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PUERTO RICO ENVIRONMENTAL QUALITY BOARD

Assessment of Nitrate Contamination of the Upper Aquifer in the Manatí-Vega Baja Area, Puerto Rico

Water-Resources Investigations Report 99-4040

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By Carlos Conde-Costas and Fernando Gómez-Gómez

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San Juan, Puerto Rico: 1999

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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic meter per day (m^3/d)	264.2	gallon per day
cubic meter per second (m^3/s)	35.31	cubic foot per second
cubic meter per year (m^3/y)	0.0008107	acre-foot per year
gram per day (g/d)	0.002204	pound per day
hectare (ha)	2.471	acre
kilogram (kg)	2.204	pound
kilogram per hectare per year (kg/ha·y)	0.8193	pound per acre per year
kilometer (km)	0.6214	mile
liter (L)	0.2642	gallon
liter per second (L/s)	15.85	gallon per minute
meter (m)	3.281	foot
meter squared per day (m^2/d)	10.76	foot squared per day
meter per kilometer (m/km)	5.280	foot per mile
millimeter	0.03937	inch
millimeter per year (mm/y)	0.03937	inch per year
square kilometer (km^2)	0.3861	square mile

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

°F = (°C x 1.8) + 32

Abbreviated water-quality units used in report:

mg/L	milligrams per liter
µg/L	micrograms per liter
‰	per mil

Acronyms used in report:

NCCD	North Coast Climatic Division
PRASA	Puerto Rico Aqueduct and Sewer Authority
PRDOH	Puerto Rico Department of Health
PREQB	Puerto Rico Environmental Quality Board
USGS	U.S. Geological Survey

Assessment of Nitrate Contamination of the Upper Aquifer in the Manatí-Vega Baja Area, Puerto Rico

By **Carlos Conde-Costas** *and* **Fernando Gómez-Gómez**

Abstract

A ground-water resources assessment was conducted between 1992 and 1995 to define the quality of ground water within the upper aquifer, especially the areal concentration of nitrates and to estimate the nitrate loads from the principal potential sources. A general water-quality assessment was made of the entire Manatí, Puerto Rico 7.5-minute topographic quadrangle. An area of about 33 square kilometers that constitutes the part of the upper aquifer with drainage to the Laguna Tortuguero was studied in more detail.

Nitrate in ground water in the study area is derived primarily from fertilizer used in the cultivation of pineapples and from septic tank effluent in rural communities. In the part of the Laguna Tortuguero ground-water drainage basin overlying the upper aquifer, approximately 600 hectares are used for pineapple cultivation, and 255 hectares consist of rural un-sewered communities. Potential nitrate loads from these land uses were estimated to be 760 kilograms of nitrogen per hectare per year from cultivated pineapple fields, and 200 kilograms of nitrogen per hectare per year from un-sewered rural communities. Of the potential nitrate load accounted in fertilizer use at the pineapple farms, an average of 210 kilograms of nitrogen per year is incorporated by the plants or mineralized in soil, and an estimated 550 kilograms of nitrogen per hectare per year is available for volatilization or leached from fields. It is possible that of the 550 kilograms of nitrogen per hectare per year only an average of 45 kilograms of nitrogen per hectare per year may result in nitrate load to the upper aquifer. Much of the un-accounted 550 kilograms of nitrogen per hectare per year is possibly contained in transient storage within the vadose zone.

The results of the study indicate that the part of the upper aquifer with nitrate-nitrogen concentrations near or above 10 milligrams per liter is contained primarily within the Laguna Tortuguero ground-water drainage basin. The nitrate concentrations in the upper aquifer down-gradient of the area of greatest nitrate load are between 6.8 and 10.0 milligrams per liter, and ground water beneath the Parcelas Marquez rural community may have an average nitrate concentration equal to about 23 milligrams per liter. Storm runoff from urban sewered areas is not a major source of nitrate to the aquifer and was found to have mean nitrate concentrations ranging from 0.02 to 0.63 milligram per liter. Storm runoff from pineapple fields had mean nitrate concentrations that ranged from 3.4 to 14.6 milligrams per liter with concentrations generally increasing in direct relation to the duration of the storm runoff event. A concentration of 10 milligrams per liter was found to occur in most storm runoff events lasting at least 60 minutes.

INTRODUCTION

The Manatí-Vega Baja area, located within the Manatí, Puerto Rico 7.5-minute topographic quadrangle in north-central Puerto Rico, has been subjected to extensive agricultural, industrial, and urban development (fig. 1). Three main hydrogeologic units compose the area's limestone aquifer system: an unconfined upper aquifer, a middle confining unit, and a confined lower aquifer. This study involves only the upper aquifer, where nitrate concentrations exceeding the drinking water standard of 10 milligrams per liter (mg/L) of nitrate as nitrogen (NO_3-N) (U.S. Environmental Protection Agency, 1990, 1995) have resulted in the abandonment of public water-supply wells.

The upper limestone aquifer underlying the northern half of the quadrangle is the principal source of water in the area, providing approximately 37,000 cubic meters per day (m^3/d) for public supply, 4,900 m^3/d for industrial self-supplied use, and an estimated 900 m^3/d for agricultural use (Conde-Costas and Rodríguez-Rodríguez, 1997). Public-water supply withdrawals within the Manatí quadrangle area constitute about 70 percent of the total public water-supply withdrawals within the municipalities of Manatí and Vega Baja.

Since the early 1980's, NO_3-N concentrations exceeding 10 mg/L have been documented at wells in the Manatí-Vega Baja area (Gómez-Gómez and Guzmán-Ríos, 1982; Guzmán-Ríos and Quiñones-Márquez, 1984, 1985; Román-Más and Ramos-Ginés, 1988). Between 1988 and 1990, NO_3-N concentrations equal to or exceeding 10 mg/L were detected at three public-water supply wells located within the same general area (Barrio Coto Sur at Manatí). These findings led to the closure of the three public-supply wells, resulting in a lost production of 3,900 m^3/d. The use of fertilizers in pineapple fields (the main agricultural activity), septic tank discharges, livestock facilities, and illegal dump sites were considered to be the most probable causes of the high nitrate concentrations detected at the affected public water-supply wells (Puerto Rico Environmental Quality Board, 1992). Storm-runoff conveyed into sinkholes from agricultural and urban areas through drainage ditches and storm-runoff sewers was suspected of exacerbating the problem in localized areas.

Purpose and Scope

The U.S. Geological Survey (USGS) in cooperation with the Puerto Rico Environmental Quality Board (PREQB), conducted a ground-water quality assessment in the Manatí-Vega Baja area between 1992 and 1995. The purpose of the study was to (1) define the ground-water quality conditions of the upper aquifer in the Manatí-Vega Baja area, specifically as to the areal distribution of nitrate and to identify the principal potential sources of the contaminant; (2) estimate the nitrate loads from major sources identified; and (3) characterize the quality of runoff, in terms of nitrate concentration, from pineapple fields and from urban sewered areas.

This report documents the techniques and procedures used in the acquisition and interpretation of water-quality and hydrogeologic data. Also included is the ancillary data obtained from other sources or previous studies in the area, such as, ground-water withdrawals, water use for domestic purposes, discharge from Laguna Tortuguero through the ocean outlet channel, and fertilizer use at pineapple fields to support the findings.

The Manatí-Vega Baja area referred to in this report is located within the Manatí 7.5-minute topographic quadrangle. The study focuses on an area of about 33 square kilometers (km^2) that constitutes the part of the Laguna Tortuguero drainage basin as defined by Bennett and Giusti (1972) that overlies the upper aquifer (fig. 2). Specifically, the study focuses on the area north of latitude 18°25' and south of highway PR-2, where high nitrate concentrations have been detected. North of latitude 18°25' the hydrogeologic units that constitute the upper aquifer become saturated with water. The southern part of the Laguna Tortuguero drainage basin (south of latitude 18°25'), with an area of about 47 km^2, was included as part of a general ground-water quality assessment.

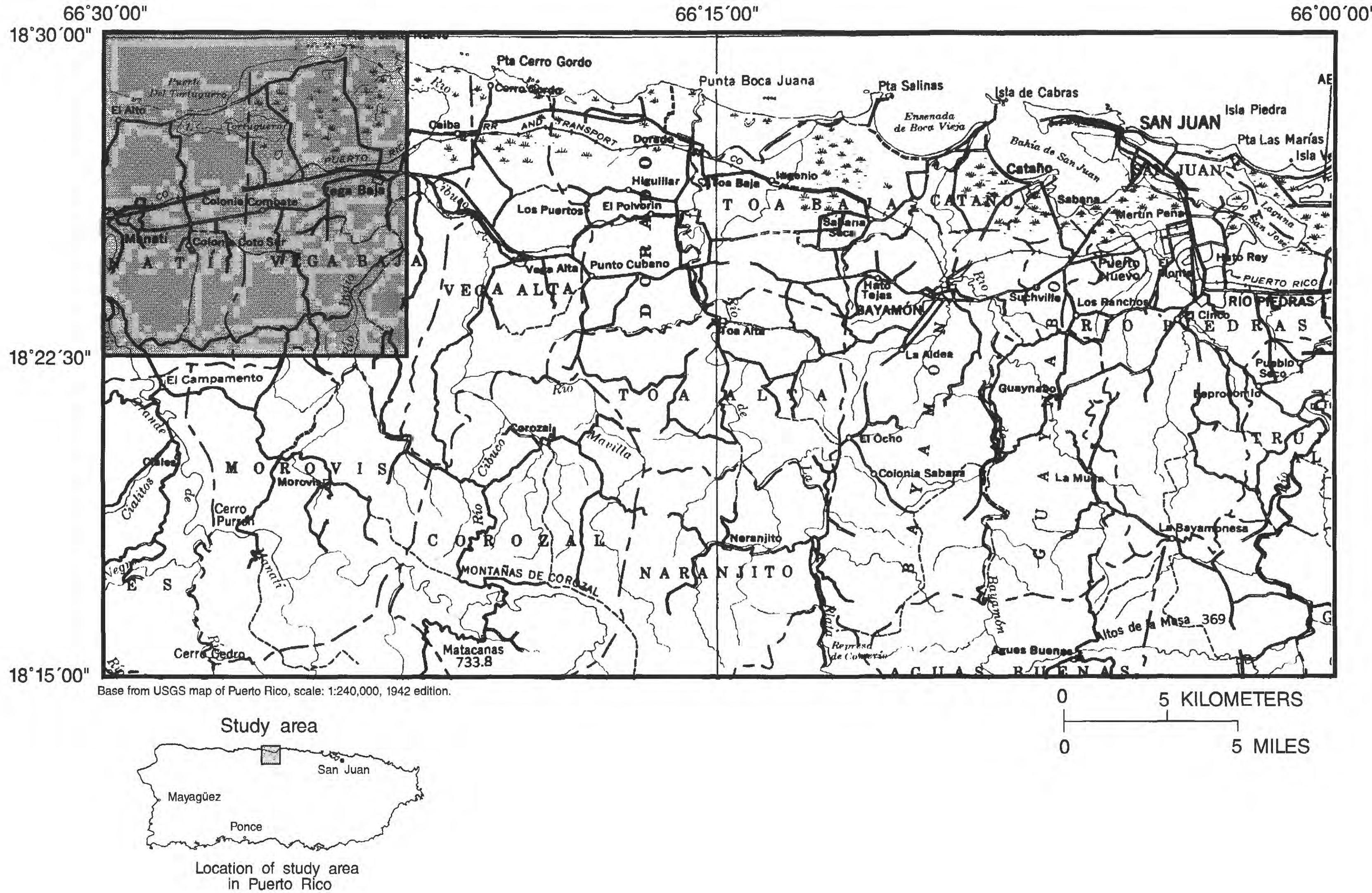


Figure 1. Location of the Manatí quadrangle area in north-central Puerto Rico.

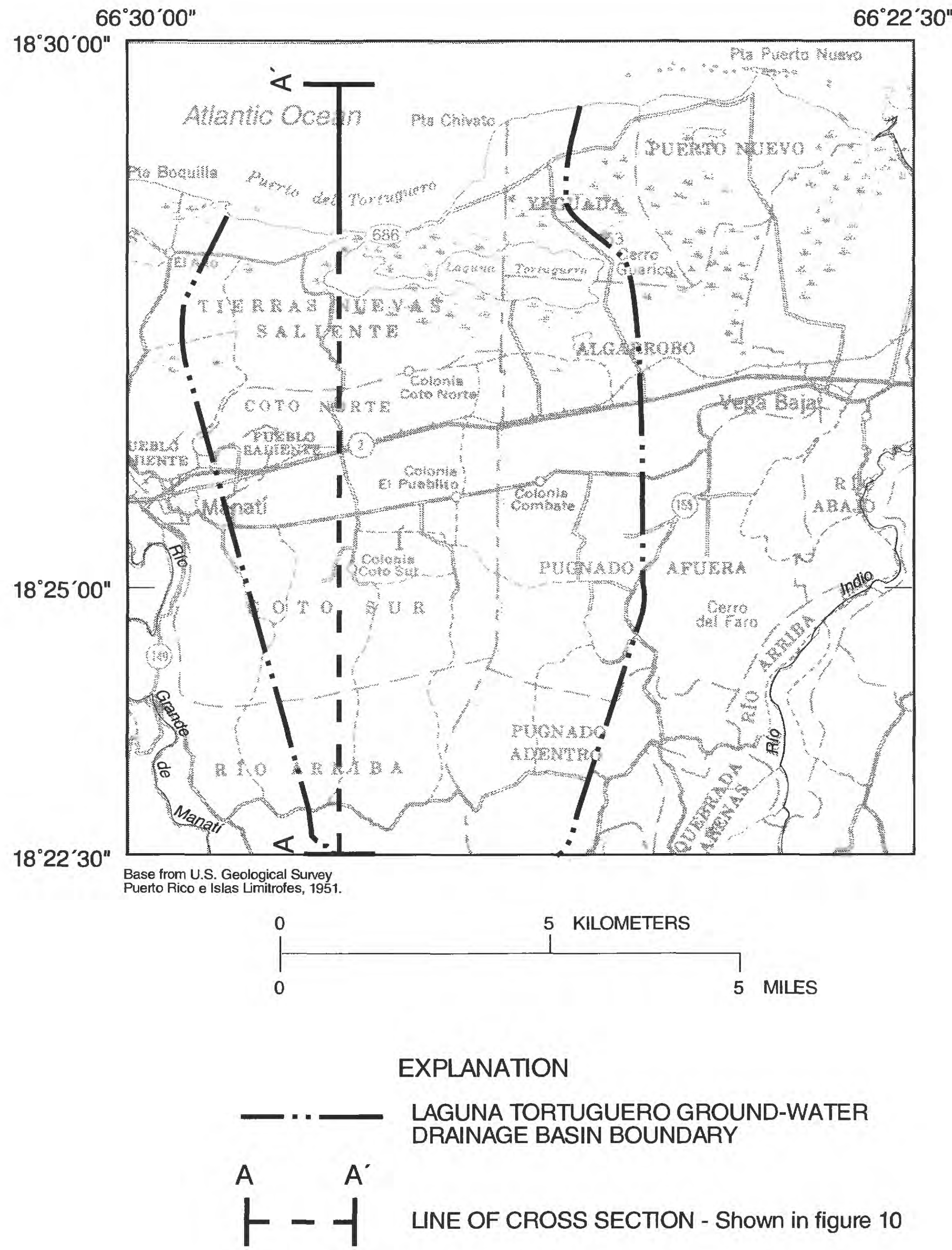


Figure 2. The Manatí quadrangle area and the Laguna Tortuguero ground-water drainage basin in the north-central Puerto (drainage basin as defined by Bennet and Guisti, 1972).

Methods and Procedures

Prior to this assessment, ground-water quality data were sparse in the Manatí-Vega Baja area. Therefore, ground-water samples were obtained at 29 wells, one spring, and one intermittently flowing stream to define existing ground-water and surface-water conditions (table 1; fig. 3). Water samples were analyzed for common ions, trace metals, nutrients, selected stable isotopes (deuterium, oxygen-18, sulfur-34, and nitrogen-15), pesticides, and synthetic organic compounds. Field determinations were made for pH, temperature, specific conductance, and total alkalinity (as calcium carbonate, $CaCO_3$). All samples obtained for determination of common ions, trace metals, and nutrients were filtered on-site through a 0.45 micron inert filter. Results of the synoptic water-quality survey, conducted between August 25 and November 12, 1992, are reported by Conde-Costas and Rodríguez-Rodríguez (1997). Throughout this report, all references to nitrate refer to dissolved nitrate reported as nitrogen. All samples were analyzed at the U.S. Geological Survey laboratories in Arvada, Colorado and Ocala, Florida. Procedures and methods for on-site and laboratory measurements and for collecting, treating and shipping samples are given in publications in the series "Techniques of Water Resources Investigations of the U.S. Geological Survey" (Wood, 1976; Skougstad and others, 1979; Wershaw and others, 1987).

Six observation wells were drilled in order to obtain ground-water quality data within agricultural areas and to supplement existing potentiometric data. One observation well was drilled upgradient from the pineapple farms (Perica), three were drilled within and downgradient of the area at which elevated nitrate concentrations have caused the abandonment of several public water-supply wells (Palo Alto 2, Hill 1 and Hill 2). Two of the observation wells were drilled adjacent to sinkholes (Palo Alto 1 and Palo Alto 3). The observation wells were constructed to a maximum depth of about 54 meters (m) below the water table. They were cased with 10.2 centimeter (cm) inside diameter PVC pipe and screened with a slotted PVC casing within the saturated zone.

A monthly sampling program to monitor seasonal changes, in nitrate concentrations was established from June 1994 to May 1995 at nine active wells (wells 8, 9, 13, 14, 16, 17, 25, 29, and 36; fig. 4). Ground-water levels measured during March 1995 at 34 selected wells were used to construct a potentiometric-surface map of the upper aquifer showing the configuration of the water table and ground-water withdrawal rates (Conde-Costas and Rodríguez-Rodríguez, 1997). The potentiometric-surface map was used to determine the general direction of ground-water flow in the study area and to provide the basis in defining nitrate contamination sources affecting wells sampled.

