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PUERTO RICO AQUEDUCTS AND SEWERS AUTHORITY
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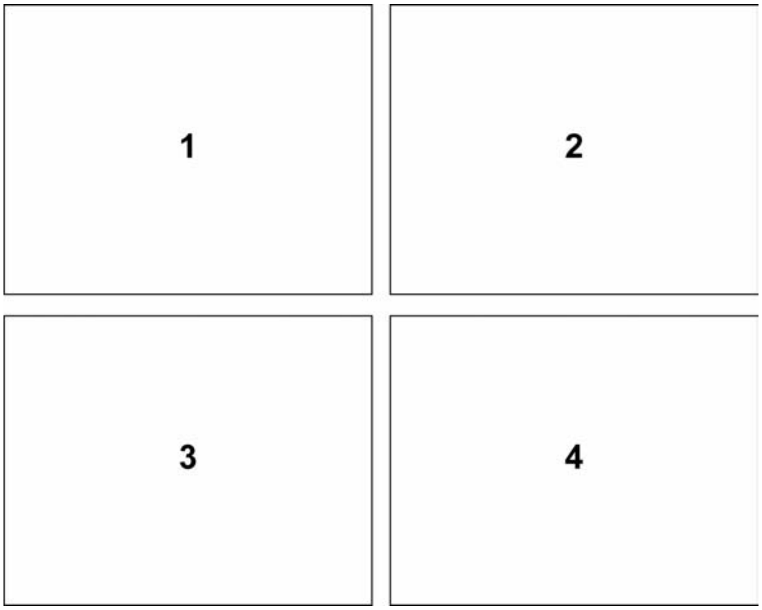
Evaluation of Hydrologic Conditions and Nitrate Concentrations in the Río Nigua de Salinas Alluvial Fan Aquifer, Salinas, Puerto Rico, 2002-03

Scientific Investigations Report 2006-5062

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



Cover photographs

1) Turf grass crop near the Aguirre area, Salinas, Puerto Rico.
2) Plantain crop near the Aguirre area, Salinas, Puerto Rico.
3) Poultry house at the Hucar area, Salinas, Puerto Rico.
4) Corn crop near the Aguirre area, Salinas, Puerto Rico.

Photographs taken by José M. Rodríguez on 2003.

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U.S. Department of the Interior
P. Lynn Scarlett, Acting Secretary

U.S. Geological Survey
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Conversion Factors, Datum, Water-Quality Units, and Acronyms

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	10.76	square foot (ft^2)
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
liter (L)	0.2642	gallon (gal)
	Flow rate	
cubic meter per year (m^3/yr)	0.000811	acre-foot per year (acre-ft/yr)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year (ft/yr)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
liter per second (L/s)	15.85	gallon per minute (gal/min)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
	Mass	
gram (g)	0.002205	pound (lb)
kilogram (kg)	2.205	pound (lb)
kilogram per year (kg/yr)	2.205	pound per year (lb/yr)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
	Application rate	
kilograms per hectare per year [(kg/ha)/yr]	0.8921	pounds per acre per year [(lb/acre)/yr]

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

$$°F = (1.8 \times °C) + 32$$

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 "Sea Level Datum of 1929".

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μs/cm at 25 °C)

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Abbreviated water-quality units used in this report:

μg/L	microgram per liter
mg/L	milligram per liter
μm	micrometer

Acronyms used in this report:

GPS	global positioning system
MCL	maximum contaminant level
PRASA	Puerto Rico Aqueducts and Sewers Authority
PRDNER	Puerto Rico Department of Natural and Environmental Resources
PREPA	Puerto Rico Electric Power Authority
PRIFA	Puerto Rico Infrastructure Financing Authority
PWSS	Public-Water Supply System
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Evaluation of Hydrologic Conditions and Nitrate Concentrations in the Río Nigua de Salinas Alluvial Fan Aquifer, Salinas, Puerto Rico, 2002-03

By José M. Rodríguez

Abstract

A ground-water quality study to define the potential sources and concentration of nitrate in the Río Nigua de Salinas alluvial fan aquifer was conducted between January 2002 and March 2003. The study area covers about 3,600 hectares of the coastal plain within the municipality of Salinas in southern Puerto Rico, extending from the foothills to the Caribbean Sea. Agriculture is the principal land use and includes cultivation of diverse crops, turf grass, bioengineered crops for seed production, and commercial poultry farms.

Ground-water withdrawal in the alluvial fan was estimated to be about 43,500 cubic meters per day, of which 49 percent was withdrawn for agriculture, 42 percent for public supply, and 9 percent for industrial use. Ground-water flow in the study area was primarily to the south and toward a cone of depression within the south-central part of the alluvial fan. The presence of that cone of depression and a smaller one located in the northeastern quadrant of the study area may contribute to the increase in nitrate concentration within a total area of about 545 hectares by "recycling" ground water used for irrigation of cultivated lands.

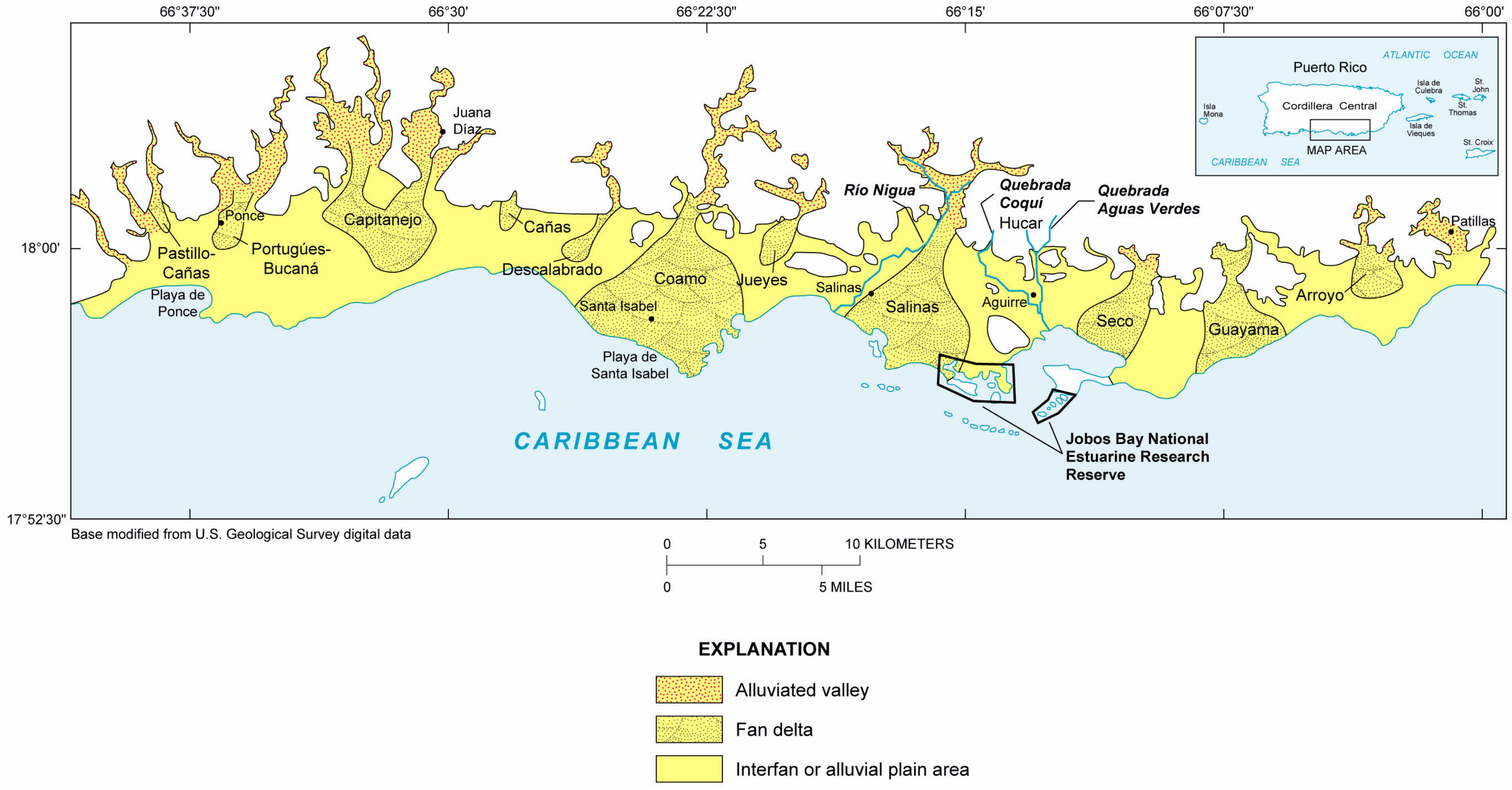
In an area that covers about 405 hectares near the center of the Salinas alluvial fan, nitrate concentrations increased from 0.9 to 6.7 milligrams per liter as nitrogen in 1986 to 8 to 12 milligrams per liter as nitrogen in 2002. Principal sources of nitrate in the study area are fertilizers (used in the cultivated farmlands) and poultry farm wastes. The highest nitrogen concentrations were found at poultry farms in the foothills area. In the area of disposed poultry farm wastes, nitrate concentrations in ground water ranged from 25 to 77 milligrams per liter as nitrogen. Analyses for the stable isotope ratios of nitrogen-15/nitrogen-14 in nitrate were used to distinguish the source of nitrate in the coastal plain alluvial fan aquifer.

Potential nitrate loads from areas under cultivation were estimated for the principal crops in the area. The load estimates ranged from 18 kilograms per hectare per year as nitrogen for sorghum crops to 430 kilograms per hectare per year as nitrogen for turf-grass farms. Potential nitrate load from poultry farm wastes and from communities with septic tanks were estimated at about 580 and 47 kilograms per hectare per year as nitrogen, respectively. Results obtained from the analyses of the stable isotope ratios of nitrogen-15/nitrogen-14 in nitrate samples indicated that the high nitrate concentrations are from poultry wastes near the foothills, whereas artificial fertilizers were estimated to contribute between 39 to 97 percent of the total nitrate in the central part of the alluvial fan.

Introduction

Since 1998, increased nitrate concentrations in ground water in the Río Nigua de Salinas alluvial fan aquifer and the foothills north of the fan at Salinas, Puerto Rico (fig. 1), have been reported by the Puerto Rico Department of Natural and Environmental Resources (PRDNER). Baseline nitrate concentrations in ground water throughout most of the alluvial fan were generally less than 5 mg/L as nitrogen in samples obtained in 1986-87 (F. Gómez-Gómez, U.S. Geological Survey, written commun., 2002). The increase in nitrate concentrations has been of concern to local government agencies because of the potential impact to public-supply water wells and to the Jobos Bay National Estuarine Research Reserve. The source of drinking water in the Salinas area is the Salinas alluvial fan aquifer, which supplies about 18,200 m^3/d to the Puerto Rico Aqueduct and Sewer Authority (PRASA) public supply wells. Additionally, about 3,800 m^3/d are withdrawn by the Puerto Rico Electric Power Authority (PREPA) for steam production and domestic use at the Aguirre thermoelectric power plant. About 12 farms in the area use an estimated 21,600 m^3/d of ground water to irrigate their crops.

The U.S. Geological Survey (USGS), in cooperation with the PRASA, PRDNER, and Puerto Rico Infrastructure Financing Authority (PRIFA), conducted a ground-water quality study in the Río Nigua de Salinas alluvial fan between January 2002 and March 2003. The objectives of the study were to: (1) define the hydrologic conditions of the alluvial aquifer in the Río Nigua de Salinas alluvial fan, with emphasis on the distribution of nitrate concentrations; (2) identify potential sources leading to elevated nitrate concentrations; (3) estimate the nitrate loads from major sources identified; and (4) estimate the ground-water withdrawals by principal use categories in the area. Results of this study will be used by Commonwealth and Federal Government agencies in developing strategies that can aid in containment of high nitrate ground water to minimize degradation of fresh ground water in the coastal plain alluvial fan aquifer and coastal estuarine resources that are dependent on aquifer discharge.



Base modified from U.S. Geological Survey digital data

Figure 1. Location of the Río Nigua de Salinas study area in relation to the South Coastal Plain alluvial aquifer of southern Puerto Rico (modified from Renken and others, 2002).

Purpose and Scope

The purposes of this report are to: (1) describe the hydrologic conditions in an agricultural area in the South Coastal Plain of Puerto Rico, and (2) present the results of water-quality data collected from wells in the Río Nigua de Salinas alluvial fan and the Hucar area foothills, with an emphasis on nitrate concentrations. The water-quality data that were collected for analysis include common dissolved constituents, nitrate, and the stable isotope ratios of hydrogen-2/1, oxygen-18/16, and nitrogen-15/14. As part of the study, data also were obtained to define ground-water withdrawals by major use categories, the potentiometric surface of the aquifer, land use, and estimates of nitrate loads to the aquifer from fertilizer application, land disposal of poultry wastes, and domestic septic-wastes from unsewered communities.

Methods

An inventory of the wells within the study area was conducted to update the USGS Ground-Water Site Inventory database (fig. 2 and table 1). The locations of the wells were confirmed using a global positioning system (GPS) unit. Well construction data were obtained from interviews with owners and from data in files at the USGS, Caribbean Water Science Center. Land-use data were obtained using 1999 aerial photographs and from field visits and interviews with farmers in the study area. Anderson level II land-use classification (Anderson and others, 1976) was used to characterize the land use in the area. A modification was added to the classification system to distinguish between crop types in the area and between residential areas with and without sewer systems. Information on crops cultivated and fertilizer application rates were obtained by interviewing farmers and by field reconnaissance.

Ground-water levels were measured at 57 wells during the period from July 9 to 11, 2002. The measurements were used to prepare a potentiometric-surface map of the alluvial fan aquifer within the study area. The potentiometric-surface map was used to delineate the general direction of ground-water flow and to aid in identifying the sources of nitrate affecting the sampled wells.

Ground-water samples were collected from wells during synoptic water-quality surveys conducted in March, November, and December 2002. A total of 19 wells were sampled in March and 24 wells between November and December 2002. Samples also were collected on a monthly basis from four wells to determine the temporal variation in nitrate concentrations. Analyses were made for common dissolved constituents (cations, anions, boron, iron) and nutrients (organic nitrogen, ammonia, nitrate, nitrite, and phosphorus) from water samples, hydrogen isotopes ($^{2}H/^{1}H$) and oxygen isotopes ($^{18}O/^{16}O$) in water, and nitrogen isotopes ($^{15}N/^{14}N$) in nitrate. Field determinations were made for temperature, specific conductance, pH, and total alkalinity (as calcium carbonate). All samples were collected from active production wells as near as possible to the pump discharge and before discharge to storage tanks. Field measurements were obtained and water samples for laboratory analyses were collected and preserved according to USGS protocol (U.S. Geological Survey, variously dated). Samples for the major dissolved constituents were analyzed in the USGS National Water Quality Laboratory in Denver, Colorado, and the Ocala Quality of Water Service Unit in Ocala, Florida.

Analyses of ^{18}O and ^{2}H in water samples were performed in the USGS Isotope Fractionation Laboratory in Reston, Virginia. Results for oxygen and hydrogen isotopes are reported as delta units (δ) per mil relative to the Vienna Standard Mean Ocean Water and are normalized on scales such that the oxygen and hydrogen isotopic values of Standard Antarctic Precipitation are -55.5 per mil and -428 per mil, respectively (Coplen, 1994).

Water samples for nitrogen isotopes were analyzed in a contract laboratory using mass spectrometry with analytical uncertainty of about +/- 0.15 per mil. Collected samples were filtered (0.45 m) into 1-liter plastic bottle and kept chilled at 4 °C. Nitrogen isotope ratios are reported in per mil relative to nitrogen (N_2) in air.

The concentrations of ^{18}O, ^{2}H, and ^{15}N are defined by the expression:

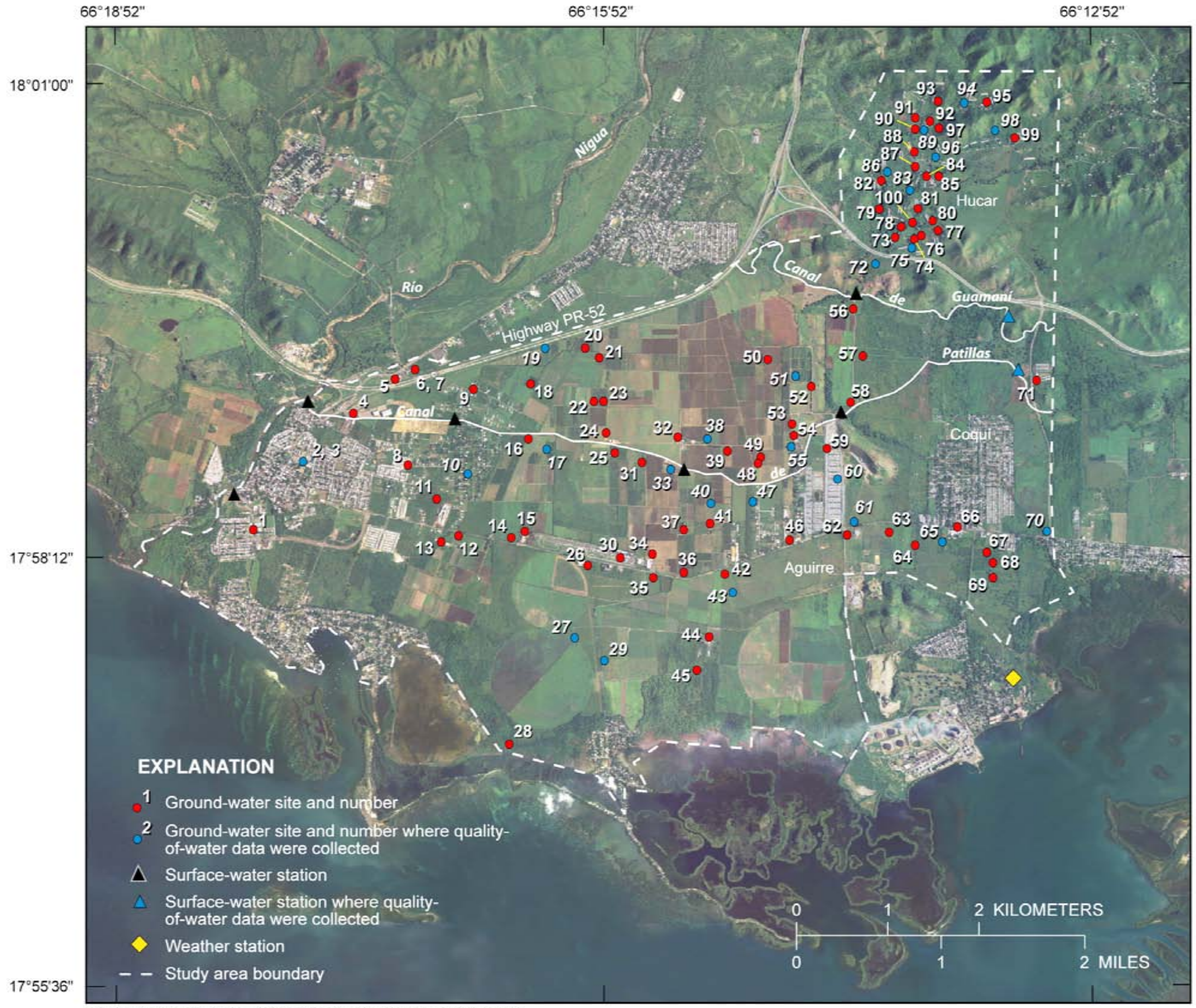
$$\delta\ (‰) = [(R\ sample\ /\ R\ standard)-1] \times 1{,}000$$

where

δ (‰) are delta units in per mil, and R corresponds to the ratios of $^{18}O/^{16}O$, $^{2}H/^{1}H$, and $^{15}N/^{14}N$.

