evaluate the hydrogeology of the municipio of Carolina, Puerto Rico

[OW, observation well and piezometer; AB, abandoned well; PWS, public supply well; * non-U.S. Geological Survey test well; **, U.S. Geological Survey test well; --, data not available; PRASA, Puerto Rico Aqueduct and Sewer Authority]

Well or piezometer number (plate 2)	Name	Site identification number[1]	Use	Depth of well (feet)	Depth of screened interval (feet)
1	Car-tw1**	182250655541	OW	53	41-51
2	Car-tw2**	182307655543	OW	48	37-47
3	Car-3	182224655660	AB	--	--
4	Car-4	182319655625	OW	--	--
5	Car-tw5**	182409655639	OW	37	25-35
6	Car-6	182402655628	AB	--	--
7	Car-tw7**	182406655626	OW	53	41-51
8	Car-tw8**	182413655553	OW	52	40-50
9	Car-tw9**	182426655625	OW	37	24-34
10	Car-tw10**	182347655552	OW	52	39-49
11	Car-tw11**	182318655541	OW	38	26-36
12	Car-tw12**	182322655555	OW	38	26-36
13	Car-tw13**	182413655507	OW	49	38-48
14	Car-tw14**	182315655502	OW	49	37-47
15	Car-tw15**	182320655513	AB	--	--
16	Car-tw16**	182310655518	OW	47	36-46
17	Car-tw17**	182307655506	OW	49	37-47
18	Car-tw18**	182301655521	OW	50	37-47
19	Car-19	182301655521	AB	--	--
20	Car-20	182249655501	AB	--	--
21	Car-tw21**	182348655633	OW	35	23-33
22	Car-22	182438655703	AB	--	--
23	Car-23	182435655709	AB	--	--
24	Car-tw24**	182331655615	OW	32	20-30
25	Geochem test well*	182413655657	AB	225	--
26	Car-26	182501655649	AB	--	--
27	PRASA Urrutia	182217655538	PWS	--	--
28	Geochem test well*	182443655703	AB	150	--
29	PRASA Pozo Las 400	181742655459	PWS	--	--
30	Barrazas Municipio	181814655627	PWS	--	--

[1] Site identification number: Unique number for each site based on the latitude and longitude of the site. First six digits are latitude, next six digits are longitude. Latitude and longitude are given in degrees, minutes, and seconds.

Table 9. Summary of chemical analysis results of water samples from selected wells in the municipio of Carolina, Puerto Rico

[Concentrations are given in milligrams per liter (mg/L) unless otherwise noted; µg/L, micrograms per liter; µS/cm; microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; Ca, Calcium; Mg, Magnesium; Na, Sodium; K, Potassium; HCO_3, bicarbonate; Cl, Chloride; SO_4, Sulfate; F, Fluoride; SiO_2, Silicate; Fe, Iron; Mn, Manganese; --, data not available]

Well name and identification number	Date	Latitude Longitude[1]	pH	Total hardness as $CaCO_3$	Dissolved constituents: Ca	Mg	Na	K	Alkalinity as HCO_3	Cl	SO_4	F	SiO_2	Fe	Mn	Solids	Specific conductance (µS/cm)	Ground-surface elevation, in feet above mean sea level	Depth to water (feet)	Depth of screened interval (feet)
Car-1	9/14/98	18°22′50" 65°55′41"	8.0	475	88	62	136	0.9	707	119	43	0.3	67	79	2,591	800	1,440	32.86	23.67	45-55
Car-5	9/16/98	18°24′09" 65°56′39"	7.6	207	53	19	53	0.7	350	25	7	0.2	52	5,272	1,377	381	585	25.83	13.56	28-38
Car-8	9/16/98	18°24′13" 65°55′53"	7.3	534	168	28	55	3.6	615	184	55	0.2	28	18	1,357	818	1,097	20.89	19.57	33-43
Car-2	9/14/98	18°23′07" 65°55′43"	7.1	355	73	42	38	0.7	339	127	17	0.2	69	535	2,622	506	861	35.40	32.01	30-40
Car-12	9/14/98	18°23′22" 65°55′55"	7.2	221	39	30	36	0.4	178	62	51	0.2	65	5,931	509	378	554	26.66	11.00	26-36
Car-10	9/16/98	18°23′47" 65°55′52"	7.7	92	12	15	37	1.1	332	53	44	0.2	35	12	1,692	472	752	23.70	13.46	38-48
Car-13	9/16/98	18°24′13" 65°55′07"	8.1	52	19	1	41	1.1	310	25	20	0.4	12	7	<3	171	326	42.31	40.51	38-48
Car-14	9/14/98	18°23′15" 65°55′02"	7.3	927	236	82	525	2.7	518	1,215	34	0.1	32	30	905	254	4,340	25.65	27.05	37-47
Car-18	9/14/98	18°23′01" 65°55′21"	7.9	387	84	43	127	0.8	490	154	61	0.5	56	49	1,842	770	1,272	25.06	18.75	39-49
Car-24	9/16/98	18°23′31" 65°56′15"	7.7	239	48	29	26	0.5	183	72	37	0.2	49	40	3,084	356	599	26.52	12.56	20-30
Pozo las 400[2]	3/23/99	18°17′42" 65°54′59"	7.5	351	88	32	52	0.7	--	57	25	0.2	40	370	19	496	822	--	--	--
Barrazas municipio[3]	3/23/99	18°18′14" 65°56′27"	7.5	182	48	15	28	1.6	--	38	30	0.1	54	17	70	321	484	--	--	--

