Characterization of Springflow in the North Coast Limestone of Puerto Rico Using Physical, Chemical, and Stable Isotopic Methods

U.S. GEOLOGICAL SURVEY Water-Resources Investigations Report 97-4122

Prepared in cooperation with the

PUERTO RICO AQUEDUCT AND SEWER AUTHORITY

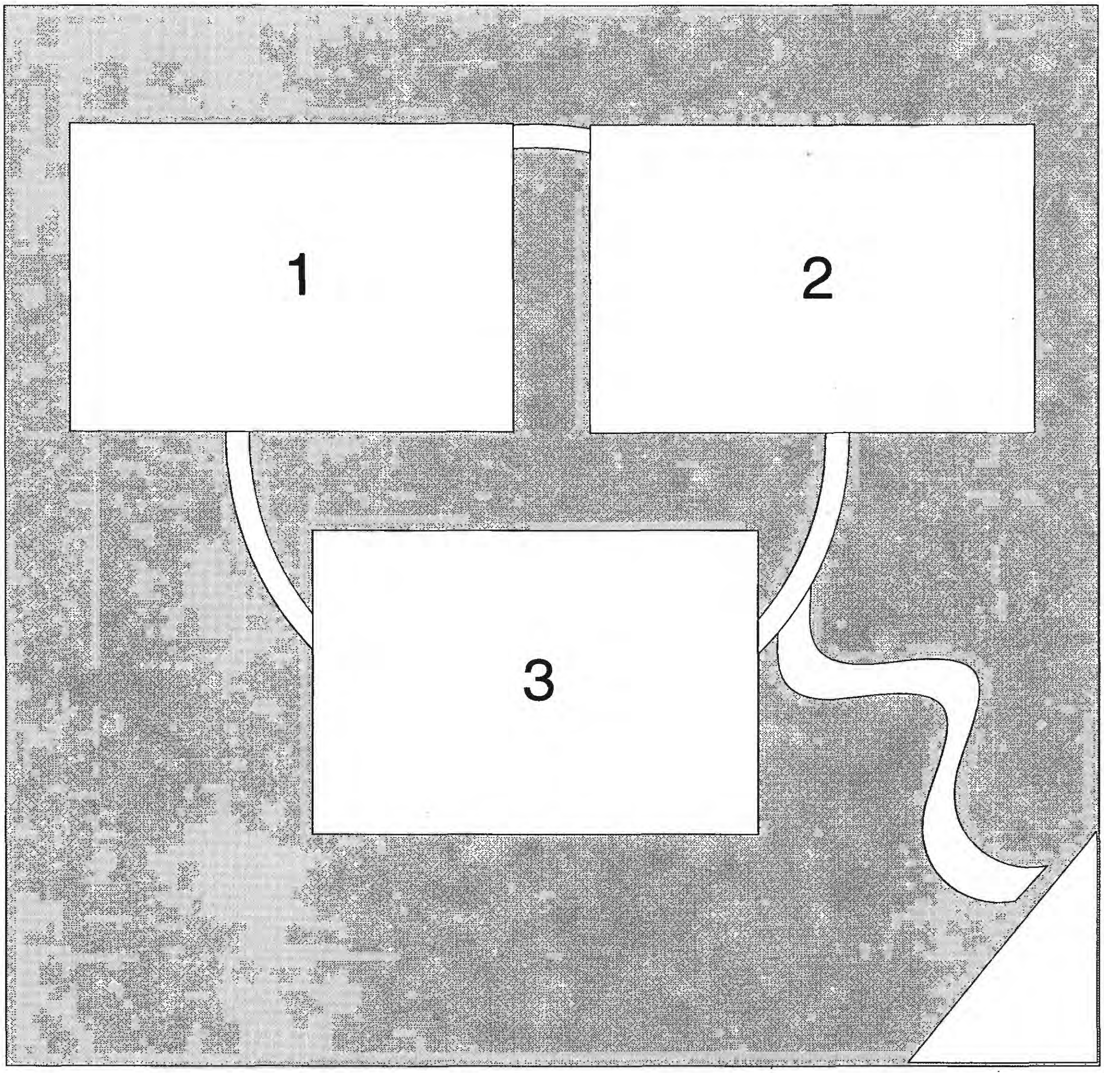

Photo 1. and Photo 2.

Photographs of Ojo de Agua spring at Vega Baja, Puerto Rico -- A diffuse-type spring whose flow has been regulated by the local authorities for recreational purposes. The photo 1 view is looking to the north from the spring outlet, and the photo 2 view is looking to the south towards the spring outlet.

Photo 3.

Photograph of Ojo de Guillo spring at Manatí, Puerto Rico -- A conduit-type spring during high-flow conditions. This photo was taken looking to the north from the spring outlet.

Photos taken in 1993 by Jesús Rodríguez-Martínez

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San Juan, Puerto Rico
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U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
foot (ft)	0.348	meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallons (Mgal)	0.04381	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per day
square mile (mi^2)	259.0	hectare
square kilometer (km^2)	0.3861	square mile
cubic feet per second (ft^3/s)	448	gallons per minute

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

$$°F = (1.8 \times °C) + 32$$

Abbreviated water-quality units used in this report:

mg/L	milligrams per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius
µg/L	micrograms per liter

Acronyms used in this report:

GMWL	Global Meteoric Water Line
GWSI	Ground Water Site Inventory
LMWL	Local Meteoric Water Line
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Survey
PRASA	Puerto Rico Aqueduct and Sewer Authority
USGS	U.S. Geological Survey
USEPA	U.S. Environmental Protection Agency
WATSTORE	Water Storage and Retrieval

Characterization of Springflow in the North Coast Limestone of Puerto Rico Using Physical, Chemical, and Stable Isotopic Methods

***By* Jesús Rodríguez-Martínez**

Abstract

The carbonate sequence of middle Tertiary age of the north coast of Puerto Rico is characterized by the presence of numerous springs in the coastal areas. In order to advance the understanding of the hydrologic role of the springs in the north coast limestone aquifer system of Puerto Rico, a 4-year study was conducted by the U.S. Geological Survey in cooperation with the Puerto Rico Aqueduct and Sewer Authority. As part of this study, data were collected on the chemical, physical, bacteriological, oxygen-18, and deuterium composition of water from springs in the Dorado to Rincón area, in northwestern Puerto Rico. A group of springs in the Dorado to Arecibo area was selected for more detailed monitoring. Oxygen-18 and deuterium composition was also determined for water wells and monthly rainfall composites at a series of sites in the study area.

Springs are associated with all the carbonate units of the middle Tertiary sequence of the northern karst belt of Puerto Rico, except the Camuy and San Sebastian Formations. These springs mostly drain the unconfined parts of the upper and lower aquifers in the north coast limestone aquifer system. There are no first and second order springs in the north coast limestone and of those present fifth and sixth order springs are the most numerous type. Springflow at the springs measured during the study ranged from less than 0.1 to 61 cubic feet per second.

Springs in the north coast limestone can also be classified by their response to rainfall. There is little or no short-term response to rainfall at springs such as Ojo de Agua in Vega Baja, Mameyes in Manatí, and Mackovic in Vega Alta. These springs are known as diffuse-type springs. Other springs such as Maguayo in Dorado, Ojo de Guillo in Manatí, and San Pedro in Arecibo exhibit a strong short-term response to rainfall and are known as conduit-type springs. Spring water temperature, during the study, ranged from 22.5 to 28 °C and resembled air temperature. Specific conductance ranged from 289 to about 4,000 microsiemens per centimeter, and pH ranged from 6.9 to 7.8.

Calcium, sodium, bicarbonate, and chloride are the main ionic species in water from the springs sampled during the study. The main water type is calcium-bicarbonate and secondary water types are calcium-bicarbonate-chloride and sodium-bicarbonate-chloride. A seasonal and short-term transient relation exists, particularly in conduit-type springs, between springflow, physical properties, and water quality.

Temporal and spatial variations in the oxygen-18 and deuterium composition of modern precipitation are significantly larger than those of springs and ground water in the study area. Regional flow in the upper aquifer appears to attenuate or average the variations in isotopic composition of rainfall. There is, however, a regional gradient in the deuterium composition of water from the upper aquifer in the north coast limestone, with isotopically heavier water occurring further north.

It was possible to determine the source of water contributing to springs at some sites with more detailed data collection and analysis. A drainage basin of about 10 square kilometers was

delineated for the Ojo de Agua spring in Vega Baja, for a base flow of 2 cubic feet per second and an estimated subregional recharge rate of around 20 inches per year. A delineation of drainage basins for conduit-type springs in the study area such as San Pedro, Ojo de Guillo, Maguayo, and others is very difficult because the boundaries of these systems are highly responsive to changing hydraulic conditions such as rapid and short-term variations in the hydraulic head distribution as a consequence of rainfall. However, a preliminary drainage basin of about 6 square kilometers was delineated for the San Pedro spring for a base flow of 2 cubic feet per second and an estimated subregional annual recharge of 12 inches.

INTRODUCTION

The aquifers within the middle Tertiary carbonate sequence of the north coast of Puerto Rico constitute the island's most important ground-water source. This carbonate sequence is highly karstified and is characterized by the presence of numerous springs in the coastal plain and along the banks of the rivers with channels cut into the limestone bedrock and the alluviated valleys of major streams (fig. 1, in pocket at end of report). Springs generally having flows smaller than flows from these springs also are found along the southern boundary of the carbonate sequence.

The hydrologic character of these springs is largely unknown. Previous studies describing the hydrology of Puerto Rico's north coast have not addressed the recharge areas of the major springs or their interaction with rivers and aquifers. Some of the springs along the north coast were previously described as part of a major reconnaissance of the principal springs in Puerto Rico by the U.S. Geological Survey (USGS) in cooperation with the Commonwealth of Puerto Rico (Guzmán-Ríos, 1988). The discharge from some of the principal springs in this ground-water province can be as high as 20 Mgal/d (F. Gómez-Gómez, USGS, written commun., 1991) as compared to ground-water withdrawals which are estimated at about 85 Mgal/d (W. Molina, USGS, written commun., 1995). Therefore, accounting for ground-water discharge at springs is critical to understanding the ground-water resource and its potential to sustain additional development.

Purpose and Scope

This report presents the results of a hydrologic assessment of springs located in the north coast limestone formations in the area between the municipalities of Dorado and Rincón with a more detailed analysis at selected springs in the Dorado to Arecibo area to determine whether the source of their discharge is from local or regional recharge (fig. 1; table 1). The study was conducted between October 1992 and September 1996 by the USGS in cooperation with the Puerto Rico Aqueduct and Sewer Authority (PRASA). The scope of this study encompassed the following activities in order to achieve the study objectives.

An inventory made using the USGS Ground Water Site Inventory (GWSI) data base and augmented with field reconnaissance of 67 springs identified in the study area (fig. 1; table 1). All springs documented in this inventory were surveyed at least twice during the study for instantaneous discharge, specific conductance, temperature, and pH. They were classified according to their discharge using the Meinzer System (Meinzer, 1927) and also as conduit-type or diffuse-type springs according to the relation between flow and rainfall.

Springs selected from the inventory for more detailed monitoring were the Ojo de Guillo spring in Manatí (10), Maguayo spring in Dorado (1), Ojo de Agua spring in Vega Baja (5), and the San Pedro (18), Zanja Fría (11), Bambú #1 (22), and Los Chorros (16) springs in Arecibo, where numbers in parenthesis refer to the spring identification number shown in table 1. Continuous recordings devices were installed to measure springflow in the San Pedro (18) and Ojo de Guillo (10) springs. Discharge measurements were made at all selected springs except the Bambú #1 (22) and Los Chorros (16) springs in Arecibo because of the absence of adequate sections to measure flow. Temperature, specific conductance, and pH were recorded during both low-and high-flow conditions at all selected springs.

Table 1. Names, identification numbers, and locations of springs included in this study and shown in figure 1
[Dm, "detailed monitoring"]

	Spring name	Identification number	Latitude	Longitude	Municipality
Dm	Maguayo	1	18°24'46"	66°15'55"	Dorado
	Mackovic	2	18°27'58"	66°22'26"	Vega Alta
	La Poza	3	18°28'27"	66°23'24"	Vega Baja
	Don Vicente Morales	4	18°28'20"	66°23'24"	Vega Baja
Dm	Ojo de Agua at Vega Baja	5	18°26'57"	66°25'06"	Vega Baja
	Ojo de Agua at Morovis	6	18°20'04"	66°26'38"	Morovis
	Sonadora	7	18°20'19"	66°28'53"	Ciales
	Aguas Frías	8	18°22'18"	66°29'10"	Manatí
	Mamey	9	18°27'59"	66°30'41"	Manatí
Dm	Ojo de Guillo	10	18°25'41"	66°31'36"	Manatí
Dm	Zanja Fría	11	18°27'24"	66°39'20"	Arecibo
	La Pileta	12	18°23'28"	66°39'44"	Arecibo
	La Punta	13	18°21'06"	66°40'23"	Arecibo
	Cascada	14	18°23'30"	66°40'44"	Arecibo
	Opiola	15	18°23'17"	66°40'46"	Arecibo
	Los Chorros	16	18°21'23"	66°40'52"	Arecibo
	Sumidero	17	18°22'04"	66°41'06"	Arecibo
Dm	San Pedro	18	18°24'35"	66°41'45"	Arecibo
	Marrero #2	19	18°25'14"	66°42'50"	Arecibo
Dm	Marrero #1	20	18°25'11"	66°42'53"	Arecibo
	Bambú #2	21	18°24'29"	66°43'08"	Arecibo
	Bambú #1	22	18°24'27"	66°43'12"	Arecibo
	[1]Río Tanamá Dam	23	18°24'30"	66°43'22"	Arecibo
	PVC	24	18°21'48"	66°44'42"	Arecibo
	Odilio Jiménez	25	18°21'36"	66°44'53"	Arecibo
	San Rafael	26	18°21'30"	66°45'21"	Arecibo
	Cambijas	27	18°22'44"	66°45'25"	Arecibo
	Avispa	28	18°23'48"	66°45'38"	Arecibo
	Luis Pérez #2	29	18°22'08"	66°45'40"	Arecibo
	Luis Pérez #1	30	18°22'09"	66°45'43"	Arecibo
	Ruiz	31	18°23'39"	66°46'10"	Arecibo
	Eligio Rosado	32	18°22'03"	66°46'16"	Hatillo
	Basilio	33	18°23'40"	66°46'25"	Hatillo
	Sonadora	34	18°24'10"	66°47'43"	Hatillo
	Aserradero	35	18°23'22"	66°47'49"	Hatillo

Table 1. Names, identification numbers, and locations of springs included in this study and shown in figure 1—Continued

Spring name	Identification number	Latitude	Longitude	Municipality
Público	36	18°24'15"	66°48'04"	Hatillo
Rivera #2	37	18°23'26"	66°48'17"	Hatillo
Pozo del Muerto	38	18°21'50"	66°48'36"	Hatillo
Romero #1	39	18°23'03"	66°48'56"	Hatillo
Méndez #1	40	18°23'05"	66°48'59"	Hatillo
Romero #2	41	18°23'18"	66°49'03"	Hatillo
Negrón	42	18°23'36"	66°49'01"	Hatillo
Márquez	43	18°27'43"	66°49'41"	Hatillo
River Bank	44	18°17'28"	66°49'49"	Utuado
Cortez	45	18°22'33"	66°50'15"	Camuy
Bonilla	46	18°23'03"	66°50'26"	Camuy
Ojo Claro	47	18°29'30"	66°51'13"	Camuy
Martínez	48	18°23'18"	66°51'31"	Camuy
La Cántara	49	16°23'18"	66°51'39"	Camuy
Zumbadora	50	18°23'45"	66°53'40"	Camuy
Malabi	51	18°24'16"	66°54'20"	Camuy
Lago	52	18°23'54"	66°55'14"	Quebradillas
Muñiz	53	18°24'14"	66°55'16"	Quebradillas
Charcas	54	18°23'58"	66°55'37"	Quebradillas
Medina	55	18°23'52"	66°5549"	Quebradillas
Río #2	56	18°23'57"	66°55'53"	Quebradillas
Salto Collazo	57	18°20'06"	66°56'46"	San Sebastián
Máximo	58	18°23'16"	66°57'56"	Isabela
Soto Quintín	59	18°23'44"	66°58'09"	Isabela
Municipio	60	18°23'34"	66°58'10"	Isabela
Velázquez	61	18°24'07"	67°02'24"	Isabela
Ferrer	62	18°23'58"	67°03'35"	Isabela
La Salle	63	18°23'58"	67°04'04"	Moca
Salas	64	18°24'18"	67°04'28"	Moca
Victoria	65	18°24'26"	67°08'15"	Aguadilla
Méndez #2	66	18°24'29"	67°08'22"	Aguadilla
Ojo de Agua in Aguadilla	67	18°26'02"	67°11'27"	Aguadilla
Alers	68	18°22'44"	67°12'14"	Aguadilla

[1] Surface-water site

The concentration of major dissolved constituents and the stable isotopes of oxygen and hydrogen were measured at different flow conditions for a group of springs located in the study area between Dorado and Arecibo (fig. 1). Concentrations of the stable isotopes of oxygen and hydrogen were also measured, at least once, for a number of other springs in the study area.