Acknowledgments

The author wishes to thank the farm owners in the Salinas area for permitting access to their properties during the data-collection phase of the study, personnel from the PREPA and the PRASA for providing access to wells during the collection of water samples, Ms. Carmen González and Ms. Iris Tirado of the Jobos Bay National Estuarine Research Reserve for their support during the investigation, and Ms. Kathia Catalá, graduate student of the University of Puerto Rico, for her assistance during the quality-of-water data collection phase of the study. A special thanks is extended to Fernando Gómez-Gómez, U.S. Geological Survey, for his mentoring and advice during the data analyses and preparation of this report.



U.S. Army Corp of Engineers (USACE) 2004 orthophotos for the Salinas area.

Figure 2. Location of ground-water sites and surface-water stations in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico.

Table 1. Inventory of wells in the Salinas study area, Puerto Rico.

[Locations field checked during this study; --, no data]

Site number (see figure 2)	Latitude	Longitude	Status	Depth, in meters below land surface	Water level, in meters below land surface	Well instantaneous discharge (liters per second)	Estimated mean annual withdrawal rate (cubic meter per day)
1	175826	661806	Active	--	4.18	--	1098
2	175850	661744	Active	36.57	--	--	2271
3	175851	661746	Active	36.57	8.84	--	2195
4	175908	661726	Active	--	8.84	8.20	1779
5	175922	661712	Active	54.86	11.70	19.87	1741
6	175924	661704	Active	--	--	--	1476
7	175924	661704	Active	--	20.45	11.99	1022
8	175848	661707	Unused	--	10.24	--	0
9	175918	661641	Unused	36.27	14.84	--	0
10	175845	661645	Active	30.48	11.55	--	--
11	175838	661654	Unused	52.42	12.53	--	0
12	175823	661646	Active	--	7.80	35.33	871
13	175823	661646	Unused	--	--	--	0
14	175824	661629	Active	--	--	41.01	379
15	175824	661625	Active	--	11.73	--	265
16	175859	661622	Active	54.86	--	31.55	265
17	175855	661615	Active	45.72	--	34.70	379
18	175918	661619	Unused	42.67	17.49	--	0
19	175931	661616	Active	53.34	--	50.47	1893
20	175930	661603	Unused	44.50	16.89	--	0
21	175927	661556	Active	--	--	15.77	151
22	175911	661558	Active	--	--	12.62	379
23	175910	661555	Unused	--	14.78	--	0
24	175859	661553	Active	--	--	25.24	303
25	175851	661541	Active	32.00	12.56	15.77	1136
26	175814	661559	Unused	--	11.64	--	0
27	175748	661606	Unused	48.77	8.53	110.41	4542
28	175708	661629	Unused	--	0.52	--	0
29	175739	661556	Active	--	7.31	15.77	454
30	175814	661547	Active	--	15.03	--	--
31	175854	661552	Active	--	11.64	22.71	606
32	175858	661527	Active	--	--	31.55	757
33	175851	661530	Active	91.44	12.10	37.85	643
34	175815	661537	Unused	--	12.98	--	0
35	175811	661536	Unused	--	10.85	--	0

Table 1. Inventory of wells in the Salinas study area, Puerto Rico.—Continued

[Locations field checked during this study; --, no data]

Site number (see figure 2)	Latitude	Longitude	Status	Depth, in meters below land surface	Water level, in meters below land surface	Well instantaneous discharge (liters per second)	Estimated mean annual withdrawal rate (cubic meter per day)
36	175810	661527	Active	36.57	21.76	49.84	1779
37	175825	661526	Active	30.48	--	--	15
38	175858	661516	Active	--	15.85	26.81	0
39	175856	661510	Active	42.67	15.27	41.01	1893
40	175832	661516	Active	33.53	10.12	32.81	757
41	175827	661516	Active	71.62	--	--	1136
42	175811	661510	Unused	--	15.00	--	492
43	175804	661507	Unused	45.72	15.54	104.10	2650
44	175747	661514	Active	21.33	--	--	--
45	175735	661518	Unused	--	5.27	--	0
46	175821	661447	Active	38.10	8.87	--	--
47	175835	661457	Active	33.53	10.76	34.07	--
48	175851	661457	Active	--	16.73	26.81	1893
49	175849	661457	Active	--	--	26.81	--
50	175925	661453	Unused	--	--	--	0
51	175919	661444	Active	--	19.84	12.62	454
52	175915	661436	Unused	91.44	17.22	--	379
53	175859	661444	Active	--	--	--	379
54	175856	661443	Active	--	--	--	379
55	175855	661444	Active	--	16.00	--	189
56	175943	661421	Unused	--	11.25	--	0
57	175927	661420	Unused	--	13.20	--	0
58	175909	661422	Unused	--	12.95	--	0
59	175855	661431	Unused	--	13.23	--	0
60	175845	661428	Active	22.86	12.59	22.08	--
61	175827	661422	Active	--	--	--	1628
62	175825	661425	Active	41.15	7.47	24.61	908
63	175827	661411	Unused	--	10.45	--	0
64	175820	661359	Active	--	--	--	--
65	175822	661349	Active	35.96	7.83	--	1136
66	175826	661344	Unused	24.38	5.94	--	0
67	175819	661334	Active	45.72	--	--	--
68	175812	661332	Active	45.72	--	28.39	1741
69	175809	661332	Unused	28.95	4.54	--	0
70	175823	661309	Active	--	3.66	8.20	719

Table 1. Inventory of wells in the Salinas study area, Puerto Rico.—Continued

[Locations field checked during this study; --, no data]

Site number (see figure 2)	Latitude	Longitude	Status	Depth, in meters below land surface	Water level, in meters below land surface	Well instantaneous discharge (liters per second)	Estimated mean annual withdrawal rate (cubic meter per day)
71	175916	661312	Active	--	9.48	--	--
72	175958	661415	Active	19.20	--	3.79	--
73	180009	661406	Active	--	4.88	--	--
74	180007	661400	Active	30.48	--	--	--
75	180008	661359	Active	30.48	7.92	1.26	--
76	180010	661357	Active	32.00	--	1.26	--
77	180012	661351	Active	--	7.25	--	--
78	180014	661404	Active	--	--	--	--
79	180019	661411	Active	13.72	--	1.26	--
80	180015	661356	Active	20.73	--	--	--
81	180018	661358	Active	15.24	--	--	--
82	180031	661409	Active	30.48	--	--	--
83	180024	661401	Active	19.81	--	--	--
84	180031	661354	Unused	--	--	--	--
85	180031	661352	Unused	22.86	6.52	--	--
86	180033	661409	Active	13.72	6.98	1.26	4
87	180034	661357	Active	21.33	--	--	--
88	180039	661358	Active	24.38	7.13	--	--
89	180046	661354	Active	19.81	10.76	--	--
90	180046	661355	Active	92.96	--	--	--
91	180050	661355	Active	106.67	12.62	--	--
92	180049	661353	Active	30.48	10.15	--	--
93	180056	661351	Active	38.10	--	--	--
94	180057	661340	Active	45.72	7.80	--	--
95	180057	661332	Active	45.72	10.88	--	--
96	180037	661352	Active	16.76	--	--	--
97	180046	661350	Unused	30.48	11.06	--	--
98	180047	661327	Active	24.38	--	1.01	--
99	180054	661322	Active	48.77	13.26	--	--
100	180014	661359	Unused	--	--	--	--

Description of Study Area

The Río Nigua de Salinas alluvial fan is located in the southern coast of Puerto Rico. The study area includes about 3,600 ha that overlie the alluvial fan aquifer and about 194 ha in the foothills to the north of the alluvial fan that overlie volcanic rocks (fig. 1). The limits of the study area are the Río Nigua de Salinas to the west, the Quebrada de las Aguas Verdes (an intermittent stream) to the east, the hydrologic divide formed by the foothills to the north, and the Caribbean Sea to the south.

The municipality of Salinas (fig. 2), historically has been one of the most intensively used agricultural areas in the South Coastal Plain of Puerto Rico (fig. 1). Mono-culture cultivation of sugarcane and its processing at the former Central Aguirre sugar mill constituted the major economic activity at Salinas from the early 1900s to the mid 1970s. By the mid 1980s, however, most sugarcane cultivation in the coastal plain had been abandoned, the sugar mill ceased operations, and agricultural lands were either left fallow, parceled out for use in cultivation of diversified crops, or used for suburban developments.

Climate

The south coast of Puerto Rico is warmer and drier than the other parts of the island owing to the rain shadow effect of the east-west trending Cordillera Central mountain range on the prevailing northeast trade winds. The mean annual rainfall in the coastal plain near the study area is about 1,016 mm (Aguirre Central National Weather Service station 660152, from 1955 to 2004), as compared to about 1,956 mm in the mountains to the north at 728 m altitude (Jajome Alto National Weather Service station 664867) and about 1,346 mm on the northern coast in San Juan (National Weather Service station 668812). From 1955 to 2004, the mean monthly rainfall in the area ranged from 29.7 to 175 mm at the Aguirre weather station (fig. 3). A relative dry season occurs from December to April, with March being the driest month. A relative wet season occurs from May to November, with October being the wettest month. During the 2002-03 periods, 10 of the 14 months had below average rainfall (fig. 3). Mean annual temperature in the South Coastal Plain is about 3 to 5 °C higher than in the mountains. Mean monthly maximum temperatures at the Aguirre Central weather station ranged from 30 °C in January to 32 °C in August between1955 to 2004.

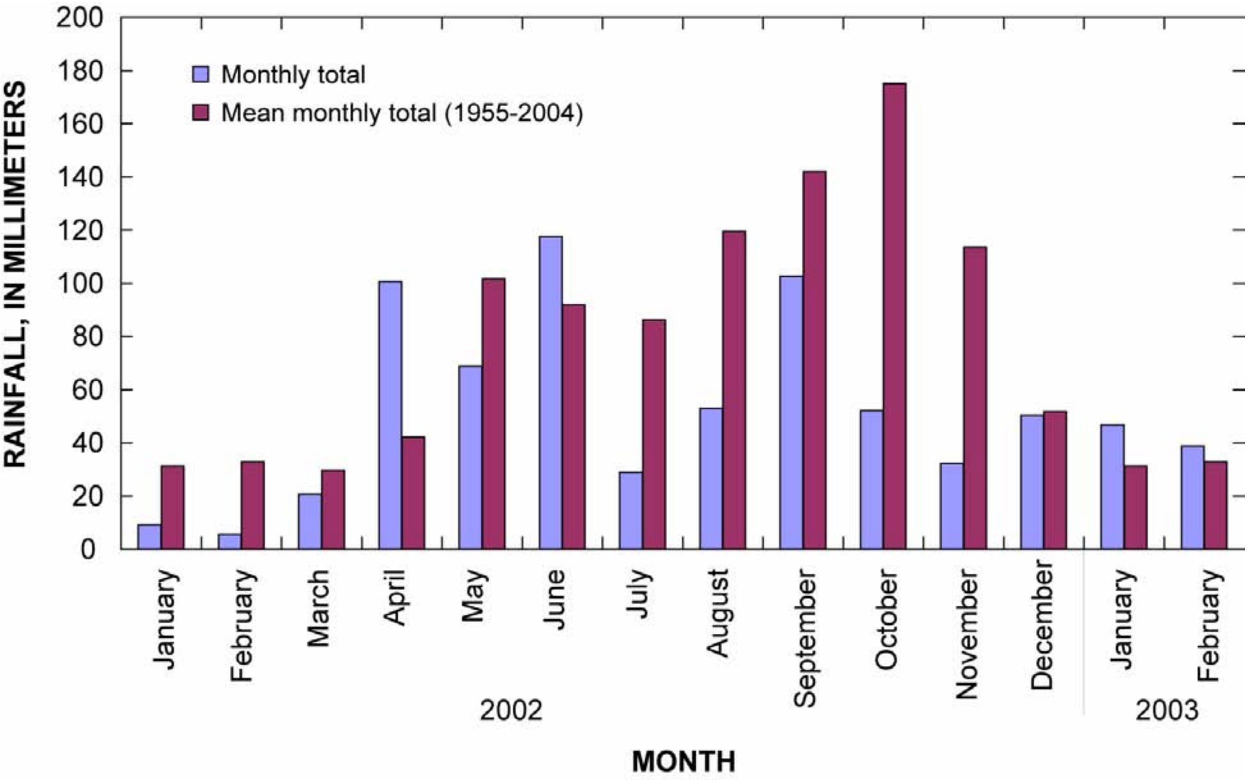


Figure 3. Graph showing distribution of monthly total (2002-03) and mean monthly total (1955-2004) rainfall at the Aguirre Central National Weather Service station 660152, Salinas, Puerto Rico.

Physiographic Features

The South Coastal Plain of Puerto Rico is characterized by a parched vegetative cover, except at areas under irrigation or near intermittently flowing streams. The Río Nigua de Salinas alluvial fan extends from the town of Salinas in the west to the suburban development of Coquí in the east. Altitude in the alluvial fan ranges from sea level (NGVD 1929) to about 40 m above sea level. The coastal plain at Salinas is separated from the Caribbean Sea by a zone of marsh, mangrove, swamp, and tidal flats. The plain is interrupted along the east by two knolls that rise to as much as 90 m above the plain and form hydrologic barriers along their extensions. The hills to the north also form a hydrologic barrier to the Hucar area basin. The highest altitude of the hills enclosing the basin in the north is about 240 m above sea level. A series of discontinuous hills, where the altitude ranges from 100 to 140 m above sea level, are located along the east, west, and south of the Hucar drainage basin. The altitude of the basin floor in the Hucar area ranges from about 45 m in the inland part of the coastal plain to 90 m above sea level.

Land Use

During 2002, land uses in the approximately 3,800 ha of the study area included agriculture, urban, and industrial use. Agricultural land use, which includes cropland/pasture land and confined poultry feeding operations, was active within about 35 percent of the study area. About 51 percent of the study area consisted of uncultivated land. Urban areas included about 13 percent, of which only half had sewer connections. Industrial land use consisted of only 1 percent of the area (fig. 4).

Major crops in the coastal plain include plantains, bananas, corn, sorghum, and papaya. Poultry farms are located in the foothills north of the alluvial fan within the Hucar drainage basin. A total of 29 poultry farms were in operation within an approximate 194-ha area during 2002, with a production of about 1.8 million chickens per year (Robert, 2001).

Hydrologic Conditions in the Salinas Area

An understanding of the hydrologic regime in the Salinas area is required to aid water managers in their endeavors to protect the coastal estuarine resources along the southern coast of Puerto Rico. This section describes the hydrogeologic setting, ground-water flow and hydraulic characteristics, and isotopic composition of ground water and surface water in the Salinas area.

Hydrogeologic Setting

The study area is within the South Coastal Plain alluvial aquifer and extends from the coast to the bedrock hills north of the coastal plain. The aquifer in the Salinas area includes three principal hydrogeologic units: (1) an upper zone typically composed of varying proportions of sand, gravel, and clay with the fraction of finer sediments increasing coastward; (2) the fan deltas and alluvial deposits (principal ground-water flow zone); and (3) the regolith unit composed of weathered bedrock of various types (Quiñones-Aponte and others, 1997). Ground water within the sand and gravel beds of the upper zone is mostly unconfined; however, as the amount of fine-grained material increases coastward, this upper zone becomes a semiconfining unit to the principal ground-water flow zone within the fan delta and alluvial deposits. The thickness of the upper zone is about 23 m along the coastline and varies from 3 to 12 m along its northern limit. The upper zone supplies water to domestic wells, with yields ranging from 0.32 to 0.63 L/s (Quiñones-Aponte and others, 1997).

The fan delta and alluvial deposits encompass most of the coastal plain within the study area (fig. 5). The thickness of the fan delta deposits in the Salinas area is mainly controlled by horst and graben structures and may be as much as 107 m thick (Quiñones-Aponte and others, 1997). Along the eastern edge of the alluvial fan near the bedrock outcrops, the thickness of the alluvial deposits may not be greater than 46 m and the underlying regolith as much as 15 m thick (fig. 6).