In order to provide data for assessing nitrate (NO_3) contamination sources, the stable isotope ratio of nitrogen-15 to nitrogen-14 ($^{15}N/^{14}N$) was analyzed from samples obtained at 21 selected wells. The procedure measures the relative ratio of the rare nitrogen isotope (^{15}N) to the common or lighter isotope (^{14}N). Stable nitrogen isotope analyses were performed by the mass spectrometry method at the USGS Central Laboratory in Arvada, Colorado. Concentrations are reported relative to a standard (atmospheric nitrogen) as delta (δ) values in units of per mil (‰), $\delta\ ^{15}N\ (‰) = [(R-R_{standard})/R_{standard}] \times 1{,}000$, where R and $R_{standard}$ are the isotopic ratios, $^{15}N/^{14}N$, of the sample and standard, respectively. Results can be qualitatively related to contamination from fertilizer or animal waste (Kreitler and others, 1979).

Land use was considered in the study in order to define potential nitrate contamination sources. Among the land uses with potential for nitrate contamination of the upper aquifer are agricultural areas under cultivation, fertilizer storage facilities, livestock facilities, closed municipal landfills, and rural communities with a high density of septic tanks. However, on an areal basis the most important nitrate sources are the agricultural areas under pineapple cultivation and the rural communities without sewer service. The relative contribution of nitrate to the upper aquifer from domestic wastewater disposal in rural communities and fertilizer use at pineapple fields was obtained from mass balance calculations.

Table 1. Identification and construction characteristics of wells within the Manatí quadrangle, Puerto Rico

[n/a, not applicable; n/d, no data; (?), unknown date of measurement; ddmmss, degree-minute-second; obs., observation; (a), spring; (b), surface water; quality of water analyses published by Conde-Costas and Rodríguez-Rodríguez (1997)]

Map number (fig. 3)	Well name	Latitude (ddmmss)	Longitude (ddmmss)	Depth of well, to nearest meter	Depth to static water level, nearest meter (year)	Site sampled in synoptic survey	
						Yes	No
1	Río Arriba 3	18°23'12"	66°27'49"	67	38 (1995)	X	
2	Río Arriba 2	18°23'16"	66°27'36"	91	35 (1995)	X	
3	Catala	18°23'20"	66°25'52"	46	n/d	X	
4	Beauchamp	18°23'28"	66°25'29"	n/d	11 (1985)	X	
5	Escalfullery	18°25'30"	66°28'53"	122	69 (?)	X	
6	Monserrate Sur	18°24'12"	66°29'49"	55	9 (1995)	X	
7	Perica	18°24'26"	66°26'04"	128	74 (1995)		X
8	Hill 1	18°25'06"	66°28'02"	125	89 (1995)		X
9	Mónaco	18°25'15"	66°29'01"	152	76 (1995)	X	
10	Hill 2	18°25'16"	66°28'24"	105	82 (1995)		X
11	Palo Alto 1	18°25'31"	66°26'26"	122	78 (1995)		X
12	Roche artesian well	18°25'38"	66°27'59"	625	n/d		X
13	Coto Sur 1	18°25'40"	66°27'54"	91	71 (1995)	X	
14	Coto Sur 6	18°25'42"	66°27'36'	145	74 (1995)	X	
15	Pugnado Afuera 2	18°25'45"	66°24'38"	104	74 (1995)	X	
16	Coto Sur 5	18°25'46"	66°27'12"	152	81 (1995)	X	
17	Coto Sur Warehouse	18°25'46"	66°27'30"	n/d	79 (1995)	X	
18	Palo Alto 3	18°25'48"	66°25'10"	98	75 (1995)		X
19	Pugnado Afuera 3	18°25'50"	66°26'18"	n/d	76 (1995)		X
20	Coto sur 2	18°25'52"	66°26'47"	119	79 (1995)	X	
21	Pugnado Afuera 1	18°25'53"	66°24'29"	46	n/d	X	
22	Coto Sur 3	18°25'54"	66°27'49"	66	73 (1995)	X	
23	Manatí 3	18°26'05"	66°29'25"	61	20 (1984)	X	
24	Palo Alto 2	18°26'14"	66°26'15"	94	73 (1995)		X
25	Procter & Gamble	18°26'15"	66°27'35"	73	53 (1995)	X	
26	Alturas	18°26'16"	66°24'10"	n/d	67 (1985)	X	
27	Córdova Dávila	18°26'17"	66°29'02"	61	28 (?)	X	
28	Atenas	18°26'30"	66°27'40"	73	46 (?)	X	
29	Sobrino	18°26'34"	66°25'48"	122	49 (1983)		X
30	Marista	18°26'38"	66°27'22"	n/d	14 (1970)		X
31	Vega Baja 3	18°26'44"	66°24'05"	43	24 (1995)	X	
32	Owens Illinois	18°26'43"	66°26'02"	n/d	27 (1995)		X
33	Vega Baja 4	18°26'47"	66°23'59"	n/d	23 (1995)		X
34	Vega Baja 2	18°26'51"	66°24'16"	37	23 (1969)	X	
35	Ojo de Agua (a)	18°26'57"	66°25'06"	n/a	n/a	X	
36	Jacinto Cubano	18°27'01"	66°29'02"	n/d	n/d		X
37	Cruz Rosa Rivas	18°27'05"	66°29'52"	n/d	36 (1995)	X	
38	Rabanos	18°27'14"	66°29'24"	49	34 (1995)	X	
39	NC-9	18°27'35"	66°23'43"	469	3 (1987)	X	
40	Boquillas	18°27'51"	66°29'37"	40	12 (?)	X	
41	Quebrada (b)	18°23'05"	66°26'49"	n/a	n/a	X	

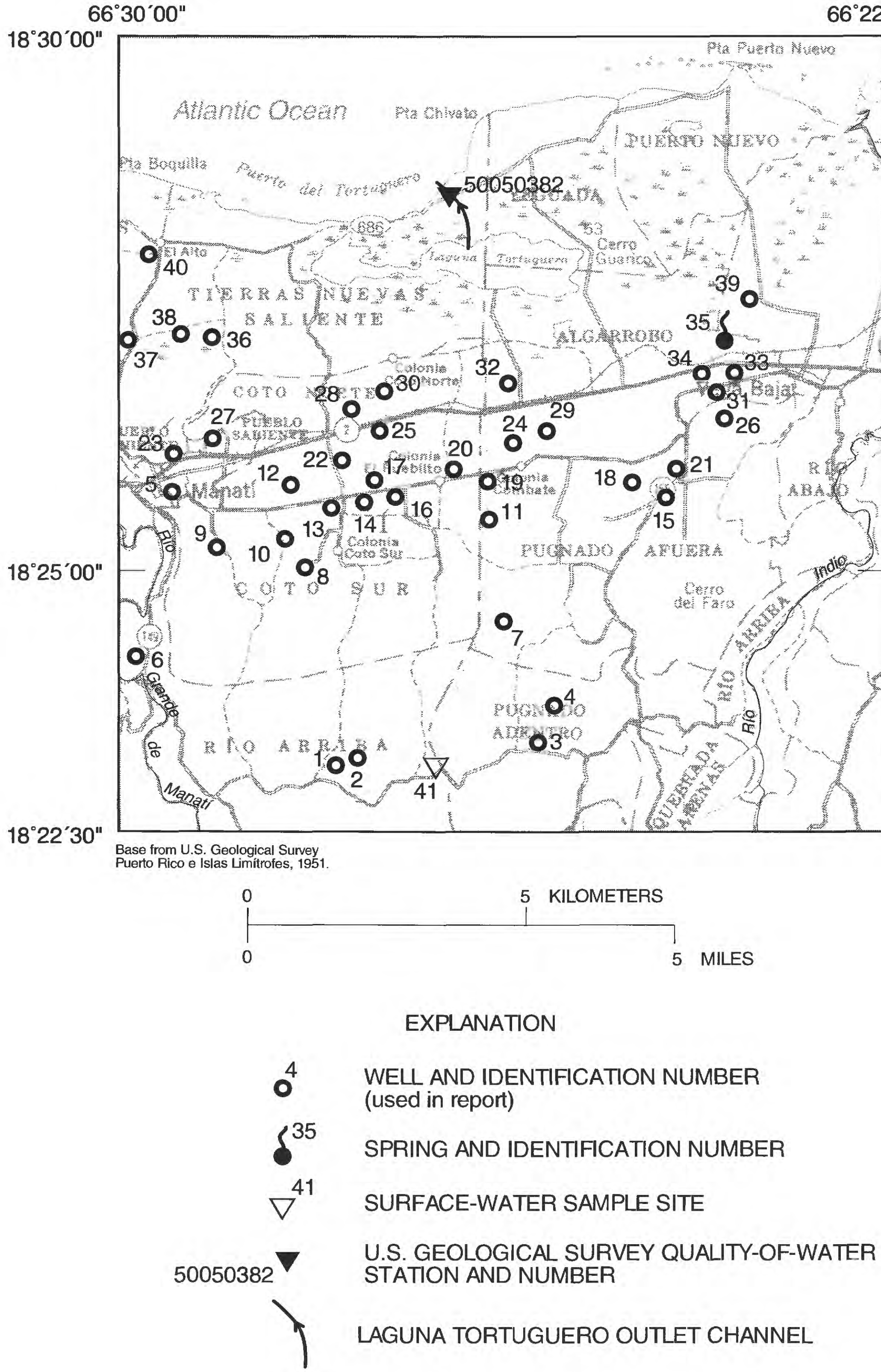


Figure 3. Location of wells, springs, and surface-water sites sampled in the Manatí quadrangle area, north-central Puerto Rico.

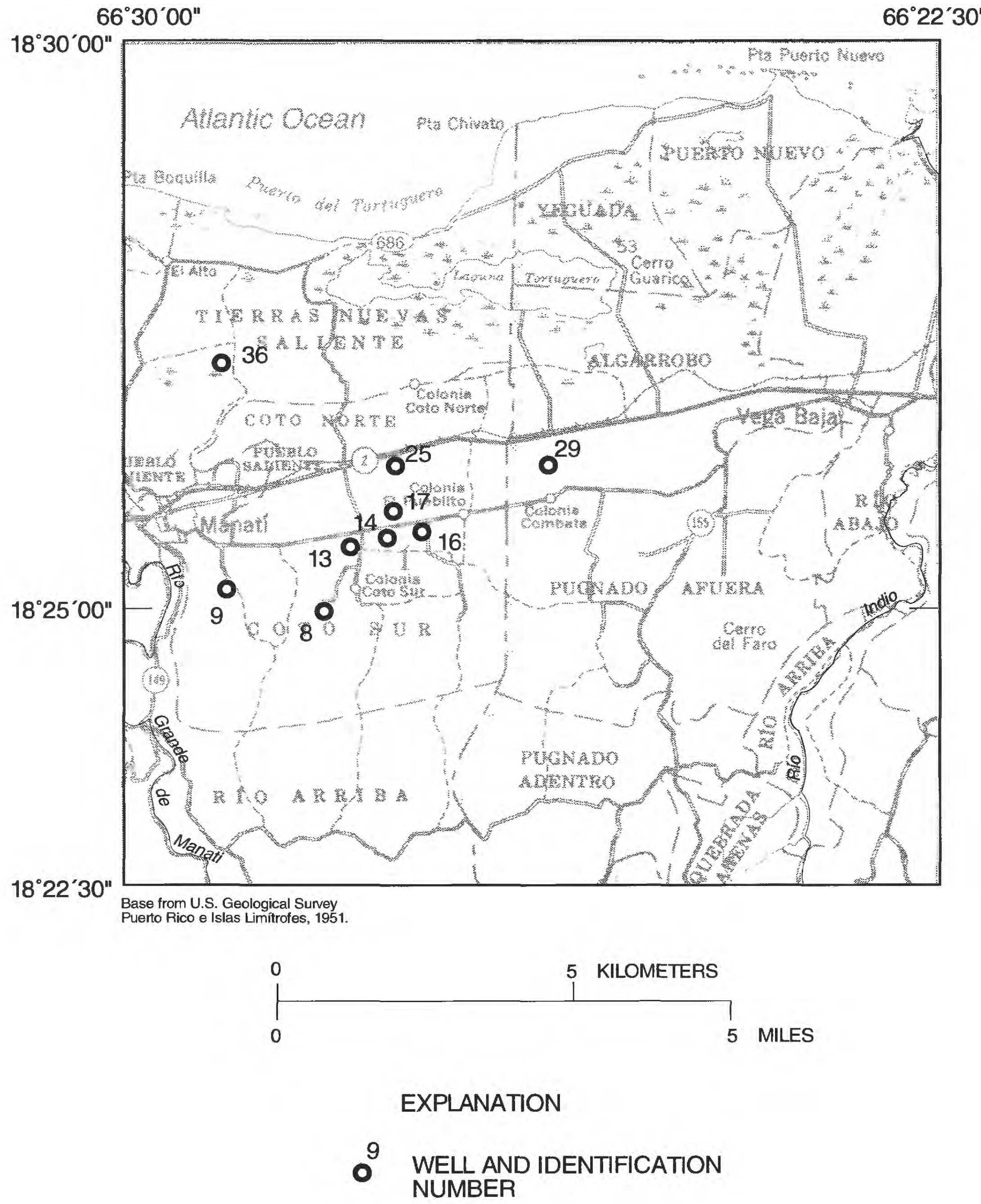


Figure 4. Wells sampled on a monthly basis to define seasonal variation in nitrate, Manatí quadrangle area, north-central Puerto Rico.

The estimated household wastewater discharge to septic tanks was estimated from domestic water use data available for 1982 for public-water supply unsewered customers (Torres-Sierra and Avilés, 1986). The per capita total nitrogen excreted by humans, which averages 17 grams per day (Kaplan, 1987), was used in calculating the maximum potential nitrate load from septic tanks to the sub-surface. Current nitrogen fertilizer application rates and procedures were provided by the Puerto Rico Land Authority, Pineapple Program (W. Gandía-Torres, Puerto Rico Land Authority, Pineapple Program, written commun., 1995). Two surface-water monitoring stations were established in the study area to characterize the nitrate concentration of storm runoff from an urban-sewered area and a pineapple farm area draining into sinkholes.

Acknowledgments

The authors acknowledge the valuable cooperation of the mayor of the municipality of Manatí, Honorable Juan Aubín-Manzano and his staff, and the Comité Timon de Calidad Ambiental de Manatí (COTICAM), especially its president, Frank Coss, for making the necessary arrangements for informational meetings between residents of Manatí, government agencies, and local industries related to the nitrate contamination of the local aquifer. Appreciation is extended to agronomist, Walter Gandía-Torres of the Puerto Rico Land Administration, Pineapple Program, for his valuable assistance and support throughout the investigation. Also, our appreciation is extended to landowners of the Manatí-Vega Baja area who provided access to their property and other support necessary to conduct this assessment.

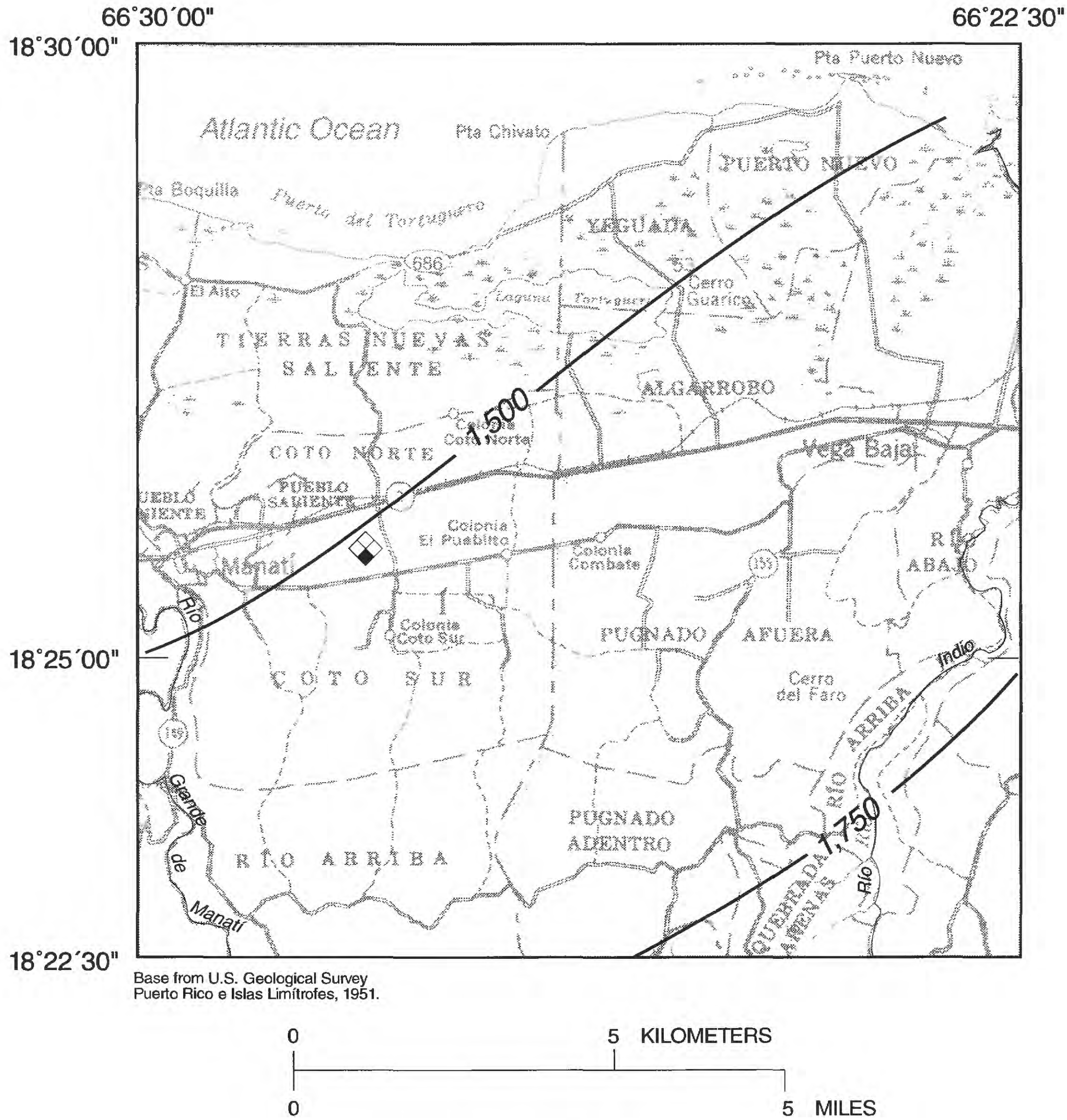
DESCRIPTION OF THE STUDY AREA

Climate

The Manatí quadrangle area lies within the North Coast Climatic Division (NCCD) of Puerto Rico as classified by the U.S. National Weather Service (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1982). The NCCD is characterized as a flat-coastal land exposed to the trade winds which blow almost constantly from the northeast. Mean monthly temperatures on the north coast vary by only 3 degrees Celsius (°C) from an annual mean temperature of about 25.5 °C. The mean annual rainfall in the study area increases inland from slightly less than about 1,500 millimeters (mm) near the coast to as much as 1,750 mm south of the town of Manatí (fig. 5). Rainfall records from the long-term National Weather Service meteorological station at Manatí identify a relatively dry season from December to April, with February and March commonly being the driest months. A relatively wet period occurs from May to November, with November commonly being the wettest month (fig. 6). Rainfall statistics for Arecibo, about 20 kilometer (km) west of Manatí and within the same climatic division, indicate that annually, on average, rainfall equals or exceeds 2.5 mm on about 99 days and 5 mm on about 36 days (National Weather Service records, 1951-75). Rainfall events of 2.5 mm per day or more occur on an average of 10 days per month from October through December, and 5 days per month in February and March.