Water samples were obtained from selected wells and from the Río Tanamá to determine the oxygen-18 and deuterium concentrations (fig. 1; table 2). These data were used to assist in the regional isotopic characterization of the upper aquifer and to determine the relation between discharge at springs and regional ground-water flow in the upper aquifer.

Rain gages were installed between Dorado and Arecibo to measure daily rainfall and obtain a monthly rainfall composite for the determination of oxygen-18 and deuterium (fig. 1; table 3). Additional precipitation data were obtained from National Weather Service rainfall stations in the municipalities of Morovis (Morovis 1N) and Utuado (Dos bocas) (fig. 1; table 3).

Previous Investigations

Studies by Giusti (1978) and Guzmán-Ríos (1988) concluded that springs are a conspicuous hydrologic feature of the northern karst belt of Puerto Rico. Giusti (1978), in the first study of note on the hydrogeology of the northern karst belt of Puerto Rico, recognized differences in the hydrologic behavior of the springs in the area of study. However, Giusti's main emphasis was in defining the hydrologic, physical, and chemical character of the regional ground-water-bearing units and only marginally considered the springs. Giusti (1978) observed, for example, that a few springs flow only after heavy rains, that those contributing water to rivers issue from cliffs, and those discharging near the coast rise through the blanket sands or swamp deposits producing features like Caño Tiburones, a freshwater wetland in north central Puerto Rico. He also noted that the preponderance of springs on the west sides of river valleys could be explained by the effect on the pattern of ground water of the eastward tilting of the Puerto Rican platform, believed to have occurred during the Pleistocene. Giusti (1978) collected and published the first chemical and physical data on springs in the northern karst belt of Puerto Rico. Guzmán-Ríos (1988), as part of a reconnaissance of the main springs in Puerto Rico, included data on the physical, chemical, and bacteriological characteristics of selected springs in the northern karst belt.

Acknowledgments

The author is grateful to the many landowners who permitted access to their properties and aided in locating many of the higher order springs.

REGIONAL SETTING

The climate in the northern karst belt of Puerto Rico is classified as humid tropical. The study area is mostly underlain by carbonate rocks of middle Tertiary rocks characterized by karst topography. The north coast limestone aquifer system has been divided in three hydrogeologic units: an upper aquifer continuing a basal saline water zone in the coastal areas, an intervening confining unit, and a lower aquifer. Springs mostly drain the unconfined parts of the upper and lower aquifers. Permeability contrasts between successive geologic units appears to be the main factor controlling the occurrence of springs in the northern karst belt.

Climate

The climate in the northern karst belt of Puerto Rico is classified as humid tropical (Calvesbert, 1970). The average annual rainfall ranges from about 60 inches at the north coast to about 90 inches in the south where the limestones are in contact with the igneous rocks of the Cordillera Central, an east-west trending mountain range transecting Puerto Rico. The annual variation in rainfall follows that of the entire island: a generally dry period with scanty rainfall from

Table 2. Names, identification numbers, and locations of wells included in this study and shown in figure 1

Well name	Identification number	Latitude	Longitude	Municipality
Vivoni	1	18°23'24"	66°17'26"	Dorado
Pámpano	2	18°23'19"	66°18'52"	Dorado
Santa Ana	3	18°25'15"	66°18'55"	Dorado
Coto Sur	4	18°25'46"	66°27'12"	Vega Baja
Río Arriba #3	5	18°23'12"	66°27'12"	Vega Baja
Boquillas	6	18°27'52"	66°29'37"	Manatí
Parcha	7	18°23'43"	66°32'32"	Barceloneta
Fortuna	8	18°26'47"	66°33'08"	Barceloneta
Pajonal #2	9	18°23'23"	66°33'11"	Barceloneta
Pajonal #1	10	18°23'05"	66°33'47"	Barceloneta
Florida #7	11	18°21'33"	66°34'28"	Florida
Garrochales #3	12	18°27'36"	66°35'58"	Arecibo
Sabana Hoyos #1	13	18°23'32"	66°36'07"	Arecibo
Sabana Hoyos #2	14	18°23'51"	66°36'11"	Arecibo
Jovales #2	15	18°21'51"	66°37'31"	Arecibo
Jovales #1	16	18°21'44"	66°37'46"	Arecibo
Jovales #3	17	18°22'48"	66°37'59"	Arecibo
Miraflores #1	18	18°25'28"	66°38'55"	Arecibo
Miraflores #2	19	18°25'29"	66°38'57"	Arecibo
Arecibo #6	20	18°25'09"	66°42'32"	Arecibo
Esperanza #2	21	18°22'37"	66°45'17"	Arecibo
Bayaney #2	22	18°21'17"	66°45'32"	Hatillo
Pajuil #1	23	18°25'50"	66°47'25"	Hatillo
Piedra Gorda #1	24	18°26'33"	66°52'41"	Camuy
El Rey #1	25	18°28'15"	66°56'19"	Quebradillas
El Rey #2	26	18°28'13"	66°56'15"	Quebradillas
Rocha #1	27	18°25'38"	67°01'59"	Quebradillas
[1]NC–8	—	18°25'17"	66°19'43"	Vega Alta

[1] Test well drilled in 1986 as part of the study on the hydrogeology of the north coast limestone of Puerto Rico (Rodríguez-Martínez, 1995).

Table 3. Station names, identification numbers, and locations where precipitation was recorded and monthly rainfall composites were collected for delta oxygen-18 and delta deuterium determination (stations numbers and locations are shown in figure 1)

Station name	Identification number	Latitude	Longitude	Municipality
Valparaíso	[1] 1	18°25'57"	66°09'52"	Cataño
Morovis 1N	2	18°20'00"	66°20'00"	Morovis
Pugnado Afuera	[2] 3	18°24'09"	66°24'54"	Vega Baja
San Agustín	[2] 4	18°23'28"	66°42'35"	Barceloneta
Dos Bocas	5	18°20'00"	66°40'00"	Utuado
Hato Viejo	[2] 6	18°23'36"	66°42'35"	Arecibo

[1] Only the delta oxygen-18 and delta deuterium of the monthly rainfall composites were used (F. Gómez-Gómez, USGS, written commun., 1996).

[2] Location at which monthly rainfall composites were collected for delta oxygen-18 and delta deuterium determination.

December to March or April, a short rainfall period in April or May, an irregular rainfall period in June–July, and a relatively wet season that normally lasts from August through November. The wettest months are usually September and October.

Precipitation data for the period of study were obtained for the Dorado to Arecibo area in the northern karst belt from the National Weather Service (National Oceanic and Atmospheric Administration, 1993–96) and from three stations installed for the study (figs. 1, 2). The two stations maintained by the National Weather Service (NWS) were Morovis 1N and Dos Bocas located in the municipalities of Morovis and Utuado, respectively (fig. 1). The stations installed for the study were in Barrio Pugnado Afuera of Vega Baja, Barrio San Agustín in Barceloneta, and Barrio Hato Viejo in Arecibo (fig. 1). The rainfall stations at Pugnado Afuera and Hato Viejo were maintained from April–May 1993 to March–May 1994. The rainfall station at San Agustín remained active from July 1993 to December 1995. Rainfall from about mid-1993 through 1994 was below normal throughout northern Puerto Rico. This rainfall deficiency was the largest recorded in 30 years. As a result of this drought and in order to be able to compare the precipitation data and associated variables, such as springflow, collected during this study with data from previous normal years, the longer term precipitation data of the NWS and San Agustín stations were used.

The variation in annual rainfall from 1993 to 1995 was considerable as a result of the drought mentioned above. At the Dos Bocas station the annual rainfall was 55 inches in 1993, (70 percent of normal), 43 inches in 1994 (55 percent of normal), and 78 inches in 1995 (near normal) (fig. 2). The average annual rainfall for this station is 78 inches (National Oceanic and Atmospheric Administration, 1995). At the Morovis 1N station the annual rainfall was 67 inches in 1993 (94 percent of normal), 46 inches in 1994 (64 percent of normal), and 68 inches in 1995 (96 percent of normal). The average annual rainfall for this station is 71 inches (National Oceanic and Atmospheric Administration, 1993–96). At both stations the monthly rainfall values were consistently below the normal monthly values during 1993 and 1994 (fig. 2). At the San Agustín station the rainfall data for 1993 were limited to six months (July–December) and the annual rainfall data for 1994 were 54 inches.

The average annual air temperature on the northern karst belt is about 24 °C and normally varies only a few degrees from winter to summer. During the study period the monthly average temperature at the Dos Bocas station ranged from 21 to 27 °C with an extreme low of 11 °C and a maximum of 33 °C (NOAA, 1993–96). Based on a correlation with precipitation, Giusti (1978) estimated an average annual evapotranspiration rate of 45 inches for the northern karst belt of Puerto Rico.

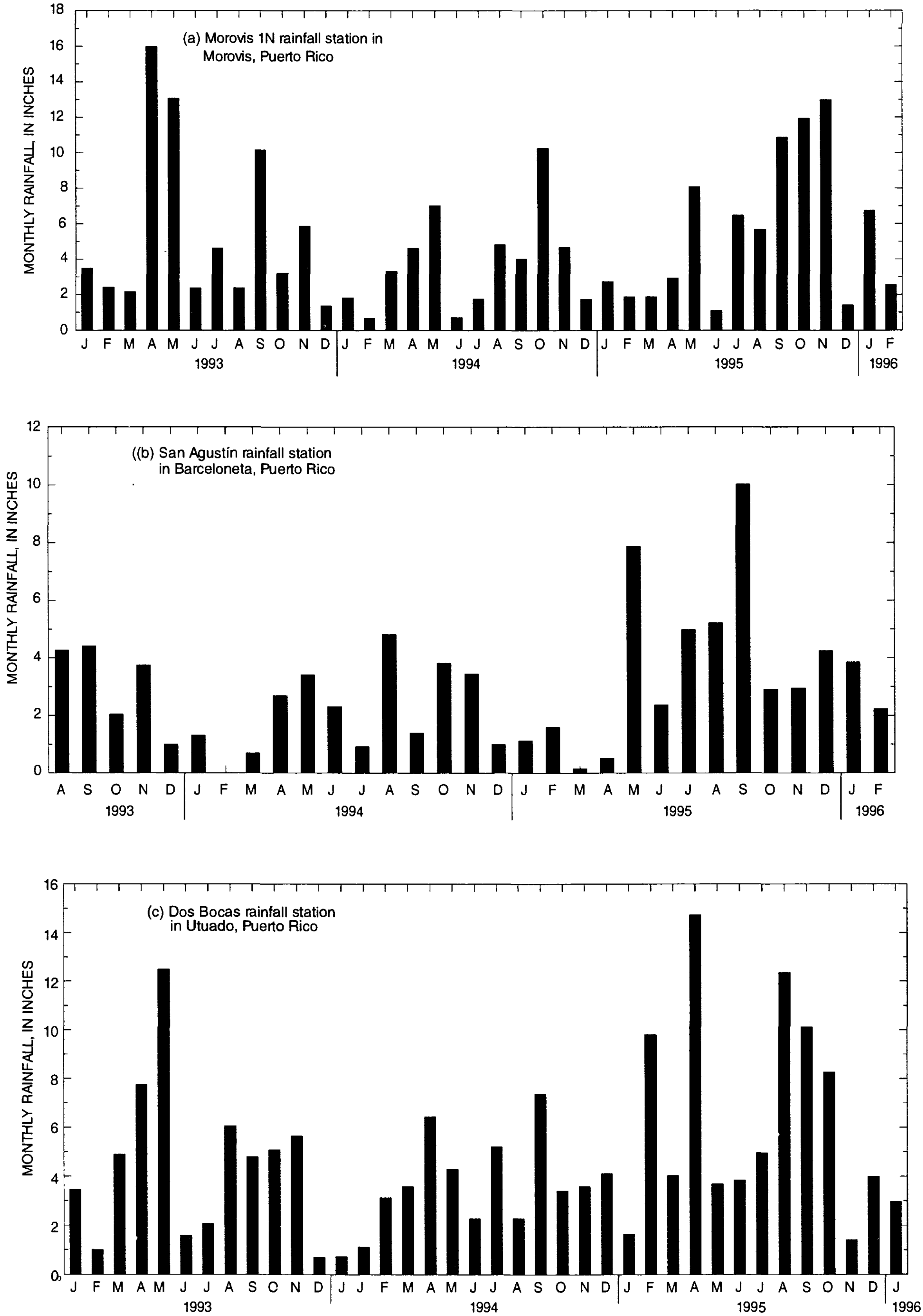


Figure 2. Monthly rainfall at three sites in the study area (locations shown in figure 1).

Geology

Several stratigraphic nomenclatures have been established for the middle Tertiary age formations of the north coast of Puerto Rico. The stratigraphic framework used in this report follows Monroe (1980) as slightly modified by Ward and others (1991).