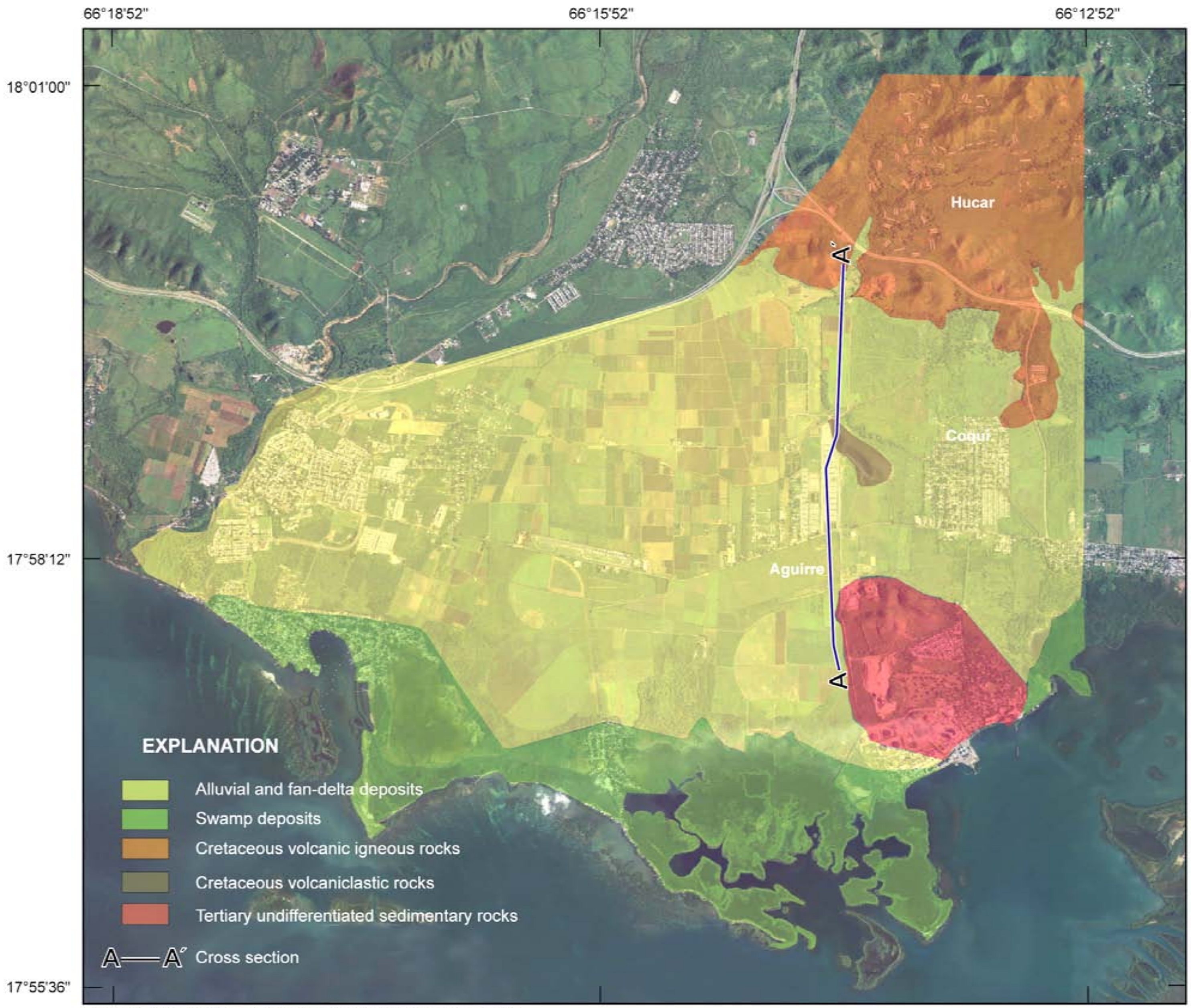
The hydraulic conductivity of the fan delta deposits in the Salinas area ranges from about 8 m/d near the foothills to greater than 30 m/d within the apex of the fan near the town of Salinas (Renken and others, 2002). During 2002, the depth to water ranged from about 8.8 to 19.8 m below land surface north of the Canal de Patillas and from 0.52 to 21.8 m below land surface in the southern part of the alluvial fan. Wells near the northern border of the alluvial fan may withdraw water from the regolith unit exclusively with yields averaging 6.3 L/s (Quiñones-Aponte and others, 1997). Well yields in the alluvial fan ranged from 8.2 to 110 L/s.

Swamp deposits comprise the southern boundary of the coastal plain in the study area and bedrock hills crop out near the Coquí and Aguirre areas (fig. 5). Swamp deposits consist of unconsolidated clay, silt, and organic matter (Glover, 1961). The outcrops west of the Coquí area consist mostly of massive cretaceous volcanic rocks with minor amounts of reef-type limestone and calcareous siltstone (Berryhill, 1960). Most rocks that crop out in the Aguirre area consist of stratified undifferentiated Tertiary sedimentary rocks: sandstone, siltstone, chert, mudstone, and minor limestone (Berryhill, 1960).

The subsurface geology of the hills near the Hucar area was described by Graves (1992) as consisting primarily of fractured volcanic igneous rocks. The hydrogeologic units in this area consist of a regolith ranging from 1.5 to 33 m thick; locally there is a transition zone, consisting of a shattered to highly fractured volcanic rock that underlies the regolith and ranges from nonexistent to 33 m below land surface (Graves 1992). Wells in the Hucar area have yields that range from 0.95 to 1.27 L/s.

U.S. Army Corp of Engineers (USACE) 2004 orthophotos for the Salinas area.

Figure 4. Land use in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002.



U.S. Army Corp of Engineers (USACE) 2004 orthophotos for the Salinas area.

Figure 5. Surficial geology of the study area and location of cross section in the Río Nigua de Salinas alluvial fan study area, Salinas, Puerto Rico (modified from Berryhill and Glover, 1960; Glover, 1961).

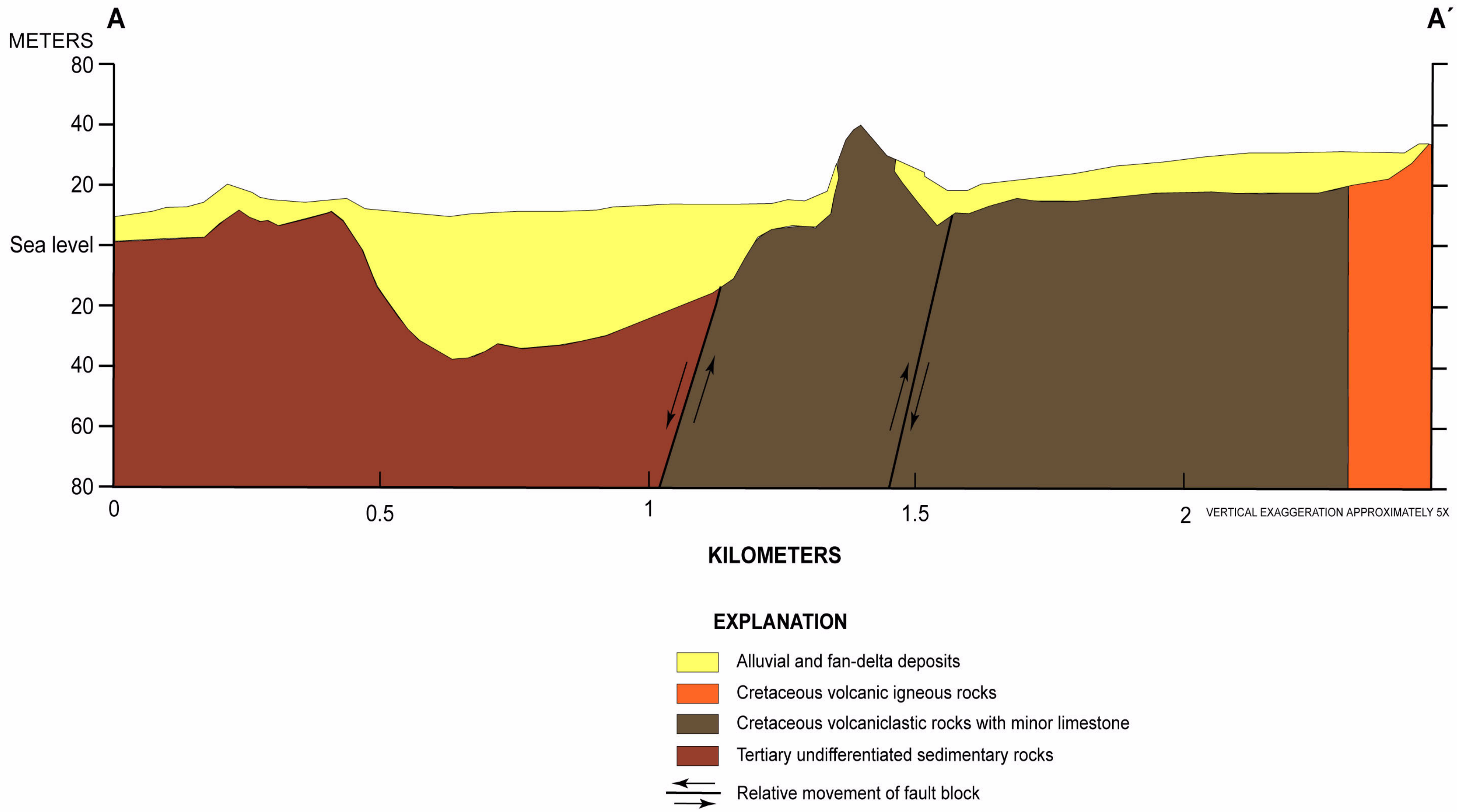


Figure 6. Generalized geologic section in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico (modified from Puerto Rico Water Resources Authority, 1972; thickness of units as interpolated from core borings and seismic data).

Ground-Water Flow and Hydraulic Characteristics

The configuration of the potentiometric surface was determined in the study area based on water-level measurements obtained during July 9 to 11, 2002 (fig. 7) (Rodríguez, 2005). Evaluation of the data indicates that ground water generally flows to the south. Additionally, two cones of depression were delineated within the study area. The major cone of depression is located in the south-central part of the study area and is caused by ground-water withdrawals by irrigation wells and by a PREPA well. A smaller cone of depression is located in the northeastern quadrant of the study area.

The potentiometric surface in the Salinas fan determined from the data collected during July 2002 was compared with the potentiometric surface as delineated for conditions in March 1986 (Quiñones-Aponte and Gómez-Gómez, 1987). The comparison of these potentiometric surfaces indicates that the ground-water levels between the Río Nigua de Salinas and the Coquí area decreased by an average of about 4.6 m between March 1986 and July 2002. This could represent an aquifer storage depletion of about 8 million m^3, using a storage coefficient of 0.10.

The storage coefficient was estimated using ground-water level change data in observation wells after intense rainfall events that occurred from 1997 to 2003, using a calculation method also applied along the northern coast of Puerto Rico following the effects of Hurricane Hortense (Gómez-Gómez, 1987). Results of the analysis indicated that the storage coefficient ranges from 0.04 to 0.10 in Piezometer G observation well (fig. 2, site 8) and from 0.07 to 0.10 in Piezometer D observation well (fig. 2, site 23).

The decline in aquifer storage is further confirmed by the declining trend in water levels at sites 8 (observation well Piezometer G) and 23 (observation well Piezometer D) for a period ranging from 6 to 12 years (fig. 8). The principal recharge occurred after rainfall on September 13, 1996, September 21, 1998, and November 11, 1999. These rainfall events were associated with the effects of Hurricanes Hortense and Georges, which made landfall on the island, and Hurricane Lenny, which passed to the south of the island. The historical data obtained from site 23 in the central part of the study area indicate a declining water-level trend from 1999 to 2003, with a total decline of about 9.75 m. Historical data from site 23 near the urban center of Salinas indicate a declining trend after 1999 of about 6 m by July 2003.

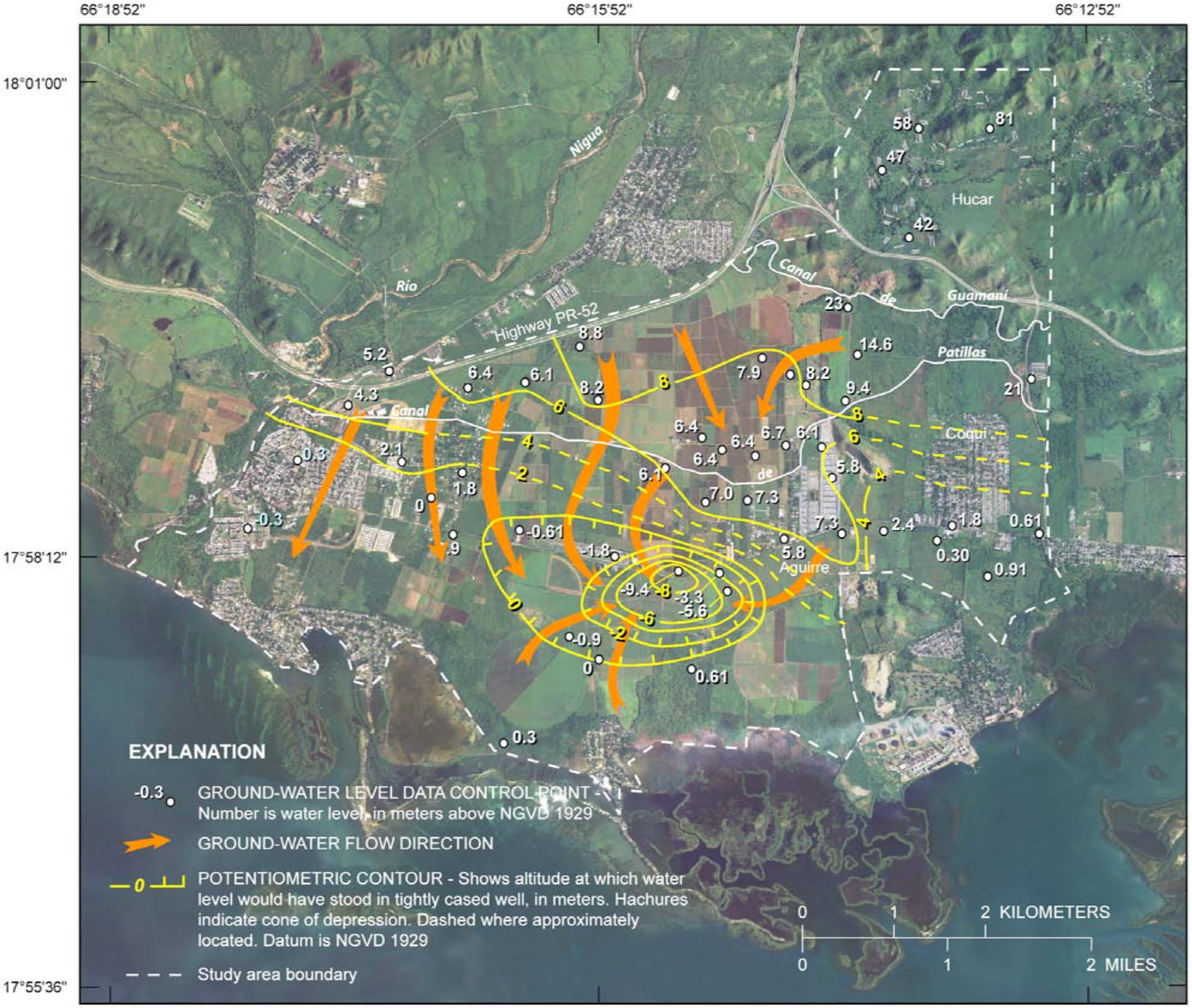
Ground-water withdrawals in the coastal plain section of the study area were estimated to be about 43,500 m^3/d during 2002 and distributed as follows: 21,580 m^3/d for irrigation, 18,170 m^3/d for pubic-supply withdrawals by the PRASA, and 3,780 m^3/d for industrial withdrawals by the PREPA. In the Hucar area, ground-water withdrawals were estimated to be about 121 m^3/d mostly for use at poultry farms.

Recharge to the Salinas fan occurs from rainfall, infiltration from unlined segments of irrigation canals, and streamflow infiltration (Quiñones-Aponte and others, 1997). An additional source of recharge was infiltration of irrigation return flows when furrow irrigation was used for sugarcane cultivation. This practice declined, however, during the 1970s and may have been completely abandoned by the mid 1980s. The relative amount of recharge provided by the three aquifer recharge sources can vary on a temporal basis (years) because it is dependent on ground-water withdrawal rates, rainfall amounts (on any given year), and irrigation deliveries especially in areas where surface-water irrigation is active (or along unlined segments of the irrigation canals).

Isotopic Composition in Ground Water and Surface Water

Gómez-Gómez (1991) used the stable isotopes of hydrogen and oxygen in water to estimate the relative amount of surface-water-derived ground water in the South Coastal Plain alluvial aquifer for conditions existing in 1986. To estimate the contribution of surface water to aquifer recharge in the study area, the isotopic "signatures" of surface water and native ground water, where rainfall is the only source of aquifer recharge, were defined. In this study, ground water from eight wells (sites 72, 75, 83, 86, 89, 94, 96, and 98) in the Hucar area was analyzed for stable isotopes to define the isotopic composition of native ground water (table 2). The average delta deuterium (δ^2H) and delta oxygen-18 ($\delta^{18}O$) in ground water obtained in the Hucar area, where rainfall is reasonably assumed to be the sole recharge source, were -24.7 +/-1.6 ‰ and -4.0 +/- 0.2 ‰, respectively. These values are relatively close to δ^2H = -21.5 +/- 1.3 ‰ and $\delta^{18}O$= -3.7 +/- 0.4 ‰ defined by Gómez-Gómez (1991) for ground water from an area in the Río Nigua de Salinas alluvial fan not recharged by surface water.