[1] Datum for latitude and longitude is NAD 27. Location of wells are shown on plate 2.
[2] Public-supply well operated by the Puerto Rico Aqueduct and Sewer Authority.
[3] Public-supply well operated by the municipio of Carolina.

Table 10. Lineament number and type in the municipio of Carolina, Puerto Rico

[Ln, lineament; Ls, lineament of structural or geologic significance; Lt, lineaments of unspecified origin including linear or straight land-surface features]

Lineament number (plate 2)	Type of lineament
Ln 004	Ls
Ln 004-B	Ls
Ln 005	Ls
Ln 007	Ls
Ln 010	Ls
Ln 011	Ls
Ln 012	Ls
Ln 013	Ls
Ln 016	Ls
Ln 017	Ls
Ln 018	Lt
Ln 019	Lt
Ln 020	Ls
Ln 021	Ls
Ln 024	Ls
Ln 025	Ls
Ln 026	Ls
Ln 027	Ls

Locally, low flows (and equivalent ground-water flows) within similar hydrogeologic terranes can differ as a result of variable land cover and the resulting recharge and evapotranspiration rates. Typically in tropical areas, stream low flow in volcanic terranes is controlled by relatively high rainfall infiltration provided by forest cover (Bruijnzeel, 1990). Removal of forest cover and change in land use for agricultural purposes was found to result in a reduction of stream low flow from an equivalent of 6 to 2 in/yr of rainfall (Ramos-Ginés, 1997). The effects of evapotranspiration on shallow ground water can be important during the dry season, and even with a constant land cover, variations may occur in the low flows, particularly along the riparian zones. Urbanized areas can affect low-flow discharge by reducing areal rainfall infiltration. Urbanized areas also can increase recharge by leakage of water from sewer mains, or by infiltration from septic tanks in unsewered areas and by leakage from water-distribution pipelines. Low flows in any drainage basin reflect the prevailing precipitation patterns (effective recharge). Thus, ground-water flow and equivalent low flow in any drainage basin will change as variations in effective recharge occur as a result of changes in the precipitation pattern or land use.

The ground-water flow estimates included low-flow measurements from drainage subbasins of variable size. Even though ground-water flow estimates were normalized on a unit area basis for comparison between hydrogeologic terranes, it is possible that drainage-basin size has some effect on the low-flow values. For example, as the basin size increases, the distribution of elements that determine ground-water transmissivity and storage (primary porosity, fractures, joints, bedding planes, thickness of the weathered zone) and climatological factors (precipitation, evapotranspiration) become increasingly heterogeneous. Similarly, land cover may vary within the basin. This departure from uniformity in these factors may result in an uneven generation of low flow across the basin. Thus, measured low flows may only partially represent the spatial variation of ground-water flow in the aquifer(s). This effect, after normalization, is referred to as the residual effect (Farvolden and Nunan, 1970). The residual effect seems to be important in basins covering tens to hundreds of square miles. Because the basins in the current study do not exceed 10 mi^2 in area, the residual effect may be minimal or none.