The middle Tertiary sequence of the north coast of Puerto Rico is separated into seven formations with outcrop areas largely characterized by karst topography (fig. 3a). The seven formational units constitute a homoclinal sequence that dips gently northward at an average of 3 to 4 degrees. Dips near the coast average about 2 degrees whereas steeper gradients of 6 to 7 degrees are found at the southern limit of the northern karst belt (fig. 3b). These formational units in ascending order are the San Sebastián Formation (coastal and fluvial terrigenous clastics, marginal marine clay and limestone); Lares Limestone (middle and outer-platform carbonate rocks); Mucarabones Sand, which is in part chronostratigraphically equivalent to the Lares Limestone and the lower part of the Cibao Formation (marginal marine clays and minor fluvial clastics); Cibao Formation (claystone, marl, and limestone containing terrigenous material) and its members, the Montebello Limestone (mid-platform carbonates), the unnamed "mudstone unit," and the Quebrada Arenas and Río Indio Limestones (inner platform terrigenous limestones); Aguada Limestone (inner platform carbonate); Aymamón Limestone (mid-platform coral-rich limestone); and, Camuy Limestone (an inner platform terrigenous limestone). In coastal areas the middle Tertiary beds are overlain by surficial deposits (assorted mixtures of sand, silt, and clay) of late Pliocene to Holocene age. The middle Tertiary age sequence of the north coast is underlain by late Cretaceous and early Tertiary limestones, volcanoclastics, and minor turbidites (Monroe, 1980; Meyerhoff and others, 1983).

With the exception of the area east of the Río de la Plata, the land surface is characterized by sinkholes and other solutional features. In the area west of the Río Grande de Arecibo, the karst topography is largely characterized by "cockpit" topography and rivers whose courses are partly underground or highly entrenched. Between the Río Grande de Arecibo and Río de la Plata the coastal land surface is characterized by isolated limestone hills (mogotes) and undulating surficial deposits. In this part of the island, dissolution processes are generally still very active in the intermogote areas. The karst topography in the area east of the Río de la Plata is characterized by low topographic relief with little or no active dissolution of limestone and surface, rather than underground, drainage (Monroe, 1976)

Hydrogeology

The north coast limestone aquifer system has been divided into three principal hydrogeologic units: an upper aquifer containing a basal saline-water zone in the coastal regions; an intervening confining unit; and a lower aquifer (fig. 3b). A local confined ground-water flow zone has been identified within the middle confining unit.

Most of the upper aquifer consists of the Aymamón Limestone and the underlying Aguada Limestone. Locally it also includes the uppermost rocks of the unnamed upper member of the Cibao Formation. The upper aquifer contains water under unconfined conditions except in coastal areas where it is confined by overlying surficial deposits.

The regionally extensive confining unit is composed largely of the unnamed upper member of the Cibao Formation, a calcareous clay and marl unit. In the area between Manatí and Dorado the confining unit also includes the unnamed mudstone unit and the undifferentiated Río Indio and Quebrada Arenas Limestone Members of the Cibao Formation. East of the Río de la Plata the confining unit consists of the unnamed upper member of the Cibao Formation. A water-bearing zone of local extent has been documented within the confining unit between Arecibo and Manatí (Rodríguez-Martínez, 1995).

The lower aquifer contains water under confined conditions except in the outcrop areas where it is under water-table conditions. The lower aquifer consists mostly of the Montebello Limestone Member of the Cibao Formation, the Lares Limestone, and the Mucarabones Sand. In the outcrop areas it consists also of the Río Indio and Quebrada Arenas Limestone Members of the Cibao Formation and locally of minor sand and gravel deposits of the San Sebastián Formation.

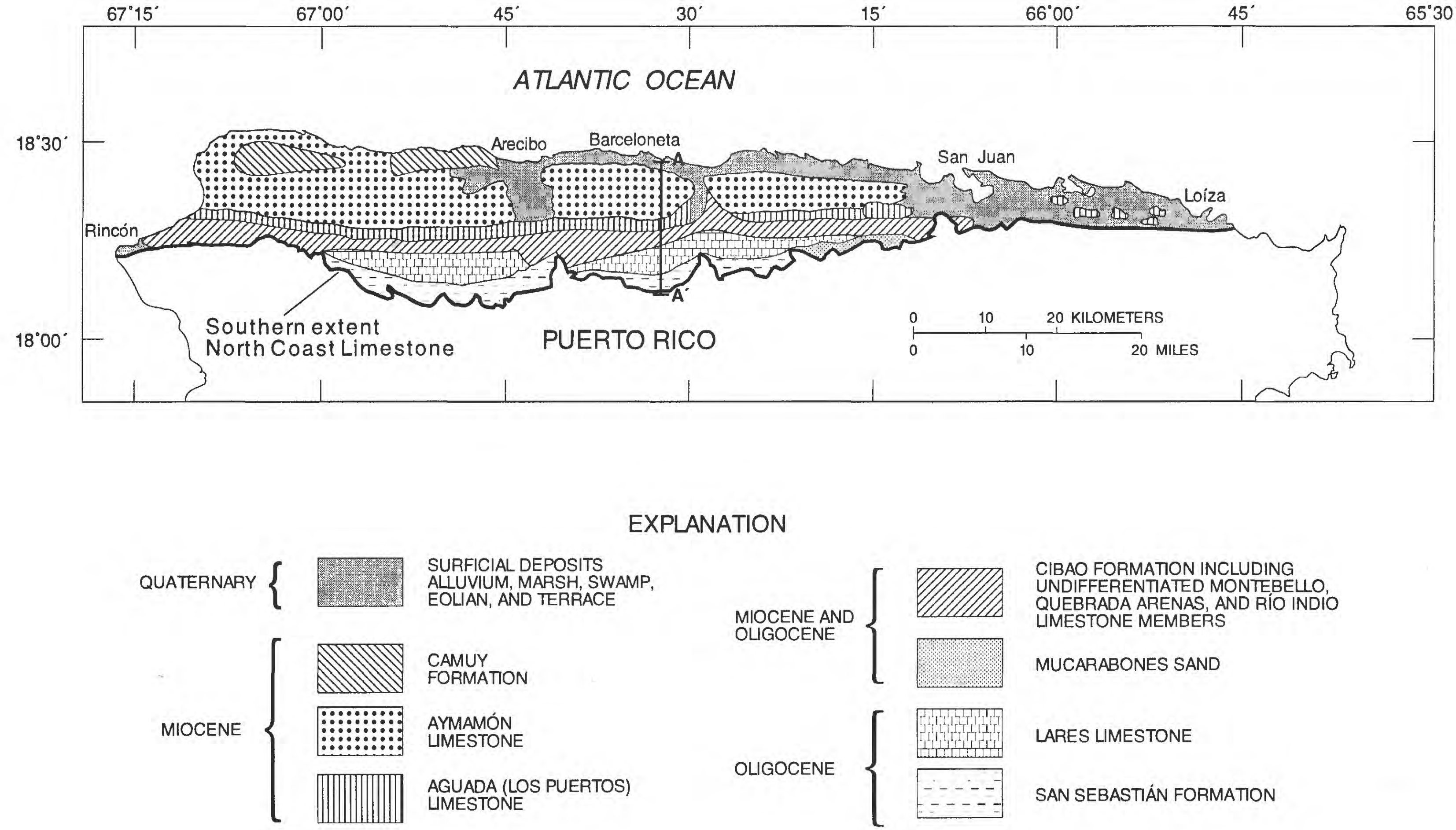


Figure 3a. Generalized geologic map of the north coast limestone (modified from Monroe, 1980).

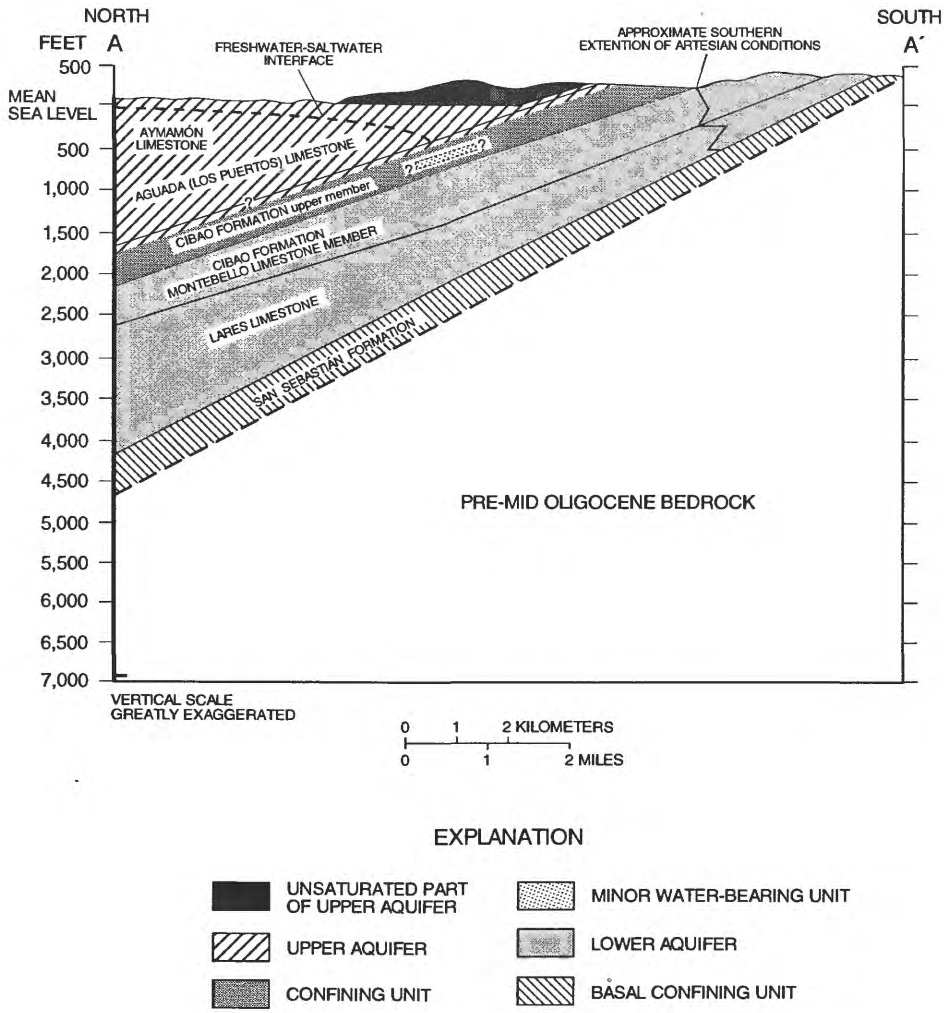


Figure 3b. Generalized north-south hydrogeologic geologic section of the north coast limestone (Rodríguez-Martínez, 1995)—Continued.

The Camuy Formation is the uppermost stratigraphic unit of the middle Tertiary sequence and is highly terrigenous. The hydrologic value of this unit is minimal because its base is above the water-table surface of the upper aquifer and it is limited to the area west of Arecibo. The San Sebastián Formation at the base of the sequence is highly clayey and, thus, poorly permeable.

Springs are associated with all the carbonate units of the middle Tertiary sequence of the northern karst belt, except the Camuy and San Sebastián Formations. Springs drain the unconfined parts of both the upper and lower aquifers. Springs that drain the unconfined part of the lower aquifer normally issue from the outcrop areas of the Lares Limestone and the Montebello Limestone Member of the Cibao Formation. The springs that drain the unconfined part of the upper aquifer issue from both the outcrop and coastal subsurface areas of the Aguada and Aymamón Limestones. No spring is known to issue from the confined part of the lower aquifer.

Permeability contrast between successive geologic units appears to be the main factor controlling the occurrence of springs in the northern karst belt. Large permeability contrasts, found (1) at the base of the Aguada Limestone at or near the contact with the upper member of the Cibao Formation and (2) at the base of the Lares Limestone at or near the contact with the San Sebastián Formation, result in numerous springs (for example, Bambú #1 spring in Arecibo (22) and the Salto Collazo spring (57), respectively). The smaller permeability contrast between the Montebello Limestone and the Lares Limestone appears responsible for the occurrence of correspondingly fewer springs, such as Los Chorros spring (16).

Structure

Geophysical and geological studies do not provide evidence for the existence of faults cutting across the entire middle Tertiary age sequence. Local faulting or fracturing may be responsible for the observed alignment of some topographic features in the northern karst belt, such as limestone hills (mogotes), limestone ridges, sinkholes, and straight river segments (Meyerhoff and others, 1983; Ward and others, 1991). This local faulting or fracturing, as well as minor folding, appear to be related to deep seated structural features in the underlying Late Cretaceous and Early Tertiary rocks beneath the middle Tertiary sequence. Analyses of the alignment of topographic features indicates that most straight segments of karst valleys in the north coast region represent sets of regional fractures (Ward and others, 1991). For example, between the Río Grande de Arecibo and the Río Grande de Manatí, prevalent trends of karst valleys (fracture systems) are N. 1°-20° E., N. 10°-30° W., N. 70°-90° E., and N. 80°-90° W. (Ward and others, 1991). Ground-water flow in the outcrop areas of the upper and lower aquifers appears to be highly controlled by fractures and consequently most of the springs in these areas are of the conduit type. Ground-water flow in the mid-valleys and more coastal areas of the upper aquifer seems to occur along vertically and laterally discontinuous permeable zones that may be connected by fractures and, as a result, springflow is mostly of the diffuse type.

The underlying Late Cretaceous and early Tertiary rocks have been displaced by faults that strike predominantly northwest (Meyerhoff and others, 1983). Geophysical and geological evidence indicate that a number of structural highs have compartmentalized the basin where the middle Tertiary age sequence was deposited into a series of sub-basins (Meyerhoff and others, 1983). The effect of this compartmentalization appears to have been greater during the deposition of the Lares Limestone and the Cibao Formation than when the Aguada Limestone, Aymamón Limestone, and Camuy Formation were deposited.

A large number of the springs in the north coast limestone belt discharge into the west bank of streams. Giusti (1978) concluded that an eastward tilt of the Puerto Rican platform, believed to have occurred during the Pleistocene, was responsible for this preferential discharge direction. However, various springs are known to discharge into the east bank of the rivers indicating that the eastward tilt is not the sole factor in determining the discharge directions of springs in the north coast.

Results of studies in other karst areas provide another explanation that may explain this observed phenomenon. A consistent change in the orientation of karst conduits as they pass from the vadose (unsaturated) to the phreatic (saturated) zone has been documented in several karst terranes (Palmer, 1987). It has been observed that the parts of karst conduits in the unsaturated zone in general are preferentially oriented along the dip while those parts in the saturated zone are nearly parallel to the local strike of the strata (Palmer, 1987). These flow patterns seem to result from the prevalence of gravity flow in those portions of conduits in the unsaturated zone and of pressure differential-induced flow in the saturated zone. Gravity-induced flow tends to follow the steeper slope (maximum gradient) which normally is along the dip while saturated flow preferentially follows passages of greater width or diameter, which tend to occur along the strike of the strata, inasmuch as the width or diameters of passages (fractures, bedding planes, and so on) normally decrease with distance along the dip of the strata. This is particularly true in those cases where the strata sequence is more exposed along the strike than the dip, which is the case of the middle Tertiary age sequence in the north coast of Puerto Rico. Palmer (1987) also states that of two possible strike directions available to the incoming unsaturated flow ground water normally follows the shorter distance to the nearest river. An anticlinal structure in the Camuy to Aguadilla area seems to control the orientations of springs like Ojo de Agua in Aguadilla (67), that discharges toward the west, Ojo Claro in Camuy (47) that discharges toward the north, and Alers in Rincón (68) that discharges toward the south. Something similar occurs in the Río Grande de Arecibo to Río Tanamá area in Arecibo where a structural flexure is responsible for a ground water divide that diverges springflow between these two rivers.