Physiographic Features

The Manatí quadrangle is located within the North Coastal Plain and the Interior Limestone Belt of the Northern Humid Foothills geographic regions of northern Puerto Rico (fig. 7). These regions extend eastward from Aguadilla in northwest Puerto Rico to Luquillo, a distance of about 150 km (Picó, 1975). The north coast limestone belt, however, only extends from Aguadilla to Toa Alta, a total distance of about 100 km, having its maximum width of about 18 km near Camuy. Within the Manatí quadrangle, the north coast limestone belt includes the area generally to the south of the town of Manatí.



EXPLANATION

— 1,750 — LINE OF EQUAL RAINFALL, VALUES IN MILLIMETERS PER YEAR. Contour interval 250 millimeters

◈ NATIONAL WEATHER SERVICE PRECIPITATION OBSERVATION STATION

Figure 5. Mean annual rainfall distribution in the Manatí quadrangle, north-central Puerto Rico (modified from rainfall distribution map of Puerto Rico by Colón, 1983).

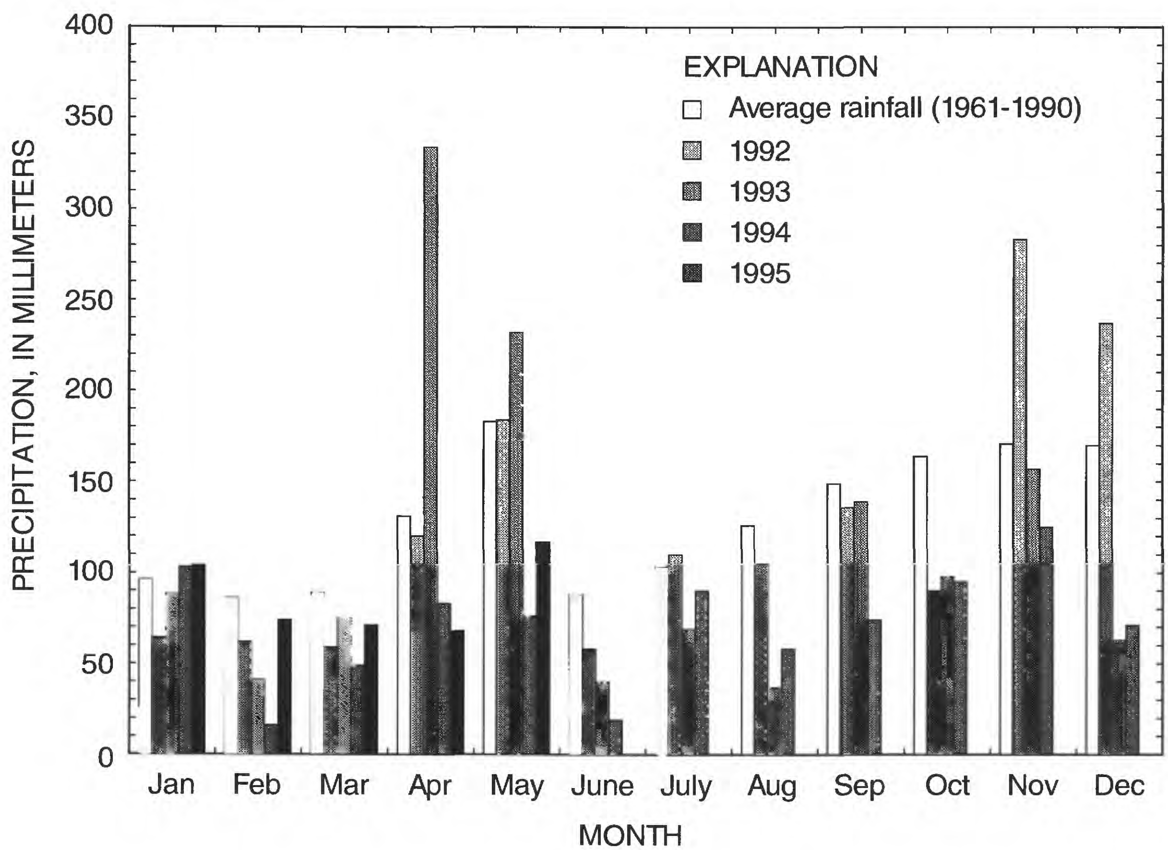


Figure 6. Long-term monthly average rainfall and rainfall amount during period of study at Manatí, Puerto Rico (period of study from January 1992 to May 1995).

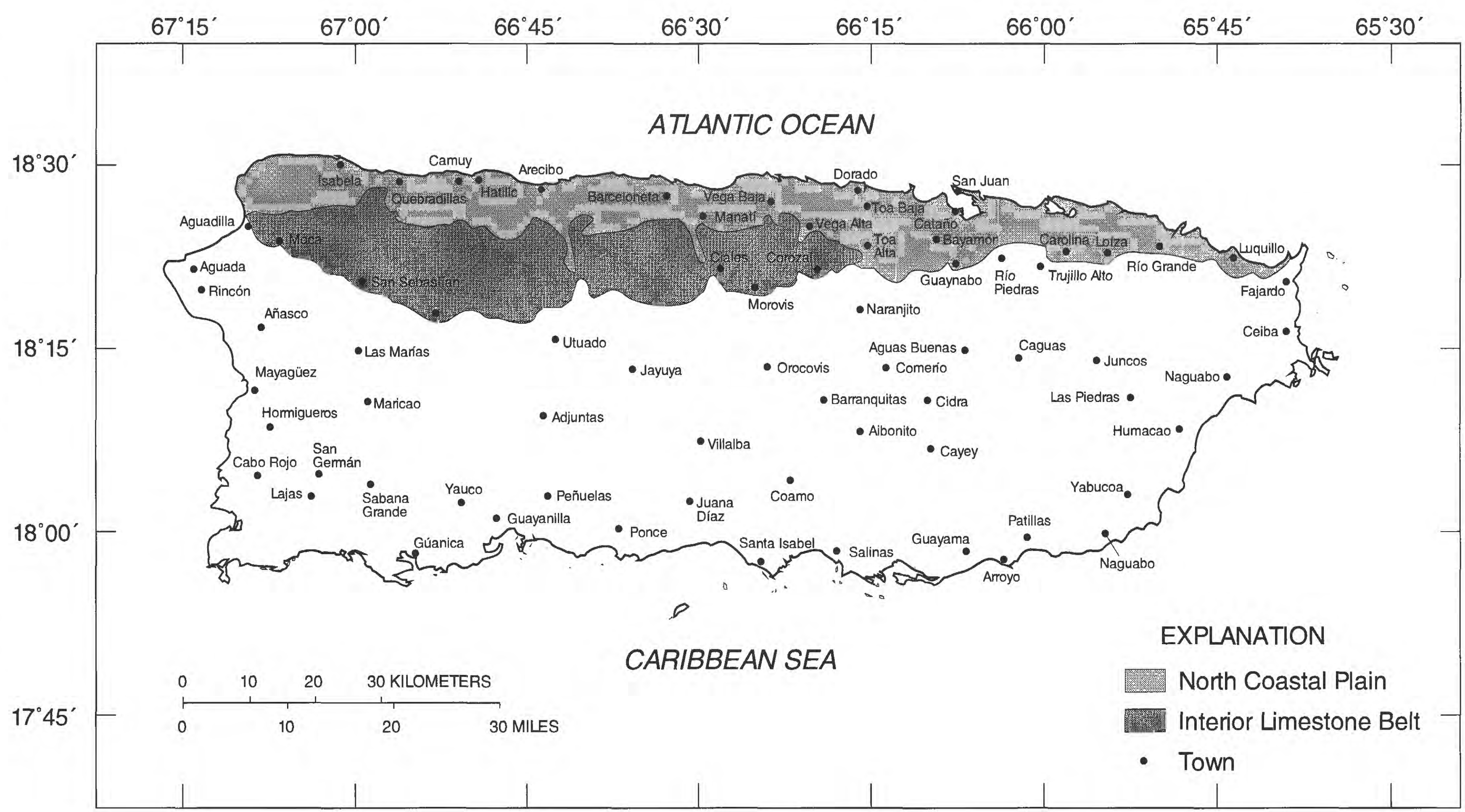


Figure 7. North Coastal Plain and Interior Limestone Belt geographic regions of Puerto Rico (adapted from Picó, 1975).

A well defined tropical karst topography characterizes most of the land surface in the Manatí quadrangle area. The term "karst" is used to describe terranes with characteristic topographic features formed through the dissolution of soluble carbonate bedrock (Monroe, 1980). The predominant karst landforms include "mogotes" (steep-sided hills of limestone surrounded by nearly flat alluviated plains) in areas north of latitude 18°25', and tower karst in areas south of latitude 18°25'. The unconsolidated deposits that compose the nearly flat alluviated plains overlie a highly karstified limestone bedrock varying in thickness from only a few meters to as much as 30 meters (m) within relatively short distances. Within the area of the mogote karst relief, reddish soils cover most of the plains between the mogotes. The predominant soil series within these areas are the Bayamón clay and Bayamón sandy clay loam. These soils are strongly acidic (pH 4.5 to 5.5), have a low organic matter content (1 to 3 percent in the surface layer above 0.3 m depth), and a relatively high permeability of 0.004 to 0.014 millimeters per second (Acevedo, 1979).

Near the coast the most important physiographic feature in the study area is Laguna Tortuguero, which is one of only two fresh-to-slightly saline-water lagoons (dissolved solids concentration ranging from 700 to 2,000 mg/L) in Puerto Rico. It has a surface area of about 224 hectares (ha) and a mean depth of 1.2 m (Quiñones-Marquez and Fusté, 1978). The annual discharge of Laguna Tortuguero to the ocean was gaged at the outlet channel during a one year period (July 1974 to June 1975). Flow during this period ranged from about 31,000 m^3/d (July 1974) to about 171,000 m^3/d (October 1974), with an annual average daily discharge of 55,000 m^3/d (Quiñones-Marquez and Fusté, 1978). The lagoon is the principal natural discharge feature of the upper aquifer within the Manatí quadrangle. The southern part of the study area is characterized by a cone karst consisting of multiple closed depressions separated by steep-sided hills (Monroe, 1976).

The most relevant karst features affecting ground-water quality in the study area are sinkholes, which occur singly or in groups in close proximity to each other throughout the undulating plains north of latitude 18°25'. The term sinkhole refers to an area of localized surface subsidence, or collapse, due to dissolutional processes, which results in a funnel shaped closed depression of moderate dimensions. Sinkholes are natural drainage areas in karst terranes and represent the most important mode of aquifer recharge. Solution sinkholes at the base of limestone outcrops which form the mogotes serve as discrete sources of ground-water recharge and represent highly susceptible point sources of contamination within land areas developed for agricultural, industrial, and urban use. The number of sinkholes in a given area generally depends on the nature of the land surface and the degree of karstification within the underlying bedrock. Sinkholes with the greatest potential for funneling contaminants directly to the aquifer are those in which the limestone bedrock is exposed at the bottom. Where such conditions exist, contaminants rainwater in runoff pass directly to the aquifer through conduits in the limestone bedrock without the retention or degradation provided within the solum (upper part of soil profile penetrated by roots and soil biota) or the saprolite (unconsolidated residual material underlying the soil and grading to hard bedrock below).

Land Use

Land use is the most important factor which can be related to ground-water contamination in the Manatí quadrangle. The relatively flat lands have been subject to extensive agricultural, industrial, and urban development, from which all runoff is conveyed to the subsurface through natural depressions and sinkholes or by injection wells. Land use in 1995 within the approximately 7,900-hectare (ha) Laguna Tortuguero ground-water drainage basin, as defined by Bennett and Giusti (1972), was distributed as follows: 570 ha consisting of Laguna Tortuguero and hydric soils on the periphery of the Laguna Tortuguero; 4,300 ha in pasture or fallow plain mostly contained in the area north of latitude 18°25'; 600 ha in cultivated pineapple fields; 170 ha in urban community (sewered); 320 ha in rural community (un-sewered); 277 ha in industrial use; and 1,663 ha of rugged terrain (mogotes and cone karst) with minimal or no agricultural use and mostly in native vegetative cover contained primarily in the area south of latitude 18°25' (fig. 8).

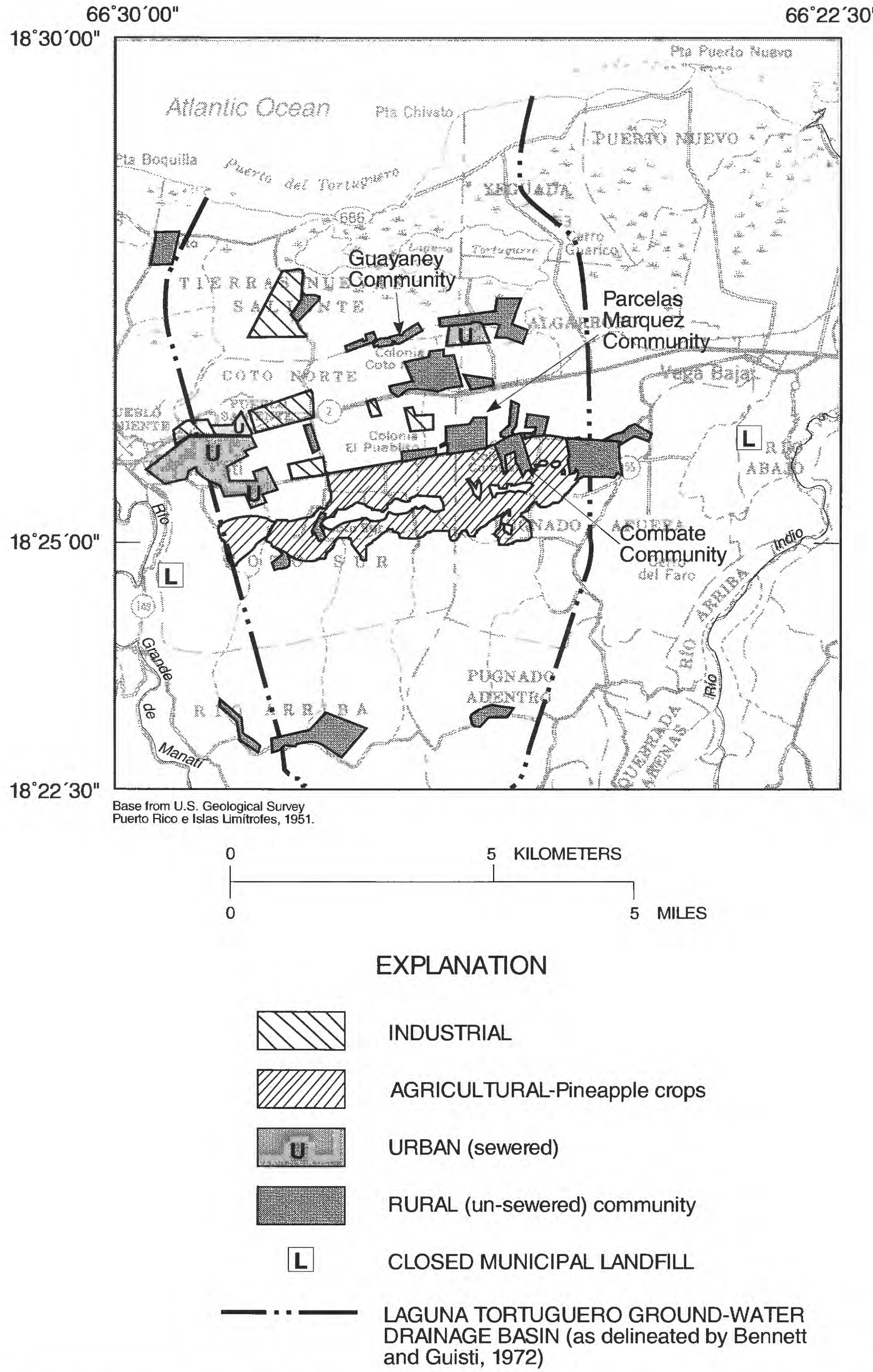


Figure 8. Selected major land uses within the Laguna Tortuguero ground-water drainage basin, north-central Puerto Rico.