RESULTS AND INTERPRETATION

The municipio of Carolina was differentiated into five hydrogeologic terranes (CarHT) (plate 2). Although some of the hydrogeologic terranes extend beyond the boundaries of the municipio of Carolina, only their aerial extent within the municipio is presented. The hydrogeologic terranes are listed and described below in decreasing order of ground-water development potential.

CarHT1-This hydrogeologic terrane consists of alluvium, swamp deposits, silica sand, and terrace deposits of Quaternary age, and is restricted to the northernmost part of the coastal plain. The terrane also includes the underlying Aymamón and Aguada Limestones of Tertiary age. The land surface slope in this area does not exceed 15 degrees. The soil cover thickness ranges from 5 to greater than 6 ft. The soil cover permeability mostly ranges from 0.06 to 2.0 in/hr but locally can be as high as 20 in/hr. Water-bearing rocks of CarHT1 contain saltwater near the coast (plate 2) and freshwater inland.

Ground water occurs mostly under semi-confined conditions, suggesting the sources of recharge lie primarily at upgradient in parts of the potentiometric surface near the contact area between the relatively impermeable Tertiary and Cretaceous volcanic rocks and the unconsolidated Quaternary deposits. Hydraulic conductivity estimates derived from instantaneous injection and recovery tests (slug tests) range from 5 to 6 feet per day (ft/d) in water-bearing strata predominantly composed of fine sand beneath the overlying silt and clay deposits in the coastal plain. Transmissivity measurements in CarHT1 are scarce and range from 600 to 800 feet squared per day (ft^2/d) in wells completed in unconsolidated Quaternary deposits. Transmissivity values reported in wells completed in both the alluvium and the underlying limestone exceed 800 ft^2/d. Hydraulic testing and analysis indicate that sustained well yields range from 50 to 125 gallons per minute (gal/min). Higher sustained well yields can be expected for wells completed in the underlying limestone.

CarHT2- This hydrogeologic terrane consists of alluvium and Quaternary terrace deposits underlain by the Cibao Formation and undifferentiated igneous rocks. The Cibao Formation underlies the alluvium and Quaternary deposits in a 0.5-mile-wide area, and by undifferentiated igneous rocks farther inland (plate 2). The land surface slope in CarHT2 does not exceed 15 degrees. The soil cover is fairly uniform, ranging between 5 and 6 ft thick, with an infiltration capacity ranging between 0.06 and 2.0 in/hr. The alluvium, as with CarHT1, is composed mostly of sand, clay, and sandy clay. The Cibao Formation consists of rubbly sandy limestone interbedded with sandy clay and fossiliferous calcareous claystone (Monroe, 1977). The water-bearing unit consists mostly of the sand and gravel strata within the Quaternary alluvium and terrace deposits. Locally, the limestone beds of the underlying Cibao Formation, and farther inland the upper weathered zone of the undifferentiated igneous rocks, may be part of the water-bearing unit.

Ground water is under semi-confined conditions in CarHT2, and is primarily fresh except in some downstream areas of the Río Grande de Loíza where saltwater intrudes as far inland as the Highway PR-3 bridge. The unconsolidated Quaternary deposits of CarHT2 are hydraulically continuous with the Quaternary deposits of CarHT1 (fig. 4). Hydraulic conductivity data obtained from slug and recovery tests range from 4.6 to 17 ft/d. Transmissivity is reported to range from 200 to 600 ft^2/day in wells completed in unconsolidated deposits. The higher values correspond to zones composed of medium sand. Transmissivity is less than 200 ft^2/d, with values ranging mostly between 40 and 100 ft^2/d in wells open to the weathered, commonly fractured layer that caps underlying igneous rocks (Dames and Moore, 1999). Sustained yields to wells completed in the weathered and fractured igneous bedrock zone range between 20 and 50 gal/min.

CarHT3- This hydrogeologic terrane comprises rocks of the Aymamón and Aguada Limestones and minor amounts of the Limestone Member of the Guaracanal Formation. The Aymamón and Aguada Limestones are continuous and equivalent to the underlying limestone of CarHT1. Topographic slopes exceed 15 degrees in this terrane. The soil cover in CarHT3 is comparatively thin and locally absent. Because of its steep slopes and limited geographic extent, no wells have been drilled in this hydrogeologic terrane. However, the effective recharge rate for areas having similar hydrogeologic characteristics elsewhere in the north coast limestone belt is estimated to range mostly between 9 and 12 in/yr (Giusti, 1978). This hydrogeologic terrane may serve as a recharge area for CarHT1.