METHODS OF DATA COLLECTION AND ANALYSIS

Physical, chemical, and stable isotopic methods were used to characterize the springflow in the north coast limestone belt of Puerto Rico. The data collection also included ground-water and rainfall water samples in order to be able to compare springflow with modern precipitation and ground-water flow in the upper aquifer.

Physical

Discharge measurements were made at all the springs in the study, either continuously or at discrete intervals. Instantaneous discharge measurements at discrete intervals were made at least twice (during the wet and dry seasons) in all of the springs using current-meter and volumetric methods. Discharge measurements were more frequent at the following springs in the Dorado to Arecibo area that were selected for more detailed monitoring: San Pedro (18), Ojo de Guillo (10), Maguayo (1), Ojo de Agua in Vega Baja (5), Zanja Fría (11), Bambú #1 (22), and Los Chorros (16). The current-meter method mostly used was that of the equal-width increments (Buchanan and Somers, 1984). Daily average discharges at the San Pedro (18) and Ojo de Guillo (10) springs were estimated from a relation that was developed between daily gage-height readings collected by continuous recording devices and the instantaneous measurements made at these springs. The pH, specific conductance, and temperature were also measured at the springs selected for detailed monitoring along with discharge. The pH was measured with an Orion Portable pH/ISE 290A[1] meter and the specific conductance was measured with a portable YSI model 331[1] conductivity and salinity meter. The specific conductance measured was corrected to a temperature of 25 °C. The physical data were stored in the USGS National Water-Data Storage and Retrieval System (WATSTORE) computer data base and in the Caribbean District GWSI.

Chemical

The concentrations of major dissolved constituents (including, bicarbonate, other major ions, and nutrients) were determined at different flow conditions for the group of springs selected for detailed monitoring. Both water samples for major ion and nutrient composition were chilled with ice while in transit to the U.S. Geological Survey Central Laboratory in Denver. The USGS Central Laboratory is approved by the U.S. Environmental Protection Agency (USEPA) and uses USEPA standard methods.

The main ion and nutrient data were stored in the USGS National WATSTORE computer data base. The major ion and nutrient data were also collected in the Caribbean District GWSI.

Complete chemical analyses with less than 5 percent error in charge balance were plotted in a trilinear diagram (Piper, 1953) to describe the predominant water-types in the sampled springs. Existing water-quality data were compared with results from this study to determine if changes in spring water quality have occurred with time.

[1] Use of firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Government.

Bacteriological

Water samples from selected springs in the Dorado to Arecibo area were also analyzed for fecal coliform. Fecal coliforms are the fraction of the coliform bacteria group that is present in the gut or the feces of warm-blooded animals. The presence of fecal coliform organisms may indicate recent and possibly dangerous contamination.

The procedure used in this study to determine the concentration of fecal coliforms (Streptococci Fecal and Coliform Fecal) is described by Slack and others (1973). Water samples were filtered in the field immediately after collection and the filters were placed on a nutrient medium containing a color indicator.

Oxygen-18 and Deuterium Isotopes

Water samples for the determination of oxygen-18 (^{18}O) and deuterium (^{2}H) concentration were collected from springs in the area between the municipalities of Dorado and Rincón. However, the sampling for these isotopes was more intense at a group of springs in the area between Dorado and Arecibo: Maguayo (1), Ojo de Agua in Vega Baja (5), Ojo de Guillo (10), and Zanja Fría (11), San Pedro (18), Los Chorros (16), and Bambú #1 (22). The ^{18}O and ^{2}H concentration were also determined for monthly rainfall composites collected at the following stations: Valparaíso in Cataño, Pugnado Afuera in Vega Baja, San Agustín in Barceloneta, and Hato Viejo in Arecibo. The determination of ^{18}O and ^{2}H concentration were done at the USGS Central Laboratory in Denver Colorado and also at the laboratory of the Isotope Fractionation Project in Reston, Virginia.

The concentrations (activities) of ^{18}O and ^{2}H in the hydrologic cycle are expressed as the ratios of the main isotopes that comprise the water molecule ($^{18}O/^{16}O$ and $^{2}H/^{1}H$). The isotope ratios are expressed in delta units (δ) as per mil (parts per thousand or ‰) differences relative to an arbitrary standard known as Vienna standard mean ocean water (VSMOW):

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

where R and $R_{standard}$ are the isotope ratios, $^{2}H/^{1}H$ or $^{18}O/^{16}O$, of the sample and the standard, respectively. The accuracy of measurement is usually better than plus or minus 0.2 ‰ for $\delta^{18}O$ and plus or minus 2 ‰ for δD.

PHYSICAL, CHEMICAL, AND BACTERIOLOGICAL CHARACTERISTICS OF SPRING WATERS

In some of the springs, immediate, short-term changes in physical, chemical, and bacteriological properties were observed. These short-term changes were superimposed on longer term changes, which resemble the seasonal changes in the upper aquifer. Limited data that were available before this study are consistent with the patterns observed at some springs.

Springflow

The spring classification system developed by Meinzer (1927), which considers the magnitude of the base flow, was used to classify the springs in the north coast limestone belt (table 4). According to this classification system there are no first and second-order springs (base flow exceeding 100 and 10 ft^3/s, respectively, in the north coast limestone belt of Puerto Rico. Of the 67 springs identified for this study 10 are third order springs (base flow between 1.0 and 10 ft^3/s), four are fourth order (base flow between 0.22 and 1.0 ft^3/s), 14 are fifth order (base flow between 0.022 and 0.222 ft^3/s), 19 are sixth order (base flow between 0.002 to 0.022 ft^3/s), six are seventh order (base flow between 0.0005 and 0.002 ft^3/s), and 14 are eight order (base flow of a few drops per second). For the purpose of this study, magnitude eight springs also include springs that normally are dry and only flow after rainfall.

The inventoried springs were also classified as conduit- or diffuse-type springs according to their response to rainfall (White, 1969). Conduit-type springs are those whose discharge responds rapidly to rainfall events. During periods of heavy precipitation, the spring hydrograph resembles the flood peak of a

Table 4. Classification of inventoried springs according to Meinzer scale and response to rainfall
[—; not applicable]

Spring name and number (as shown in table 1 and figure 1)	[1]Spring order according to Meinzer (1923)	Spring type according to response to rainfall; Conduit (C) or Diffuse (D)	Spring name and number	Spring order	Spring type according to response to rainfall; Conduit (C) or Diffuse (D)
Maguayo (1)	4	C	Aserrado (35)	8	C
Mackovic (2)	4	D	Público (36)	6	C
La Poza (3)	8	C	Rivera #2 (37)	6	C
Don Vicente Morales (4)	8	C	Pozo del Muerto (38)	6	C
Ojo de Agua at Vega Baja (5)	3	D	Romero #1 (39)	6	C
Ojo de Agua at Morovis (6)	5	C	Méndez #1 (40)	6	C
Sonadora (7)	4	C	Romero #2 (41)	6	C
Aguas Frías (8)	3	C	Negrón (42)	8	C
Mamey (9)	3	D	Márquez (43)	6	C
Ojo de Guillo (10)	4	C	River Bank (44)	6	C
Zanja Fría (11)	3	D	Cortez (45)	5	C
La Pileta (12)	8	C	Bonilla (46)	6	C
La Punta (13)	5	C	Ojo Claro (47)	3	D
Cascada (14)	8	C	Martínez (48)	6	C
Opiola (15)	3	C	La Cántara (49)	8	C
Los Chorros (16)	3	C	Zumbadora (50)	6	C
Sumidero (17)	8	C	Malabi (51)	6	D
San Pedro (18)	3	C	Lago (52)	5	C
Marrero #1 (19)	5	C	Muñiz (53)	7	C
Marrero #2 (20)	5	C	Charcas (54)	5	C
Bambú #2 (21)	8	C	Medina (55)	5	C
Bambú #1 (22)	5	C	Río #2 (56)	5	C
Río Tanamá Dam (23)	5	—	Salto Collazo (57)	8	C
PVC (24)	8	C	Máximo (58)	3	C
Odilio Jiménez (25)	8	C	Soto Quintín (59)	8	C
San Rafael (26)	3	C	Municipio (60)	6	C
Cambijas (27)	7	D	Velázquez (61)	7	C
Avispa (28)	6	C	Ferrer (62)	6	C
Luis Pérez #2 (29)	6	C	La Salle (63)	6	C
Luis Pérez #1 (30)	6	C	Salas (64)	6	C
Ruiz (31)	8	C	Victoria (65)	5	C
Eligio Rosado (32)	7	C	Méndez (66)	5	C
Basilio (33)	5	C	Ojo de Agua in Aguadilla (67)	7	D
Sonadora (34)	7	C	Alers (68)	7	D

[1] Classification of springs according to base flow.

Magnitude	Base flow discharge
First	100 ft^3/s or more
Second	10 to 100 ft^3/s
Third	1.0 to 10 ft^3/s
Fourth	0.22 to 1.0 ft^3/s
Fifth	0.022 to 0.22 ft^3/s
Sixth	0.0022 to 0.022 ft^3/s
Seventh	0.0005 to 0.002 ft^3/s
Eighth	Few drops per second

surface stream. The conduit-type springs are fed by a well-defined and integrated system of enlarged conduits which behave as a system of pipes. Conduit-type springs also undergo significant and rapid changes in physical and chemical properties in response to rainfall. On the other hand, the diffuse-type springs are those whose discharge, chemical, and physical properties either do not change or vary only slightly in response to rainfall events. In general, the diffuse springs exhibit the same seasonal trends in flow, chemical, and physical properties as the aquifers they drain. These springs are fed by water moving along primary pores, joints, and bedding planes that have been slightly enlarged by solution.

Both perennial and ephemeral springs exist in the north coast limestone belt. The perennial springs discharge from both the upper aquifer and unconfined areas of the lower aquifer. The discharge area of many perennial springs also includes conduits in the unsaturated zone above the water table surface that only flow during periods of heavy rain or higher water tables. These perennial springs flow even during periods of low rainfall such as the one that occurred during this investigation. On the other hand, the ephemeral springs are either poorly connected or are not connected to the saturated zone, and discharge mostly from conduits in the unsaturated zone. The duration of flow in these springs depends both on the frequency and intensity of rainfall in their catchment areas and the storage capacity of the conduits in the unsaturated zone. Almost all the ephemeral springs included in this investigation dried up or were reduced to a mere trickle during the period of deficient rainfall already mentioned.

Preliminary estimates of total springflow in the north coast limestone aquifer system are about 20 Mgal/d (F. Gómez-Gómez, USGS, written commun., 1991). In these estimates, a separation into perennial and ephemeral springflow is not explicit. Only the "base flow" component of springflow from perennial springs is considered part of the hydrologic budget of the north coast limestone aquifer system. This base flow component represents the regional aquifer flow. Springflow from the ephemeral springs and high-flow components of perennial springs result from transient changes in local hydrologic conditions as a result of runoff-producing rainfall events and, consequently, do not represent regional ground-water flow. The ephemeral springflow consists of water that after infiltration into the subsurface migrates through the unsaturated zone into nearby discharge outlets, providing no significant recharge to the regional aquifer system. The interaction of this influx of water with the saturated zone is minimal to none.

The base flow at perennial and ephemeral springs during most of the study period was below normal because of the rainfall deficient months. Data collected from continuous recording devices installed at some springs, as well as discrete discharge measurements at other springs, reveal that springflow in the north coast limestone aquifer system exhibits both a seasonal variation and a short-term increase in discharge directly related to rainfall events. Seasonal variations in springflow tend to follow the seasonal variations in recharge to the upper aquifer which in turn reflect the annual variations in rainfall. Seasonal variations with minor responses to short-term increases in rainfall occur at perennial springs such as Ojo de Agua spring at Vega Baja (5) and Zanja Fría spring at Arecibo (11). This also appears to be true at Ojo Claro spring in Camuy (47), Mamey spring in Manatí (9), and Mackovic spring in Vega Alta (2), based on limited discharge data collected at these springs. All of these springs are referred to as diffuse-type springs.

Springs such as Maguayo (1), Ojo de Guillo (10), San Pedro (18), Los Chorros (16), and Ojo de Agua in Aguadilla (67), along with other springs exhibit a strong short-term response to rainfall superimposed on a broader seasonal response and are known as conduit-flow springs (table 4). A seasonal fluctuation could also be present in ephemeral springs (magnitude eight) when there is sufficient and continuous, although variable, rainfall in their catchment areas to maintain the water level above the discharge outlet. The non-perennial character of these springs will only become evident during extended periods of deficient rainfall, as was the case during part of this study, when most of the ephemeral springs, including the Aserradero (35) and Márquez (43) springs, ceased flowing (field inspections and oral commun. by local residents, 1992–95).

The Ojo de Agua spring in Vega Baja (5) is a typical diffuse-flow spring. The flow at this spring, determined from discrete discharge measurements, ranged from 1.4 to 5.9 ft^3/s (fig. 4; table 5a). The flow at this spring exhibited both a seasonal trend and a long-term trend probably resulting from the rainfall deficiency that occurred during the study period. During this extended dry period (that included most of 1994 and part of 1995), the seasonal trends were much less pronounced than during the study period of Guzmán-Ríos (1988). An immediate response to rainfall events was not observed at Ojo de Agua spring (5) which reflects the great capacity of the aquifer feeding this spring to attenuate high recharge events within its ground-water flow capture zone (Obarti-Segrera, 1987). Because of this attenuation, or "filter capacity," the flow variation at this spring generally follows the seasonal rainfall pattern and reflects the variation in the diffuse flow of that part of the upper aquifer it drains.

The San Pedro spring in Arecibo (18) and Ojo de Guillo spring in Manatí (10) are typical conduit-flow springs and are representative of springs draining aquifer areas which offer little attenuation to rainfall-runoff influx. The daily mean flow (discharge) at San Pedro spring (18), as measured by a continuous recording device, ranged from 3 to 61 ft^3/s (fig. 5; table 5b). The daily mean flow discharges at Ojo de Guillo spring (10), which was also equipped with a continuous recording device, ranged from 0.9 to 30 ft^3/s (fig. 6; table 5c). Flow at these two springs clearly demonstrated a strong and immediate response to rainfall, superimposed on the longer and more subdued seasonal trend that reflects diffuse ground-water flow. The conduit flow, manifested by short-term flow peaks and subsequent recessions, is considered to reflect locally induced and transient flow conditions that are separated from the regional and long-term ground-water flow system.