HYDROGEOLOGIC SETTING

The north coast limestone ground-water province includes three hydrogeologic units: an upper aquifer contained in the early Miocene Aymamón and Aguada Limestones, a middle confining unit consisting of the upper member of the early Miocene Cibao Formation, and a lower aquifer in the Oligocene Lares Limestone (fig. 9) (Rodríguez-Martínez, 1995). Only the upper aquifer is of interest in this study because nitrate concentrations exceeding 10 mg/L have not been detected from the lower aquifer.

The upper aquifer is unconfined and consists of a wedge of freshwater floating above saline water and thinning toward the coast (fig. 10). The thickness of the freshwater lens ranges from about 33 m near the eastern shore of Laguna Tortuguero as determined at the USGS test well NC-14 (Rodríguez-Martínez and others, 1992) to as much as 130-m thick near highway PR-2 at the USGS test well NC-4 (Rodríguez-Martínez and others, 1992). At test well NC-4 the top of the Cibao Formation was determined to be approximately 50 m below the saline-freshwater interface. The thickness of the freshwater lens possibly reaches its maximum at about latitude 18°26' (about 0.5 km south of test well NC-4). Freshwater extends throughout the entire thickness of the upper aquifer from approximately latitude 18°26' to latitude 18°25'. The Aguada Limestone is not saturated and ground-water flow only occurs as conduit or thin sheet-like flow above the Cibao Formation inland of latitude 18°25'.

Transmissivity in the freshwater portion of the upper aquifer ranges from 14,000 meters squared per day (m^2/d) within the Aymamón Limestone to 60 m^2/d in the Aguada Limestone (Renken and Gómez-Gómez, 1994). The maximum depth to the water-table is about 140 m below land surface near the southern limit of the upper aquifer (potentiometric-surface altitude of about 10 m above sea level), about 65 m below land surface where the freshwater lens possibly has its maximum thickness within the Aguada Limestone, at about latitude 18°26', and is generally 50 m or less north of about latitude 18°27' (fig. 10).

Recharge to the upper aquifer occurs throughout the outcrop areas of the Aymamón and Aguada Limestones as direct rainfall infiltration and as direct inflow of surface runoff draining into sinkholes. Along the southern limit recharge occurs as infiltration of runoff from ephemeral streams that originate within the outcrop area of the Cibao Formation. The areal recharge for the upper aquifer in the area south of Laguna Tortuguero and north of latitude 18°25' has been estimated to average about 420 millimeters per year (mm/y), increasing from 250 mm/y near the coast to 500 mm/y inland (Heisel and others, 1983). Recharge from the Río Grande de Manatí, Río Cibuco, and Río Indio is insignificant since these streams function basically as gaining streams (ground-water drains) through their entire length (Heisel and others, 1983). Discharge from the upper aquifer is primarily to Laguna Tortuguero and to wells.

The water budget for the Laguna Tortuguero ground-water basin as delimited by Bennett and Giusti (1972) was estimated to be 0.8 cubic meter per second (m^3/s) distributed as follows: 0.2 m^3/s discharging directly to the sea; 0.2 m^3/s discharging south of the lagoon through springs and areal seepage and draining into the lagoon; and about 0.4 m^3/s distributed between direct flow into the lagoon and discharge through springs and swampy areas north of the lagoon, with subsequent drainage back into the lagoon. The annual flux into Laguna Tortuguero of 18.9 million cubic meters per year (m^3/y) estimated by Bennett and Giusti (1972) is comparable to the 20 million m^3/y gaged discharge to the ocean reported by Quiñones-Márquez and Fusté (1978). The average of 30 bi-monthly instantaneous discharge measurements obtained between February 1990 and December 1994 at the USGS water quality monitoring station (50038200) is 0.31 m^3/s or equivalent to 9.8 million m^3/y (Curtis and others, 1991, 1992; Díaz and others, 1993, 1994, 1995). The apparent reduction in discharge from Laguna Tortuguero to the ocean is in general agreement with the water budget terms since ground-water withdrawals have increased from about 2.7 million m^3/y at the time of Bennett and Giusti's assessment (about 1969) to approximately 15.3 million m^3/y in 1995 (Conde-Costas and Rodríguez-Rodríguez, 1997).

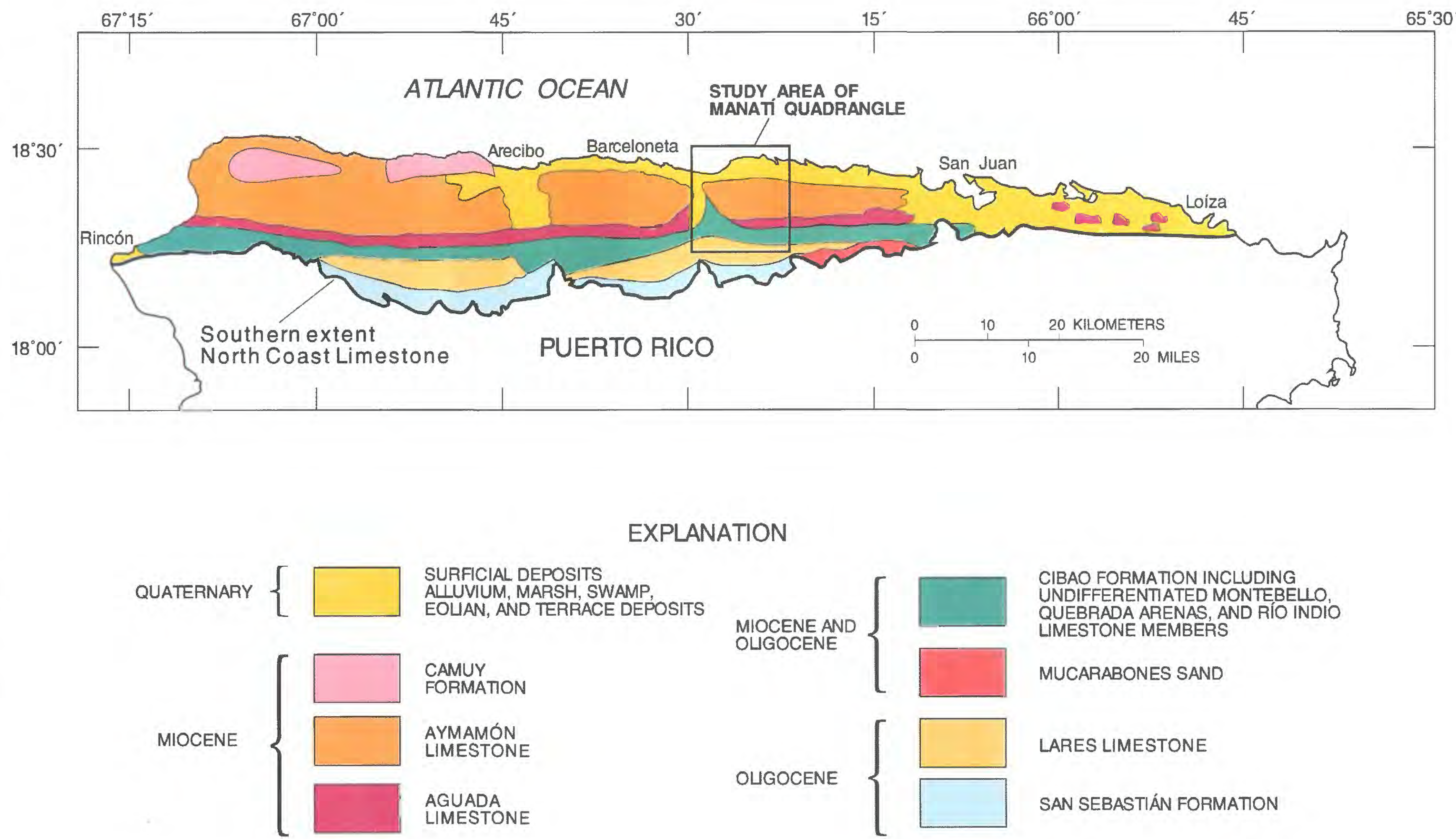


Figure 9. Surficial geology of the North Coast Limestone Ground-Water Province and location of the Manatí quadrangle area, Puerto Rico (from Rodríguez-Martínez, 1995).

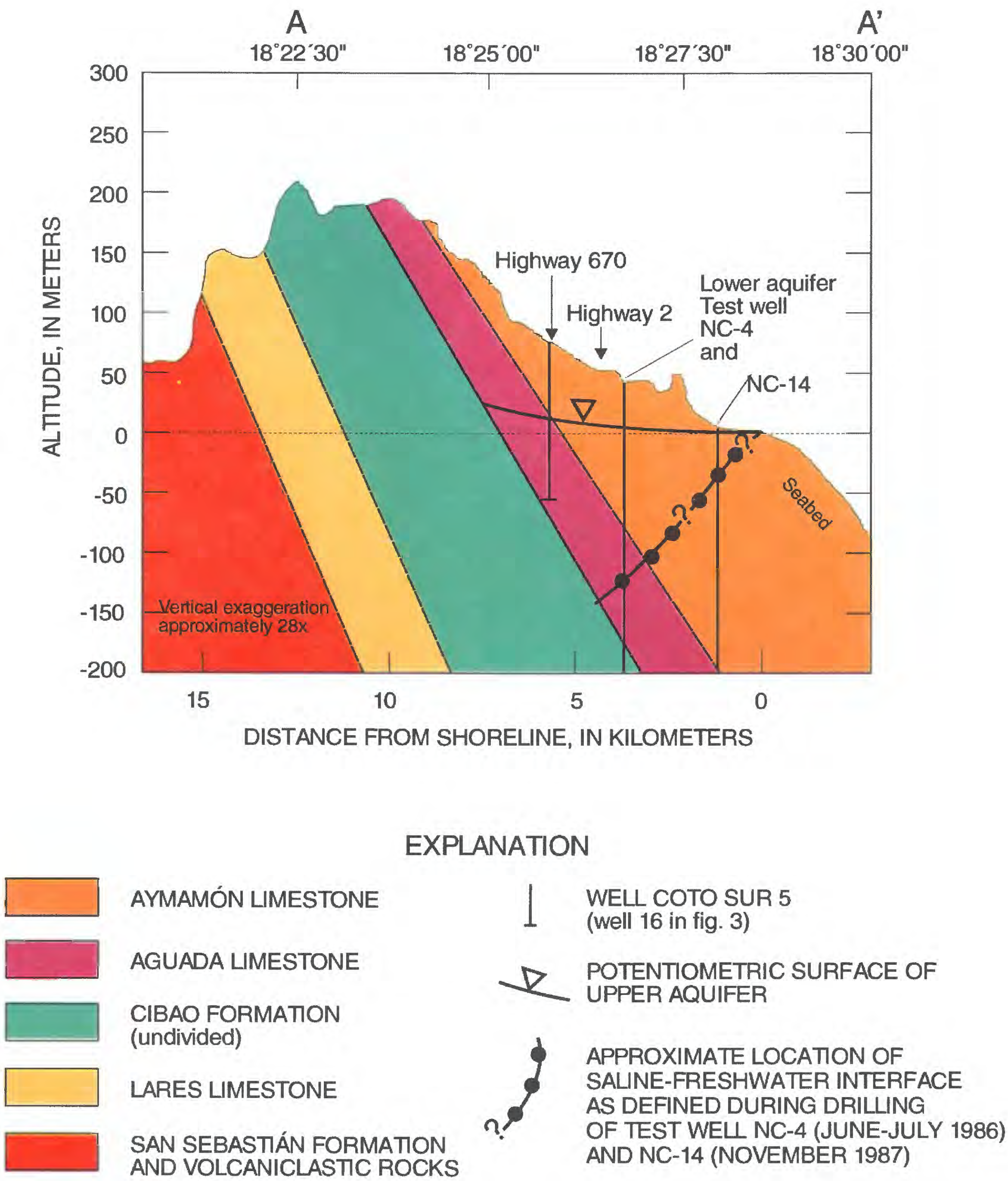


Figure 10. Generalized hydrogeologic cross section of the Manatí area, north-central Puerto Rico (section representative of local aquifer conditions at about longitude 66°27′30″, prior to about 1972; refer to fig. 2 for location).

Ground water in the Manatí quadrangle generally flows northward. Its movement in the upper aquifer under pre-development conditions (prior to significant ground-water development which commenced about 1969) generally followed a northward path from latitude 18°25', with discharge mainly to Laguna Tortuguero (Bennett and Giusti, 1972). Bennett and Giusti (1972) estimated the potentiometric surface gradient to average from 0.6 to 1.2 meters per kilometer (m/km) from the coast along longitude 66°27' to latitude 18°25' (6.5 km from the coast) when ground-water withdrawals were only about 2.7 million m^3/d. Ground-water withdrawals within the Manatí quadrangle increased rapidly during the 1970's to about 12.2 million m^3/y in 1980 and may have reached a maximum of about 17.3 million m^3/y in 1989 (Gregory Cherry, USGS, written commun., 1998). The resulting effect was a general lowering of the potentiometric surface, a reduction of base flow discharge from Laguna Tortuguero, and development of a cone of depression to the south of Laguna Tortuguero, generally along highway PR-670. The cone of depression was centered at a public water-supply well field consisting of six wells with a total ground-water withdrawal rate of about 0.13 m^3/s (fig. 11) (Renken and Gómez-Gómez, 1994). However, by 1995 the cone of depression had practically gone away (fig. 12). The rise in ground-water levels in the area of the cone of depression can be attributed to abandonment of several public water-supply wells, yielding a total of 0.045 m^3/s, which had nitrate concentrations above 10 mg/L, in addition to a general reduction of ground-water withdrawals at nearby public water-supply wells.

NITRATE ASSESSMENT

A synoptic ground-water quality survey conducted within the Manatí quadrangle area between August and November 1992 confirmed the presence of nitrate concentrations near or exceeding 10 mg/L at wells to the south of highway PR-2 and north of the pineapple fields along highway PR-670 (fig. 13) (Conde-Costas and Rodríguez-Rodríguez, 1997). In addition, dieldrin, an organochlorine pesticide, was present throughout the upper aquifer in the study area. Dieldrin was detected at concentrations ranging from 0.01 (the analytical limit of detection) to 0.24 microgram per liter (μg/L) at 13 of 16 sampled wells (Conde-Costas and Rodríguez-Rodríguez, 1997). The highest concentrations generally were found near an agricultural fertilizer warehouse well (number 17 in fig. 13). This well also had a concentration of 6.0 μg/L of toxaphene and 0.24 μg/L of dieldrin. Of these pesticides, dieldrin has generally been the second most prevalent organochlorine pesticide detected throughout Puerto Rico, based on bottom sediment analyses of samples collected from estuaries, reservoirs and streams during the late 1960's and mid 1970's (unpublished data, in U.S. Geological Survey WATSTORE data base). Dieldrin was intensively used on sugar cane crops in Puerto Rico until about 1976. DDT and its metabolites, DDD and DDE, are the most prevalent organochlorine pesticides in bottom sediments, but their concentration in ground water was below the analytical detection limit of 0.01 μg/L. In addition, several of the wells sampled had chloride concentrations ranging from 160 to 330 mg/L, which may be indicative of localized salt-water up-conning (wells number 16, 21, 28, 34, and 38, in fig. 13).

Nitrate Source Identification

In natural waters nitrogen occurs principally as nitrate due to rapid oxidation of its reduced or organic forms. Nitrate is readily transported in water and is stable over a considerable range of conditions. When nitrate is present in the soil, the nitrate rapidly dissolves into and moves with percolating water. Because nitrate is negatively charged, it is not held by the soil particles and is highly mobile in ground water since it is highly soluble. Its solubility in water is as much as 880,000 milligrams of $NaNO_3$ per liter at 20 °C or equivalent to 144,940 milligrams of NO_3-N per liter (Perry, 1969).

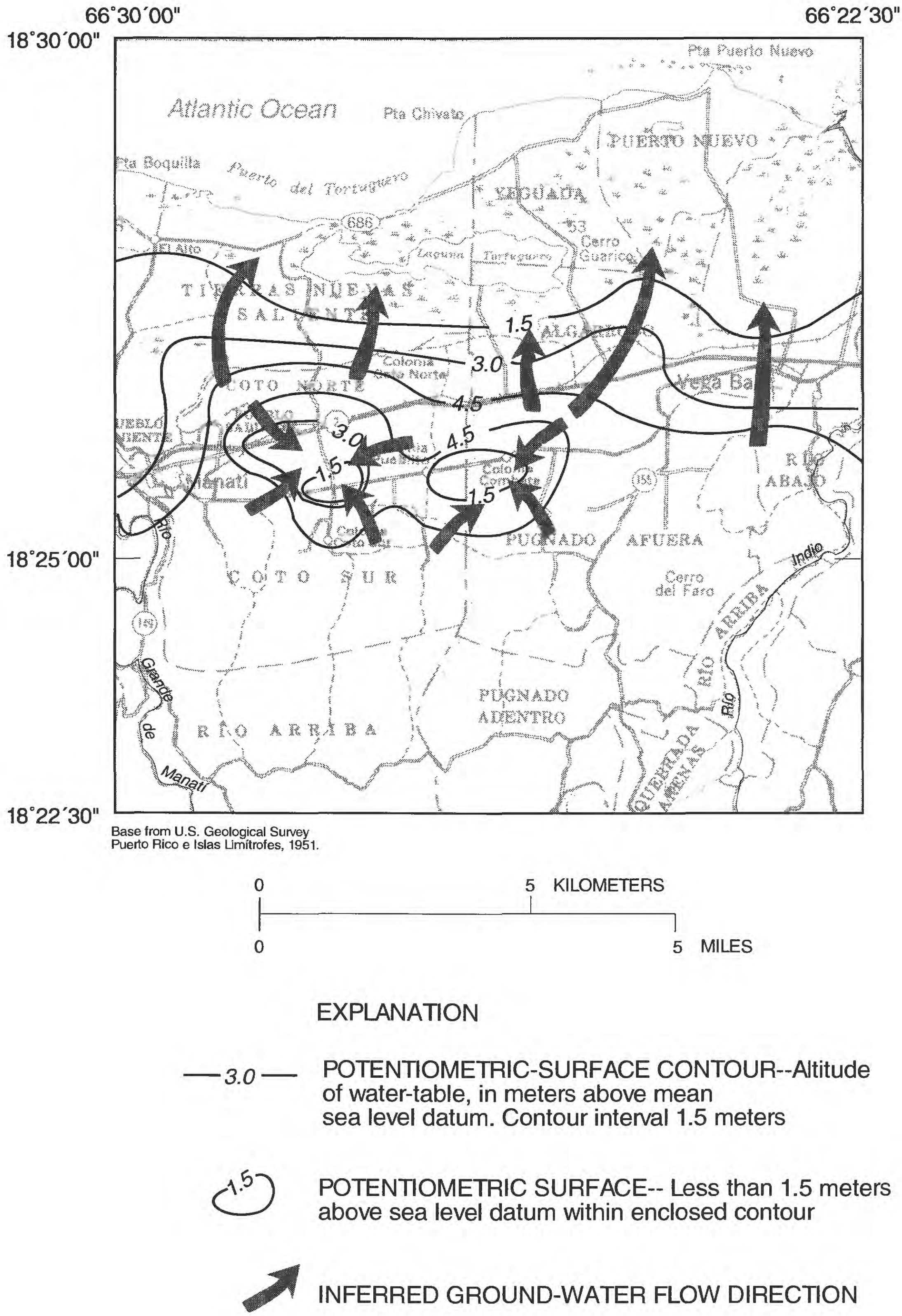


Figure 11. Potentiometric surface in the Manatí quadrangle in north-central Puerto Rico for average conditions between 1980 and 1990 (modified from Renken and Gómez-Gómez, 1994).