CarHT4- This hydrogeologic terrane consists of generally well-stratified volcaniclastic rocks (sandstone, breccia, and minor mudstone) with slopes generally exceeding 15 degrees. Small amounts of Quaternary alluvium may be present in the vicinity of streams. The soil cover ranges from 1.5 to 3 ft in thickness and the infiltration capacity ranges from 0.6 to 2.0 in/hr. In general, ground water moves preferentially along bedding planes and in the upper weathered zone. Fracturing is locally significant and may control ground-water movement. In the Quebrada Limones and Quebrada Lajas drainage basins, a fractured, brecciated volcanic sandstone contains water under confined conditions, which strongly suggests that the movement of ground water is controlled by fractures. Wells sited in this hydrogeologic terrane are restricted to slopes that do not exceed 15 degrees. Reported well yields range from 10 to 20 gal/min. Well yields may be higher in the vicinity of streams where yields are partially or entirely sustained from induced stream seepage. Ground-water flow estimates for CarHT4 range from negligible to 0.25 ft^3/s-mi^2, equivalent to an effective recharge that ranges from almost zero to 3 in/yr; however, the average effective recharge ranges between 1 and 2 in/yr (table 11).

CarHT5- This hydrogeologic terrane consists of volcanic mudstones, lavas, and intrusive rocks of Cretaceous and early Tertiary age. Slopes in this terrane generally exceed 30 degrees. The rocks in CarHT5 are generally massive with poorly developed stratification. This hydrogeologic terrane contains poor water-bearing unit unless fractures connected to recharge sources are present. A thin weathered zone in the intrusive rocks might serve as locally important water-bearing units. Neither the hydraulic properties nor the ground-water flow of the weathered zone in the intrusive rocks are known.

The hydrogeologic terranes with the highest ground-water development potential are CarHT1 and CarHT2, where gravels and sand beds within the Quaternary alluvium and Quaternary terrace deposits are the main water-bearing units. CarHT1 also includes potential aquifers within the underlying limestone units. CarHT2 may contain water-bearing strata in the upper weathered zone of the igneous bedrock and in the limestone units of the Cibao Formation. A synoptic survey of water levels measured in wells on August 11, 1998, indicated that ground-water levels ranged from 6 to 41 ft below land surface. The potentiometric map indicates that the Río Grande de Loíza acts as a major drain for CarHT1 and CarHT2 aquifers as inferred by the potentiometric surface (plate 2). Discharge from the aquifer to the streambed may have increased due to the effect of sand and gravel mining activities along the Río Grande de Loíza, which is suggested by the 3-ft closed contour shown on the potentiometric surface map in plate 2. Ground water may also discharge in wetland areas located at the Torrecilla Baja and Torrecilla Alta wards. CarHT3 has a limited ground-water development potential, largely because of its limited geographic extent and steep slope. Sections A-A' and B-B' (plate 2) show subsurface stratigraphic relations of CarHT1, CarHT2, and CarHT3. These three

Table 11. Hydrogeologic features of selected subbasins in the municipio of Carolina, Puerto Rico

[*, subbasin extends beyond the borders of the municipio of Carolina; mi^2, square miles; ft^3/s-mi^2, cubic feet per second per square mile; gal/min-mi^2, gallons per minute per square mile; in/yr, inches per year; <, less than]

Identification number and description of subbasin	Area (mi^2)	Ground-water flow (ft^3/s-mi^2) as derived from the Q-90 flow (gal/min-mi^2)[1]	Effective recharge (in/yr) as derived from the Q-90 flow	Ground-water flow (ft^3/s-mi^2) as derived from the Q-98 flow (gal/min-mi^2)[1]	Effective recharge (in/yr) as derived from the Q-98 flow	Hydrogeologic terranes that comprise the drainage subbasin, in order of areal extent
1. Río Canovanillas at Barrio Carruzos*	9.10	0.20 (90)	3	0.1 (45)	2	CarHT4, CarHT5
2. Quebrada Maracuto at Barrio Santa Cruz 8*	6.31	0.17 (80)	2	0.08 (40)	1	CarHT4, CarHT5
3. Quebrada Pastrana near Mariana at Barrio Cacao	0.79	0.25 (113)	4	0.13 (60)	2	CarHT4
4. Quebrada Pastrana near mouth at Barrio Cacao	1.25	0.10 (45)	1	< 0.1	< 0.1	CarHT4