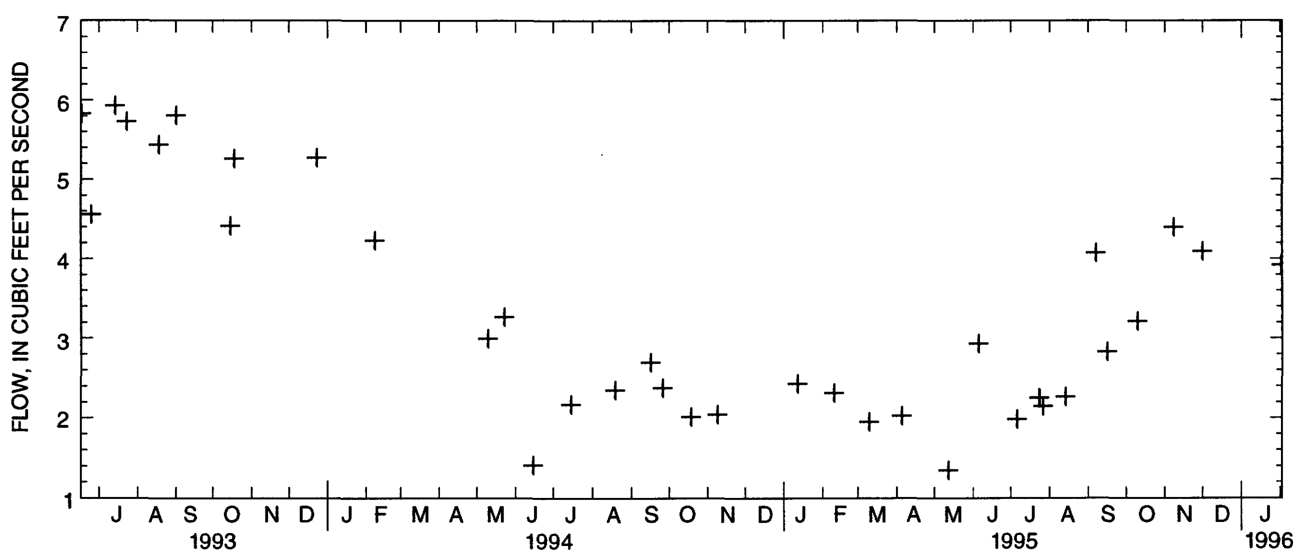


Figure 4. Temporal variation in discharge at Ojo de Agua spring in Vega Baja, Puerto Rico.

Table 5a. Specific conductance, temperature, pH, and instantaneous discharge at Ojo de Agua spring in Vega Baja, Puerto Rico

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; —, data not available]

Date	Specific conductance (μS/cm)	Temperature (degrees Celsius)	pH	Instantaneous discharge (cubic feet per second)
June 17, 1993	—	25.0	—	2.7
June 25, 1993	—	26.0	—	4.6
July 14, 1993	990	26.0	—	5.9
July 20, 1993	1,000	25.5	—	—
July 23, 1993	950	25.0	—	5.7
August 19, 1993	900	25.0	—	—
September 1, 1993	—	25.0	—	5.8
October 18, 1993	—	—	—	5.3
November 15, 1993	920	25.5	—	—
January 28, 1994	980	26.0	—	—
February 8, 1994	—	—	—	4.3
March 2, 1994	920	26.0	—	—
May 10, 1994	—	—	7.2	—
June 15, 1994	950	26.0	—	1.4
June 16, 1994	950	26.0	—	—
July 15, 1994	900	27.0	—	2.1
August 19, 1994	1,000	26.0	8.5	2.4
September 16, 1994	1,000	20.6	—	2.7
September 26, 1994	1,000	20.6	7.8	2.4
October 19, 1994	1,000	25.0	—	—
November 9, 1994	—	—	—	2.1
January 3, 1995	910	25.2	—	—
January 12, 1995	950	26.0	6.8	2.4
February 10, 1995	1,000	26.5	—	2.3
March 10, 1995	950	25.0	—	2.0
April 5, 1995	—	—	—	2.0
May 12, 1995	990	25.9	—	1.4
May 16, 1995	850	25.5	7.0	—
June 5, 1995	990	25.6	—	2.9
July 3, 1995	930	26.9	—	—
July 6, 1995	930	27.5	6.9	2.0
July 24, 1995	900	26.8	—	1.3
July 28, 1995	890	25.5	—	—
August 10, 1995	890	27.1	6.8	—
August 14, 1995	950	27.3	7.3	2.3
August 24, 1995	940	25.4	7.0	—
September 7, 1995	930	25.5	6.9	—
September 11, 1995	940	25.0	6.8	—
September 16, 1995	875	26.0	6.5	2.8
October 10, 1995	861	25.5	—	3.2
February 6, 1996	920	25.3	6.5	—

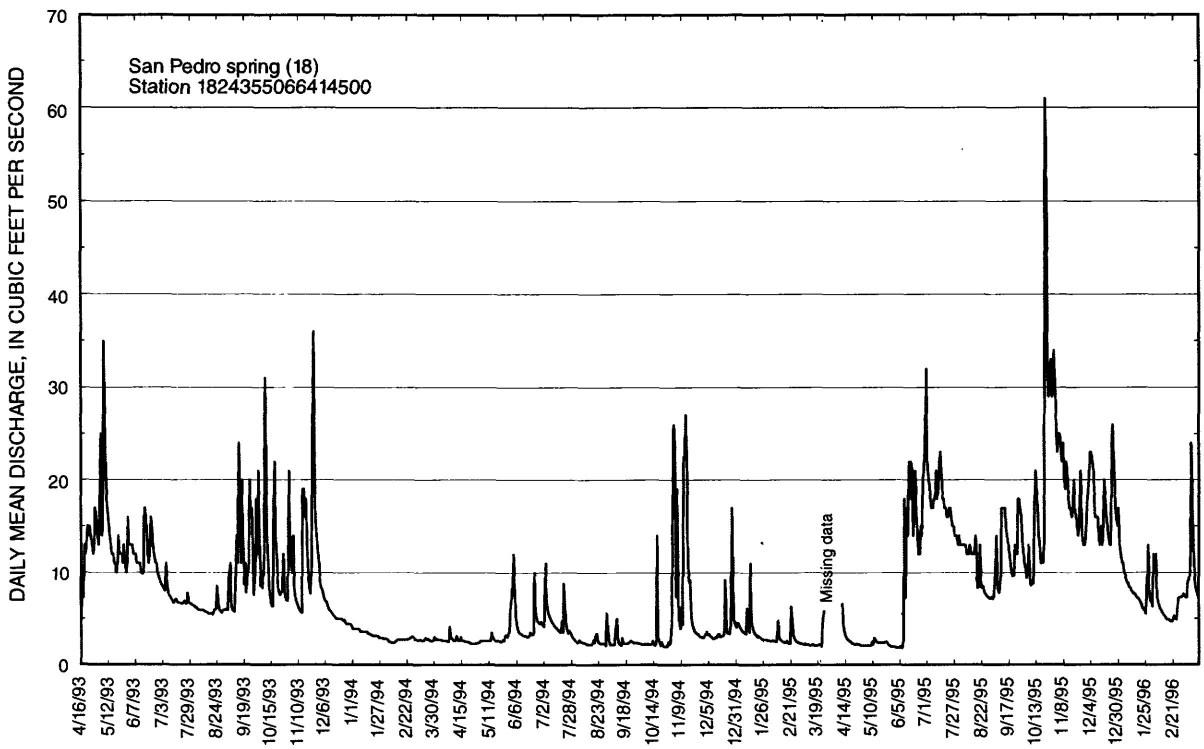


Figure 5. Daily mean discharge at the San Pedro spring from April 16, 1993, to January 23, 1996.

Table 5b. Specific conductance, temperature, pH, and instantaneous discharge at San Pedro spring in Arecibo, Puerto Rico

[µs/cm, microsiemens per centimeter; —, data not available]

Date	Specific conductance (µS/cm)	Temperature (degrees Celsius)	pH	Instantaneous discharge (cubic feet per second)
June 25, 1993	—	25.0	—	9.8
July 7, 1993	492	24.6	—	7.0
July 20, 1993	490	24.0	—	—
July 22, 1993	500	24.5	—	—
July 23, 1993	495	24.3	—	8.0
August 10, 1993	494	24.6	—	—
August 17, 1993	498	24.0	—	—
September 1, 1993	540	25.0	—	—
October 5, 1993	—	25.5	—	10.0
October 19, 1993	488	24.5	—	16.0
November 15, 1993	520	24.5	—	—
November 19, 1993	502	24.5	—	—
December 1, 1993	490	24.1	—	—
December 7, 1993	485	24.5	—	—
December 8, 1993	495	—	—	—

Table 5b. Specific conductance, temperature, pH, and instantaneous discharge at San Pedro spring in Arecibo, Puerto Rico—Continued

Date	Specific conductance (µS/cm)	Temperature (degrees Celsius)	pH	Instantaneous discharge (cubic feet per second)
December 13, 1993	487	24.6	—	4.7
December 14, 1993	489	24.1	—	—
December 15, 1993	492	24.1	—	—
December 21, 1993	489	25.1	—	—
February 8, 1994	—	—	—	2.7
May 23, 1994	—	24.0	—	3.5
June 7, 1994	—	—	—	5.5
June 16, 1994	465	25.0	—	15.1
July 14, 1994	460	24.0	7.7	3.0
August 3, 1994	480	25.0	—	2.5
September 1, 1994	450	24.0	7.0	2.6
September 19, 1994	500	24.0	7.7	2.2
October 18, 1994	440	24.0	—	5.2
October 19, 1994	440	—	—	—
December 13, 1994	—	26.5	7.1	3.7
January 18, 1995	—	—	—	—
January 23, 1995	500	25.0	7.0	—
February 3, 1995	500	24.0	7.0	2.3
February 10, 1995	500	24.0	7.0	—
March 7, 1995	470	24.0	6.9	—
April 5, 1995	—	—	—	—
May 16, 1995	410	24.5	7.1	—
May 17, 1995	399	—	—	24.9
May 18, 1995	443	—	7.0	13.7
May 19, 1995	484	24.0	—	—
May 23, 1995	450	24.5	7.0	—
May 24, 1995	470	24.5	7.0	—
May 25, 1995	495	24.1	6.7	—
June 8, 1995	398	24.5	6.7	—
July 25, 1995	472	26.1	7.1	7.2
August 11, 1995	370	27.0	6.8	15.6
August 14, 1995	472	26.5	7.2	10.0
August 18, 1995	450	24.5	—	—
September 11, 1995	495	25.0	—	—
September 16, 1995	369	—	—	—
September 17, 1995	382	—	—	—
September 18, 1995	390	26.8	7.1	—
September 21, 1995	321	26.0	—	24.8
October 11, 1995	359	26.5	6.9	15.9
February 6, 1996	523	23.7	—	—

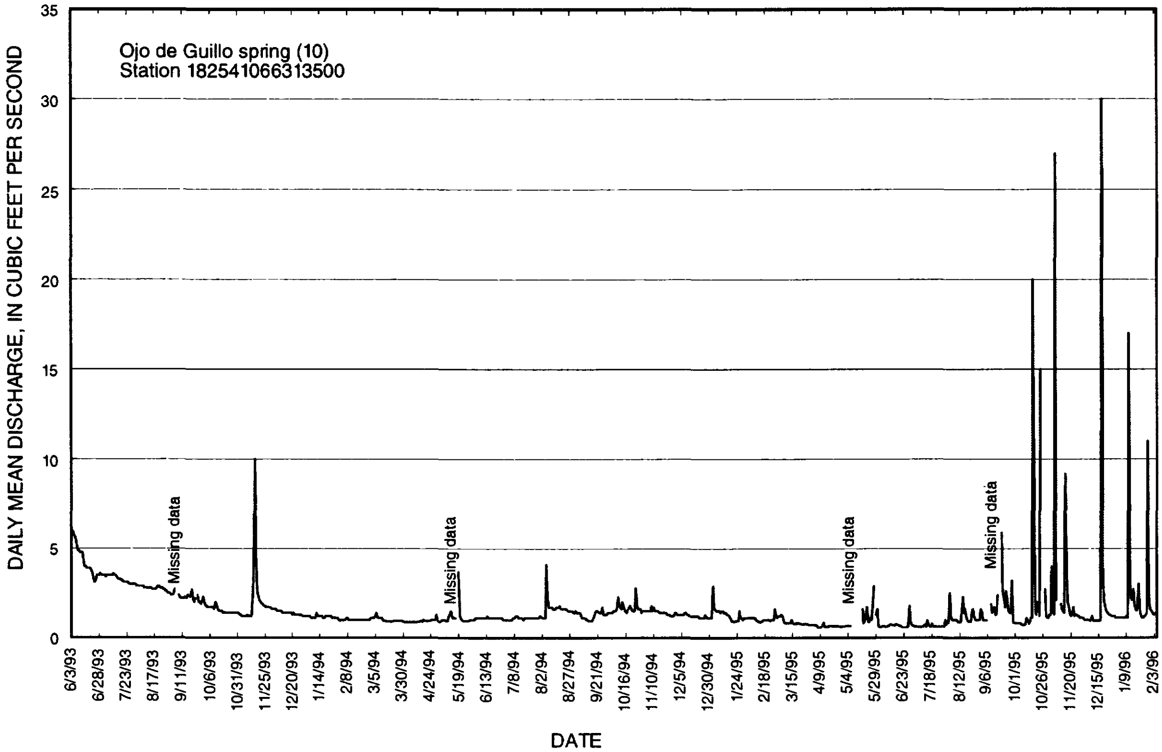


Figure 6. Daily mean discharge at the Ojo de Guillo spring from June 3, 1993, to January 27, 1996.

Conduit flow results from rainfall-runoff infiltration and the subsequent partial or complete infilling of the conduits feeding the springs. The term conduits refers to both a single conduit or a network of conduits with a varying degree of integration. When a large pulse of rainfall-runoff water is in "storage" in the conduits, a hydraulic mound may form that acts as a barrier minimizing the diffuse flow of ground water from the aquifer. As soon as the head differential between the aquifer and the rainfall-runoff water held in the conduit network is reduced to a certain level the diffuse flow increasingly interacts with the conduit flow until it becomes the sole flow component at the spring. Giusti (1978) described flows caused by infiltration of heavy rainfall-runoff events as shallow and transient flows and noted that they behave similarly to surface-runoff within a stream channel and do not constitute effective recharge to the aquifer. The transient nature of conduit flow can be better observed in hydrographs for the San Pedro (18) and Ojo de Guillo (10) springs, where two recession slopes are seen (figs. 7, 8). The recession slope that follows the flow peak predominantly represents the actual draining of rainfall runoff generated by an intense rainstorm event from the conduits of both springs. The later part of the hydrographs have slopes which are much less steep and are clearly separated from the early part of the hydrographs, particularly at San Pedro spring (18), and represent increasing drainage from the aquifer (regional ground-water diffuse flow). The Maguayo spring in Dorado (1) is also of the conduit-type. The flow at this spring, determined from discrete discharge measurements, ranged from 0.06 to 1.14 ft^3/s (table 5d). In general, the conduit networks of these three springs seem to route the water inputs to nearby streams during high rainfall conditions and to drain the upper aquifer during low-water conditions. Discharge measurements at the Bambú #1 spring in Arecibo (22) ranged from 0.03 to 0.07 ft^3/s (table 5e) and indicate a behavior resembling that of a conduit-type spring. Springflow data collected during this study also indicate that general flow conditions have not changed at the Ojo de Guillo (10), Ojo de Agua in Vega Baja (5), and San Pedro (18) springs since they were last surveyed in the early 1980's (Guzmán-Ríos, 1988).