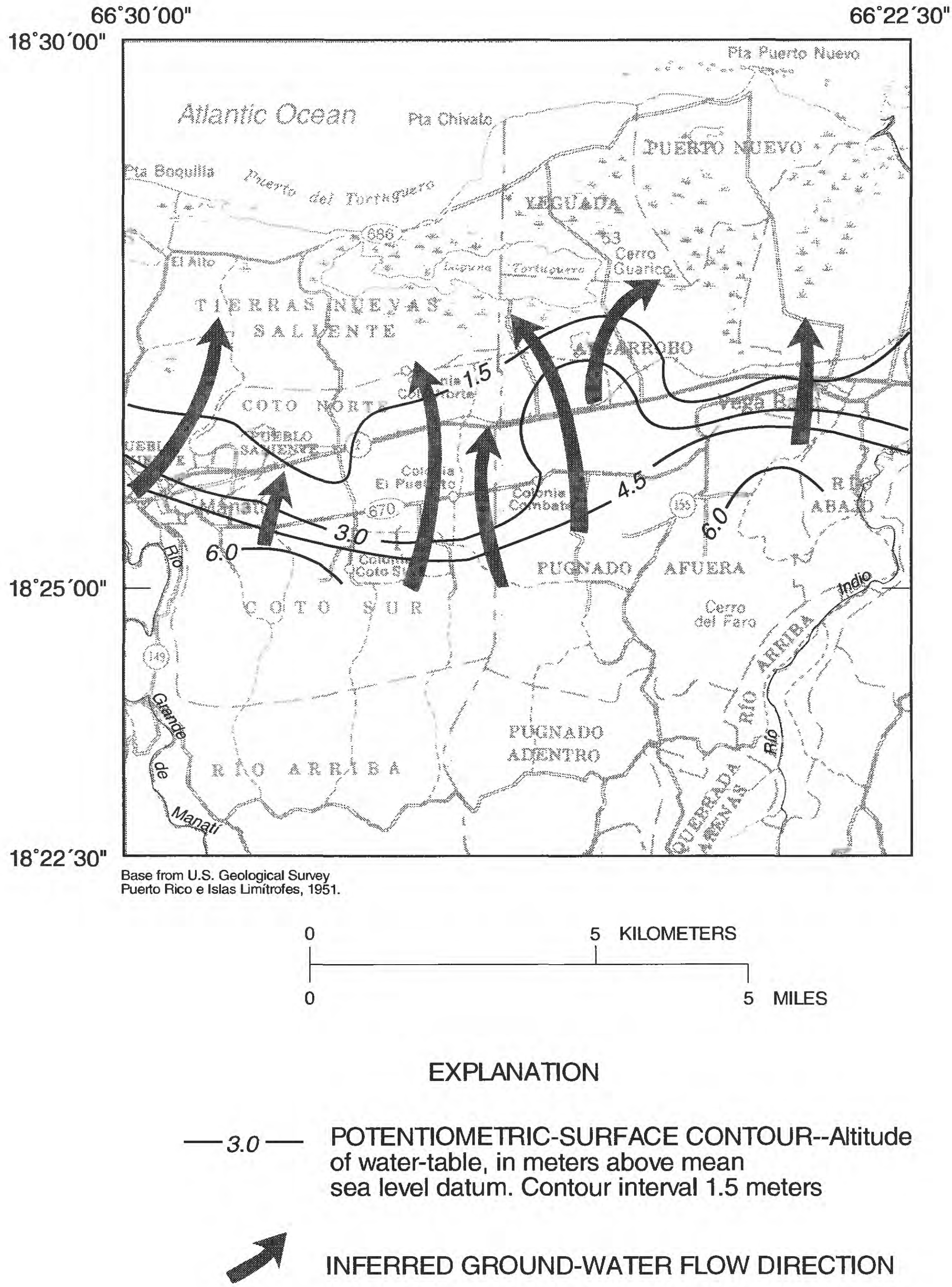


Figure 12. Potentiometric surface in the Manatí quadrangle in north-central Puerto Rico during March 1995 (Conde-Costas and Rodríguez, 1997).

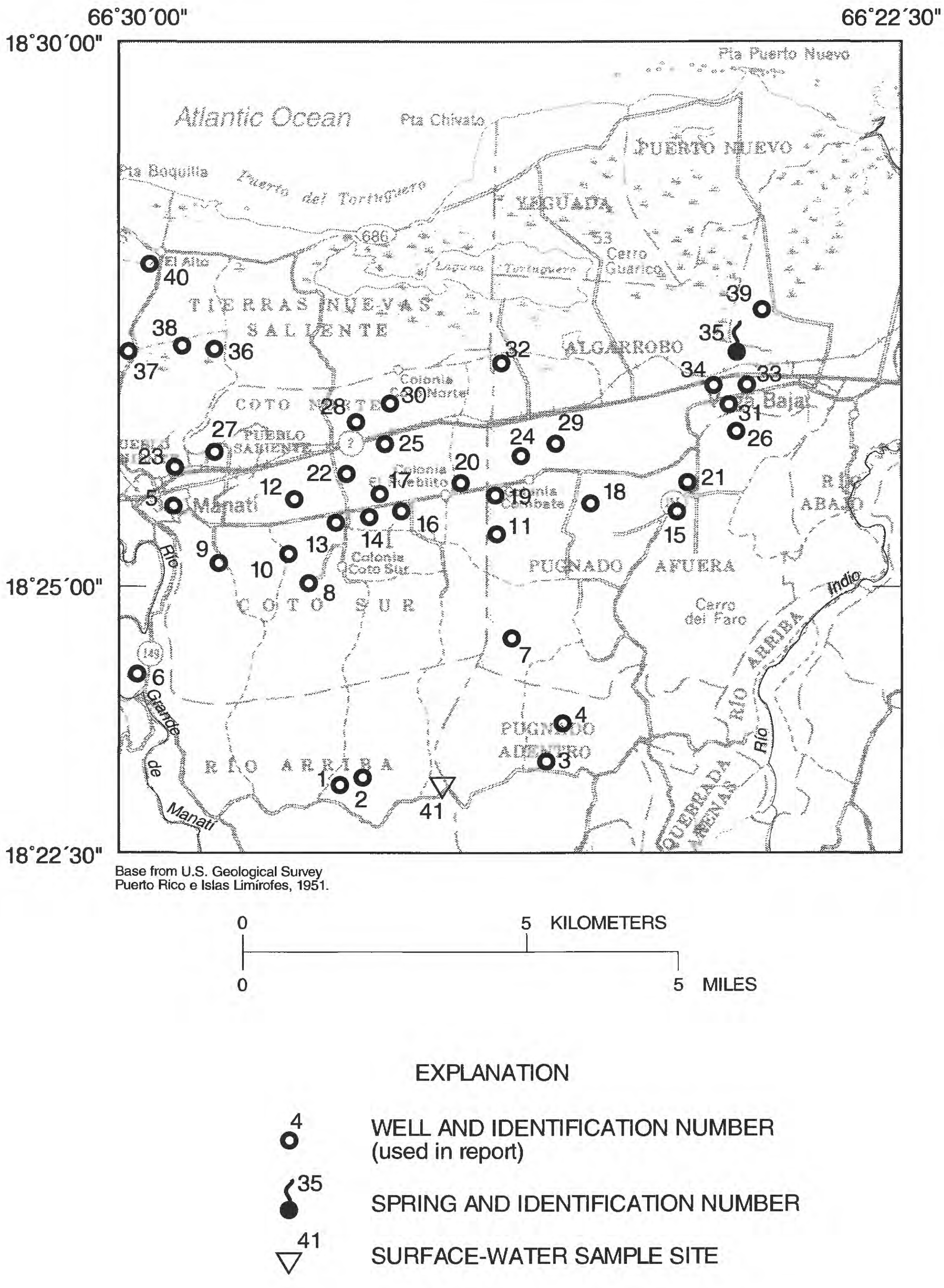


Figure 13. Location of wells, springs and surface-water sites sampled during synoptic survey conducted August-November 1992 in the Manatí quadrangle area, north-central Puerto Rico.

Nitrate contamination sources can be classified in two major categories: point and non-point sources. Point sources have clearly identifiable origins, whereas non-point sources refer to sources of contamination that originate from an extensive area or from a number of points within a region, rather than from one or a few identifiable sites. Technically, the term “non-point source” is defined to mean any source of water pollution that does not meet the legal definition of “point source” of the Clean Water Act, Section 502 (14). The definition of “point source” is any discernible, confined, and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged (Clean Water Act, Section 502 (14)). The term does not include agricultural stormwater discharges and return flows from irrigated agriculture. Agricultural point sources include fertilizer production and storage facilities, as well as intensive animal husbandry operations.

In the Manatí-Vega Baja area, non-point sources of contamination such as cultivated farm land and septic tank leachate in rural communities have a greater potential than point sources for increasing nitrate concentrations in the upper aquifer because these are the predominant land uses and nitrate contamination sources within recharge areas of the upper aquifer. Fertilizers used in the cultivation of pineapples and disposal of domestic wastewater are considered the most important nitrate contributors to the upper aquifer on an areal basis in the study area. Other potential sources are livestock (dairy or hogs) manure disposal and abandoned landfills. The first two of these sources are controlled by local regulations and limited mainly to areas distant from public water-supply well fields. The potential contamination threat from closed sanitary landfills (fig. 8) is not addressed in the study.

The principal nitrogen fertilizer used on the pineapple crops is urea, $CO(NH_2)_2$, which due to the extent of the cultivated farm land is also the principal source of nitrate in the study area. The urea is applied at concentrations that range from 9,200 to 18,380 mg/L as N at 15- to 30-day intervals during the crop cycle (W. Gandía-Torres, Puerto Rico Land Authority, Pineapple Program, written commun., 1997). Urea is transformed into ammonium carbonate $(NH_4)_2 CO_3$ and nitrate by bacteria within the soil zone. The potential for oxidation of urea, or nitrogenous compounds in general, to nitrate in the unsaturated zone is increased as a result of the depth to ground water, which is generally greater than 65 m throughout the limestone belt in the study area. Septic tank leachate is a likely source of nitrate in ground water based on the fact that rural communities within the high-nitrate-concentration area dispose their domestic wastewater in septic tanks which are not adequately constructed (disposal of effluent is not through leaching fields but mainly to porous limestone bedrock near the land surface) and the relatively high density of septic tanks in some communities, such as at Combate where there are approximately 18 housing units per hectare (hu/ha). The conveyance of runoff through drainage ditches that intercept runoff from large tracts of agricultural areas (as much as 45 ha) to sinkholes may also contribute to increased nitrate concentrations in the upper aquifer in localized areas.

Nitrate Concentrations in Ground Water

Areally, ground-water nitrate concentrations in the study area can be expected to be higher in agricultural areas with pineapple crops and rural communities with a high density of septic tanks. However, it is important to note that nitrate concentrations in ground-water samples are associated not only with land use in the vicinity of a sampled well, but also with the total saturated aquifer thickness penetrated by the well from which the sample is collected, the screened interval in the well open to the aquifer, and the yield of the well. In the study area a comparison of ground-water quality can be made, generally, between high-yield wells producing 9 liters per second (L/s) or more (applicable to all public-water supply and some industrial-use wells in the study area) and low-yield wells producing 3 L/s or less (applicable to all observation wells constructed as part of the study and all agricultural-use wells in the study area). Typically, the high-yield wells in the Manatí quadrangle have 25.4-cm diameter casings and penetrate at least 30 m into the upper aquifer. Samples from these wells are more representative of the aquifer at the locality. The active low-yield wells are used primarily on an intermittent basis, generally have 15.2-cm diameter casings and penetrate less than 15-m into the upper aquifer (table 1).

Within the Laguna Tortuguero ground-water drainage basin, six active wells (wells 9, 13, 14, 17, 25, and 36, in fig. 13) and four of the observation wells (wells 8, 11, 18, and 24, in fig. 13) had nitrate concentrations above 10 mg/L on at least one sample date (table 2). Most of the indicated wells are located within pineapple farms or rural areas having a high density of septic tanks, except wells 9 (Mónaco) and 36 (Jacinto Cubano). Well 9, located about 2 km west of the high nitrate concentration area, is within an urban sewered community and within an area where ground-water flow may either be from the Río Grande de Manatí valley or from areas to the south or southeast (figs. 11 and 12). Well 36 is located within pasture land used by a dairy farm, but also is sited about 3 km north and within the ground-water flow path of the principal high nitrate concentration area. The scheduled monthly nitrate sampling program implemented at selected wells (wells 9, 13, 14, 16, 17, 25, 29, and 36, in fig. 13) from June 1994 to May 1995, to determine the variability of NO_3-N during the study period indicated that concentrations of nitrate remained consistently near or above 10 mg/L throughout the year only at wells 13, 17, 25, 29, and 36. Nevertheless, there were two wells that had a change in nitrate concentration from an average of about 6 mg/L to as much as 14 mg/L from one sampling date to the next (wells 9 and 14). The variation in nitrate concentration at well 14 (Coto Sur 6) can be attributed to fertilizer application at adjacent pineapple fields and rapid runoff infiltration through nearby sinkholes. The variation in nitrate concentration at well 9 (Mónaco) only occurred on one sampling occasion and cannot be related to any specific cause. The highest nitrate concentration obtained was 18 mg/L as nitrogen at well 17 (an agricultural-use well located at a fertilizer warehouse and having a yield of about 3 L/s). The concentration of nitrate at well 17 (Coto Sur Warehouse) ranged from 15 to 18 mg/L. At well 8 (Hill 1 observation well) the concentration of nitrate ranged from 14 to 16 mg/L. This observation well is located within pineapple fields and is open to the upper aquifer from the water table to one half the aquifer's estimated total thickness at the site.

Nitrate Load to Upper Aquifer

The potential nitrate load to the upper aquifer from septic tanks was computed from domestic water-use data (Torres-Sierra and Avilés, 1986) and the per capita total nitrogen excreted by humans, which averages 17 grams per day (g/d) (Kaplan, 1987). Domestic water-use data available for 1982 for the municipality of Manatí indicates that approximately 4,160 m^3/d of water was supplied to 5,852 households (domestic household connections) of the public water-supply distribution system without sewage service. This would be equivalent to a domestic wastewater discharge of about 0.71 m^3/d per household connection and also equal to about 0.20 m^3/d per person, based on an average of 36 persons per 10 housing units (hu), which is the average for Puerto Rico (U.S. Department of Commerce, 1991). Based on an average rural housing density of nine hu/ha, which is typical for the area having ground water with a high nitrate concentration, a nitrate effluent discharge to the subsurface within rural communities of 85 mg/L of nitrogen per hectare is computed (assuming all nitrogenous compounds excreted will result in nitrate based on rapid oxidation of nitrogen). This is equivalent to an annual load of about 200 kilograms of nitrogen per hectare per year (kg-N/ha·y) from rural communities without sewer connections. If the nitrate load of 200 kg-N/ha·y is diluted with the estimated 500 mm/y of aquifer recharge (Heisel and others, 1983), then the nitrate concentration reaching the aquifer would be 27 mg/L instead of 85 mg/L as nitrogen. The calculated maximum potential nitrate load from rural communities would be expected to vary among communities, since the housing density ranges from about 18 hu/ha at the Combate community to about 4 hu/ha at the Guayaney community (fig. 8). It can be expected that in adequately constructed septic tanks, a significant part of the nitrogen is lost to the atmosphere by denitrification and by sludge removal from the digestion chamber. Thus the actual estimated unit area nitrate load from a specific rural un-sewered

Table 2. Nitrate concentration at selected wells in the Manatí quadrangle, Puerto Rico

[(day) values in parentheses correspond to sample date; concentration value followed by a number, example, 1.5 at 18, indicates well sampled during drilling at 18 meters below water table surface; for well location refer to figure 13; mg/L, milligrams per liter; NO_3-N, nitrate as nitrogen; ?, unknown]