[1] Streamflow equalled or exceeded 90 percent of the time.

hydrogeologic terranes are largely restricted to the lower Río Grande de Loíza coastal plain, where the terranes are hydraulically continuous (fig. 4). Elsewhere in the municipio of Carolina, only CarHT2 is present in an irregular, discontinuous pattern. Although CarHT4 has a lower ground-water development potential than CarHT1, CarHT2, and CarHT3, it exhibits a well-developed stratification with a predominant coarse-grained texture that, in general, tends to enhance the potential for storage and transmissivity. CarHT5, because of its fine-grained nature and poorly developed stratification, has the lowest ground-water development potential of all the hydrogeologic terranes in the municipio of Carolina. In both CarHT4 and CarHT5, however, the ground-water development potential may be locally enhanced by the presence of lineaments and associated fractures (plate 2), particularly, where these features intersect. The lineament traces were classified and grouped into two types. Shown in plate 2 and defined in table 10, the lineament types are described as follows:

Ls- lineament of structural or geologic significance, including, but not limited to fault traces, lithologic contacts, failure escarpments, and terrace surfaces, and

Lt- lineaments of unspecified origin including straight or linear mountain ridge tops, stream valleys, gullies or erosional surfaces near major river valleys.

As shown in plate 2, the mapped traces reveal the presence of structural lineaments (Ls) that form two distinct sets, based on the trend or azimuth. A substantial number of lineaments trend west and northwest with lengths varying between less than 0.6 to about 1.3 mi. The other set of Ls trend northeast, and are characterized by intersecting or terminating abruptly near or against the northwest-trending lineaments. In general, the Ls have most likely originated from either structural or pronounced lithologic or geomorphic changes on the ground surface. The topographic lineaments (Lt) identified follow straight and pronounced gullies or ridges, and do not appear to indicate geomorphic anomalies associated with geologic structures. However, further analysis could reveal that Lt are the result of concentrated erosion along pre-existing fractures or shear zones. In general, the majority of the traced lineaments in the municipio of Carolina highlands seem to be related to incised ravines and stream valleys, which are in turn related to the presence of linear structures, as indicated by field corroboration. According to the mapped lineaments, the highlands of the municipio of Carolina contain areas with potential for ground-water development. The most promising areas seem to be the entrenched valleys in the Quebrada Pastrana and Mariana Sectors. Another area with some ground-water development potential seems to be the stream valleys northeast of Barrazas, in the intersection between roads PR-853 and PR-856 (plate 2).

The possibility of saltwater intrusion may limit ground-water development in the more coastal portions of CarHT1. This may also be true for portions of CarHT2 because of its hydraulic continuity with CarHT1. During base-flow conditions, saltwater moves upstream along the Río Grande de Loíza and thins out near the Highway 3 bridge. Therefore, the potential for intrusion of saltwater into the aquifer is greatest in upstream areas of CarHT1 during base-flow conditions. This saltwater wedge also might seriously limit the fresh ground-water development potential in CarHT2. The ground-water development potential of CarHT1, CarHT2, and CarHT3 also is limited in the vicinity of the municipal landfill because of the threat of contamination.

The concentrations of major dissolved constituents were determined for water samples collected from 10 wells completed in CarHT1 and CarHT2 and from the Pozo las 400 and Barrazas municipio public -supply wells completed in CarHT4 (table 9). Concentrations of manganese exceeded United States Environmental Protection Agency secondary standards (50 micrograms per liter (μg/L)) for drinking water at all wells except at Car-13 and Pozo Las 400 (table 9) (U.S. Environmental Protection Agency, 1973). The concentrations of dissolved iron exceeded the secondary standard of USEPA (300 μg/L) at the Car-5, Car-2, Car-12, and Pozo Las 400 well sites. The hardness of sampled water (an indicator of the concentrations of calcium and magnesium and expressed as $CaCO_3$) is generally high. Additionally, the sanitary quality of most surface waters in the municipio of Carolina (see chapter B) indicates that wells completed in bedrock units or outliers of CarHT2 near streams are highly susceptible to contamination by fecal material.

SUMMARY AND CONCLUSIONS

To meet the need for an adequate supply of safe drinking water, the USGS in cooperation with the Office of the Mayor of the Municipio of Carolina, conducted an integrated surface-water, water-quality, and ground-water assessment of the municipio of Carolina. Because the supply of safe drinking water becomes critical during dry periods, the surface-water assessment focused on low-flow characteristics of streams in the municipio of Carolina.