The isotopic composition of the surface water in the study area is more difficult to define because it is dependent primarily on the isotopic signature of water delivered to the fan by way of the Canal de Patillas and Canal de Guamaní irrigation canals (fig. 9). The isotopic signatures of surface water delivered by the irrigation canals during this study were as follows: δ^2H = -3.7 ‰ and $\delta^{18}O$ = -1.6 ‰ for two samples collected from the Canal de Patillas, and δ^2H = -7.4 ‰ and $\delta^{18}O$= -2.0 ‰ for one sample from the Canal de Guamaní. Values of δ^2H and $\delta^{18}O$ for the Canal de Guamaní during this study were close to the average values δ^2H = -10.1 +/- 2.4 ‰ and $\delta^{18}O$ = - 2.6 +/- 0.5 ‰ obtained by Gómez-Gómez (1991) for surface water sources. Results obtained for the Canal de Patillas during this study, however, were significantly different from those obtained by Gómez-Gómez (1991) from the same irrigation canal. Because of this difference, the values of δ^2H and $\delta^{18}O$ for the Canal de Guamaní were used as the isotopic signature for surface water in the area.



U.S. Army Corp of Engineers (USACE) 2004 orthophotos for the Salinas area.

Figure 7. Potentiometric surface in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, July 9-11, 2002 (modified from Rodríguez, 2005).

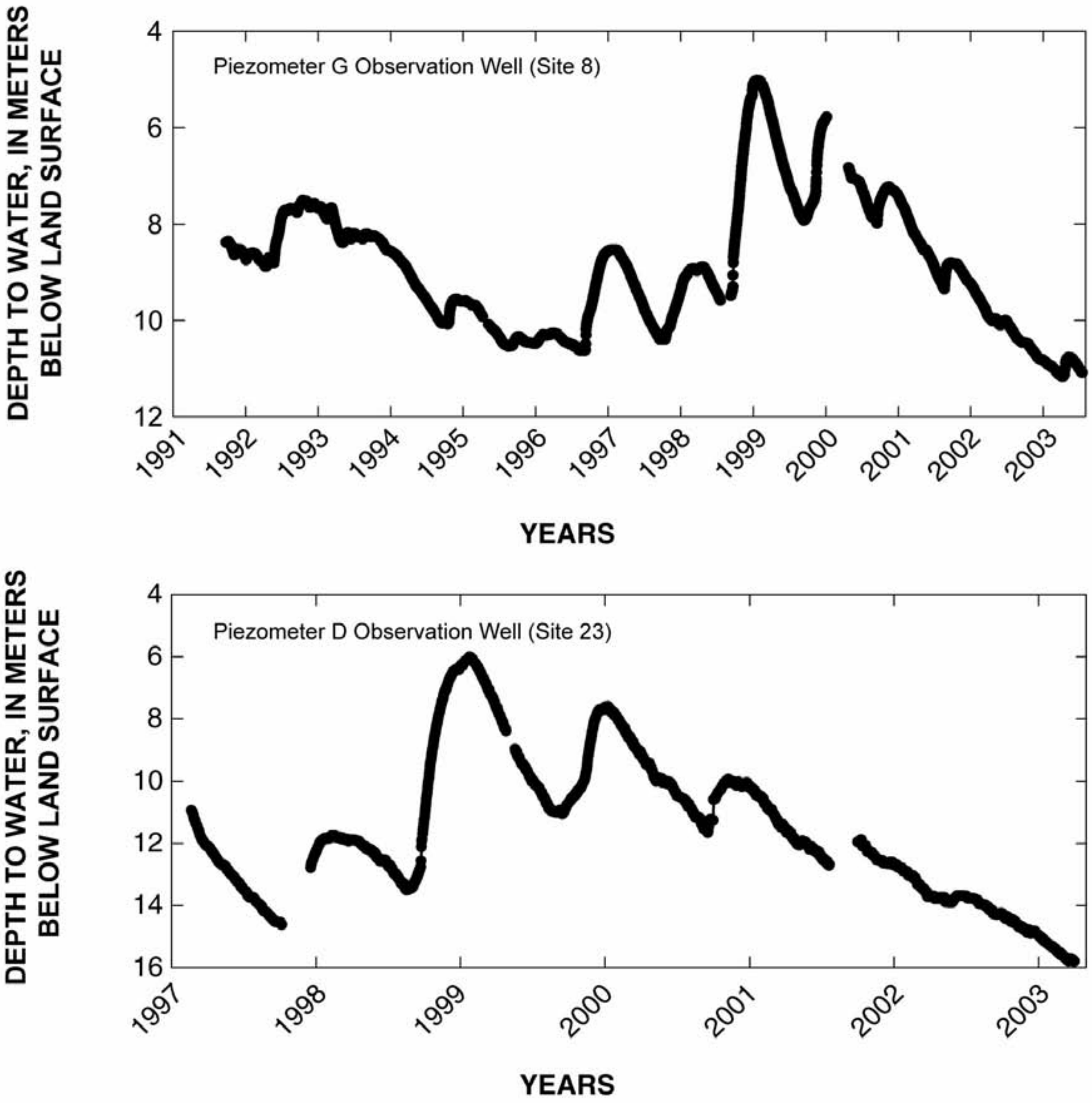


Figure 8. Ground-water levels at sites 8 and 23 in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico. Site location are shown in figure 2. Break indicates missing or insufficient data.

Table 2. Hydrogen and oxygen isotopes in ground-water samples collected from selected sites in the Salinas area, Puerto Rico.

[δ^2H, delta deuterium; δ^{18}O, delta oxygen-18]

Site number (see figure 2)	Latitude	Longitude	Date	δ^2H (per mil)	δ^{18}O (per mil)	Estimated surface-water percent using δ^2H	Estimated surface-water percent using δ^{18}O	Estimated average surface-water percent (used in figure 9)
2	175850	661744	3/11/2002	-21.3	-3.94	20	6	Not used
4	175913	661719	7/11/2002	-22.6	-3.80	12	10	11
10	175845	661645	3/12/2002	-18.1	-3.50	38	25	32
12	175823	661646	7/09/2002	-19.1	-3.35	33	32	32
15	175823	661624	7/09/2002	-17.5	-3.30	41	35	38
17	175855	661615	3/19/2002	-21.2	-3.61	20	20	20
19	17593	661616	3/06/2002	-21.4	-3.96	19	2	Not used
27	175748	661606	3/05/2002	-15.3	-2.89	54	56	55
29	175739	661556	3/11/2002	-14.5	-3.03	59	48	54
33	175851	661530	7/10/2002	-19.1	-3.51	32	24	28
38	175858	661516	3/06/2002	-22.2	-3.87	14	6	Not used
40	175829	661504	7/09/2002	-17.7	-3.36	40	32	36
43	175804	661507	3/05/2002	-17.9	-3.22	39	39	39
46	175821	661446	3/11/2002	-13.5	-2.84	65	59	61
55	175854	661445	7/10/2002	-19.9	-3.58	28	21	24
61	175827	661422	3/07/2002	-16.6	-3.08	47	46	46
65	175822	661349	3/11/2002	-15.5	-3.00	53	50	52
70	175823	661309	3/07/2002	-11.2	-2.51	78	74	76
72	175958	661415	3/18/2002	-23.5	-3.80	Values of δ^2H and δ^{18}O obtained from sites 72 to 98 were used to calculate the isotopic composition of native ground water		
75	180008	661359	3/13/2002	-23.4	-4.05			
83	180024	661401	3/14/2002	-22.5	-3.78			
86	180033	661409	3/14/2002	-25.5	-3.99			
89	180046	661354	3/13/2002	-24.7	-4.17			
94	180057	661340	3/06/2002	-26.6	-4.24			
96	180037	661352	3/18/2002	-24.2	-4.01			
98	180047	661327	3/13/2002	-27.2	-4.24			

The following equations were used to define the percentage of surface-water-derived ground water in the Salinas study area:

Percent surface-water-derived recharge

$$= \frac{(\delta^2 H_{gw}) - (\delta^2 H_w)}{(\delta^2 H_{gw}) - (\delta^2 H_{sw})} \times 100\,, \qquad (1)$$

where

$\delta^2 H_{gw}$ is the average hydrogen isotopic composition (-24.7 ‰) for native ground water,

$\delta^2 H_w$ is the hydrogen isotopic composition for the well water sample, and

$\delta^2 H_{sw}$ is the hydrogen isotopic composition (-7.4 ‰) for surface water.

Percent surface-water-derived recharge

$$= \frac{(\delta^{18} O_{gw}) - (\delta^{18} O_w)}{(\delta^{18} O_{gw}) - (\delta^{18} O_{sw})} \times 100\,, \qquad (2)$$

where

$\delta^{18} O_{gw}$ is the average oxygen isotopic composition (-4.0 ‰) for native ground water,

$\delta^{18} O_w$ is the oxygen isotopic composition for the well water sample, and

$\delta^{18} O_{sw}$ is the oxygen isotopic composition (-2.0 ‰) for surface water.

The percentage obtained using each of the equations was comparable with the difference generally less than 10 percent in most of the sampled wells in the study area. Differences greater than 10 percent were observed in the western and northwestern parts of the study area at sites 2 and 19 (fig. 2). Despite the limited number of samples, the estimated percentages indicated a systematic pattern of recharge water sources in parts of the aquifer (fig. 9). The results obtained in this study generally follow the same pattern observed in 1986 (Gómez-Gómez, 1991) with the highest percentage surface-water-derived ground water (greater than 50 percent) occurring within the southeastern part of the aquifer and in the Coquí area (figs. 1 and 9). These areas coincide with areas where surface-water measurements obtained in the irrigation canal showed the greatest decrease in flow (fig. 9).

Water-Quality Evaluation with Emphasis on Nitrate Concentrations

Ground-water quality samples were obtained within the study area during March, November, and December 2002. Data were collected from a total of 25 wells, of which 18 were sampled twice and 7 only once. Although analyses were made for major ions and nutrients, the focus of this section is on nitrate concentrations because their increase in the ground-water supply has been of utmost concern to water managers.

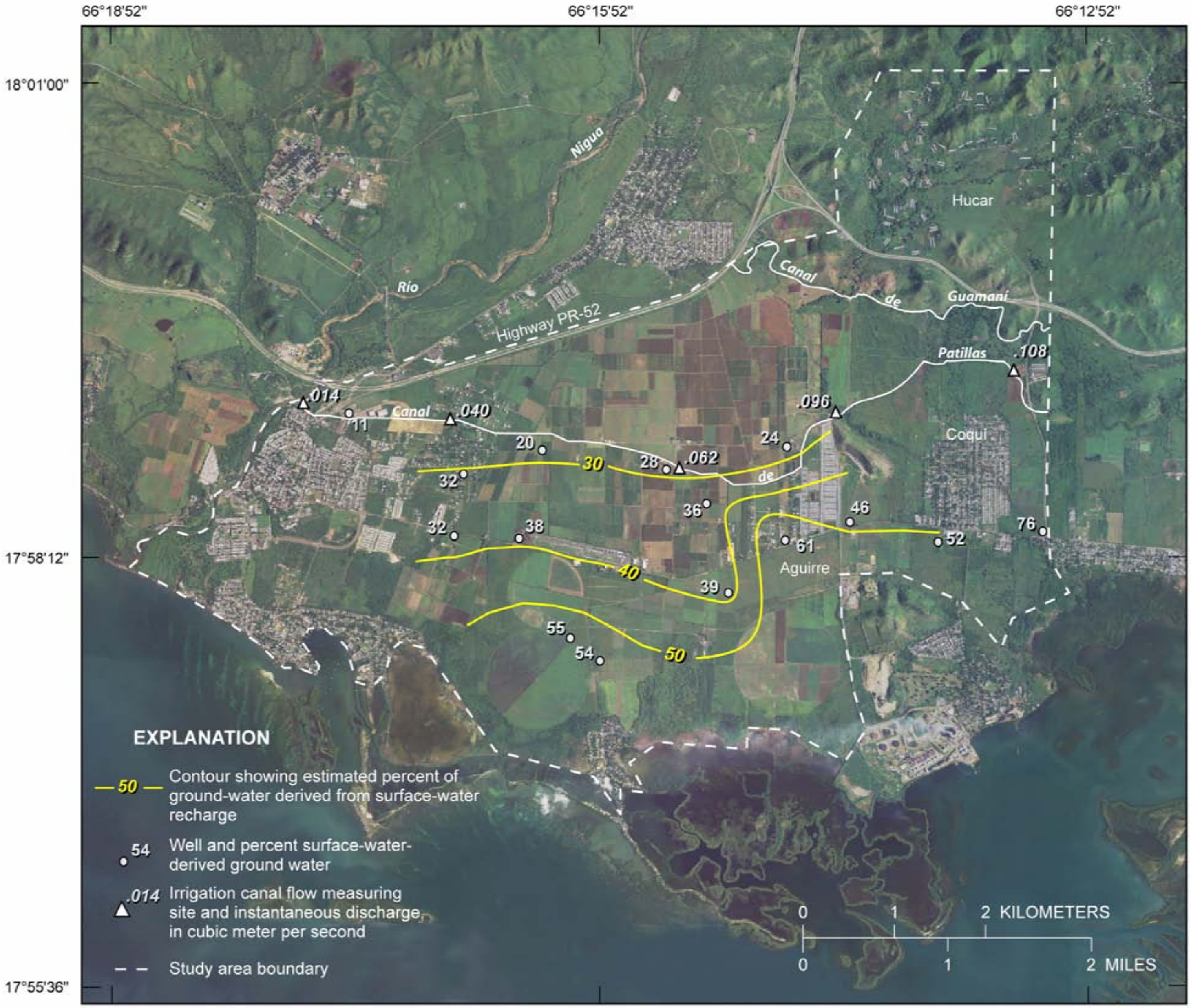
Common Dissolved Constituents

Physical and chemical characteristics were analyzed from selected ground-water sites in the study area (table 3). Chemical analyses were made for dissolved solids and include the major ions (calcium, magnesium, potassium, sodium, chloride, fluoride, sulfate, and silica) and two trace constituents (boron and iron). Physical characteristics that were measured on site include pH, specific conductance, temperature, and alkalinity.

The major ion species concentrations were used to develop trilinear diagrams to characterize the ground water. Only two major water types are present in the study area: calcium-bicarbonate and sodium-bicarbonate type ground waters. The predominant type ground water in most wells, however, is of a calcium-bicarbonate type and is shown as Group I in the trilinear diagram (fig. 10). Samples from sites 43, 51, 55, 72, 83, 86, and 96 plotted within the calcium-bicarbonate type water also can be grouped within a distinct cluster (shown as Group II in fig. 10) toward the central part of the trilinear diagram indicating a mix with ground water of a calcium-chloride or sodium-bicarbonate type. The sites in Group II include four wells located in the foothills and three wells located in the alluvial fan. The depth of the wells in the Hucar area ranges from 19.8 to 45.7 m below land surface (Group I) and from 13.7 to 19.8 m below land surface (Group II). Calcium-chloride type ground water is known to be the prevalent water type in deep ground water contained within the clastic units underlying the alluvial deposits of the South Coastal Plain alluvial aquifer near Ponce west of the study area (Gómez-Gómez, 1991). Chloride accounts for more than 40 percent of the anions in Group II wells.

Ground water of a sodium-bicarbonate type is characteristic of ground water contained within the interfluvial areas of the South Coastal Plain alluvial aquifer, of which the sample collected from site 70 in the interfluvial area east of the Salinas fan is typical (figs. 2 and 10). Sodium-bicarbonate type ground water also is found at depth in the Santa Isabel alluvial fan (west of Salinas) and within the regolith zone overlying volcanic bedrock units, which are rich in feldspathic minerals to the north of the coastal plain (Gómez-Gómez, 1991).

A change in type of water over time (between 1961 and 2002) is observed when major ion concentrations analyzed from ground-water samples collected at three sites in the study area are plotted in a trilinear diagram (fig. 11). Site 43 within the cone of depression in the alluvial fan (fig. 2), shows a trend from the calcium-bicarbonate type to sodium-bicarbonate (fig. 11). Site 51 within the inland part of the alluvial fan (fig. 2) shows a change from calcium-bicarbonate to calcium-chloride type. Well 72, which is located at the base of the foothills, indicates a change from sodium-bicarbonate to calcium bicarbonate (fig. 11). The change at site 43 could result from the extraction of ground water from deeper in the aquifer, and the change at site 72 could be caused by changes in the characteristics of recharge water.



U.S. Army Corp of Engineers (USACE) 2004 orthophotos for the Salinas area.

Figure 9. Estimated percent surface-water-derived ground water in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002. Values represent the average percent using hydrogen and oxygen isotopes analyses at selected wells.

Table 3. Physical and chemical characteristics in ground-water samples collected from selected sites in the Salinas area, Puerto Rico.