Table 5c. Specific conductance, temperature, pH, and instantaneous discharge at Ojo de Guillo spring in Manatí, Puerto Rico

[µS/cm, microsiemens per centimeter; —, data not available]

Date	Specific conductance (µS/cm)	Temperature (degrees Celsius)	pH	Instantaneous discharge (cubic feet per second)
June 25, 1993	—	24.5	—	3.45
July 14, 1993	—	—	—	3.37
July 20, 1993	520	25.2	—	—
July 23, 1993	520	24.1	—	—
August 10, 1993	581	25.0	—	—
August 19, 1993	490	25.2	—	—
August 27, 1993	540	24.5	—	—
September 1, 1993	530	24.5	—	2.48
September 22, 1993	520	25.5	—	—
October 19, 1993	541	24.9	—	—
November 15, 1993	520	24.5	—	—
December 1, 1993	526	24.3	—	—
December 7, 1993	550	24.6	—	—
December 13, 1993	549	24.9	—	—
December 14, 1993	548	24.7	—	—
December 15, 1993	570	25.2	—	—
February 8, 1994	—	—	—	1.09
March 16, 1994	540	24.5	—	—
May 19, 1994	400	24.0	—	—
June 7, 1994	—	—	—	1.10
June 16, 1994	500	25.0	—	—
July 15, 1994	500	24.0	—	0.98
August 9, 1994	550	24.0	—	1.63
September 16, 1994	—	24.0	—	0.94
September 19, 1994	550	24.0	—	1.50
September 21, 1994	485	24.0	7.6	1.42
October 18, 1994	490	24.0	—	1.52
October 19, 1994	490	—	—	—
January 18, 1995	550	26.0	7.0	1.03
February 10, 1995	550	24.0	—	0.95
March 7, 1995	550	24.0	6.9	1.08
April 6, 1995	—	—	—	0.73
May 17, 1995	462	—	—	0.98
May 19, 1995	—	—	—	0.74
June 29, 1995	540	27.0	7.2	0.84
July 24, 1995	550	26.1	—	0.62
August 10, 1995	540	27.2	7.0	0.83
September 19, 1995	382	26.5	7.0	3.47
October 10, 1995	463	25.2	6.7	0.96
February 6, 1995	517	24.3	—	—

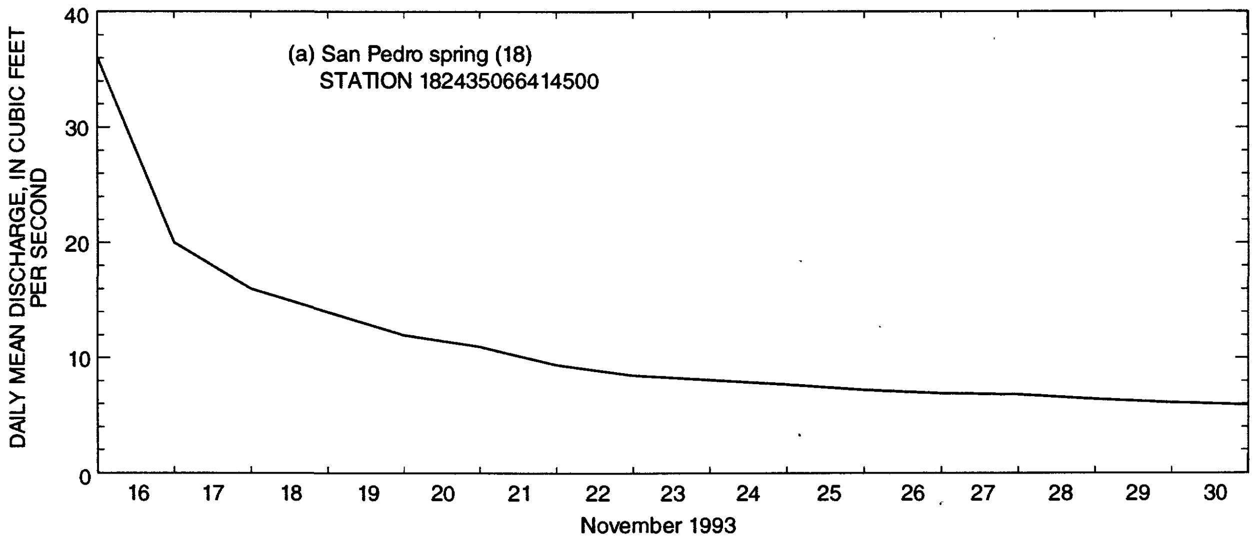


Figure 7. Daily mean discharge at San Pedro spring from November 15 to December 1, 1993.

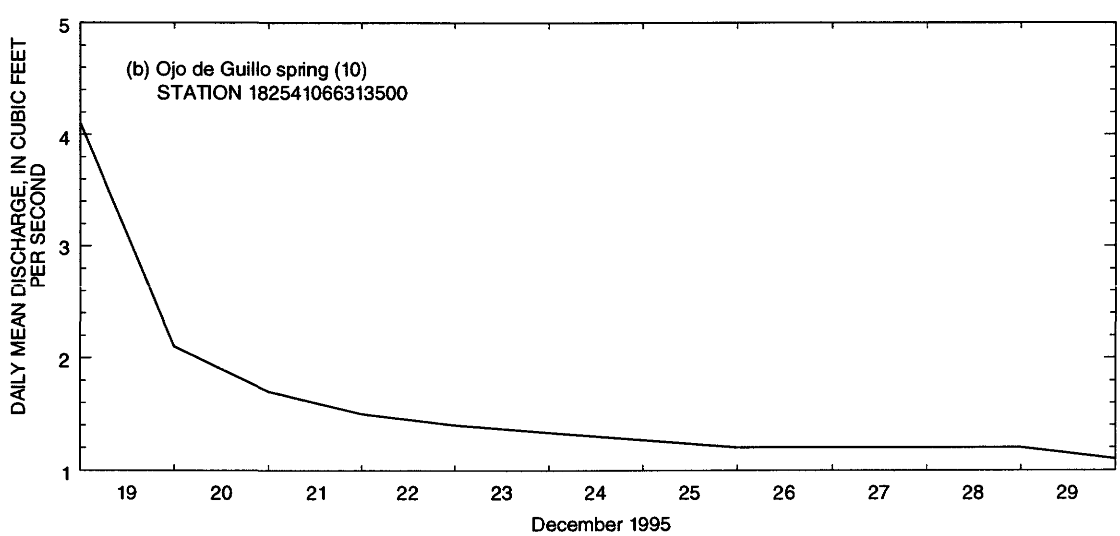


Figure 8. Daily mean discharge at Ojo de Guillo spring from November 18 to December 30, 1995.

Table 5d. Specific conductance, temperature, pH, and instantaneous discharge at Maguayo spring in Dorado, Puerto Rico

[μS/cm. microsiemens per centimeter; —, data not available]

Date	Specific conductance (μS/cm)	Temperature (degrees Celsius)	pH	Instantaneous discharge (cubic feet per second)
March 2, 1994	590	25	—	—
May 17, 1994	550	26	—	0.55
June 13, 1994	330	25	—	0.27
June 16, 1994	600	25	—	—
July 19, 1994	600	25	—	—
August 16, 1994	650	—	—	0.47
August 27, 1994	600	26	—	—
September 27, 1994	600	—	—	0.60
October 24, 1994	450	—	7.3	0.81
January 31, 199	600	28	7.4	0.65
February 27, 1995	350	24	7.4	1.14
February 28, 1995	450	24	7.3	—
April 6, 1995	—	—	—	0.06
April 13, 1995	—	—	—	0.14
June 14, 1995	600	26	7.0	0.17
July 21, 1995	630	26	6.8	0.18

Table 5e. Specific conductance, temperature, pH, and instantaneous discharge at other springs in the north coast of Puerto Rico included in this study

[μS/cm, microsiemens per centimeter; <, less than; —, data not available. Spring name and location shown in table 1 and figure 1, respectively.]

Spring name and identification number	Date	Specific conductance (μS/cm)	Temperature (degrees Celsius)	pH	Instantaneous discharge (cubic feet per second)
Mackovic (2)	09-21-94	1,050	27.0	—	1.00
Mackovic (2)	10-31-94	1,000	27.0	—	1.41
La Poza (3)	10-27-94	4,000	27.0	7.4	<0.01
Mamey (9)	01-20-96	2,000	25.5	—	[1]0.50
Zanja Fría (11)	03-02-94	1,190	26.0	—	2.20
La Pileta (12)	06-02-94	370	25.0	—	—
Opiola (15)	12-14-95	346	—	—	4.00
Sumidero (17)	08-11-94	360	25.0	7.5	<0.01
Sumidero (17)	04-04-95	380	25.5	—	<0.01
Bambú #2 (21)	07-07-94	430	23.0	7.5	0.01
Bambú #2 (21)	07-07-95	445	24.1	8.1	0.01
Bambú #1 (22)	08-11-94	450	—	—	0.04
Bambú #1 (22)	08-31-95	451	25.5	7.5	0.03
Bambú #1 (22)	09-21-95	426	24.0	—	0.07
Bambú #1 (22)	02-06-96	478	22.8	7.1	<0.05
PVC (24)	11-01-94	450	25.0	7.9	<0.01
Odilio Jiménez (25)	11-01-94	700	24.0	7.8	—

Table 5e. Specific conductance, temperature, pH, and instantaneous discharge at other springs in the north coast of Puerto Rico included in this study—Continued

Spring name and identification number	Date	Specific conductance (µS/cm)	Temperature (degrees Celsius)	pH	Instantaneous discharge (cubic feet per second)
San Rafael (26)	11-02-94	395	27.0	7.7	0.02
Cambijas (27)	11-01-94	650	—	7.5	—
Avispa (28)	06-02-94	430	24.0	—	<0.01
Avispa (28)	11-01-94	700	27.0	7.8	<0.01
Luis Pérez #2 (29)	11-02-94	460	—	8.0	—
Luis Pérez #1 (30)	11-01-94	390	—	8.0	0.03
Ruiz (31)	03-31-94	394	25.0	—	0.01
Eligio Rosado (32)	11-02-94	500	24.0	7.7	0.02
Basilio (33)	03-31-94	740	25.0	—	<0.01
Basilio (33)	11-14-94	485	26.0	7.9	<0.01
Aserradero (35)	03-31-94	380	24.0	—	<0.01
Aserradero (35)	11-15-94	450	27.0	7.8	<0.01
Aserradero (35)	04-04-95	380	25.5	—	<0.01
Público (36)	03-31-94	318	24.5	—	<0.01
Público (36)	11-17-94	350	24.0	8.0	<0.01
Rivera #2 (37)	03-31-94	560	27.0	—	<0.01
Rivera #2 (37)	11-15-94	505	26.0	8.1	<0.01
Pozo del Muerto (38)	04-04-94	510	26.0	—	0.01
Romero #1 (39)	03-29-94	690	27.0	—	0.01
Romero #1 (39)	11-16-94	500	27.0	7.5	0.02
Romero #2 (41)	11-17-94	600	25.0	7.9	0.02
Romero #2 (41)	03-29-94	550	28.0	—	0.01
Negrón (42)	11-17-94	650	27.0	7.6	<0.01
Márquez (43)	03-31-94	690	23.5	—	<0.01
Márquez (43)	04-04-95	385	—	—	—
River Bank (44)	04-05-94	320	26.5	—	0.01
River Bank (44)	11-18-94	550	25.0	8.1	0.02
Cortez (45)	03-31-94	700	24.5	—	<0.01
Bonilla (46)	03-29-94	342	27.5	—	0.03
Ojo Claro (47)	04-07-94	2,050	26.5	7.5	0.30
Ojo Claro (47)	04-05-95	2,740	—	7.0	0.70
Martínez (48)	03-29-94	432	24.6	—	0.01
La Cántara (49)	03-28-94	540	28.5	—	<0.01
Zumbadora (50)	03-22-94	502	24.5	—	0.01
Zumbadora (50)	11-08-94	490	26.0	7.8	<0.01
Zumbadora (50)	04-05-95	460	—	7.9	0.01
Malabi (51)	03-22-94	345	22.5	—	0.01
Malabi (51)	11-08-94	400	24.0	7.5	<0.01
Lago (52)	11-08-94	550	26.0	7.5	0.03

Table 5e. Specific conductance, temperature, pH, and instantaneous discharge at other springs in the north coast of Puerto Rico included in this study—Continued

Spring name and identification number	Date	Specific conductance (µS/cm)	Temperature (degrees Celsius)	pH	Instantaneous discharge (cubic feet per second)
Muñiz (53)	03-22-94	315	23.5	—	<0.01
Muñiz (53)	11-08-94	400	25.0	7.6	<0.01
Muñiz (53)	04-21-95	—	—	8.2	—
Charcas (54)	03-18-94	463	25.5	—	0.02
Charcas (54)	11-08-94	500	27.0	—	<0.01
Medina (55)	03-18-94	416	24.5	—	<0.01
Medina (55)	11-08-94	450	26.0	8.0	<0.01
Medina (55)	04-21-95	425	25.0	—	<0.04
Río #2 (56)	03-18-94	289	24.0	—	0.01
Río #2 (56)	04-21-95	293	—	8.2	0.07
Salto Collazo (57)	04-05-95	405	—	—	0.03
Máximo (58)	03-15-94	680	26.5	—	0.10
Máximo (58)	11-07-94	700	25.0	6.9	<0.01
Soto Quintín (59)	03-15-94	500	24.0	—	0.20
Soto Quintín (59)	04-20-95	—	—	8.2	0.80
Municipio (60)	03-15-94	560	26.0	—	<0.01
Municipio (60)	11-07-94	490	25.0	7.4	0.30
Municipio (60)	04-20-95	—	—	—	<0.01
Velázquez (61)	03-10-94	460	24.5	—	0.10
Ferrer (62)	03-10-94	730	25.5	—	0.10
Ferrer (62)	10-26-94	700	27.0	6.6	<0.01
La Salle (63)	03-10-94	540	25.5	—	0.01
La Salle (63)	10-26-94	780	27.2	6.8	0.03
La Salle (63)	04-04-95	385	—	—	0.01
Salas (64)	03-10-94	680	23.5	—	<0.01
Salas (64)	10-26-94	800	24.5	7.0	<0.01
Victoria (65)	03-03-94	520	25.0	—	<0.01
Méndez (66)	03-29-94	520	26.0	—	0.01
Ojo de Agua in Aguadilla (67)	03-03-94	520	25.5	6.9	0.50
Ojo de agua in Aguadilla (67)	10-25-94	500	—	7.8	—
Ojo de agua in Aguadilla (67)	04-04-95	480	25.0	—	1.3
Alers (68)	03-08-94	720	26.0	—	0.01
Alers (68)	10-25-94	700	27.0	7.4	<0.01
Alers (68)	04-20-95	—	—	7.4	<0.01

[1] Estimated

Temperature, Specific Conductance, and pH

Temperature, specific conductance, and pH were measured at most springs in the study area twice a year, during the wet and dry seasons (tables 5a, 5e). They were measured more frequently at a group of springs in the area between Dorado and Arecibo where more detailed monitoring was done. These physical properties provide an indication of the potential of springs as local water-supply sources.