Low-flow and flow-duration characteristics were evaluated at one continuous-record gaging station and seven partial-record stations (tables 1, 2). The continuous-record station is located along Río Canóvanas, a second-order tributary to the Río Grande de Loíza. The seven partial-record stations are distributed among three second-order and one third-order streams with drainage to the Río Grande de Loíza (plate 1). Streamflow-frequency analysis indicates that for two of the stations, a discharge of about 0.1 ft^3/s was equalled or exceeded 99 percent of the time. Analysis indicates that the surface-water discharge of 1.6 ft^3/s in Quebrada Grande at the Río Grande de Loíza was equalled or exceeded 99 percent of the time, which is equivalent to a yield per unit area of 0.12 $ft^3/s\text{-}mi^2$. This yield is relatively high when compared to the 99th percentile exceedance of about 0.05 $ft^3/s\text{-}mi^2$ for the Quebrada Maracuto and Río Canovanillas drainage basins.

In addition to low-flow analysis in the surface-water assessment, important surface-water resource information was compiled, including the location of a potential reservoir site, flood-hazard areas, water-supply filtration plants (active or under construction), public waste-water treatment facilities (active and closed), drainage-basin boundaries, and stream-gaging station locations (plate 1). The stream low-flow statistics document the general hydrology under current land and water uses. Low-flow characteristics may substantially change as a result of streamflow diversions for public supply, increase in ground-water development, waste-water discharges, land-use changes, and flood-control measures; the current analysis provides baseline information to determine future impacts and to develop water budgets. For example, during the period of this water-resources assessment, several major hydrologic modifications were underway that will affect the flow of surface water in the near future. Among these is the construction of a new 2.0-Mgal/d filtration plant with an intake in the Río Grande de Loíza upstream of highway PR-3. A new 10.0-Mgal/d filtration plant is being constructed in the adjacent municipio of Canóvanas; the new filtration plant will be supplied from both Río Canovanillas and Río Canóvanas, and will possibly replace the Canóvanas urban filtration plant.

All perennial streams in the municipio of Carolina are classified as Class SD waters on the basis of their designated use. This classification applies to surface waters intended for use (or with the potential for use) as a raw water source of public supply, propagation and preservation of desirable aquatic species, as well as primary and secondary contact recreation. With the exception of surface waters used for primary contact recreation, the sanitary quality standard (goal) for Class SD waters in Puerto Rico is primarily based on fecal coliform concentrations (Junta de Calidad Ambiental de Puerto Rico, 1990). To meet the sanitary quality standard, the fecal coliform geometric mean concentration obtained from five samples collected in sequential order should not exceed 2,000 colonies per 100 mL, and not more than one in five should exceed a concentration of 4,000 colonies per 100 mL.

The results of long-term monitoring of bacterial concentrations of surface water at two sites, Quebrada Blasina in Carolina and Río Grande de Loíza below the town of Trujillo Alto (upstream of Carolina), indicate that the sanitary quality is generally poor in Quebrada Blasina. Whereas, the sanitary quality in the Río Grande de Loíza has generally been in compliance with the fecal coliform sanitary quality goal established in July 1990. For this study, a sanitary quality survey was conducted during base-flow conditions primarily to define fecal waste pollution from sources that discharge directly to or in the vicinity of stream courses. A qualitative classification method was developed and was primarily based on the fecal coliform concentration goal established for Class SD surface waters by the Junta de Calidad Ambiental de Puerto Rico (1990). The method was applied to rank the sanitary quality at sampling stations where at least two samples were obtained during stream base-flow conditions.

Because only 29 sampling stations were used to delimit the sanitary quality of approximately 87 stream miles, it was necessary to develop a rationale to interpolate and extrapolate station rankings. This required using the prefix **presumed** before each of the rankings, because the bacteriological concentrations at various sampling stations along a given stream reach were significantly different at distances as little as 0.6 mile. In summary, 87 of the 91 stream miles with drainage to or within the municipio of Carolina were ranked as follows: 29.4 miles, **poor**; 50.0 miles, **fair**; and 16.6 miles, **acceptable**. No stream segment in the study area was ranked as **good**. The geometric mean of fecal coliform and fecal streptococcus concentrations (in number of colonies per 100 mL) for each of the established rankings were as follows: **poor** –16,208 and 7,744; **fair** –2,015 and 1,148; and **acceptable** –333 and 305, respectively.