[Concentrations are given in milligrams per liter, unless otherwise noted; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; $CaCO_3$; calcium carbonate; Ca, calcium;
Mg, magnesium; K, potassium; Na, sodium; Cl, chloride; F, fluoride; SO_4, sulfate; SiO_2, silica; B, boron; Fe, Iron; <, less than the analytical detection limit]

Site number (see figure 2)	Latitude Longitude	Date of sample collection	pH	Specific Conductance (µS/cm)	Temperature (degrees Celsius)	Alkalinity, (mg/L as $CaCO_3$)	Ca	Mg	K	Na	Cl	F	SO_4	SiO_2	B (µg/L)	Fe (µg/L)	Dissolved solids, sum of constituents
2	175850	03/11/2002	7.5	798	28.2	276	80.2	22.6	1.07	46.7	50	0.3	67.8	35.6	160	< 10	470
	661744	12/12/2002	7.4	834	28.2	280	88.8	24.7	0.97	50.4	53.6	0.27	70.9	37.9	170	< 10	496
10	175845	03/12/2002	7.6	694	28	246	72.3	21.6	0.98	35.4	41.5	0.3	50.2	34.2	90	< 10	404
	661645	11/20/2002	7.7	715	28.1	244	76.6	22.4	1.06	35.7	42.6	0.3	52.9	34	100	< 10	412
17	175855	03/19/2002	7.5	786	27.5	267	78.5	24.2	1.13	47.4	48.2	0.2	59.2	33.5	130	< 10	453
	661615	11/21/2002	7.5	789	27.6	261	79.9	24.8	0.98	49.6	47.8	0.23	59.5	35.6	120	< 10	455
19	175931	03/06/2002	7.8	683	28.4	216	70.5	20.1	1	37	45.8	0.2	58.6	33	90	< 10	396
	661616	11/21/2002	7.7	691	28.4	216	74.1	21	0.87	37.3	45.6	0.17	59.3	33.7	100	< 10	402
27	175748	03/5/2002	7.7	867	27.3	336	77.7	26.5	0.89	65.7	42.5	0.4	49.4	41.1	200	< 10	506
	661606	11/19/2002	7.6	930	27.4	269	84.6	28.4	0.85	68.7	44.5	0.3	56.2	40.3	199	< 10	485
29	175739	03/11/2002	7.4	808	27.6	308	69.7	26.3	1.02	56.5	42.4	0.3	50.2	36.6	170	< 10	468
	661556	12/12/2002	7.4	812	27.7	303	74.2	27.3	0.91	57.3	42.1	0.31	49.2	37.9	180	< 10	471
33	175851	12/05/2002	7.8	796	27.4	253	82.9	26.2	1.04	44.4	53.8	0.27	71.3	38	180	< 10	470
	661530																
38	175858	03/06/2002	7.2	848	28.1	256	83	27.6	0.94	47.4	60	0.3	72	36.7	110	< 10	482
	661516	11/21/2002	7.6	844	28.3	243	83.9	28.2	0.85	47.8	58.9	0.3	71.9	37.2	120	< 10	475
40	175832	12/10/2002	7.5	823	28.1	254	82.5	25	1.18	47.5	53.1	0.29	65.7	35.9	130	< 10	464
	661516																
43	175804	03/05/2002	7.4	1160	27.5	335	79.8	21.6	1.22	129	95.2	0.3	95	40.1	340	< 10	663
	661507																
47	175835	12/10/2002	7.3	905	27.8	276	85.8	27.9	0.98	64.2	69.1	0.31	62.2	39.7	170	< 10	516
	661457																
51	175919	11/22/2002	7.6	1180	28.2	277	109	20.5	0.94	102	137	0.58	65.5	38.6	350	< 10	640
	661444																
55	175855	11/22/2002	7.6	1160	28.5	298	97.1	26.5	0.87	99.8	126	0.4	68	38.9	300	< 10	636

Table 3. Physical and chemical characteristics in ground-water samples collected from selected sites in the Salinas area, Puerto Rico.—Continued

[Concentrations are given in milligrams per liter, unless otherwise noted; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; $CaCO_3$; calcium carbonate; Ca, calcium;

Site number (see figure 2)	Latitude Longitude	Date of sample collection	pH	Specific Conductance (µS/cm)	Temperature (degrees Celsius)	Alkalinity, (mg/L as $CaCO_3$)	Ca	Mg	K	Na	Cl	F	SO_4	SiO_2	B (µg/L)	Fe (µg/L)	Dissolved solids, sum of constituents
	661444																
60	175845	12/10/2002	7.1	966	27.9	313	97.5	29.3	0.82	59	81.6	0.36	41	38.3	180	< 10	536
	661428																
61	175827	03/07/2002	7.3	947	27.7	300	79.9	26.2	1	71.6	77.5	0.3	49	37.3	210	< 10	523
	661422	12/12/2002	7.3	970	27.8	302	86.3	27.6	0.97	73.7	84.7	0.28	49.7	38.8	210	< 10	543
65	175822	03/11/2002	7.6	904	27.8	323	76	24.1	1.04	73.6	71.3	0.4	41.3	36	220	<10	518
	661348	12/12/2002	7.5	943	27.9	316	84.4	26.4	0.93	80.5	74.9	0.32	46.1	37.9	250	< 10	541
70	175823	03/07/2002	7.9	1390	28.5	508	27	9.1	0.6	270	85	1.7	110	34	832	< 10	842
	661309	12/12/2002	7.7	1410	28.5	494	29.8	9.73	0.51	277	90.3	1.52	111	36.6	890	< 10	853
72	175958	03/18/2002	7.4	1690	28.2	435	91.2	58.5	0.23	160	174	0.6	84.8	46.1	330	< 10	876
	661415	11/27/2002	7.4	1560	28.4	433	88.5	56.3	0.22	157	142	0.62	85.1	47.9	330	< 10	837
75	180008	03/13/2002	7.5	982	28.8	288	94	30	0.6	54	72	0.3	68	39	158	< 10	531
	661359	11/26/2002	7.3	1160	29	274	116	36.3	0.47	57.6	84.2	0.3	68.7	44.2	160	< 10	572
83	180024	03/14/2002	7.3	1720	29.2	433	75.2	64.5	0.33	172	175	0.7	81.3	46.5	400	< 10	875
	661401	11/26/2002	7.4	1660	28.9	426	78.1	65.4	0.35	164	164	0.76	80.4	47.4	380	< 10	856
86	180033	03/14/2002	7.3	2150	27.7	430	130	94	1.8	170	240	0.9	90	55	325	< 10	1040
	661409	11/19/2002	7.4	2120	27.9	413	123	88	1.7	182	228	0.9	86	53.2	326	< 10	1011
89	180046	03/13/2002	7.2	1460	28.4	471	124	45.5	1.22	100	110	0.7	61.1	38.7	210	< 10	764
	661354	11/20/2002	7.3	1450	28.4	471	129	47.1	1.26	100	113	0.7	9.8	39.1	207	< 10	723
94	180057	03/06/2002	7.1	1420	28.8	464	156	49.2	0.67	59.8	100	0.4	59.6	43.6	140	< 10	748
	661340	11/26/2002	7.2	1420	29.2	474	158	50.4	0.67	58.4	100	0.33	56.9	42.9	140	< 10	752
96	180037	03/18/2002	7.5	1850	28.8	361	120	57	0.5	160	180	0.8	57	41	335	< 10	833
	661352	12/05/2002	7.5	1620	28.8	358	111	49.5	0.42	142	141	0.87	63.4	43.8	320	< 10	767
98	180047	03/13/2002	7.2	1180	28.2	292	120	33	0.3	56	na	0.3	na	39	139	< 10	na
	661327	11/19/2002	7.4	1120	28.2	280	124	31.4	0.27	55.8	83.9	0.3	23.5	40	150	< 10	527

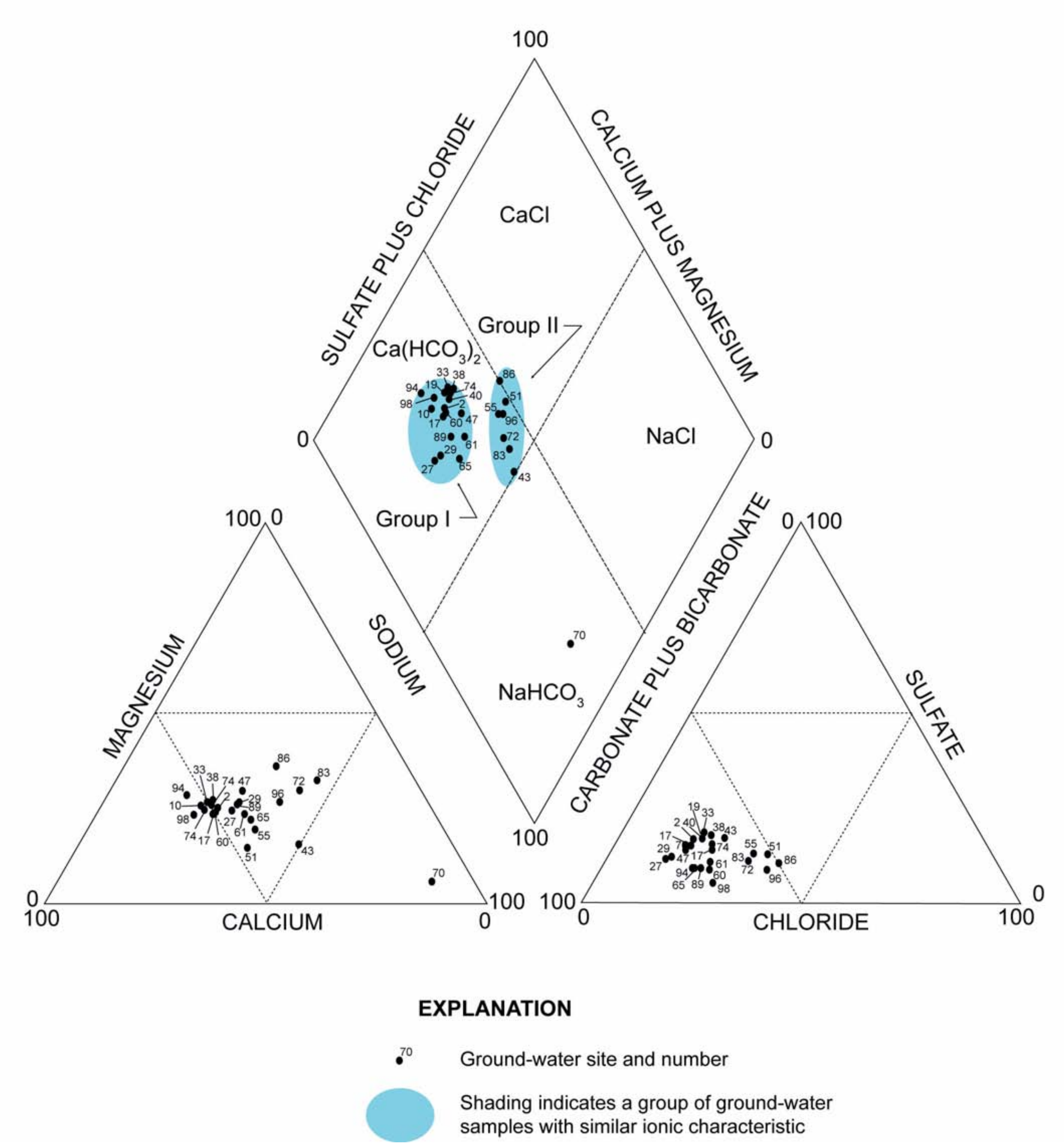


Figure 10. Trilinear diagram of ground-water samples collected in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002. Site locations are shown in figure 2.

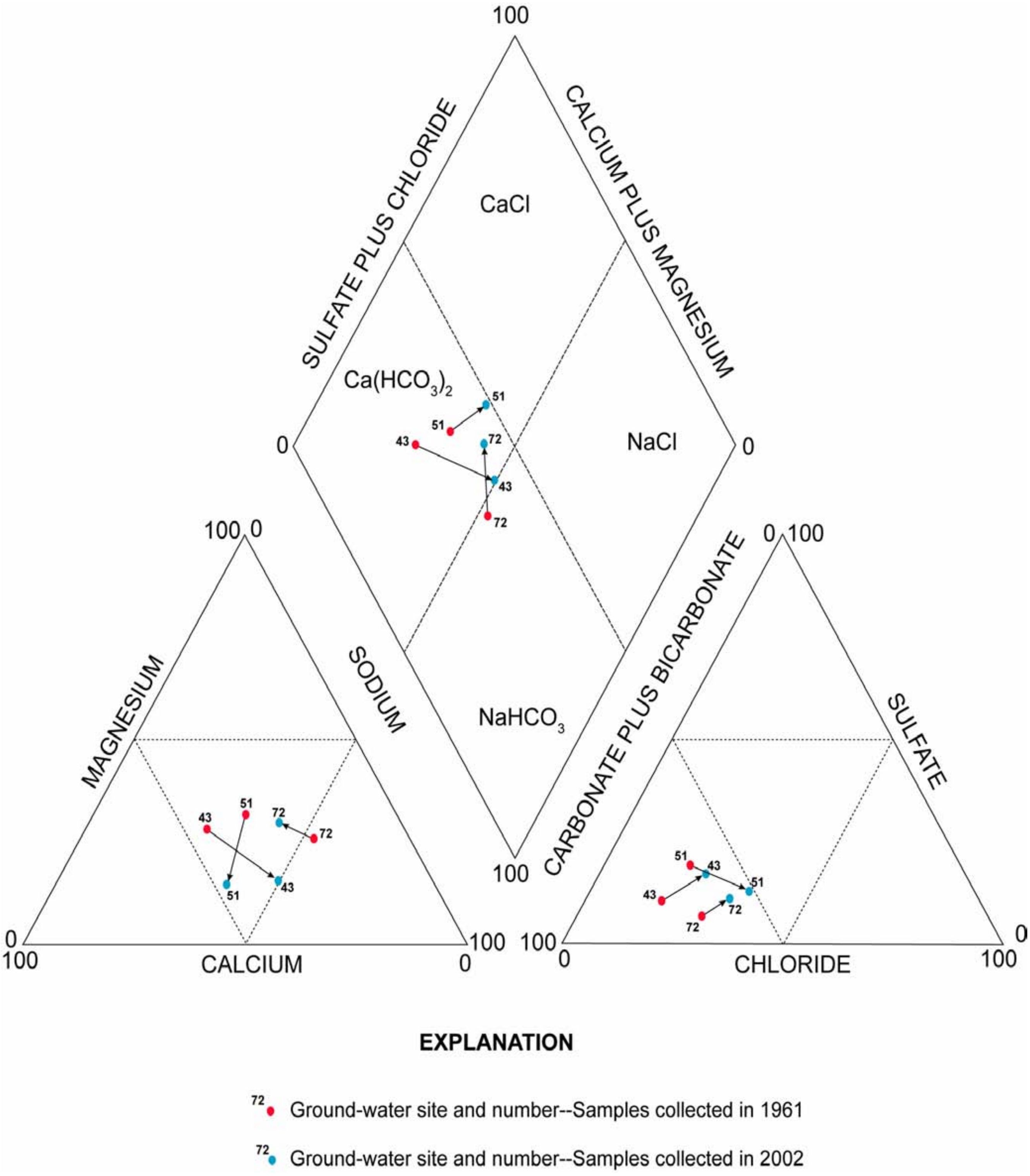


Figure 11. Trilinear diagram of ground-water samples collected in the Río Nigua de Salinas alluvial fan at selected sites in 1961 and 2002, Salinas, Puerto Rico. Site locations are shown in figure 2.

The concentrations of dissolved solids (fig. 12) in the study area are highest in ground water contained in the foothills of the Hucar area where the average is about 756 mg/L. Within the alluvial fan, dissolved-solids concentrations generally increased in a southeasterly direction, from about 400 to 485 mg/L near the center of the fan, except within the cone of depression where deep ground water that is higher in dissolved solids could be induced toward the pumping wells. Within the cone of depression, the dissolved-solids concentration was 663 mg/L. Within the northeastern quadrant of the alluvial fan, the dissolved-solids concentration is a mix of ground water from the foothills with that recharged in the coastal plain. A comparison of the dissolved-solids distribution in 2002 with that obtained in 1986 (Gómez-Gómez, 1991) indicates the same general pattern of dissolved-solids concentrations in the coastal plain except in the northeastern quadrant, where the dissolved-solids concentrations were between 360 and 650 mg/L in 1986 and between 516 and 640 mg/L in 2002.

Nitrate

During the 2002 water-quality survey, average nitrate (NO_3-N) concentrations ranged from 0.67 to 15 mg/L at ground-water sites in the coastal plain and from 25 to 76 mg/L at ground-water sites in the Hucar area (table 4 and fig. 13A). Comparison of NO_3-N concentrations found during the study with those obtained during November 1961 (McClymonds and Díaz, 1972) (fig. 13B) indicates the concentrations have increased from a baseline concentration of about 0.6 mg/L in the Hucar area and by about a factor of two within the coastal plain. Concentrations of NO_3-N during February 1986 (F. Gómez-Gómez, U.S. Geological Survey, written commun., 1986) within the coastal plain were not much different than those found in 1961. In 1986, NO_3-N concentrations within the greater part of the alluvial fan averaged 3.5 mg/L (ranging from 0.6 to 6.7 mg/L in a set of seven samples) and may have been near 1.2 mg/L in the northeastern quadrant of the alluvial plain.

The NO_3-N concentration pattern in 2002 (fig. 13A) indicates movement of ground water with elevated concentrations from the base of the foothills in the Hucar area (fig. 2, site 72) toward the northeastern quadrant of the alluvial fan along the western side of the bedrock outcrops. Another area of high NO_3-N concentrations (fig. 13A) was detected at the center of the fan, extending toward the ground-water pumping centers that produced the major cone of depression (fig. 7). The concentrations of NO_3-N greater than the maximum contaminant level (MCL) of 10 mg/L for drinking water (U.S. Environmental Protection Agency, 2003) were detected in three wells in the alluvial fan and in all the wells sampled at the foothills. All wells that exceeded the MCL for NO_3-N are used for agricultural purposes.

Monthly ground-water samples were collected at selected sites in the study area to determine NO_3-N concentration variability during the study period. Sites 10 and 38 in the alluvial fan and sites 86 and 98 in the Hucar area were sampled on a monthly basis from March 2002 to February 2003 (fig. 14). Site 10 is in a residential, unsewered suburban area, site 38 is in an agricultural area dedicated to plantain/banana crops, and sites 86 and 98 are located within the poultry farms (refer to fig. 4). The data indicate that the NO_3-N concentrations at all four sites over the 1-year time period did not vary by more than 20 percent from the initial concentrations measured in March 2002. As shown in figure 14, the most important factor judged to be the cause of a change in concentration between sample dates is rainfall, which can result in local aquifer recharge where the aquifer is unconfined (the condition at all the reference sampled sites). Site 98 was the only location where local rainfall recharge, occurring throughout the bedrock outcrop areas contributed to dilution of NO_3-N concentrations. At sites 38 and 86, the increase in NO_3-N concentrations could be due to infiltration of NO_3-N from sources related to agricultural activities near the wells–such as fertilizer use at plantain/banana farms and poultry wastes disposal on land surface, respectively–during periods when rainfall is sufficient to induce localized aquifer recharge.

Identification of Nitrate Sources

Nitrate is one of the primary forms of dissolved nitrogen in natural waters resulting from the rapid oxidation of its reduced or organic forms. Nitrate generally is the dominant form in waters containing dissolved oxygen and is highly soluble and readily transported in ground water. Nitrate in ground water can originate from organic nitrogen complexes–such as animal manure or septic waste discharges, which are converted to ammonia nitrogen through the processes of ammonification (decomposition of the organic matter into ammonium ions) and to nitrate by nitrification (the oxidation of ammonium to nitrate). Nitrification is an aerobic process that can lead to accumulation of nitrate in ground water (Chapelle, 1993). Denitrification is the process by which nitrate is reduced to nitrogen gas and is the prevalent process by which nitrate is lost from ground water. Denitrification, however, occurs only in a reducing environment (anaerobic conditions) and by denitrifying bacteria, such as *Pseudomonas denitrificans*.