The temperature variations recorded at most springs were minor and in general follow the seasonal changes in the ambient air temperature. Spring water temperature ranged from 22.5 °C at Los Chorros spring (16) to 28 °C at Zanja Fría spring (11) during the study. In some springs, particularly the conduit-type springs, increases of one to two degrees of very short duration (less than a day after cessation of an intense rainfall event) are associated with the first "slugs" of water being discharged after a significant rainfall. This was observed at Maguayo spring (1) where the temperature ranged from 24 to 26.1 °C in conjunction with a rainfall event that occurred during February 27–28, 1995. In other springs with rapid response to rainfall, such as Ojo de Guillo (10), San Pedro (18), and to a lesser extent Los Chorros (16), these fluctuations were not observed or were negligible and within the margin error of the temperature measurements. Either the temperature fluctuations associated with the recently recharged "pulses" of water did not occur at these springs because recharge water temperature was similar to ground-water temperature, or the difference was dissipated during the transit from the entrance to the discharge point.

The specific conductance of water from the springs studied ranged from 289 µS/cm at the Río #2 spring in Quebradillas (56) to 4,000 µS/cm at the La Poza spring in Vega Baja (3) (tables 3a–3e). A specific conductance of 2,500 µS/cm was measured on one occasion at the Ojo Claro spring in Camuy (47), but at the time of sampling the outlet of this spring was inundated by a high tide. Except where a connection is "suspected" between rivers and springs this range closely resembles that of the freshwater and transition zones of the upper aquifer (Román-Más and Ramos-Ginés, 1988). In general, the specific conductance of springs increases coastward as both the freshwater-saltwater transition zone and the saltwater zones of the upper aquifer become closer to the land surface as the fresh ground-water flow zone gradually thins out.

Seasonal changes in the specific conductance of the springs in the Dorado to Arecibo area, which were monitored more closely, were minor and presumably parallel those in the regional upper aquifer as shown by several USGS studies conducted in the north coast limestone upper aquifer (Guzmán-Otero, 1994). However, superimposed on these minor seasonal changes were short-term reductions in the specific conductance of some conduit-type springs associated with flow increases after large rainfall events. At Maguayo spring (1) the specific conductance changed from near "normal" values of 600 µS/cm to as low as 330 µS/cm in June 13, 1994, and 350 µS/cm in February 27, 1995, in response to large rainfall events (table 5d). Reductions in specific conductance due to increases in flow were also measured at Ojo de Guillo (10) and San Pedro (18) springs.

Sometimes an increase in specific conductance was observed before a reduction. This situation occurred at San Pedro spring (18) after a significant dry period, and probably resulted from the removal of slow moving or stagnant water in the conduit(s). This phenomenon has been reported from springs in other karst areas (Gruver and Krothe, 1991) and probably also occurs at other conduit-type springs in the northern karst belt of Puerto Rico.

The historical data on specific conductance of the springs on the north coast of Puerto Rico are limited to that published by Giusti (1978) and Guzmán-Ríos (1988), and later compiled by Román-Más and Ramos-Ginés (1988). Comparison of the data collected for this study with that published by these authors indicates that, in general, long-term changes in specific conductance have been minimal. An exception to this has been Ojo de Agua spring in Vega Baja (5), where the specific conductance has increased from about 800 µS/cm in the 1970's (Giusti, 1978) to sustained values of 890 to 1000 µS/cm in 1994. A specific conductance of 177 µS/cm was measured at Ojo de Guillo spring (10) on March 18, 1959 (USGS, unpublished data) and March, 2, 1961 (Román-Más and Ramos-Ginés, 1988). This value is considerably lower than specific conductance values obtained more recently, which ranged from 510 µS/cm in 1981 to 550 µS/cm in 1994. The flow conditions under which these measurements of specific conductance were made are not exactly known although a discharge of 2.5 ft^3/s was estimated for March 18, 1959 (USGS, unpublished data). No discharge measurement is available for March 2, 1961. This first specific conductance value is typical of recent surface runoff, which in the case of Ojo de Guillo spring (10), could result from the inundation of its outlet every time the stage of the Río Grande de Manatí rises higher than 15 ft or from rapid rainfall- runoff infiltration into the conduit network and discharge at the spring. However, the precipitation records of the NWS revealed that a rainfall deficiency occurred during February and March of both 1959 and 1961 (NOAA, 1958–59 and NOAA, 1960–61) in north-central Puerto Rico and possibly both the Ojo de Guillo spring (10) and the Río Grande de Manatí were at base flow conditions. Consequently the value of 177 µS/cm could be representative of the base flow at Ojo de Guillo spring (10) during 1959 through 1961. The significant increase in specific conductance at Ojo de Guillo spring (10) may be explained by the recent increase in ground-water withdrawals to the south of the spring to satisfy the needs of the rapidly growing industrial sector in the Manatí and Barceloneta area. Increased ground-water withdrawals may be causing upward migration of water with higher specific conductance.

The pH of water from the springs studied ranged from 6.9 to 7.8 (almost neutral to moderately alkaline). In conduit-type springs pH also seems to also be dependent on flow. At these springs, the pH was normally higher during high flows, and tended to approach a value of 6.9. This situation was observed at San Pedro (18) and Ojo de Guillo (10) springs and to a lesser extent at Los Chorros spring (16). At the Ojo de Agua spring in Vega Baja (5), which is typical of a diffuse-type spring on the north coast, only minor fluctuations in pH were measured. The long ground-water travel time predominant in diffuse flow, contributes in maintaining a relatively stable pH. Similar small pH value fluctuations were obtained in Mamey (9), Mackovic (2), and Zanja Fría (11) springs (table 5e). These springs are located relatively near the northernmost limit of the upper aquifer, in a hydrogeologic setting similar to that of Ojo de Agua spring in Vega Baja (5).

Chemical Characteristics

Calcium and sodium were the main cations in water from the springs sampled during this study. Concentrations of calcium ranged from 51 mg/L at the Marrero 2 spring to 110 mg/L at the Ojo de Agua spring in Vega Baja (5). Sodium concentrations ranged from 4.5 mg/L at Luis Pérez #1 spring (30) to 160 mg/L at the Zanja Fría spring (11). The predominant anions in water from the springs were bicarbonate and chloride. Bicarbonate concentrations ranged from 170 mg/L at the Marrero #2 spring (19) to 390 mg/L at the Ojo de Agua and Zanja Fría (11) springs. Chloride concentrations ranged from 8.4 mg/L at the Luis Pérez #1 spring (30) to 280 mg/L at the Zanja Fría spring (11).

The main water type of the springs sampled was calcium-bicarbonate (fig. 9). Secondary water types were calcium-bicarbonate-chloride and sodium-bicarbonate-chloride. The predominant water type of the Maguayo (1), Ojo de Guillo (10), and San Pedro (18) springs appeared to be calcium-bicarbonate. The water type of the Mackovic spring (2) and the Ojo de Agua spring in Vega Baja (5) was calcium-bicarbonate-chloride, whereas the water type of the Zanja Fría spring (11) was sodium-carbonate-chloride. The water type in the springs seemed to vary from a calcium-bicarbonate type in the karst interior, near the recharge areas, to a predominant sodium-bicarbonate-chloride type in the coastal areas. This might indicate a mixing of fresh ground water with seawater which is a sodium-chloride type. This same general trend is observed in the chemical character of the ground water in wells tapping the upper aquifer (Giusti, 1978).

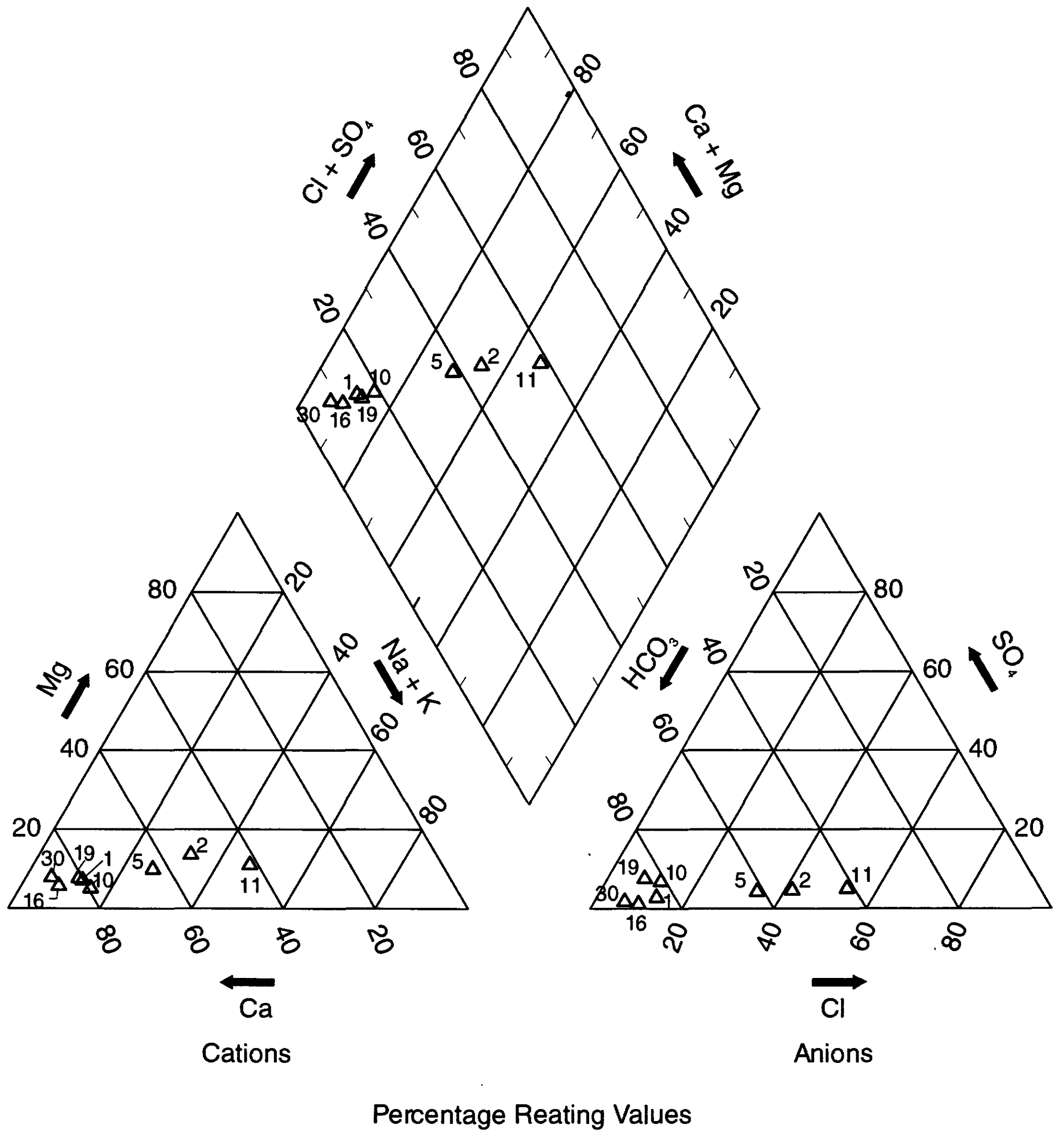


Figure 9. Trilinear diagram showing the major ionic constituents in water from selected springs in the north coast limestone belt.

The historical data available on the chemical characteristics of the main springs in the north coast prior to this investigation are limited to that presented by Guzmán-Ríos (1988) and Giusti (1976), and later compiled and published by Román-Más and Ramos-Ginés (1988). A comparison of the water-quality data collected by Guzmán-Ríos (1988) and Giusti (1978) with that collected for this study indicates that the general chemical character of the main springs in the north coast has remained unchanged over the last 20 years. The main water types as well as the principal ions remain the same. The chloride concentration, a good indicator of possible salt-water intrusion, has remained fairly constant with measured values ranging from 80 to 130 mg/L (table 6). Concentrations of nitrogen ranged from 0.2 to 1.4 mg/L and of phosphorus from 0.01 to 0.61 mg/L (table 6).

Table 6. Physical, chemical, and bacteriological analyses of water samples from selected springs in the north coast limestone belt

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; 0.7 µm/Mf, micrometers per membrane filter; KF AGAR, culture media for fecal streptococcus bacteria; mg/L, milligrams per liter; µg/L micrograms per liter; K, non-ideal count; —, data not available; <, less than; * ,value taken from Guzmán-Ríos, 1988. Spring map numbers are shown in table 1 and figure 1.]

Spring map number	Date	Spring flow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	pH (standard units)	Coliform, fecal, 0.7 µm/Mf (cols/100mL)	Streptococci, Fecal KF AGAR (cols/100ml)	Hardness total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
1*	12-06-82	0.52	572	6.7	450	320	259	92	5.8	16
1*	08-05-83	0.77	585	7.0	660	510	275	93	5.6	15
1	01-27-94	0.3	620	7.1	1,900	410	—	—	—	—
1	05-23-94	0.55	614	6.9	700	<10	270	100	5.9	16
2	09-21-94	1.00	986	7.2	590	K-180	310	100	15	72
5*	11-30-82	0.63	860	6.8	41	58	367	110	9.5	48
5*	08-11-83	3.9	820	7.1	4	1	380	110	11	47
5	06-25-93	4.55	951	—	—	27	320	110	12	66
5	07-12-93	—	—	—	—	—	—	—	—	—
5	01-27-94	4.25	980	—	4	47	—	—	—	—
5	05-23-94	2.95	900	7.0	48	360	320	110	11	53
10*	11-30-82	1.6	525	6.8	51	4	257	93	2.9	12
10*	08-04-83	1.5	522	7.0	15	10	267	94	2.9	12
10	07-12-93	—	—	—	—	—	—	—	—	—
10	11-15-93	—	—	—	—	—	—	—	—	—
10	01-27-94	1.09	460	—	400	136	—	—	—	—
10	05-23-94	1.36	454	7.0	550	120	200	76	3.6	11
10	09-21-94	1.42	485	7.2	K-140	K-120	270	100	4.9	27
11*	12-08-82	10.0	1,390	7.2	—	40	399	95	19	160
11*	08-04-83	9.5	1,420	7.4	78	670	422	100	20	150
11	01-27-94	—	1,150	6.9	22	100	—	—	—	—
11	05-23-94	—	1,250	7.1	48	360	320	97	18	120
16	09-22-94	—	322	7.8	550	610	150	56	2.6	5.9
18*	12-01-82	16	430	7.0	380	130	200	72	4.8	5.8
18*	08-03-83	8.4	470	7.4	42	52	249	83	5.1	5.6
18	06-25-93	9.79	508	—	—	—	260	96	5.1	6.2
18	07-12-93	—	—	—	—	—	—	—	—	—
18	01-27-94	2.72	500	—	12	29	—	—	—	—
19	09-22-94	—	315	7.3	4,600	20,000	140	51	3.2	6.4
30	09-22-94	—	339	7.7	35,000	27,000	160	59	3.4	4.5

Table 6. Physical, chemical, and bacteriological analyses of water samples from selected springs in the north coast limestone belt—Continued