Wells sampled on a routine basis

Well	Well name	Concentration of NO_3-N, in milligrams per liter / sample date											
		1994							1995				
		June	July	August	September	October	November	December	January	February	March	April	May
9	Mónaco	6.2 / (29)	6.6 / (28)	6.4 / (29)	6.6 / (27)	6.3 / (25)	6.4 / (21)	6.9 / (21)	6.6 / (27)	6.5 / (28)	6.4 / (22)	12.0 / (26)	6.4 / (25)
13	Coto Sur 1	13.0 / (22)	---	---	13.0 / (?)	13.0 / (25)	12.0 / (21)	12.0 / (?)	12.0 / (1)	12.0 / (23)	5.5 / (23)	12.0 / (26)	12.0 / (25)
14	Coto Sur 6	5.6 / (23)	14.0 / (28)	5.6 / (29)	5.7 / (29)	---	5.3 / (21)	5.8 / (20)	5.4 / (31)	5.5 / (23)	12.0 / (23)	6.2 / (26)	5.3 / (26)
16	Coto Sur 5	6.7 / (22)	7.0/ (29)	6.9 / (23)	7.0 / (27)	6.8 / (25)	6.8 / (21)	7.0 / (21)	6.8 / (31)	6.7 / (23)	7.1 / (30)	6.5 / (26)	---
17	Coto Sur Warehouse	16.0 / (21)	---	18.0 / (2)	17.0 / (17)	17.0 / (28)	17.0 / (30)	17.0 / (27)	17.0 / (1)	15.0 / (24)	18.0 / (30)	17.0 / (27)	---
25	Procter & Gamble	8.9 / (27)	---	10.0 / (3)	10.0 / (30)	9.8 / (31)	9.7 / (?)	---	---	9.6 / (1)	10.0 / (30)	9.0 / (27)	9.1 / (30)
36	Jacinto Cubano	10.0 / (24)	---	12.0 / (3)	11.0 / (29)	10.0 / (26)	11.0 / (30)	11.0 / (22)	10.0 / (3)	11.0 / (28)	11.0 / (22)	9.7 / (27)	10.0 / (31)

Observation wells constructed as part of project

Well	Well name	Sample date	NO_3-N in mg/L
7	Perica	2/14/95	0.68 at 48
8	Hill 1	3/20/95	1.50 at 18
8	Hill 1	3/20/95	0.08 at 33
11	Palo Alto 1	1/19/95	13 at 41
18	Palo Alto 3	1/31/95	13 at 6
18	Palo Alto 3	1/31/95	9.3 at 21
24	Palo Alto 2	1/23/95	11 at 8
24	Palo Alto 2	1/23/95	9.4 at 20

community may be significantly lower. The amount of total nitrogen discharged to optimally designed septic tanks—or septic tank systems with effluent retention of at least 24-hours and with leaching fields that enhance effluent evapotranspiration by vegetation (Metcalf and Eddy, Inc., 1972, p. 458 and 701)—and not available as soluble nitrate to the aquifer could be as much as 85 percent of the input load (Mercado, 1976). This is comparable to the results of a 1-year study to define the total nitrogen and total phosphorus load from a 15.3-ha rural (un-sewered) community at Cidra, Puerto Rico, with a housing density of about 5.2 hu/ha (Ramos-Ginés, 1997). In the study by Ramos-Ginés (1997), the accounted total nitrogen load, at a surface-water monitoring station that can be assumed to capture most, if not all, ground-water flow from the volcanic rocks drainage basin, was 16 percent (assuming a per capita nitrogen load of 17 g/d and 3.4 persons per housing unit). However, considering the relatively high density of septic tank systems in the Manatí study area, the relatively high permeability of the soils, less than adequate construction of septic tanks (no leaching fields), a relatively high areal aquifer recharge of 500 mm/y, and a high karstification of the bedrock beneath the soil, it is probable that the nitrate load to the aquifer from un-sewered communities is near the maximum potential load. This would indicate that the nitrate loads to the upper aquifer from rural communities can reasonably be estimated at 200 kg-N/ha·y. (Note: this estimated unit load is in general agreement with the nitrogen-15 analyses of ground water explained in report section "Nitrogen-15 Isotope Characterization of Nitrate Sources.")

Ground-water samples obtained on a routine basis at public water-supply wells between 1989 and 1990 by the Puerto Rico Aqueduct and Sewer Authority (PRASA) and the Puerto Rico Department of Health (PRDOH) indicated that nitrate concentrations averaged about 7 mg/L at wells penetrating almost the full thickness of the aquifer in the area from the northern perimeter of the pineapple fields, generally delimited by highway 670, to as much as 1.3 km northward (wells 14, 16, 28, and 29, in fig. 13). However, samples obtained by the PRASA between June 1989 and December 1990 at public water-supply wells Pugnado Afuera 3 and Coto Sur 2 (wells 19 and 20, respectively, in fig. 13) which lie between the pineapple fields to the south and the un-sewered Parcelas Marquez community to the north, had average nitrate concentrations of 11 and 10 mg/L, respectively, in 1989, and 14.7 and 9.9 mg/L, respectively, in 1990. Well Pugnado Afuera 3 was temporarily disconnected from the public water-supply distribution system in November 1989, and well Coto Sur 2 in June 1989, when it was determined that NO_3-N concentrations were above 10.0 mg/L.

It is likely that the nitrate increase documented at public-supply wells Pugnado Afuera 3 and Coto Sur 2 is partly due to the fact that the nitrate concentration of 85 mg/L, previously calculated for effluent discharged to the subsurface from septic tanks within adjacent rural communities, assumed a negligible nitrate concentration in the served public-water supply. If the domestic water used had a nitrate concentration near 10 mg/L, as is likely considering that well Coto Sur 2 had a nitrate concentration of 9.71 mg/L in a sample obtained on March 27, 1973 (unpublished data in USGS WATSTORE data base) and of 6.6 mg/L as nitrogen on October 19, 1980 (Gómez-Gómez and Guzmán-Ríos, 1982), then the calculated NO_3-N concentration in the domestic wastewater discharge would be 95 mg/L, and the nitrate load from septic tanks could have increased to as much as 224 kg/ha·y rather than of 200 kg/ha·y. It also is likely that if the cultivation of pineapples has remained a relatively unchanged agricultural activity for several decades, it is possible for nitrate concentrations to have increased at the public water-supply wells as a result of development of a cone of depression and induction of ground water from un-sewered areas adjacent to the cultivated fields.

The potential nitrate load from agricultural lands under pineapple cultivation is variable throughout the year as a result of variability in rainfall, runoff and fertilizer application rates (fig. 14). Although the fertilizer application rate used on pineapple crops in the study area is variable, it can be estimated to be between 1,890 to 2,100 kilograms per hectare (kg/ha) per crop cycle of about 31.5 months. This represents an average of 760 kg/ha·y on a long-term basis, which indicates that on an areal unit basis the maximum potential nitrate load from agricultural land under pineapple cultivation is about four times the 200 kg-N/ha·y potential nitrate load from rural communities without sewerage connections. In reality, a significant amount of the nitrogen fertilizer used in pineapple cultivation is incorporated into vegetation and mineralized within the soil. These amounts cannot be quantified without site-specific studies, but for the purposes of this assessment can be estimated to range from about 400 to 690 kg-N/ha per crop cycle (Py and others, 1987, p. 154-155). At the minimum nitrogen fertilizer application rate used in the study area (given in fig. 14) of 1,890 kg-N/ha per crop cycle (which includes fertilizer application to the soil prior to new planting and the foliar applications for the first crop and the ratoon crop), the amount of nitrogen available for volatilization and leached from fields would then be in the range of 1,200 to 1,490 kg-N/ha per crop cycle. This amount of nitrogen would be equivalent to an annual load of about 457 to 568 kg-N/ha·y (calculated by dividing the total crop fertilizer application in kilograms per hectare by 31.5 months and multiplying by 12). If, between 457 and 568 kg-N/ha·y of nitrate is available for volatilization or to be leached from pineapple fields to the upper aquifer, this would be equivalent to a minimum average load of about 246,000 kg of nitrate as nitrogen per year (kg-N/y) from the approximately 600 ha under pineapple cultivation (based on an annual load average of 512 kg-N/ha·y and a planted crop area of about 80 percent since approximately as much as 20 percent of the agricultural land consists of access roads). A similar calculation with the maximum fertilizer application rate of 2,100 kg-N/ha of nitrogen per crop (maximum rate used in the study area) indicates that an average of about 590 kg-N/ha·y of nitrogen could be available for volatilization and leached from fields. This represents a load of about 283,000 kg-N/y (nitrate as nitrogen) from the 600 ha area. In summary, available literature on nitrogen uptake by commercial pineapple crops and data on the fertilizer application rates used at Manatí indicates that, on average, on the order of 264,000 kg-N/y could be available for volatilization and leached from cultivated fields to the sub-surface.

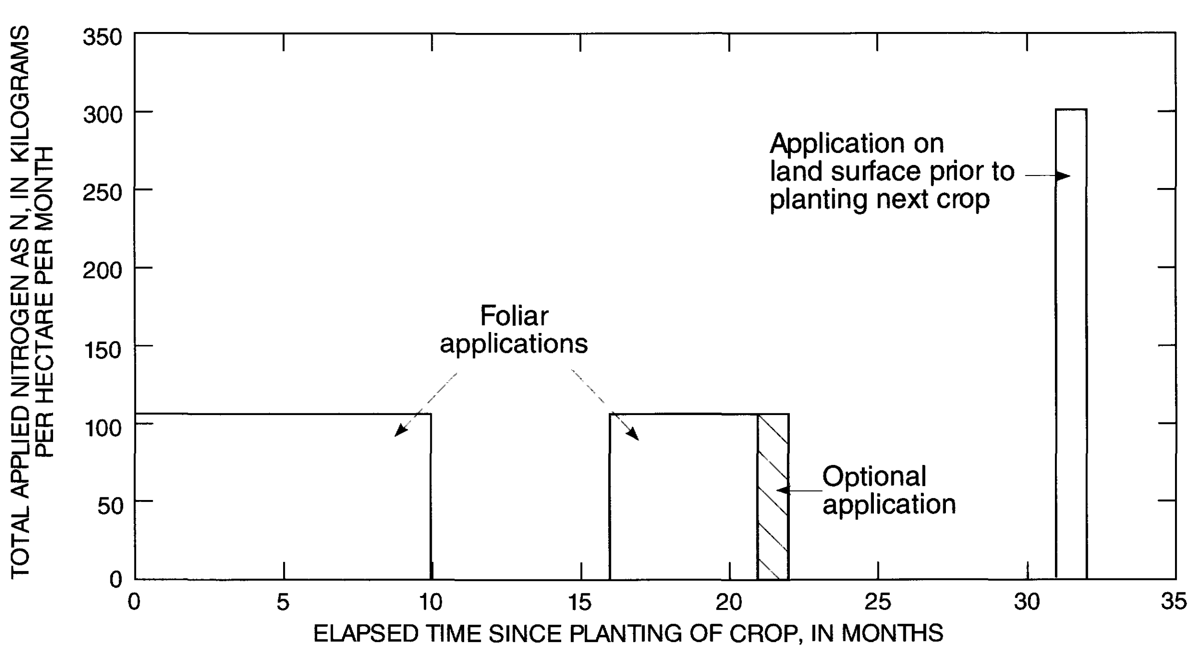


Figure 14. Nitrogen fertilizer application rate at pineapple fields in the Manatí quadrangle area, north-central Puerto Rico.

A generalized estimate of the expected nitrate concentration in ground water that would result with the calculated nitrate loads can be obtained by dividing the potential nitrate load calculated from the two principal sources overlying the upper aquifer (table 3) by the ground-water flux within the Laguna Tortuguero ground-water drainage basin. With the calculated adjusted average nitrate load from pineapple fields of 264,000 kg-N/y and of 51,000 kg-N/y from un-sewered rural communities the expected NO_3 -N concentration in ground water in the vicinity of Laguna Tortuguero would be 16 mg/L (315,000 kg/y divided by the aquifer flux of 19.5 million m^3/y x 1,000). With the maximum average nitrate load from pineapple fields of 283,000 kg-N/y, and 51,000 kg-N/y from un-sewered rural communities, the expected NO_3-N concentration would be 17 mg/L. These estimates assume that all the estimated nitrate load enters the aquifer, that there is no nitrate accumulation within the vadose and saturated zone, and that ground-water flow is under steady-state conditions (nitrate input to the aquifer equals nitrate output). Considering that the vadose zone throughout the area of greatest nitrate loads is generally greater than 70 m, it is likely that a large part of the calculated nitrate loads is in transient storage.

An estimate of the amount of nitrate which could be in transient storage in the vadose zone at areas under pineapple cultivation can be obtained from nitrate analyses at wells 14 and 16 (refer to fig. 13 for location). These wells were sampled monthly from June 1994 to May 1995 and had NO_3-N concentrations that ranged from 5.3 to 14.0 mg/L, averaging 6.9 mg/L (table 2). In order to make the calculations, the following assumptions were made:

1. Ground-water samples at wells 14 and 16, which tap almost the full thickness of the aquifer, are representative of aquifer conditions.
2. The upper aquifer extends inland only to latitude 18°25'.
3. Withdrawals at wells 14 and 16 effectively intercept ground water flowing northward within this part of the upper aquifer and may be in excess of the aquifer flux as indicated by the inland displacement of the potentiometric surface as documented in March 1995 (Conde-Costas and Rodríguez-Rodríguez, 1997).
4. Recharge to the part of the aquifer intercepted by wells 14 and 16 averages 500 mm/y as obtained by Heisel and others (1983).
5. All NO_3-N in ground water at wells 14 and 16 originates from fertilizer use at pineapple fields overlying the upper aquifer within the 1-km-wide flow path up-gradient from highway PR-670.

Table 3. Land use and calculated nitrate loads within the Laguna Tortuguero ground-water drainage basin, north-central Puerto Rico

[(a) to land; (b) to upper aquifer; assumes all nitrogen in domestic wastewater discharged to septic tanks infiltrates to the aquifer and the fraction of the average annual rate of fertilizer nitrogen application to pineapple crops not incorporated in vegetation or mineralized in the soil within 480 hectares of cultivated crop area (approximately 20 percent of pineapple farm area consists of access roads)]

Land use	Hectares	Maximum potential nitrate load, in kilograms of nitrogen per hectare per year (a)	Adjusted nitrate load, in kilograms of nitrogen per hectare per year (b)	Maximum potential nitrate load, in kilograms of nitrogen per year (b)	Adjusted nitrate load, in kilograms of nitrogen per year (b)
Rural communities	255	200	200	51,000	51,000
Pineapple farms	600	760	550	365,000	264,000
TOTAL				416,000	315,000

The mass of NO_3-N transported in northward-moving ground water toward wells 14 and 16 on an annual basis can be calculated as

$$C \times F = L,$$

$$L / \text{crop area} = U,$$

where

C is the mean annual NO_3-N concentration at wells 14 and 16 in grams per cubic meter (g/m^3, same as mg/L);

F is the ground-water flow across a 1-km-wide segment of the upper aquifer estimated as R x A, where R is the mean annual recharge rate of 0.5 m/y, A is the surface area over which recharge occurs, equivalent to the area delimited by latitude 18°25' on the south, highway PR-670 on the north and lines perpendicular to the potentiometric-surface contours as defined in March 1995 (Conde-Costas and Rodríguez, 1997) along the east and west, enclosing a 1-km-wide segment of the upper aquifer between wells 14 and 16;

crop area is the land area cultivated in pineapple crops overlying area A, or approximately 127 ha;

U is the steady-state mean annual load of NO_3-N to the aquifer required to result in the concentration C at wells 14 and 16.

Then,

$$C \times F = L,$$

$$(6.9\ g/m^3) \times [(0.5\ m/y) \times (1.7 \times 10^6\ m^2)] = L,$$

$$L = 5{,}865\ kg/y\ NO_3\text{-}N,$$

$$U = \frac{5{,}865\ kg/y}{\sim 127\ ha} \cong 45\ kg/ha \cdot y$$

This indicates that of the approximately 550 kg-N/ha·y of (which corresponds to the mean annual amount of fertilizer nitrogen estimated to be available for volatilization or leached from fields) only about 10 percent (45/550 x 100) may be entering the aquifer. Considering the assumptions made to obtain this estimate, the most important aspect is that even with a doubling of the calculated nitrate load reaching the aquifer (equivalent to stating that the aquifer flux within the 1-km-wide flow path is twice the rate assumed) the amount of NO_3-N would be less than 20 percent of the mean annual amount of fertilizer nitrogen estimated as available to be leached from fields or volatilized for either the minimum or maximum fertilizer application rates used (512 and 590 kg/ha·y).

Nitrogen-15 Isotope Characterization of Nitrate Sources

The stable isotope concentration of nitrogen-15 in nitrate ($\delta^{15}N$) was obtained at selected sites in the Manatí quadrangle to infer the source of nitrate (table 4; fig. 15). Typical $\delta^{15}N$ values in ground water derived from various sources are: (1) soil (natural vegetative decay) + 2‰ to + 9‰, with a value of + 5 ‰ the most typical; (2) commercial fertilizers, - 2‰ to + 7‰, with values of 0‰ to + 3.5‰ most typical; and (3) animal or human organic waste, + 10‰ to + 23‰, with values of + 10‰ to + 20‰ most typical (Gormly and Spalding, 1979). In the study area, the $\delta^{15}N$ value in uncontaminated ground water was assumed to be + 4.9‰, as determined at well 12 (fig. 15), which taps the artesian aquifer 600 m below the land surface. Samples obtained between 1990 and 1992 at well 17, a low-yield well (average withdrawal rate of about 100 m^3/d) tapping the upper aquifer and located at an agricultural fertilizer preparation warehouse, had nitrate concentrations of between 16 and 18 mg/L, and $\delta^{15}N$ values of + 1.8‰ (May 1, 1990) and + 2.5‰ (September 18, 1992). These are values to be expected where fertilizer-derived nitrate is the primary source of nitrate. Based on the potentiometric surface data within this period the nitrate at well 17 (fig. 11) can be considered to originate principally from localized recharge (overflow from fertilizer application tank trucks) and fertilizer derived nitrate recycling induced by intermittent pumping of the well with minimal influence of nitrate from sources other than fertilizer. The $\delta^{15}N$ signature in ground water where organic nitrogen derived primarily from domestic wastewaters sources constitutes essentially the only source of nitrate contamination ranged from + 7.2‰ to + 8.9‰ (fig. 15; wells 15, 26, 31, 33, 34, and 35, which is Ojo de Agua Spring). The average $\delta^{15}N$ value of + 2.2‰

obtained at well 17 (fertilizer preparation warehouse) and of 8.1‰ obtained from the average of five wells and the spring (15, 26, 31, 33, 34, and 35) in the eastern part of the Manatí quadrangle (area with similar hydrogeologic conditions, but without fertilizer use), indicates that these distinctly different $\delta^{15}N$ signatures can be used to infer the principal sources of nitrate contamination in conjunction with the land use (fig. 8) and potentiometric-surface maps (figs. 11, 12).