Sources of nitrate can be classified in two major categories: point and nonpoint sources. Point source is defined "as any discernible, confined, and discrete conveyance, including but not limited to, any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel, or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture" (U.S. Congress, 1977). Agricultural point sources include fertilizer production and storage facilities and intensive animal husbandry operations. Nonpoint sources are the sources of contamination that originate from an extensive area or from a number of points within a region. Nonpoint source is defined as a source that does not meet the legal definition of point source as mentioned above. In the study area, nonpoint sources of nitrate include cultivated farmland, septic tanks in rural communities, and poultry farms.

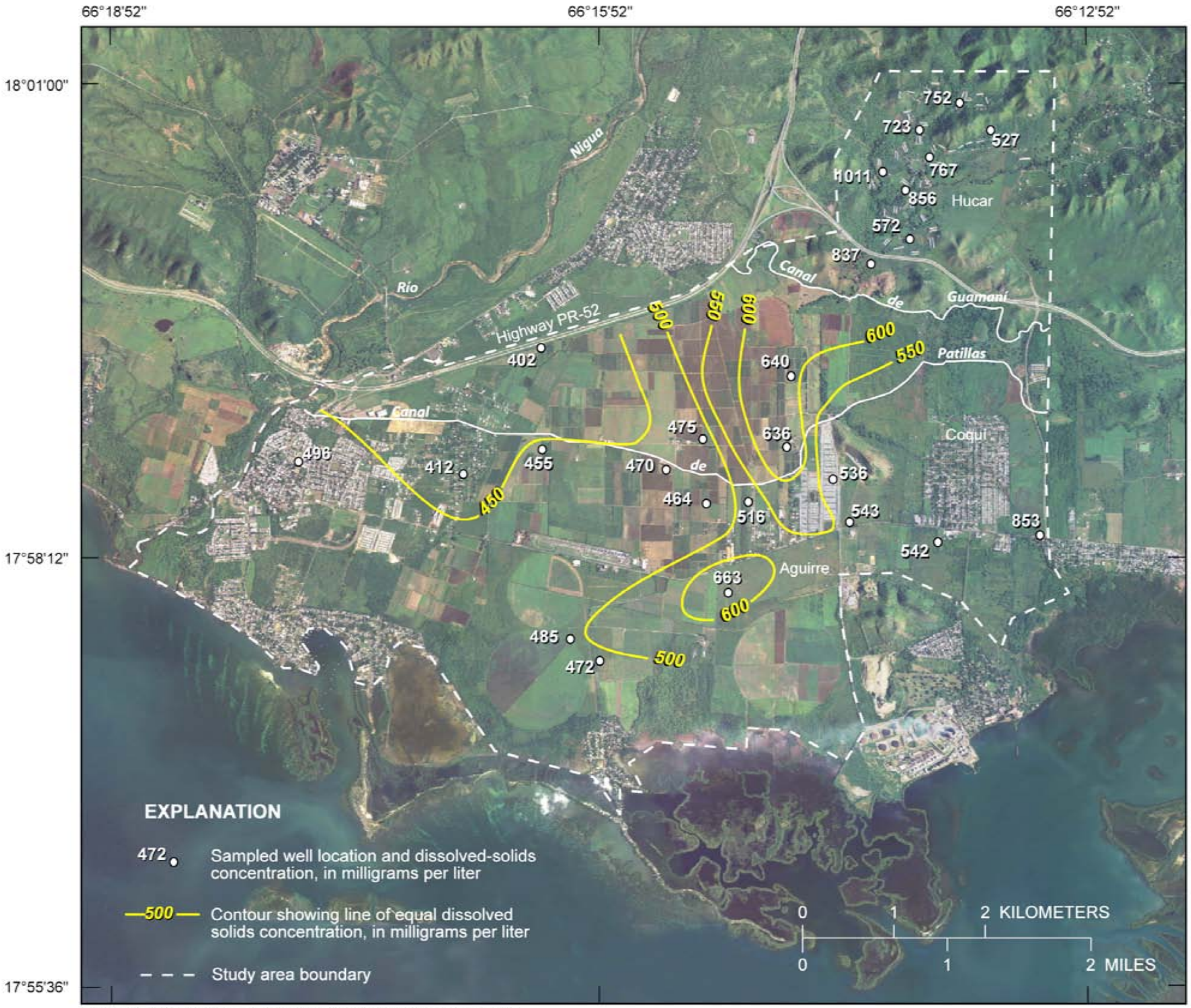


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Figure 12. Dissolved-solids concentrations in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002.

Table 4. Nutrient concentrations and delta nitrogen-15 of nitrate ($\delta^{15}N-NO_3$) in ground-water samples collected from selected sites in the Salinas area, Puerto Rico.

[Concentrations are given in milligrams per liter (mg/L) unless otherwise noted. <, less than the analytical detection limit; N, nitrogen; $\delta^{15}N$, $^{15}N/^{14}N$; P, phosphorus]

Site number (see figure 2)	Latitude Longitude	Date	Nitrogen ammonia plus organic, total (mg/L as N)	Nitrogen ammonia, total (mg/L as N)	Nitrate (mg/L as N)	$\delta^{15}N-NO_3$ (per mil)	Nitrite (mg/L as N)	Phosphorus, total (mg/L as P)
2	175850	03/11/2002	< 0.2	< 0.01	2.6	7.8	< 0.01	0.03
	661744	12/12/2002	< 0.2	< 0.01	2.9	8.8	< 0.01	0.02
10	175845	03/12/2002	< 0.2	0.01	3.4	8.9	< 0.01	< 0.02
	661645	11/20/2002	< 0.2	0.02	3.4	5.5	< 0.01	0.02
17	175855	03/19/2002	< 0.2	< 0.01	1.1	7.5	< 0.01	< 0.02
	661615	11/21/2002	< 0.2	0.03	5.2	7.4	< 0.01	< 0.02
19	175931	03/06/2002	< 0.2	< 0.01	3.1	8.4	< 0.01	< 0.02
	661616	11/21/2002	1.2	0.03	2.8	6.9	< 0.01	< 0.02
27	175748	03/05/2002	< 0.2	< 0.01	5	6.4	< 0.01	< 0.02
	661606	11/19/2002	< 0.2	< 0.01	8.5	8.8	< 0.01	< 0.02
29	175739	03/11/2002	< 0.2	< 0.01	5	4.3	< 0.01	0.03
	661556	12/12/2002	< 0.2	< 0.01	4.8	5.5	< 0.01	0.02
33	175851	12/05/2002	< 0.2	< 0.01	6.1	6.4	< 0.01	0.02
	661530							
38	175858	03/06/2002	< 0.2	< 0.01	7.6	8.1	< 0.01	< 0.02
	661516	11/21/2002	< 0.2	0.03	8.3	7.4	< 0.01	< 0.02
40	175832	12/10/2002	< 0.2	< 0.01	9.6	5.1	< 0.01	0.02
	661516							
43	175804	03/05/2002	< 0.2	< 0.01	15	4.8	< 0.01	< 0.02
	661507							
47	175835	12/10/2002	< 0.2	< 0.01	8.1	7	< 0.01	0.02
	661457							
51	175919	11/22/2002	0.9	0.02	12	6.9	<0.01	< 0.02
	661444							
55	175855	11/22/2002	< 0.2	0.02	12	7.1	< 0.01	0.02
	661444							
60	175845	12/10/2002	0.2	< 0.01	9	13.8	< 0.01	0.02
	661428							
61	175827	03/07/2002	< 0.2	< 0.01	7.9	9.2	< 0.01	0.02
	661422	12/12/2002	< 0.2	< 0.01	8	10.9	< 0.01	< 0.02
65	175822	03/11/2002	< 0.2	< 0.01	5.8	13.6	< 0.01	0.03
	661349	12/12/2002	< 0.2	< 0.01	5.3	14.3	< 0.01	< 0.02
70	175823	03/7/2002	<0.2	< 0.01	0.67	12.8	< 0.01	0.02
	661309	12/12/2002	<0.2	< 0.01	0.67	14.7	< 0.01	0.02

Table 4. Nutrient concentrations and delta nitrogen-15 of nitrate ($\delta^{15}N-NO_3$) in ground-water samples collected from selected sites in the Salinas area, Puerto Rico.—Continued

[Concentrations are given in milligrams per liter (mg/L) unless otherwise noted. <, less than the analytical detection limit; N, nitrogen; $\delta^{15}N$, $^{15}N/^{14}N$; P, phosphorus]

Site number (see figure 2)	Latitude Longitude	Date	Nitrogen ammonia plus organic, total (mg/L as N)	Nitrogen ammonia, total (mg/L as N)	Nitrate (mg/L as N)	$\delta^{15}N-NO_3$ (per mil)	Nitrite (mg/L as N)	Phosphorus, total (mg/L as P)
72	175958	3/18/2002	< 0.2	< 0.01	33	18.2	< 0.01	< 0.02
	661415	11/27/2002	0.2	< 0.01	25	18.2	< 0.01	< 0.02
75	180008	03/13/2002	< 0.2	< 0.01	26	14.1	< 0.01	< 0.02
	661359	11/26/2002	< 0.2	< 0.01	35	13.6	< 0.01	< 0.02
83	180024	03/14/2002	< 0.2	< 0.01	41	19.8	< 0.01	< 0.02
	661401	11/26/2002	0.3	< 0.01	33	20.7	< 0.01	< 0.02
86	180033	03/14/2002	< 0.2	0.02	77	15.2	< 0.01	0.03
	661409	11/19/2002	< 0.2	< 0.01	76	13.7	< 0.01	0.03
89	180046	03/13/2002	< 0.2	0.04	28	19.2	< 0.01	0.1
	661354	11/20/2002	0.2	0.03	33	20.1	0.02	0.06
94	180057	03/06/2002	0.3	< 0.01	29	21.5	< 0.01	< 0.02
	661340	11/26/2002	0.3	< 0.01	25	21.6	< 0.01	< 0.02
96	180037	03/18/2002	< 0.2	< 0.01	77	14.7	< 0.01	< 0.02
	661352	12/05/2002	< 0.2	< 0.01	60	14.7	< 0.01	< 0.02
98	180047	03/13/2002	< 0.2	< 0.01	46	16.1	< 0.01	< 0.02
	661327	11/19/2002	< 0.2	< 0.01	42	17.2	< 0.01	< 0.02

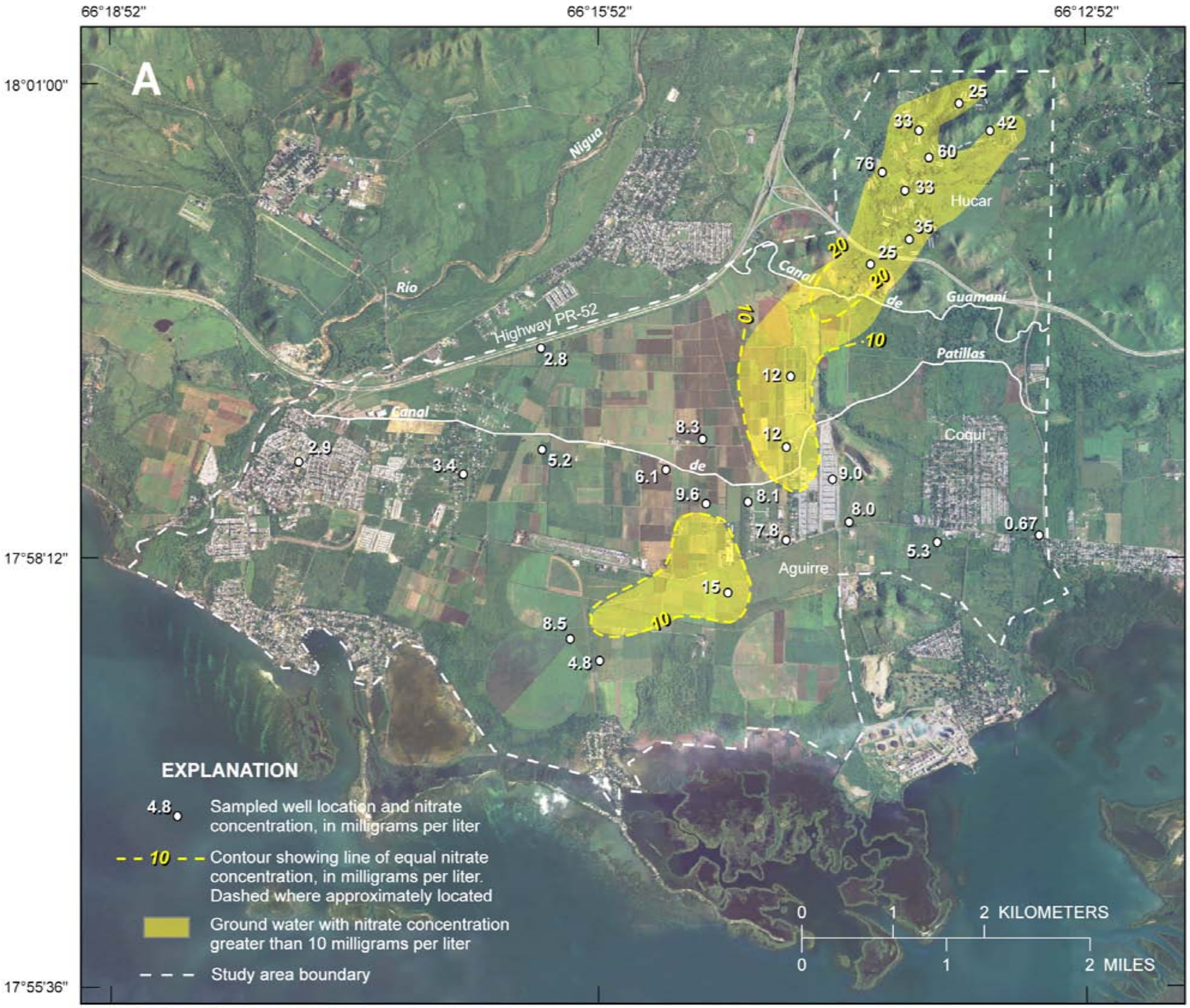

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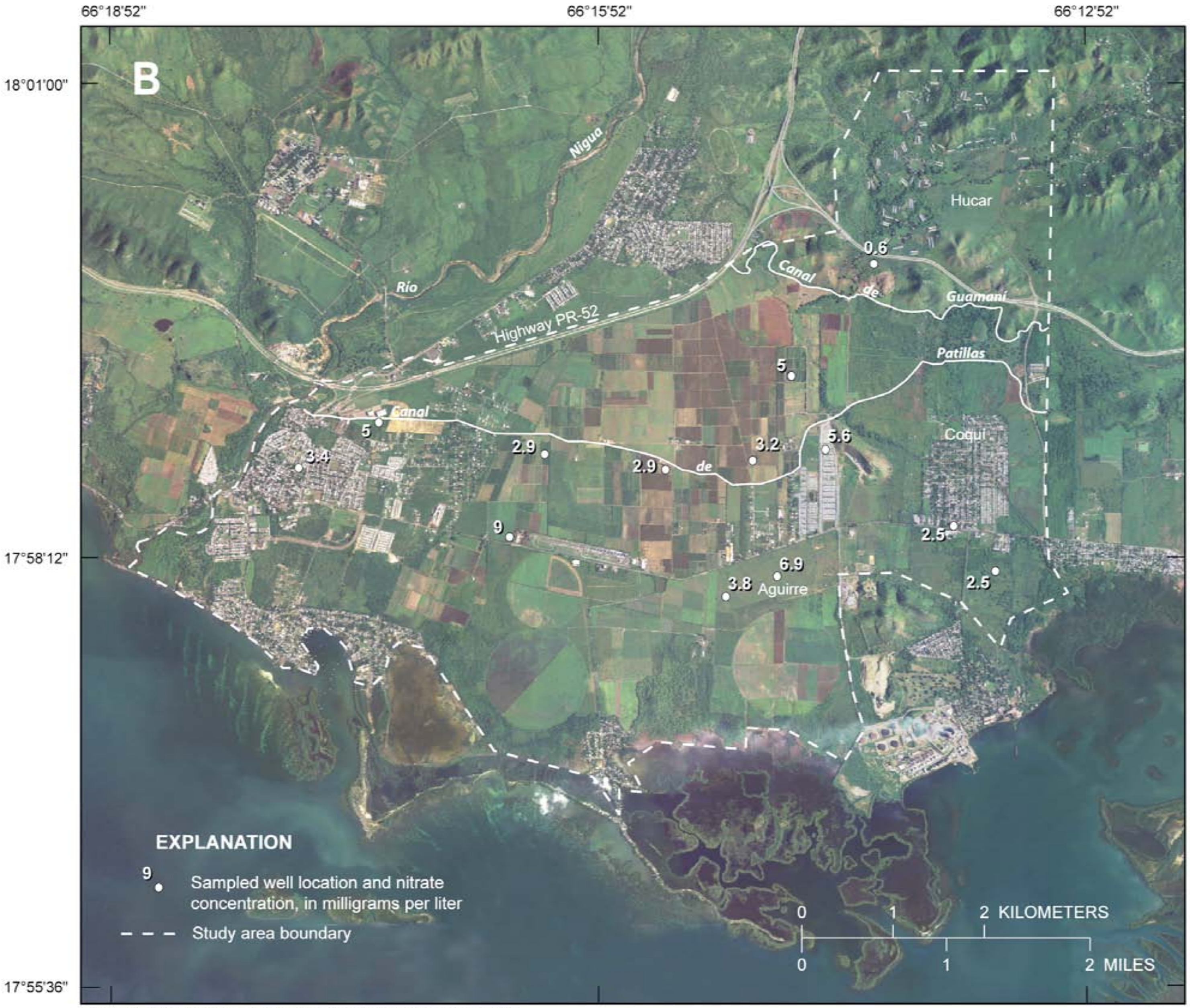
Figure 13. Nitrate concentrations in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, during (A) 2002 and (B) 1961. Data for 1961 period is from McClymonds and Díaz (1972).