Based on more than 14 years of field observations and hydrologic analysis in the Carolina area, it may be inferred that the stream courses classified as **poor** (or **presumed poor**) are contaminated from continuous sources of fecal contamination, and those classified as **fair** (or **presumed fair**) and **acceptable** (or **presumed acceptable**) from intermittent sources. In urbanized areas, potential sources of fecal contamination include illegal discharge of sewage to stormwater drains especially within the older sectors of the municipio of Carolina; overflows from sewer mains into the stormwater drains as a result of malfunctioning sanitary sewer ejectors or clogged mains; ruptured sewer mains; and leakage from sewer mains into the local aquifer. In rural areas, potential sources of fecal contamination include gray-water discharges (gray water includes all waste water from household uses except sanitary wastes) from residences and commercial establishments along stream channels; septic tank leakage or overflows; feces contamination directly into streams by unfenced livestock; and, runoff from unrestrained livestock pens near stream courses.

The stream segments with the greatest potential for development as surface- and ground-water sources are those classified as **acceptable**. However, if upstream from these segments there are parts of the stream classified as "riparian zone with potential as a source of contamination from household waste-water discharges," then development of ground-water supplies in aquifers adjacent to these streams should not be encouraged without (a) more detailed analysis of bacteriological conditions to define diurnal variations and the application of more sensitive microbiological determinations, such as recovery enhancement tests for fecal coliform and fecal streptococcus bacteria, and (b) more in-depth evaluation of the bacteriological attenuation capacity of the ground-water bearing units. In addition, a more rigorous surface-water monitoring program, including fecal coliform, fecal streptococcus, and other indicator bacteria would be important to define the variability and sources of contamination in order to implement corrective measures.

The municipio of Carolina was differentiated into five principal hydrogeologic terranes based on geologic, topographic, soil, hydrogeologic, and streamflow data. The CarHT1 hydrogeologic terrane consists mainly of Quaternary surficial deposits and the underlying Tertiary Aymamón and Aguada Limestones. CarHT2 consists of Quaternary alluvium and terrace deposits underlain by the Cibao Formation and undifferentiated igneous rocks. CarHT3 is composed of the Aymamón and Aguada Limestones, and to a lesser extent the Limestone Member of the Guaracanal Formation. CarHT4 consists of generally well-stratified volcaniclastic rocks with a varying topographic slope. CarHT5 consists of volcanic mudstone, lavas, and igneous intrusive rocks.

The CarHT1 and CarHT2 hydrogeologic terranes do not have slopes greater than 15 degrees and are generally restricted to low-lying areas. The other hydrogeologic terranes (CarHT3, CarHT4, and CarHT5) have slopes that commonly exceed 15 degrees. In CarHT4, ground water moves preferentially along bedding planes, locally along fractures, and within an upper zone of weathered material. Locally, CarHT5 can be an important water-bearing unit because of the presence of fractures. The hydrogeologic terranes CarHT1, CarHT2, and CarHT3, are potentially affected by saltwater intrusion. The Río Grande de Loíza acts as a substantial drain to the aquifers comprising CarHT1 and CarHT2.

Concentrations of iron and manganese locally exceed secondary standards for drinking water as established by the United States Environmental Protection Agency. Because poor sanitary conditions are likely in surface waters of the municipio of Carolina (see Chapter B), water-supply wells installed adjacent to these streams are susceptible to fecal bacteria contamination.

Studies indicate that in relatively impermeable formations, the maximum development of transmissivity occurs at the intersection of fractures. Consequently, when selecting potential sites for wells, preference should be given to areas with a high density of fractures or fracture intersections. Therefore, lineament analysis could substantially reduce costs and increase yields over wells located by the trial-and-error method, particularly in hydrogeologic terranes CarHT4 and CarHT5.

The results of this integrated surface-water, sanitary quality, and ground-water study presented in this report can be used as an integral part of the territorial development plan of the municipio of Carolina and contribute to implementation of measures for the sustainable development of surface- and ground-water resources. This systematic study also establishes baseline hydrologic information for the municipio of Carolina to monitor future changes in water availability and to evaluate the relation between land use, water use, and water availability.

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