The $\delta^{15}N$ data and nitrate concentrations obtained in the study indicate that fertilizer is the primary source of the nitrate in the upper aquifer throughout the central part of the Manatí quadrangle northward of the land area under pineapple cultivation. In areas to the east and west of the pineapple fields, the $\delta^{15}N$ analyses indicate that nitrate in the upper aquifer may be derived primarily from animal or human organic waste. Sources of organic waste within the eastern part of the quadrangle are primarily septic tanks in rural communities, leakage or overflow from sewer mains in urban areas, and recharge to the upper aquifer from the ephemeral streams in areas south of latitude 18°25'. Sources of organic waste within the western part of the quadrangle are leakage or overflow from sewer mains in urban areas, dairy farm-waste containment ponds and septic tanks in rural areas (northwestern part of quadrangle), and possibly leachate from the abandoned Manatí municipality open burning dump/landfill located about 0.5 km south-southwest of well number 9 (Torres-González and Gómez-Gómez, 1982).

With the ground-water quality data for nitrate concentrations and the $\delta^{15}N$ values obtained as part of this study, it is also possible to estimate the relative contribution of nitrate sources from fertilizer use in pineapple fields and from un-sewered communities, which resulted in the closure of public-supply wells Pugnado Afuera 3 and Coto Sur 2 (wells 19 and 20 in fig. 13). At this location, nitrate in ground water is principally derived from fertilizer use in the pineapple fields and septic tank effluents from the rural community of Parcelas Marquez. Samples for $\delta^{15}N$ analysis obtained at these wells on September 3 and November 12, 1992, had $\delta^{15}N$ values of + 3.5‰ and + 3.2‰, respectively. By direct proportion of the representative $\delta^{15}N$ of end-members ($\delta^{15}N$ = + 2.2‰ for fertilizer-affected areas and + 8.1‰ for organic waste affected areas) the nitrate derived from pineapple fields is calculated to be between 83 and 78 percent, and between 17 and 22 percent from septic tank effluents at wells 19 and 20, respectively. It is also possible to calculate the concentration of nitrate from septic tank effluent reaching the aquifer in the vicinity of both wells by assuming that:

a) Public-supply wells Coto Sur 6 and Coto Sur 5 (wells 14 and 16 in fig. 13) have a concentration of nitrate that is representative of the concentration that would exist throughout the upper aquifer along the northern perimeter of the pineapple fields without the contribution of nitrate from rural communities (fig. 8). These wells penetrate about 70 m of the total estimated aquifer thickness of about 100 m (fig. 10) and had an average NO_3-N concentration of 6.9 mg/L between June 1994 and May 1995 (table 2).

b) The isotopic signature of $\delta^{15}N$ derived from fertilizer is + 2.2‰, and the isotopic signature of $\delta^{15}N$ derived from domestic wastewater is + 8.1‰.

c) The relative proportion of nitrate derived from septic tank effluent and reaching a well can be calculated as follows:

$$x\,(\delta^{15}N_{septic}) + (1-x)\,(\delta^{15}N_{fert.}) = \delta^{15}N_{well},$$

where

x is the fraction of nitrate concentration derived from septic tank effluent reaching the aquifer in the vicinity of the sampled well, and 1-x is the fraction derived from fertilized pineapple fields;

$\delta^{15}N_{septic}$ is the isotopic signature of nitrate in ground water at areas in which nitrate contamination from organic waste derived from domestic wastewater (septic tank effluents) constitutes the only significant nitrate source;

$\delta^{15}N_{fert}$ is the isotopic signature of nitrate in ground-water areas in which nitrate contamination from fertilizer application in pineapple fields constitutes the only significant nitrate source; and

$\delta^{15}N_{well}$ is the isotopic concentration at the well that yielded nitrate of 10 mg/L as nitrogen or more.

Table 4. Nitrate and nitrogen-15 analyses from selected sites in the Manatí quadrangle, Puerto Rico

[PS, public-water supply; APS, abandoned public water-supply well; AG, agricultural use; IN, industrial; REC, recreational use; SW, stream flow surface-water sample; n/s, no sample; mg/L, milligrams per liter; NO_3-N, nitrate as nitrogen; $\delta^{15}N$, nitrogen-15 in nitrate; $^{15}N/^{14}N$, nitrogen-15 to nitrogen-14 ratio; all analyses by USGS except NO_3-N at wells 19 and 32 which were provided by the PRASA]

Map number (fig. 13)	Well name	Water use	NO_3-N, in mg/L	Date of NO_3-N sample	$\delta^{15}N$, in per mil	Date of $^{15}N/^{14}N$ sample
1	Río Arriba 3	PS	2.3	10./1/92	13.4	10/1/92
2	Río Arriba 2	PS	1.5	10/1/92	14.3	10/1/92
3	Catala	AG	1.2	10/2/92	10.0	10/2/92
4	Beauchamp	AG	0.4	9/29/92	7.0	9/29/92
6	Monserrate Sur	AG	n/s	n/s	9.5	11/6/92
9	Mónaco	PS	6.2	10/6/92	6.0	10/6/92
9	Mónaco	PS	6.4	5/25/95	6.1	5/30/95
12	Roche artesian well	IN	n/s	n/s	4.9	9/3/92
13	Coto Sur 1	PS	12	11/5/92	3.8	11/5/92
14	Coto Sur 6	PS	5.5	9/15/92	3.1	9/15/92
14	Coto Sur 6	PS	5.3	5/26/95	3.3	5/26/95
15	Pugnado Afuera 2	PS	7.0	8/25/92	7.7	3/1/93
16	Coto Sur 5	PS	6.2	9/14/92	3.4	9/14/92
17	Coto Sur Warehouse	AG	16	5/1/90	1.8	5/1/90
17	Coto Sur Warehouse	AG	18	9/18/92	2.5	9/18/92
17	Coto Sur Warehouse	AG	17	5/27/95	3.2	5/30/95
19	Pugnado Afuera 3	APS	7.0	12/5/90	3.2	9/3/92
20	Coto Sur 2	APS	14	11/12/92	3.4	11/12/92
22	Coto Sur 3	APS	7.5	11/12/92	3.8	11/12/92
23	Manatí 3	PS	5.2	9/24/92	12.7	9/24/92
25	Procter & Gamble	IN	9.2	9/24/92	3.8	9/24/92
26	Alturas	PS	3.8	9/16/92	8.2	9/16/92
27	Córdova Dávila	PS	6.1	9/25/92	8.1	9/25/92
28	Atenas	PS	6.5	9/25/92	4.5	9/25/92
30	Marista	unk.	6.9	10/8/92	5.4	9/25/92
31	Vega Baja 3	PS	5.6	9/15/92	7.6	9/15/92
32	Owens Illinois	IN	9.0	11/6/89	4.6	9/3/92
33	Vega Baja 4	PS	4.8	9/15/92	8.9	9/14/92
34	Vega Baja 2	PS	4.4	9/15/92	7.2	9/15/92
35	Ojo de Agua spring	REC	n/s	n/s	8.8	11/5/92
36	Jacinto Cubano	AG	11	9/30/92	10.9	9/30/92
37	Cruz Rosa Rivas	PS	2.7	9/21/92	11.9	9/21/92
38	Rabanos	PS	3.6	9/18/92	12.0	9/28/92
40	Boquillas	PS	3.8	9/17/92	11.6	9/17/92
41	Quebrada (SW)	unk.	0.4	11/6/92	7.2	9/6/92

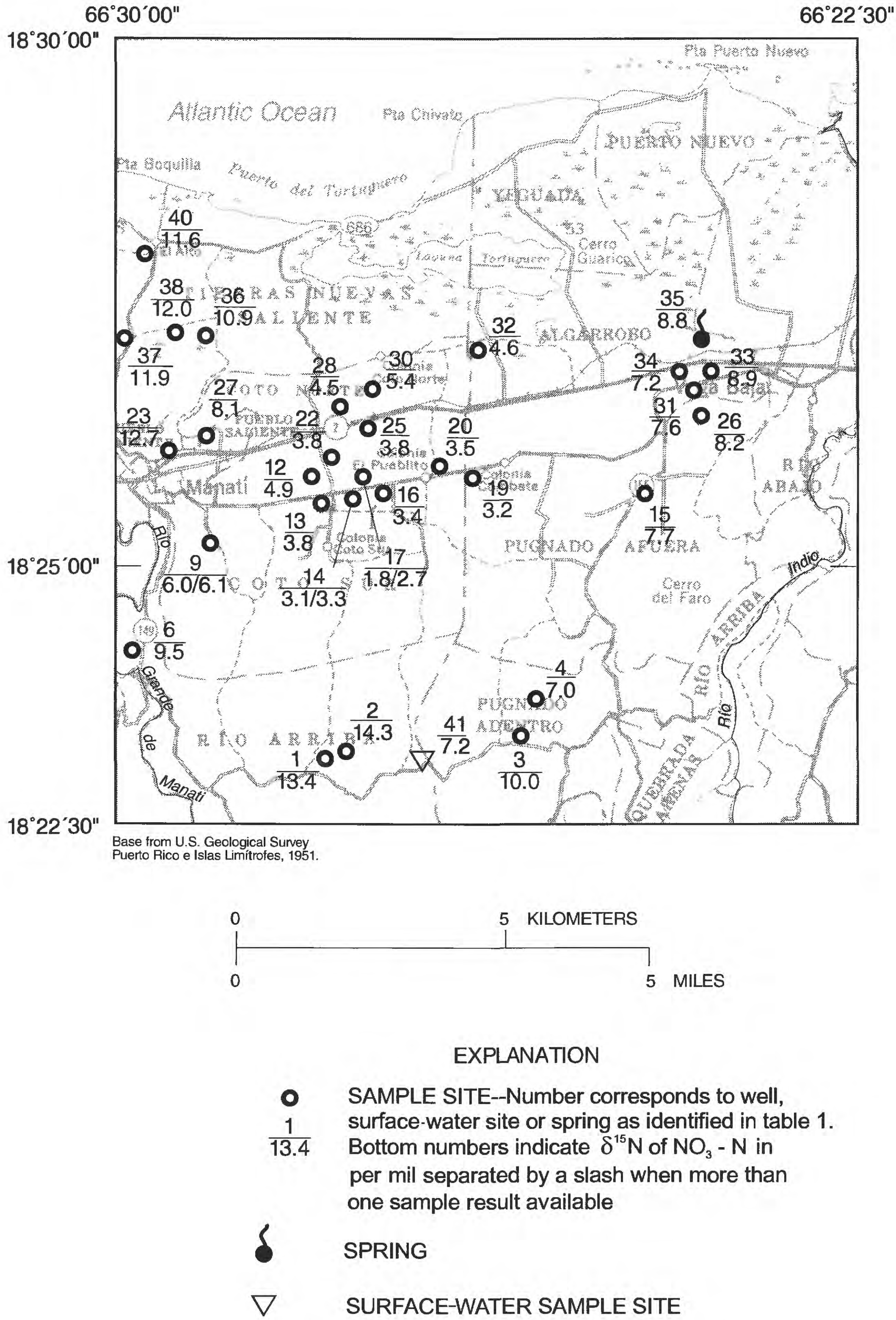


Figure 15. $\delta^{15}N$ of NO_3-N at selected wells in the Manatí quadrangle area, north-central Puerto Rico.

Note that in the above mass balance calculation no accounting is made for the nitrate derived from natural vegetative decay. This is justified since the NO_3-N concentration in the aquifer up-gradient from the impacted area is one order of magnitude lower (0.68 mg/L at observation well 7 in fig. 13 and table 2). Thus at well Coto Sur 2 the fraction of nitrate derived from septic tank effluent would be

$$x\,(8.1) + (1\text{-}x)\,(2.2) = 3.5,$$
$$x = 0.22,$$

and at well Pugnado Afuera 3

$$x\,(8.1) + (1\text{-}x)\,(2.2) = 3.2,$$
$$x = 0.17.$$

The NO_3-N concentration in ground water pumped at each well and derived from the Parcelas Marquez community at the moment the NO_3-N concentration at the well reached 10 mg/L can be calculated as follows:

$$6.9\,(1\text{-}x) + y\,(x) = 10,$$

where

6.9 corresponds to the NO_3-N concentration along the northern perimeter of the pineapple fields in the upper aquifer without the effect of septic tank effluents, as previously stated.

1-x and x are the fraction of nitrate derived from the pineapple fields and from septic tank effluent, respectively.

y is the calculated concentration of NO_3-N in ground water derived from the upper aquifer beneath the Parcelas Marquez community, in milligrams per liter;

10 represents the NO_3-N concentration at either well at the moment it equaled the maximum allowed contaminant level for public-water supply of 10 milligrams per liter.

Then y at Coto Sur 2 would be:

$$6.9\,(1 - 0.22) + y\,(0.22) = 10,$$
$$y = 21 \text{ mg/L};$$

and at Pugnado Afuera 3,

$$6.9\,(1 - 0.17) + y\,(0.17) = 10,$$
$$y = 25 \text{ mg/L}.$$

This calculation indicates that ground water beneath the Parcelas Marquez community may have an average NO_3-N concentration of about 23 mg/L. This NO_3-N concentration is in agreement with the calculated nitrate maximum potential load from septic tanks of about 200 kg-N/ha·y and the assumption that this is the nitrate load to the upper aquifer from rural communities, given the physical and hydrologic conditions in the area. The only data in support of these estimates is the NO_3-N concentration obtained at well Coto Sur 2 by the PRASA on December 5, 1989, after approximately 180 days had elapsed since pumpage was discontinued at this well. The PRASA sampled this well intensively from June 1989 to December 1990 to determine if the NO_3-N concentrations would diminish. However, the NO_3-N concentrations were found to increase to as much as 30.2 mg/L (Appendix A).

Nitrate Concentration in Storm-Runoff

Runoff into two sinkholes was monitored in order to characterize, in terms of nitrate concentration, agricultural and urban storm runoff. Agricultural storm-runoff was sampled at a drainage ditch which conveys runoff from an area of approximately 18 ha cultivated in pineapples. Urban storm runoff was sampled at the inflow of a storm-runoff retention pit (located at the intersection of highways PR-149 and PR-688), which conveys the runoff from an area of approximately 48 ha (fig. 16). Drainage from the monitoring site within the pineapple fields is conveyed into a natural sinkhole. Drainage from the urban-sewered site is conveyed to the sub-surface by storm-runoff injection wells sited within a retention pit. Both monitored sites were equipped with automated samplers.

Most storm-runoff events recorded at both locations were of relatively short duration, with about 80 percent of these lasting 70 minutes or less (14 events of a total of 17 events sampled). Overall, the duration of the storm-runoff events ranged from less than 5 to 432 minutes. An average nitrate concentration for each storm-runoff event was obtained by calculating an average nitrate concentration between instantaneous samples and assigning a relative weight to the calculated concentration based on the time interval between each sample with respect to the total duration of the storm runoff event.

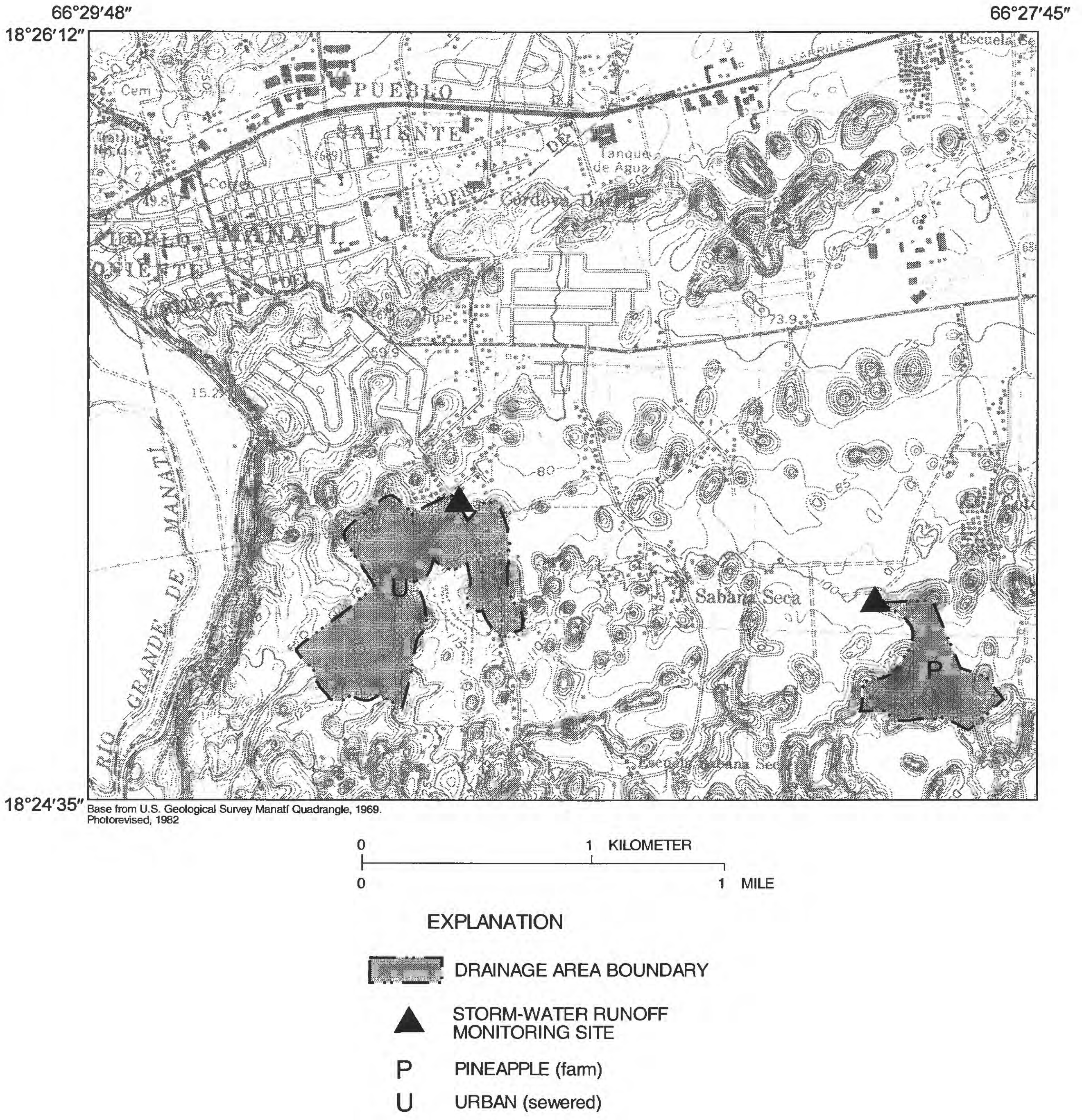


Figure 16. Location of monitoring stations used to characterized NO_3-N concentrations in storm runoff from pineapple fields and from urban sewered area in the Manatí quadrangle area, north-central Puerto Rico.