U.S. Army Corp of Engineers (USACE) 2004 orthophotos for the Salinas area.

Figure 13. Nitrate concentrations in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, during (A) 2002 and (B) 1961. —Continued Data for 1961 period is from McClymonds and Díaz (1972).

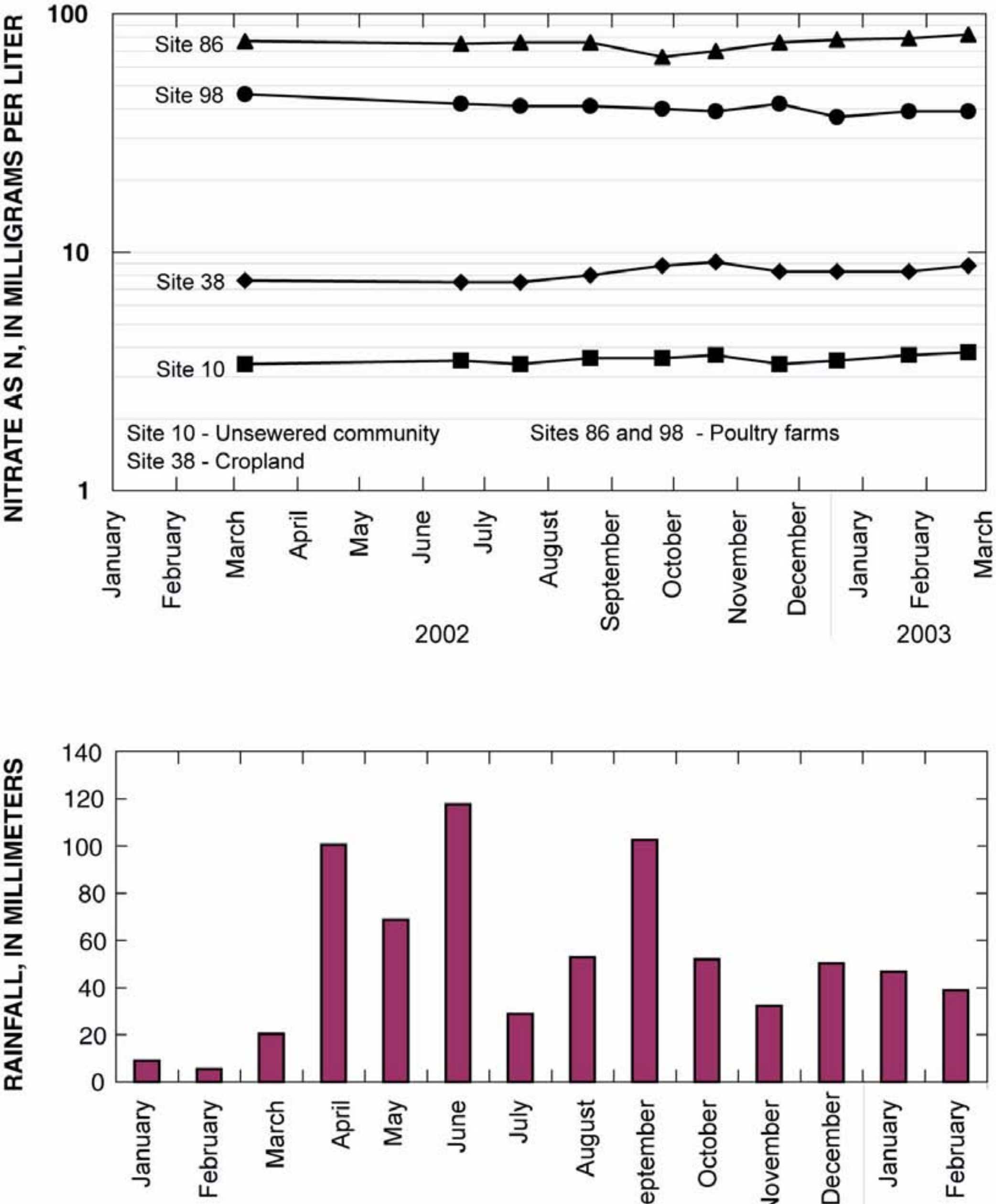


Figure 14. Variation of monthly nitrate concentrations in ground water at selected sites in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002-03.

Field reconnaissance indicated that cultivated farmland and poultry farms have the greatest potential of increasing the nitrate concentration in the aquifer in the study area owing to the intensive use of fertilizers in the cultivation of plantains, bananas, corn, papaya, and other crops and the disposal of poultry wastes on land surface. The other potential source of nitrate in the study area is leachate from septic tanks at unsewered suburban communities.

Fertilizers containing nitrogen used in the croplands within the study area include: urea ($CO(NH_2)_2$), ammonium sulfate ($(NH_4)_2SO_4$), potassium nitrate (KNO_3), and ammonium nitrate (NH_4NO_3). Urea is used mostly for plantains in combination with ammonium sulfate and potassium sulfate. Urea also is the principal form of nitrogen present in the poultry litter. Poultry litter consists of the following major constituents (Moore and others, 1998): total carbon (376 g/kg, total nitrogen (41 g/kg), ammonium as N (2.6 g/kg), nitrate as N (0.2 g/kg), phosphorus (14 g/kg), potassium (21 g/kg), chloride (12.7 g/kg), and calcium (14 g/kg).

Septic tank leachate is a likely source of nitrate in ground water in shallow aquifers. Septic tanks remove most settleable solids and floatable material and function as an anaerobic bioreactor. Septic-tank densities in a community, however, may exceed the capacity of even suitable soils to assimilate wastewater flows and retain and transform their contaminants, thus, septic tanks could represent a source of nitrate to the aquifer.

Nitrogen Isotopic Characterization of Nitrate Sources

Ground-water samples collected in the study area were analyzed for nitrogen stable isotope in nitrate, delta nitrogen-15 of nitrate ($\delta^{15}N\text{-}NO_3$), and the results are presented in table 4. The $\delta^{15}N\text{-}NO_3$ is used to infer the source of nitrate in the ground water. Typical $\delta^{15}N\text{-}NO_3$values in ground water are derived from various sources and include: (1) artificial fertilizers ranging from +2 to +6 ‰, and (2) animal or human organic waste greater than +8 ‰ (Katz and others, 1999; Bohlke, 2003). Data from a number of sites indicate there may be a tendency for nitrate in seepage from septic systems to be near the lower end of the range (+8 to +11 ‰), and nitrate in leachate from manure spreading to range toward higher values with more variability (+10 to +25 ‰) (Bohlke, 2003). The $\delta^{15}N\text{-}NO_3$ values associated with fertilizers and domestic wastewater in the Manatí area in northern Puerto Rico were estimated to be +2.2 and +8.1 ‰, respectively (Conde-Costas and Gómez-Gómez, 1999).

Ground-water samples were collected from selected sites to determine the relation of $\delta^{15}N\text{-}NO_3$ to nitrate concentration as nitrogen (NO_3-N) in the study area (fig. 15). Results indicated that NO_3-N concentrations ranged from 25 and 77 mg/L in the area of poultry farms within the Hucar drainage basin, and $\delta^{15}N\text{-}NO_3$ values were in the range +13 to +23 ‰ associated with organic-waste sources (manure spreading or seepage from septic systems) of nitrate. Ground-water samples collected from sites within cultivated farmland had NO_3-N concentrations ranging between 1.1 and 15 mg/L, and $\delta^{15}N\text{-}NO_3$ values were in the range +4.3 to +8.8‰ associated with artificial fertilizers and natural vegetative decay.

Biogeochemical reactions such as denitrification can alter the isotopic composition of nitrogen. Denitrification causes the $\delta^{15}N$ of the residual nitrate to increase as nitrate concentration decreases. Dissolved-oxygen concentrations in ground water in the Salinas fan and the Hucar area ranged from 2.9 to 5.7 mg/L, which indicate that denitrification in the saturated zone is unlikely.

The $\delta^{15}N\text{-}NO_3$ data were used in conjunction with the nitrate concentrations (table 4 and fig. 13A), land use (fig. 4), and the potentiometric surface (fig. 7) to infer the relative contribution of NO_3-N to the aquifer from two major sources–organic waste and artificial fertilizers (fig. 16). Manure spreading or animal waste have affected the ground-water resources within the northeastern quadrant of the study area along the ground-water flow path defined by the potentiometric surface from the Hucar area to the cones of depression in the coastal plain and toward the Coquí sector in the southeast. It can be inferred from the land use and $\delta^{15}N\text{-}NO_3$ data that the area near the town of Salinas is affected by seepage from sewer mains or septic systems. Artificial fertilizer use can be inferred to have contributed NO_3-N primarily to that part of the aquifer in the area delimited from the town of Salinas eastward to the south-central part of the alluvial fan. In the north-central part of the alluvial fan, NO_3-N concentrations can be inferred to be affected by both sources.

The relative proportion of NO_3-N resulting from both agricultural activities in the northeastern quadrant of the study area can be estimated as follows:

$$(X_a) \text{ x } (\delta^{15}N_a) + (1\text{-}X) \text{ x } (\delta^{15}N_b) = \delta^{15}N_{well},$$

where

X_a is the estimated fraction of NO_3-N concentration derived from fertilizer;

$\delta^{15}N_a$ is the $\delta^{15}N\text{-}NO_3$ signature estimated for artificial fertilizer, where it was assumed to constitute 100 percent of the NO_3-N in the sample at site 29 or equal to +4.3 ‰;

$\delta^{15}N_b$ is the $\delta^{15}N\text{-}NO_3$ signature of poultry wastes, which was assumed to be +19.9 +/- 1.3 ‰ (an average of samples from sites 72, 83, 89, and 94); and

$\delta^{15}N_{well}$ is the $\delta^{15}N\text{-}NO_3$ value obtained in ground water at the sampled well.

Results obtained by using the above method (fig. 17) indicate that fertilizer-derived NO_3-N is most pervasive throughout the central part of the Río Nigua de Salinas alluvial fan. Animal-waste-derived NO_3-N is the major source along a south-southeast trending plume in the direction of the Coquí community.

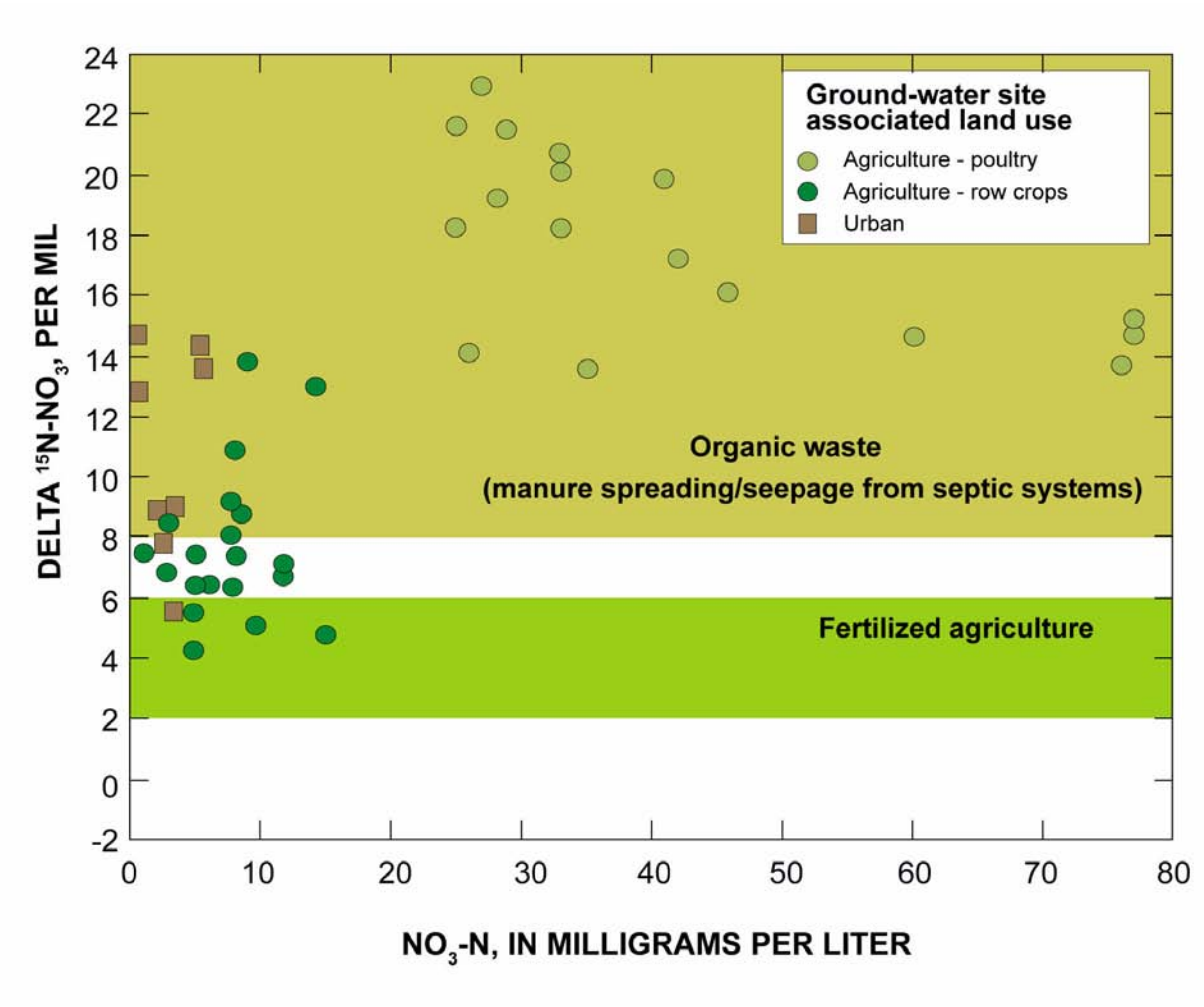


Figure 15. Relation of delta nitrogen-15 of nitrate ($\delta^{15}N-NO_3$) to concentration of nitrate as nitrogen (NO_3-N) in ground water in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002.

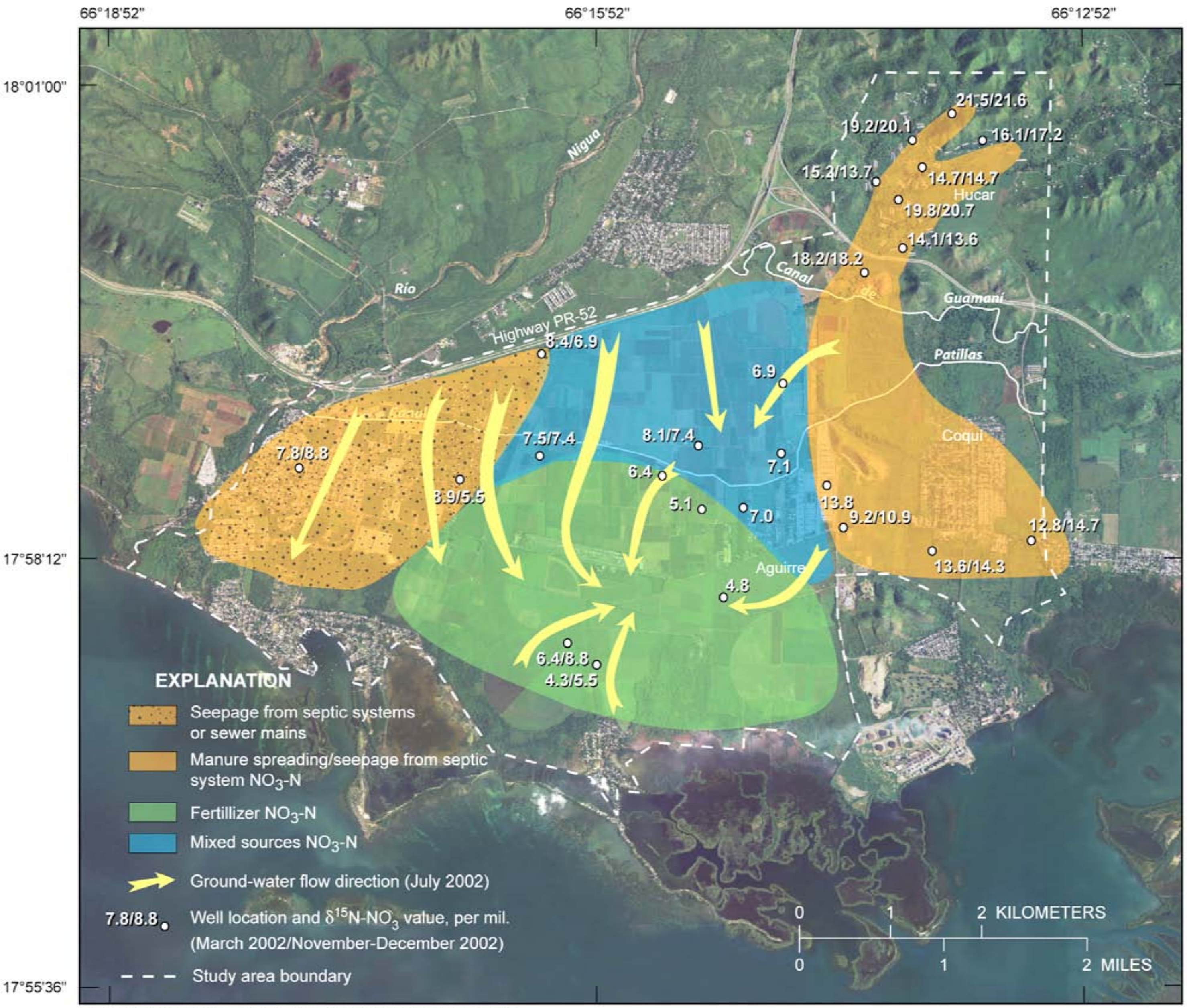


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Figure 16. Delta nitrogen-15 of nitrate ($\delta^{15}N$-NO_3) in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002 (NO_3-N is nitrate concentration as nitrogen).

U.S. Army Corp of Engineers (USACE) 2004 orthophotos for the Salinas area.

Figure 17. Estimated percent of total nitrate concentration derived from agricultural activities in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002.

Estimate of Potential Nitrate Load to the Alluvial Aquifer

Fertilizer use in cropland within the study area represents one of the major potential sources of nitrate to the aquifer. The potential nitrate load from agricultural lands under cultivation in the study area is variable depending on the type of crop and fertilizer management practices. The fertilizer application rates were estimated on the basis of data obtained from interviews of farmers. For plantains and bananas, which are the principal agricultural crops in the area (fig. 4), the fertilizer application rate was estimated to range from 157 to 410 kg/ha-yr as N. The fertilizer application rates were estimated to be 276 kg/ha-yr as N for corn, 292 kg/ha-yr as N for sorghum, 1,170 kg/ha-yr as N for turf grass, 68 kg/ha-yr as N for papayas, 104 kg/ha-yr as N for hay, and 550 kg/ha-yr as N for ornamental palms. Only a fraction of the nitrogen in fertilizer used in the cultivation of crops is available to migrate to the subsurface because most is incorporated into the vegetation with part mineralized within the soil.

The relative potential amounts of NO_3-N that can be leached to the aquifer from fertilizer use on crops, were estimated by subtracting the nitrogen uptake of the different crops in the study area from the amount of fertilizer applied to the crops. Nitrogen uptake for plantains and bananas was estimated to range from 248 kg/ha-yr as N (Universidad de Puerto Rico, 1995) to 276 kg/ha-yr as N (Irizarry and others, 1988). Using the reported maximum application rate of 410 kg/ha-yr as N, which is applied in farms near the area where higher nitrate concentrations were detected, the residual amount of nitrogen available for volatilization, mineralization, and potential migration to the aquifer was estimated to range from 134 to 162 kg/ha-yr as N. On this basis, the residual amount of nitrogen, which has the potential to be present as NO_3-N and impact the aquifer, was estimated to range from about 34,400 to 41,600 kg/yr as NO_3-N from the 257 ha of cropland in plantains/bananas.

The reported fertilizer application was about 276 kg/ha-yr as N for corn. The uptake of nitrogen was estimated at about 174 kg/ha-yr as N (Natural Resources Conservation Service, 2001) of the applied nitrogen. The amount of nitrogen available for volatilization, mineralization, and potential migration to the aquifer was about 102 kg/ha-yr as N. The residual amount of nitrogen, which has the potential to affect the aquifer, was estimated to be about 5,200 kg/yr as NO_3-N from the 51 ha of cropland in corn.

The reported fertilizer application rate was 244 kg/ha as N per 10-month crop cycle for sorghum crops. The uptake of nitrogen by sorghum was estimated to be 226 kg/ha-yr as N (Natural Resources Conservation Service, 2001). According to the application rate of fertilizer and the uptake by sorghum, the estimated quantity of nitrogen available for volatilization, mineralization, and potential migration to the aquifer was only 18 kg/ha-yr as N. The residual amount of nitrogen, which has the potential to effect the aquifer, was estimated to be about 3,800 kg/yr as NO_3-N from the 212 ha of cropland in sorghum.

The reported fertilizer application rate was 1,170 kg/ha-yr as N for turf grass, and the nitrogen uptake was between 63 and 73 percent for Zoysia grass (Bowman and others, 2002). The amount of nitrogen available for volatilization, mineralization, and potential migration to the aquifer was estimated to range from 320 to 430 kg/ha-yr as N. The residual amount of nitrogen, which has the potential to effect the aquifer in the study area, was estimated to range from 16,600 to 22,300 kg/yr as NO_3-N from the 52 ha of cropland in turf grass.

For papaya crops, the reported fertilizer application rate was about 68 kg/ha-yr as N. The uptake of nitrogen by papaya crops was estimated to be 180 kg /ha-yr as N (Natural Resources Conservation Service, 2001), which indicates that the potential amount of NO_3-N from fertilizer that is available to enter the aquifer is negligible. A summary of the NO_3-N load estimates from fertilizers applied to crops in the study area is given in table 5.

Table 5. Potential nitrogen load estimates from fertilizers applied to crops in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002.

[kg/ha-yr as N, kilogram per hectare per year as nitrogen; kg/yr as N, kilogram per year as nitrogen]

Crop	Fertilizer application rate (kg/ha-yr as N)	Potential residual nitrogen (kg/ha-yr as N)	Total residual nitrogen (kg/yr as N)
Plantains/bananas	410	134 - 162	34,400 - 41,600
Corn	276	102	5,200
Sorghum	244	18	3,816
Turf grass	1,170	320 - 430	16,600 - 22,300
Papaya	68	Negligible	Negligible

Another source of nitrate related to the agricultural activities in the alluvial fan is the "recycled" ground water used for crop irrigation. In the eastern part of the study area, ground-water nitrate concentration ranged from 8 to 12 mg/L. Ground-water withdrawals from wells in farms in this area (covering approximately 304 ha) were about 6,200 m^3/d. The estimated load of nitrogen from the irrigation water (assuming 8 mg/L) was about 59 kg/ha-yr as N or 18,100 kg/yr as N.

Poultry farms in the Hucar area are the other agricultural source of nitrate in the study area. In most of the poultry farms, partial disposal of the poultry litter is conducted about every 3 months by spreading or integrating it to the soil (Robert, 2001). The poultry litter is a mixture of manure, bedding material, wasted feed, feathers, and soil (picked up during recovery). Bedding materials, which are used to absorb liquid fractions of excreta, are principally composed of wood chips and coffee hulls. Total removal of the litter is reported to be every 3 to 4 years, with the litter taken out of the Hucar area for disposal. In addition to the periodic disposal of the litter in the farms, reported cases of litter burying occurred in 1987 and after the widespread destruction of poultry broiler houses during Hurricanes Hortense and Georges, which occurred in 1989 and 1998, respectively (Robert, 2001).

If 5.1 cm (2 in.) of litter are removed every 3 months, which is a typical value of removal (Hatzell, 1995), and using an area of 669 m^2 per poultry house, the volume of poultry litter removed is about 136 m^3/yr. Using a typical poultry litter density of 432 kg/m^3 (Natural Resource, Agriculture, and Engineering Service, 1999) and 0.032 kg as N per kilogram of poultry litter, it is estimated that about 1,900 kg/yr as N are produced in each poultry house. During 2002, a total of 53 poultry houses were in operation at 29 farms in the Hucar area, which represents a potential NO_3-N load of 100,700 kg/yr as N or 519 kg/ha-yr as N, assuming a 194-ha disposal area.

The potential nitrate load to the aquifer from septic tanks in the Aguirre area was estimated from public water-supply data and the per capita total nitrogen excreted by humans, which averages 17 g/d (Kaplan, 1987). The ground-water withdrawals from public-supply wells serving the Aguirre area was estimated at about 3,370 m^3/d. This water is distributed to about 4,200 households (U.S. Census Bureau, 2002). This represents a wastewater discharge of about 0.80 m^3/d per household and about 0.26 m^3/d per person based on a three-person family household (U.S. Census Bureau, 2002). Based on an estimated housing density in the rural community of Aguirre of five housing units per hectare, the wastewater discharge will be about 4 m^3/d per hectare. The estimated nitrate effluent from the communities will be about 31.8 mg/L as N per hectare assuming that only 50 percent of the excreted nitrogenous compounds will result in nitrate. This represents an approximate NO_3-N load of 47 kg/ha-yr as N from the communities in the Aguirre area without sewer connections. The estimated total area contained within the alluvial fan in the Aguirre area with unsewered housing is 79 ha, thus, the potential NO_3-N load is 3,700 kg/yr.

In summary, the potential NO_3-N load from sources in the Río Nigua de Salinas alluvial fan study area, expressed on a unit area basis and by total land-use area, is given in table 6. Principal NO_3-N sources are poultry wastes (519 kg/ha-yr as N and 100,700 kg/yr as N) and fertilizer use at plantain/banana farms (134-162 kg/ha-yr as N and 34,400-41,600 kg/yr as N), and turf grass farms (320-430 kg/ha-yr as N and 16,600-22,300 kg/yr as N).

A generalized estimate of the anticipated nitrate concentration in ground water was obtained within that part of the alluvial fan west of the NO_3-N plume in the northeastern quadrant of the coastal plain. The calculation was made by dividing the potential nitrate load by the estimated rainfall

Table 6. Potential nitrogen load estimates from sources in the Río Nigua de Salinas alluvial fan, Salinas, Puerto Rico, 2002.

[kg/ha-yr as N, kilogram per hectare per year as nitrogen; kg/yr as N, kilogram per year as nitrogen]

Crop/land use	Potential residual nitrogen (kg/ha-yr as N)	Total residual nitrogen (kg/yr as N)
Plantains/bananas	134 - 162	34,400 - 41,600
Corn	102	5,200
Sorghum	18	3,800
Turf grass	320 - 430	16,600 - 22,300
Papaya	Negligible	Negligible
Irrigation ground water	59	18,100
Poultry litter	519	100,700
Unsewered communities	47	3,700

recharge rate of 0.10 m/yr and a surface area of about 19 km^2 within the alluvial fan deposits west of the coastal plain hills (area generally to the west of section A-A' shown in fig. 5) and east of site 10 in figure 2. The rainfall recharge value of 0.10 m/yr, which represents 10 percent of the annual rainfall, was assumed by Giusti (1971) for the Río Coamo alluvial fan (fig. 1). Kuniansky and others (2004) used values of rainfall recharge between 4 and 12 percent of the annual rainfall for that same area. The Río Coamo alluvial fan is in the same climatic zone and located about 12 km to the west of the study area. Only rainfall recharge is used in the estimate of the anticipated nitrate concentration because the irrigation return flow from micro-drip irrigation is assumed to be negligible (Kuniansky and others, 2004). The anticipated nitrate concentration in ground water would range from about 43 to 50 mg/L (81,800 to 94,700 kg/yr as N divided by 1.9 x 10^6 m^3/yr), which would be in the range of between 6 and 30 percent of the measured concentration. The estimate of the anticipated concentration assumes that: (1) all the estimated potential nitrate load enters the aquifer, (2) no nitrate accumulation is present in the unsaturated zone, and (3) ground-water flow is in steady state. The thickness of the unsaturated zone in the area of higher nitrate concentration ranged from 12 to 15 m during 2002, which indicates that a large part of the calculated load could be in transient storage. Most of the sampled wells are screened over long intervals, which indicates that collected samples may represent a mixture of water recharged through years, and limits the methodology to be used.

The anticipated nitrate concentration in ground water calculated using the current fertilizer application rates was compared to the anticipated nitrate concentration during the period when sugarcane was the principal crop in the area. Sugarcane cultivation was the principal land-use activity in the area from the early 1900s until the 1970s. The fertilizer application rate was about 196 kg/ha-yr as N for sugarcane crops at the principal farms in the Salinas area (Universidad de Puerto Rico, 1983). The nitrogen uptake of sugarcane crops was estimated to range from 86 to 117 kg/ha-yr as N (Natural Resources Conservation Service, 2001). The amount of nitrogen available for volatilization, mineralization, and potential migration to the aquifer would have been about 79 to110 kg/ha-yr as N during the period when sugarcane was the principal crop in the area.

The anticipated nitrate concentration in ground water within the same area used in the previous calculation under present land-use conditions, except for the period when sugarcane was the principal crop in the area, was estimated using a recharge rate from rainfall infiltration and furrow irrigation return flows of 0.36 m/yr (F. Gómez-Gómez, U.S. Geological Survey, oral commun., 2003) and a potential NO_3-N load of 110 kg/ha-yr. Occupying a cultivated land area equal to the total area used in the previous calculations, the potential NO_3-N to the aquifer would be 209,000 kg/yr (1,900 ha x 110 kg/ha-yr). The anticipated nitrate concentration in the aquifer would be about 30 mg/L. Nitrate concentrations from ground-water samples collected in 1961 ranged from 2.5 to 9 mg/L (median of 3.6 mg/L), meaning that NO_3-N load to the aquifer estimated by the method described ranged only from about 8 to 30 percent of the potential NO_3-N load. Thus, a large portion of the NO_3-N fertilizer load may have been lost to volatilization or to soil mineralization, or was in transient storage.

Within the uncertainty of the methodology used, a comparison of the relation between the potential NO_3-N loads to the aquifer with the ground-water NO_3-N concentrations– for the historical and present-land use conditions– indicates that as much as 30 percent of the estimated fertilizer load reached the aquifer within cropland areas. Thus, it is possible that under the existing land-use conditions in the Río Nigua de Salinas alluvial fan, NO_3-N concentration of 15 mg/L (about 30 percent of the total applied nitrogen load) in the aquifer is near the steady-state value under existing fertilizer application rates and total cultivated acreage.

Summary and Conclusions

A study was conducted in the Río Nigua de Salinas alluvial fan and in the Hucar area, a semi-enclosed basin in the foothills north of the alluvial fan in southern Puerto Rico, with the purpose of defining the spatial distribution and sources of nitrate concentrations in the local aquifer. Agriculture land uses are predominant and include cropland, confined poultry feeding operations, and pasture. The study area encompasses part of the South Coastal Plain alluvial aquifer and bedrock hills north of the coastal plain. The principal ground-water flow zone is within the alluvial deposits, which have a thickness of as much of 107 m in the study area. The geology of the hills north of the alluvial fan consists of volcanic igneous rocks. The hydraulic conductivity in the Salinas fan ranges from 6 to greater than 30 m/d with depth to ground water during 2002 ranging from 0.52 to 21.8 m below land surface.

Estimates of surface-water-derived ground water were made using the stable isotopes of hydrogen and oxygen. Percentages of surface-water-derived recharge were higher in areas to the south of the Canal de Patillas irrigation canal near the south-central part of the alluvial fan and the Coquí area where values were greater than 50 percent. A potentiometric-surface map prepared during the study indicates that the general ground-water flow direction is south and two cones of depression are present in the area– a major cone in the south-central part of the fan and another in the northeastern quadrant of the fan. The potentiometric surface during 2002 was, on average, about 4.6 m lower as compared with that for a similar study conducted in 1986. Ground-water withdrawals in the alluvial fan were estimated at about 43,500 m^3/d in 2002. Agricultural use of ground water was about 49 percent, public-supply was 42 percent, and industrial use was 9 percent. In the Hucar area, the estimated total ground-water withdrawal by poultry farms was about 121 m^3/d.

Ground-water quality data indicated two groups of wells with characteristic water types. One group, which includes 17 of the sampled wells, presents characteristics of calcium-bicarbonate type water; the second group, which includes 7 wells, presents characteristics of calcium-bicarbonate type water mixed with ground water of calcium-chloride or sodium-bicarbonate type. The dissolved-solids concentrations in ground water in the study area averaged about 756 mg/L in the foothills of the Hucar area and ranged from about 400 to 485 mg/L near the center of the fan, except within the cone of depression where the dissolved-solids concentration was 663 mg/L. Within the northeastern quadrant of the alluvial fan, the dissolved-solids concentration is a mix of ground water from the foothills with that recharged in the coastal plain.

Nitrate concentrations above the U.S. Environmental Protection Agency maximum contaminant level for drinking water (10 mg/L) were detected in three wells in the alluvial fan and in all the wells sampled at the foothills. All of the wells exceeding the nitrate maximum contaminant level are used for agricultural purposes. Monthly ground-water samples collected from four wells in the study area between March 2002 and February 2003 indicated that nitrate concentrations at all four sites did not vary by more than 20 percent from the initial concentrations. The most important factor judged to be the cause of a change in nitrate concentration between sample dates was rainfall infiltration, which can result in aquifer recharge where the aquifer is unconfined.

Principal sources of nitrate in the study area are fertilizers used in the cultivated farm lands and broiler litter disposal at the poultry farms. Potential nitrate loads from areas under cultivation were estimated for the principal crops in the area. Potential load estimates ranged from 18 kg/ha-yr as N for sorghum crops to 519 kg/ha-yr as N in areas used for disposal of poultry litter.

Ground-water samples analyzed for the stable isotope ratios of $^{15}N/^{14}N$ (^{15}N) in nitrate indicated that organic sources (animal waste) from poultry farms are the source of high nitrate concentrations in the foothills. Values of ^{15}N in samples from wells located in the alluvial fan were in the range associated with artificial fertilizers and natural vegetative decay. Based on the predominant land use in the alluvial fan and the potential migration of ground water with elevated nitrate concentration from the foothills, the percentage of nitrate derived from fertilizer application was compared to nitrate derived from poultry-waste sources. The fertilizer-derived NO_3-N is most pervasive throughout the central part of the Río Nigua de Salinas alluvial fan, with animal-waste-derived NO_3-N being the major source in the northeastern quadrant of the study area along a south- to southeast- trending plume in the direction of the Coquí community.

The variability in the reported fertilizer application rates for similar crops in the area indicates that fertilizer-management practices in the farms located in the alluvial fan may need to be reviewed to achieve the crop production goals as well as to minimize the nitrogen movement to the aquifer. Fertilizer-management practices include the application methods, amount, timing, and sources. The installation of piezometers, especially at farms within the central part of the alluvial fan where higher nitrate concentrations were detected, can help in the monitoring of nitrate concentrations in order to define the optimal crop nitrogen fertilizer application rates to minimize aquifer concentrations greater than 10 mg/L NO_3-N. Fertilizer management in the farms in the alluvial fan should likely account for the amount of NO_3-N present in ground water used for crop irrigation, which in the eastern part of the study area ranges from 8 to 15 mg/L.

An evaluation of the current practice of poultry litter application in the farms located within the foothills of the Hucar area may help minimize further nitrate infiltration to ground water. Currently, poultry litter is applied to limited acreage in the Hucar area. The repeated applications on fields in the immediate areas surrounding the poultry farms result in a buildup of nitrogen in the soil, which increases the potential for leaching to the aquifer during rainfall and as runoff to the alluvial plain where infiltration is further enhanced.

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