Seven runoff events were sampled at the agricultural runoff monitoring site between April 1994 and February 1995. At the urban-sewered monitoring site, 10 runoff events were sampled between July 1994 and April 1995 (table 5; Appendix B). Although the data were very limited, they indicate that average concentration of nitrate in storm runoff from pineapple fields is significantly more enriched than storm runoff from an urban-sewered area by an average factor of 45; 0.2 mg/L of NO_3-N in runoff from an urban-sewered area as compared to an average of about 9.0 mg/L of NO_3-N in runoff from pineapple fields. The data also indicate that dissolved nitrate constitutes about 85 percent of the total nitrogen in runoff from pineapple fields as compared to urban runoff which is enriched primarily in organic and ammonia nitrogen, with dissolved nitrate being only 24 percent of the total nitrogen in instantaneous samples (refer to Appendix B). The urban runoff samples from the Manatí site had dissolved NO_3-N which ranged from 0.03 mg/L (10th percentile) to as much as 0.55 mg/L in a set of 29 instantaneous samples, with total nitrogen in most samples (90th percentile) not exceeding 2.04 mg/L. The maximum instantaneous concentration of total ammonia plus organic nitrogen at the urban runoff monitoring site was 5.9 mg/L (with 0.03 mg/L of NO_3-N) in a sample obtained 10 minutes into a storm runoff event lasting 432 minutes during January 25, 1995. However, the average total nitrogen concentration for the storm runoff event was calculated as 1.2 mg/L. The concentration obtained at the Manatí urban-sewered site is comparable with more detailed sampling from a similar urban-sewered community in Cidra, Puerto Rico (Ramos-Ginés, 1997). At Cidra, NO_3-N concentrations obtained in instantaneous samples (not composites) ranged from 0.01 mg/L (10th percentile) to a maximum of 0.28 mg/L in a set of 29 samples. The maximum instantaneous total nitrogen concentration obtained in the Cidra study was 6.0 mg/L as N. The Cidra urban storm runoff data also indicate that nitrate constituted less than 15 percent of the total nitrogen, or at most 1.8 mg/L.

The average NO_3-N concentration obtained in storm-runoff events from pineapple fields (9.0 mg/L) is comparable to the concentration of 13 mg/L from ground-water samples obtained near the water table at observation wells 11 and 18 (fig. 13) during their construction. In addition, the calculated average dissolved NO_3-N concentrations for the seven storm-runoff events monitored at the pineapple field shows an apparent increase in the average nitrate concentrations with increasing duration of the storm-runoff event. A linear regression fit was obtained between the average nitrate concentration calculated for the storm-runoff event and duration of the event ($r = 0.62$, $N = 7$ events); $NO_3\text{-N} = 0.076(t) + 5.67$,

Table 5. Summary of the dissolved nitrate analyses for storm-runoff samples obtained at the pineapple farm and urban sewered monitoring sites in the Manatí quadrangle, Puerto Rico

[Mean nitrate concentrations correspond to the time-weighted mean; duration of event corresponds to period of time runoff at the sampling site was above the sample intake port, which is approximately equivalent to the duration of the runoff event. NO_3-N, nitrate as nitrogen; <, less than the stated number; mg/L, milligrams per liter]

Sample date	Mean NO_3-N, in mg/L	Duration of runoff event, in minutes
Pineapple farm monitoring site		
4/29/94	14.6	75
9/6/94	10.9	70
9/19/94	8.2	20
11/9/94	7.4	70
11/11/94	11.3	25
12/8/98	7.8	50
2/28/95	3.4	3
Urban monitoring site		
7/31/94	0.04	<5
8/9/94	0.33	105
8/10/94	0.08	<5
11/11/94	0.14	<5
1/25/95, 1/26/95	0.45	432
3/6/95	0.12	<5
3/13/95	0.10	15
3/14/95	0.63	<5
3/27/95	0.02	<5
4/1/95	0.08	69

where

NO_3-N is the average nitrate concentration in the runoff event in milligrams per liter, and

t is time in minutes since runoff commenced.

This indicates that for storm-runoff events lasting more than about 60 minutes it is possible that NO_3-N concentrations will exceed 10 mg/L in pineapple fields.

SUMMARY AND CONCLUSIONS

The upper aquifer within the Manatí 7.5-minute topographic quadrangle has undergone a degradation in water quality that has resulted in a lost production of about 5,800 m^3/d from public-supply wells during the 1980's. Most of the lost production has been caused by NO_3-N concentrations that have exceeded the maximum contaminant level of 10 mg/L permitted by the Puerto Rico Department of Health at public water-supply wells. A ground-water resources assessment was conducted between 1992 and 1995 to define the quality of ground water within the upper aquifer, especially as to the areal distribution and principal potential sources of nitrates. The area of investigation included the entire Manatí quadrangle as part of the general quality of water assessment, and in more detail, an area of about 33 km^2 that constitutes the part of the upper aquifer with drainage to the Laguna Tortuguero.

The areal water quality assessment was conducted between August 25 and November 12, 1992, and included samples from 31 sites consisting of 29 wells, one spring, and one creek. Water-quality analyses included: (a) field determination of specific conductance, pH, temperature, and alkalinity, and (b) laboratory determinations at selected sites for major cations and anions, nutrients, trace metals, organochlorine insecticides, organophosphate insecticides, volatile organic chemicals, base neutral extractable compounds and acid extractable compounds at most wells, and the stable isotopes ratios of oxygen-18 to oxygen-16, deuterium to protium, nitrogen-15 to nitrogen-14, and sulfur-34 to sulfur-35. These analyses were used to establish a baseline for future reference and are included in a separate publication (Conde-Costas and Rodríguez-Rodríguez, 1997).

Nitrate in ground water in the study area is derived primarily from fertilizer used in the cultivation of pineapples and from septic tank effluents from rural communities. Within the part of the Laguna Tortuguero ground-water drainage basin overlying the upper aquifer, pineapple crops are cultivated in an area of about 600 ha, and rural communities without sewer service occupy an area of about 255 ha. The average potential nitrate loads from these land uses to the subsurface were estimated as 760 kg-N/ha·y from pineapple fields, and 200 kg-N/ha·y from un-sewered rural communities. Of the estimated 760 kg-N/ha·y accounted in fertilizer used at pineapple fields it is possible that an average of 210 kg-N/y is incorporated by the plants or mineralized in soil, and an average 550 kg-N/y is available for volatilization or leached from fields. However, the calculated nitrate load to the upper aquifer from fertilized pineapple fields may be only 45 kg-N/ha·y. The mass balance calculations indicate that the bulk of the difference between the average of 550 kg-N/ha·y of fertilizer nitrogen that is estimated to be available for volatilization or to be leached from fields and the 45 kg-N/ha·y accounted in ground water is most likely to be in transient storage within the vadose zone which has a thickness of between 65 and 140 m in areas under pineapple cultivation. Mass balance calculations made for a part of the aquifer impacted by septic tanks effluents (Parcelas Marquez community) indicate that all 200 kg-N/ha·y estimated to be available in domestic wastewater may result in nitrate load to the upper aquifer.

Nitrate mass balance calculations were made for two public-supply wells (Coto Sur 2 and Pugnado Afuera 3) that were closed as a result of NO_3-N concentrations exceeding the concentration of 10 mg/L permitted by the Puerto Rico Department of Health. The results of these calculations indicate that approximately 20 percent of the nitrate at these wells originates from septic tank effluent reaching the upper aquifer from the Parcelas Marquez community. In the analysis, wells Coto Sur 5 and Coto Sur 6, located between 1 and 1.5 km east of the closed wells, were used as index wells to determine the nitrate concentration in the upper aquifer without the nitrate load from septic tank effluents. These public-supply wells were monitored monthly during a 1-year period and found to have an average NO_3-N concentration of 6.9 mg/L. By using this value as the concentration that would exist in the upper aquifer along the northern perimeter of the pineapple cultivation area without the effect of septic tank effluents in conjunction with analyses of the stable isotopes of nitrogen, it was determined that ground water beneath the Parcelas Marquez community may have an average NO_3-N concentration of about 23 mg/L. This is in agreement with the estimated nitrate load to septic tanks in rural communities of 200 kg-N/ha·y and the assumption that the amount of nitrogen loss in the domestic wastewater to soil mineralization, denitrification, and other processes is negligible because of existing physical and hydrologic conditions.

Runoff was monitored at two locations to characterize the nitrate concentration from pineapple fields (the land use with the highest nitrate load potential) and from urban sewered areas (the future land-use trend). The results obtained indicate that average concentration of nitrate in storm runoff from pineapple fields (9.0 mg/L) is more enriched than storm runoff from an urban-sewered area (0.2 mg/L) by and average factor of 45. Storm-runoff from pineapple fields had average NO_3-N concentrations ranging from 3.4 to 14.6 mg/L (results of seven runoff events monitored). Storm-runoff from the urban-sewered area had average NO_3-N concentrations ranging from 0.02 to 0.63 mg/L (results of ten runoff events monitored). Although the number of samples obtained were few, in general, urban storm-runoff instantaneous samples contained less than 1.1 mg/L of total nitrogen with dissolved nitrate constituting between 4 and 38 percent of the total nitrogen. Runoff from pineapple fields, in general, had dissolved nitrate constituting 90 percent of the dissolved total nitrogen with a variation of between 77 to 100 percent. The data obtained at the pineapple field monitored also indicate that the average NO_3-N concentration in runoff increases in direct relation to the duration of the storm-runoff event, with a concentration of 10 mg/L occurring in most events lasting at least 60 minutes.

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APPENDIXES

Appendix A. Nitrate analyses from well Coto Sur 2 at Manatí, Puerto Rico (Sampled and analyzed by the Puerto Rico Aqueduct and Sewer Authority).

[NO_3-N, nitrate as nitrogen; mg/L, milligrams per liter]

Date	NO_3-N, in mg/L	Date	NO_3-N, in mg/L	Date	NO_3-N, in mg/L	Date	NO_3-N, in mg/L	Date	NO_3-N, in mg/L
5-Jun-89	9.8	27-Jun-89	10.5	7-Aug-89	11.4	29-Sep-89	9.4	7-Dec-89	11.3
6-Jun-89	12	28-Jun-89	11.6	9-Aug-89	11.3	2-Oct-89	9.4	20-Dec-89	8.0
7-Jun-89	10.9	1-Jul-89	10.8	11-Aug-89	12	4-Oct-89	13.5	3-Jan-90	12.0
8-Jun-89	10.2	2-Jul-89	11.4	14-Aug-89	11.6	6-Oct-89	13	24-Jan-90	12.1
9-Jun-89	12.3	3-Jul-89	11.5	16-Aug-89	12	9-Oct-89	10.9	7-Feb-90	10.0
10-Jun-89	10.2	4-Jul-89	11.2	18-Aug-89	13	11-Oct-89	9.9	7-Mar-90	7.4
11-Jun-89	10.6	5-Jul-89	11.1	21-Aug-89	10.6	16-Oct-89	12.6	4-Apr-90	11.2
12-Jun-89	10.2	6-Jul-89	11.1	23-Aug-89	11.5	18-Oct-89	11.7	6-Jun-90	14.0
13-Jun-89	10.4	7-Jul-89	11	25-Aug-89	12	20-Oct-89	10.4	3-Oct-90	11.6
14-Jun-89	8.0	8-Jul-89	11.8	28-Aug-89	10.5	23-Oct-89	13.9	5-Dec-90	30.2
15-Jun-89	10.6	9-Jul-89	10.9	30-Aug-89	11.4	25-Oct-89	12.7	17-Dec-90	28.4
16-Jun-89	11	10-Jul-89	10.6	1-Sep-89	11.4	27-Oct-89	12.8	24-Jan-90	12.1
17-Jun-89	10.4	11-Jul-89	10.9	4-Sep-89	12.6	30-Oct-89	11.8		
18-Jun-89	10.2	12-Jul-89	11.5	6-Sep-89	10.5	1-Nov-89	10.4		
19-Jun-89	10.6	14-Jul-89	11.5	8-Sep-89	11.6	3-Nov-89	12.7		
20-Jun-89	10.8	19-Jul-89	11.4	11-Sep-89	10.6	6-Nov-89	12.1		
21-Jun-89	11	24-Jul-89	11.1	13-Sep-89	9.6	8-Nov-89	13		
22-Jun-89	9.9	26-Jul-89	11.1	15-Sep-89	12	10-Nov-89	10.3		
23-Jun-89	9.7	28-Jul-89	11.8	21-Sep-89	11.8	13-Nov-89	10.2		
24-Jun-89	10.2	31-Jul-89	10.9	22-Sep-89	12.4	15-Nov-89	11.5		
25-Jun-89	9.7	2-Aug-89	11.9	25-Sep-89	11.5	22-Nov-89	11.7		
26-Jun-89	10.6	4-Aug-89	11.3	27-Sep-89	11.1	29-Nov-89	8.2		

Appendix B. Dissolved nitrogen species and dissolved nitrate at the storm runoff monitoring stations.

[m/d/y, month/day/year; total dissolved nitrogen species is sum of organic-N, ammonia-N, and nitrate plus nitrite-N; --, partial analysis for NO_3-N only; NO_3-N, nitrate as nitrogen; mg/L, milligrams per liter; <, less than]

Storm event	Sample date m/d/y	Time of sample	Total dissolved nitrogen as N, in mg/L	Dissolved nitrate as N, in mg/L	Time interval weighted NO_3-N, in mg/L for storm event	Total minutes of runoff event
Pineapple farm site						
1	4/29/94	1144	17.7	13.7	--	--
	4/29/94	1149	17.7	14.8	--	--
	4/29/94	1214	18.9	14.3	--	--
	4/29/94	1259	20.2	15.0	14.6	75
2	9/6/94	1200	5.90	5.70	--	--
	9/6/94	1205	9.70	9.50	--	--
	9/6/94	1225	11.2	11.0	--	--
	9/6/94	1235	11.2	11.0	--	--
	9/6/94	1245	11.2	11.0	--	--
	9/6/94	1300	14.0	11.6	--	--
	9/6/94	1310	15.9	14.6	10.9	70
3	9/19/94	1604	7.30	4.70	--	--
	9/19/94	1609	9.90	7.90	--	--
	9/19/94	1613	10.7	8.60	--	--
	9/19/94	1618	11.0	8.90	--	--
	9/19/94	1624	11.7	9.60	8.19	20
4	11/9/94	1550	9.40	7.10	--	--
	11/9/94	1555	9.00	7.40	--	--
	11/9/94	1615	9.30	7.20	--	--
	11/9/94	1650	10.1	7.60	--	--
	11/9/94	1700	9.60	7.50	7.38	70
5	11/11/94	1431	9.80	9.30	--	--
	11/11/94	1441	11.6	10.9	--	--
	11/11/94	1456	11.7	11.0	11.3	25
6	12/8/94	2247	8.90	7.80	--	--
	12/8/94	2242	8.80	8.00	--	--
	12/8/94	2302	9.20	7.80	--	--
	12/8/94	2332	9.00	7.80	7.81	45
7	2/28/95	0049	--	3.20	--	--
	2/28/95	0053	--	3.60	3.4	3

Appendix B. Dissolved nitrogen species and dissolved nitrate at the storm runoff monitoring stations--Continued.

Storm event	Sample date m/d/y	Time of sample	Total dissolved nitrogen as N, in mg/L	Dissolved nitrate as N, in mg/L	Time interval weighted NO_3-N, in mg/L for storm event	Total minutes of runoff event
Urban runoff site						
1	7/31/94	1739	0.65	0.04	0.04	<5
2	8/9/94	1203	0.80	0.03	--	--
	8/9/94	1223	0.91	0.35	--	--
	8/9/94	1348	1.08	0.38	0.33	105
3	8/10/94	1132	1.08	0.08	0.08	<5
4	11/11/94	1358	0.77	0.17	--	--
	11/11/94	1403	0.52	0.12	0.14	<5
5	1/25/95	2342	1.54	0.14	--	--
	1/25/95	2352	5.90	0.03	--	--
	1/26/95	0002	2.29	1.09	--	--
	1/26/95	0017	2.04	0.44	--	--
	1/26/95	0257	1.30	0.40	--	--
	1/26/95	0327	2.29	0.19	--	--
	1/26/95	0407	1.74	0.84	--	--
	1/26/95	0527	0.85	0.55	--	--
	1/26/95	0607	0.46	0.16	--	--
	1/26/95	0627	0.46	0.16	0.45	432
6	3/6/95	1350	1.05	0.05	--	--
	3/6/95	1355	0.98	0.18	0.12	<5
7	3/13/95	0348	0.34	0.04	--	--
	3/13/95	0353	0.36	0.16	--	--
	3/13/95	0358	0.41	0.11	0.10	15
8	3/14/95	0245	0.83	0.63	0.63	<5
9	3/27/95	0251	1.42	0.02	0.02	<5
10	4/19/95	0414	0.66	0.06	--	--
	4/19/95	0424	0.49	0.09	--	--
	4/19/95	0434	0.55	0.05	--	--
	4/19/95	0543	0.41	0.11	--	--
	4/19/95	0558	0.52	0.12	0.08	69

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