Spring map number	Date	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO_4)	Alkalinity, lab (mg/L as Ca CO_3)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, dissolved (mg/L)	Phosphorus, total (mg/L as P)	Nitrogen, ammonia + organic Total (mg/L as N)
1*	12-06-82	1.6	9.0	220	32	<0.1	7.8	312	—	—
1*	08-05-83	1.8	8.5	240	28	<0.1	7.5	303	—	—
1	01-27-94	—	—	—	—	—	—	—	—	—
1	05-23-94	2.3	11	266	27	<0.1	8.1	330	0.03	<0.2
2	09-21-94	2.5	22	254	140	<0.1	13	517	0.02	<0.2
5*	11-30-82	2.4	15	280	88	<0.1	9.0	437	—	—
5*	08-11-83	2.1	18	260	100	<0.1	9.3	455	—	—
5	06-25-93	2.9	26	—	130	<0.1	9.9	475	—	—
5	07-12-93	—	—	—	—	—	—	—	0.2	<0.2
5	01-27-94	—	—	—	—	—	—	—	0.02	<0.2
5	05-23-94	3.0	22	265	100	<0.1	9.9	—	—	—
10*	11-30-82	1.6	4.0	250	18	<0.1	6.4	468	0.03	<0.2
10*	08-04-83	0.9	4.8	230	19	<0.1	6.5	275	—	—
10	07-12-93	—	—	—	—	—	—	—	0.02	0.2
10	11-15-93	—	—	—	—	—	—	—	0.01	0.2
10	01-27-94	—	—	—	—	—	—	282	—	—
10	05-23-94	8	19	175	16	<0.1	7.5	—	0.02	0.2
10	09-21-94	1.6	14	244	94	<0.1	6.6	—	0.01	0.2
11*	12-08-82	4.9	41	240	280	<0.1	6.8	—	—	—
11*	08-04-83	5.1	38	240	280	<0.1	6.7	246	0.61	1.4
11	01-27-94	—	—	—	—	—	—	394	0.03	0.2
11	05-23-94	6.1	34	245	220	<0.1	6.9	755	—	—
16	09-22-94	0.4	3.1	141	9.9	<0.1	5.0	746	—	—
18*	12-01-82	11.5	9.0	200	8.8	<0.1	8.3	—	—	—
18*	08-03-83	1.0	7.7	210	10	<0.1	7.4	649	0.03	<0.2
18	06-25-93	2.2	11	—	10	<0.1	6.7	167	0.03	0.4
18	07-12-93	—	—	—	—	—	—	—	0.4	0.5
18	01-27-94	—	—	—	—	—	—	231	—	—
19	09-22-94	2.4	11	135	8.9	<0.1	10	247	—	—
30	09-22-94	0.3	4.3	164	8.4	<0.1	3.3	—	—	—

Bacteriological Characteristics

The data on the bacteriological quality of the springs in the north coast of Puerto Rico prior to this study are limited to that presented by Guzmán-Ríos (1988) for water samples obtained during 1982 and 1983. It appears that, with the exception of Ojo de Guillo spring (10), the bacteriological quality of springs sampled during this study has not deteriorated (table 6). The three water samples collected at Ojo de Guillo spring (10) during this study indicate an increase in the concentration of fecal bacteria counts of several orders of magnitude (from 4 cols/100 mL of fecal streptococci and 15 cols/100 mL of fecal coliform in 1982–83 to 136 cols/100 mL of fecal streptococci and 550 cols/100 mL of fecal coliform during this study) (table 6). However, to conclude that a definite increase has occurred more sampling is needed during different flow regimes. Two springs not previously sampled, Marrero 2 (19) and Luis Perez #1 (30) in Arecibo, had the highest concentrations of all sampled springs in both fecal streptococci and fecal coliform bacteria (table 6).

Relations of Springflow, Physical Properties, and Water Quality

Data on the physical properties, and water-quality collected at springs in the north coast limestone belt indicate that distinctive seasonal and short-term changes occur at some springs, particularly in conduit-type springs. In general, more frequent sampling during the wet and dry periods of a normal rainfall year is needed to fully characterize these seasonal relations. However, the limited data collected during this study indicate that in springs such as San Pedro (18), Ojo de Guillo (10), Los Chorros (16), Ojo de Agua in Aguadilla (67), and possibly others with a similar hydrogeologic setting where a well-integrated conduit network exists, both water quality and physical properties may undergo major changes associated with increases in flow over short periods.

This lack of a simple relation of physical properties and water quality to flow is demonstrated in the graph of specific conductance and flow at the San Pedro spring (18) (fig. 10). Although an inverse relation generally exists at this spring between specific conductance and flow, where a general decrease in specific conductance corresponds to an increase in flow, other factors appear to be affecting the system.

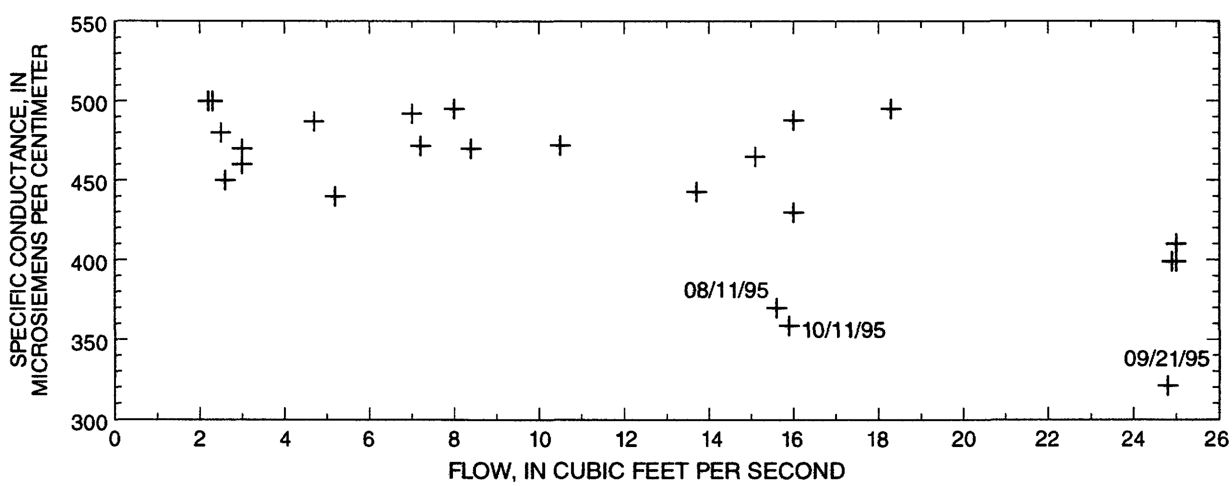


Figure 10. The relation between specific conductance and flow at the San Pedro spring in Arecibo, Puerto Rico.

The general decrease in specific conductance measured at San Pedro spring (18) can be explained by an increasing dilution of the diffuse flow by "short-time transit" water that comes either from the Río Tanamá at high stage or from rapid-rainfall runoff into the conduit network. Scatter in the plot of data shown in figure 10, particularly at discharges higher than 15 ft^3/s, probably results from the complex nature of the conduit network of San Pedro spring (18). The dates when discharge at San Pedro spring (18) was higher than 15 ft^3/s and specific conductance remained near 500 µS/cm may correspond to periods when ground water without sufficient hydraulic head held in conduits or fractures ("static storage") is discharged as saturated zone conduits and fractures are replenished by rainfall infiltration as runoff or influx from the Río Tanamá (fig. 11). However, when the specific conductance decreases significantly below 500 µS/cm, as occurred during August 11, September 21, and October 11, 1995 (fig. 10), it appears that flushing of the ground water held in "static" storage has been completed and the water subsequently discharged at the spring consists solely of rainfall-runoff infiltration or flux from the Río Tanamá, or both. This is a reasonable assumption when considering that above normal rainfall occurred during these days as a result of the hurricanes Humberto, Marilyn, and Luis passing near Puerto Rico. Concentrations of ionic species in water, which are directly related to specific conductance, should show similar variation with respect to flow. This has been documented elsewhere in the world with karst conduit-type springs (Ryan and Meiman, 1996). Springs fed by diffuse ground-water flow such as Ojo de Agua spring in Vega Baja (5), Mackovic spring in Vega Alta (2), and Zanja Fría spring in Arecibo (11) did not exhibit short-term variations in their chemical and physical properties with changes in flow.

OXYGEN-18 AND DEUTERIUM COMPOSITION OF SPRINGS IN THE NORTH COAST AND THEIR RELATION TO MODERN PRECIPITATION, GROUND WATER, AND DELINEATION OF SPRING DRAINAGE BASINS

The following information on the stable isotopes ^{18}O and ^{2}H was obtained from Freeze and Cherry (1979). Stable isotopes that occur naturally in the hydrologic cycle such as ^{18}O and ^{2}H have been used in investigations of ground water and surface water systems since the early 1950's. ^{18}O and ^{2}H are used mainly as indicators or tracers of ground-water source areas and as evaporation indicators in surface waters. Isotopic fractionation is the process by which the isotopic content of a substance changes as a result of evaporation, condensation, freezing, melting, chemical reactions, or biological processes. The condensation-precipitation history of the atmospheric water vapor controls the ^{18}O and ^{2}H content of precipitation. As a result, there are both strong continental trends in the average annual isotopic composition of precipitation and a strong seasonal variation in the time-averaged isotopic composition of precipitation at a given location. In shallow ground-water systems, as in this study, the ^{18}O and ^{2}H content of ground water are nonreactive and not affected by chemical processes that occur in deep subsurface zones and can be considered naturally occurring tracers that have concentrations determined by the isotopic composition of the precipitation that falls on the ground and on the amount of evaporation that occurs before the water penetrates below the soil zone.

$\delta^{18}O$ and δD obtained from global precipitation surveys correlate according to the relation

$$\delta D\ (‰) = 8\delta^{18}O + 10$$

which is known as the Global Meteoric Water Line (GMWL) (Dansgaard, 1964). Linear correlations with coefficients slightly different than this are obtained from studies of local precipitation. When water evaporates from soil or surface-water bodies under natural conditions, it becomes enriched in ^{18}O and ^{2}H (the $\delta^{18}O$ and δD have higher positive values than in the pre-evaporated water), and departs from the meteoric water line.

The isotope data collected during this study indicate that there is both a spatial and temporal variation in the $\delta^{18}O$ and δD in the spring waters, ground water, and precipitation in the north coast of Puerto Rico (tables 7, 8, 9). The temporal variations in $\delta^{18}O$ and δD are both short-term and seasonal. The short-term variations are normally larger and typical of conduit-type springs and result from the rapid infiltration of surface-runoff. The seasonal variations are generally less pronounced but longer and result from the annual variations in recharge.

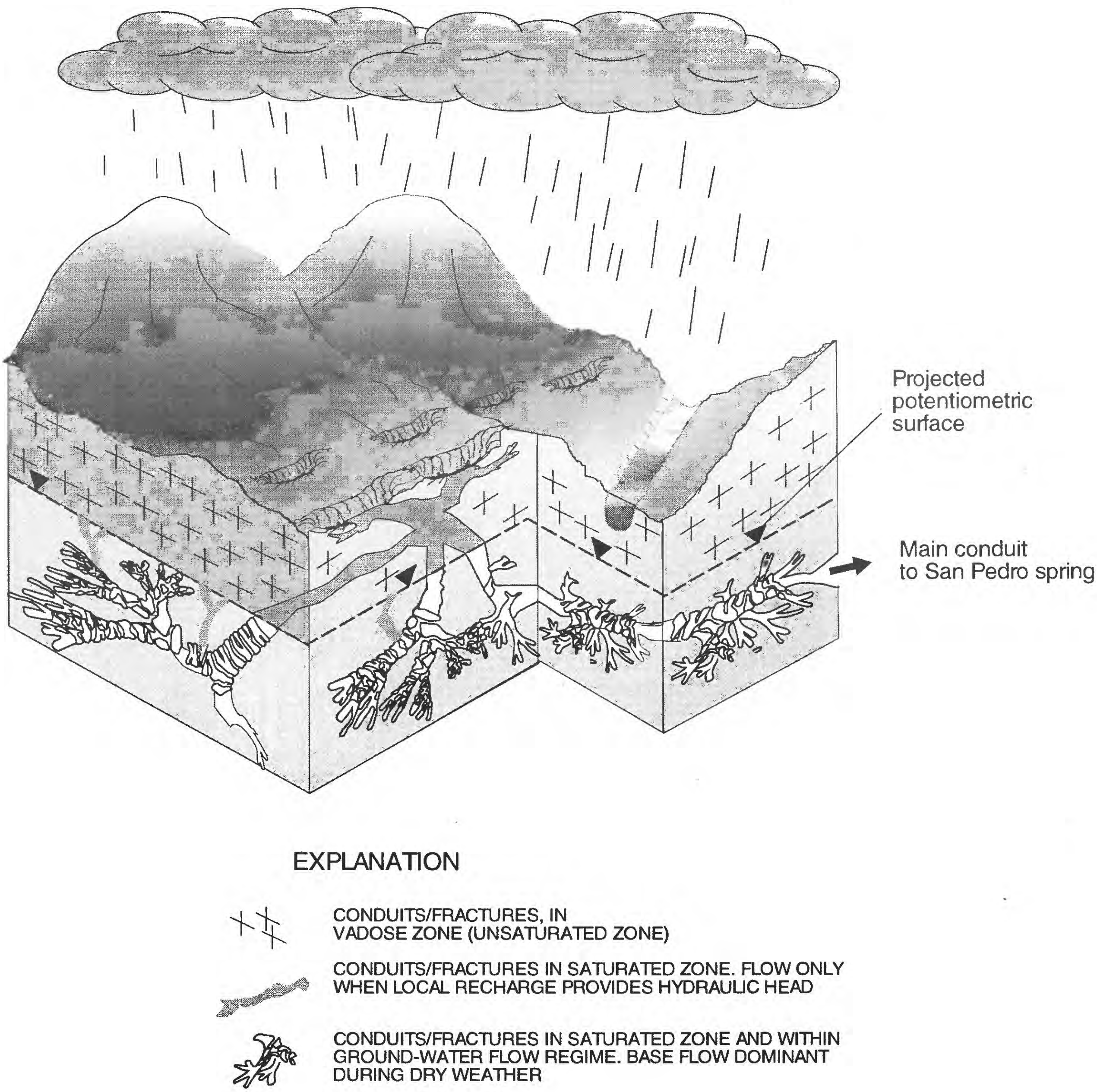


Figure 11. Schematic diagram showing the complexity of the San Pedro spring conduit network.

Table 7. Delta values of oxygen-18 and deuterium at various springs in the north coast limestone belt of Puerto Rico

[Delta values are expressed in per mil differences relative to VSMOW (Vienna Standard Mean Ocean Water). Spring map numbers are shown in table 1a and figure 1.]

Spring name and identification number	Date sampled	δD in per mil (‰)	$\delta^{18}O$ in per mil (‰)
Maguayo (1)	06-13-94	-7.2	-2.30
Maguayo (1)	07-10-94	-6.4	-2.25
Maguayo (1)	08-16-94	-6.5	-2.17
Maguayo (1)	09-27-94	-8.1	-2.38
Maguayo (1)	01-31-95	-4.3	-2.07
Maguayo (1)	02-27-95	-8.1	-2.82
Maguayo (1)	02-28-95	-5.2	-2.47
Maguayo (1)	06-14-95	-5.1	-2.11
Maguayo (1)	07-21-95	-6.6	-2.22
Maguayo (1)	08-18-95	-4.4	-2.20
Mackovic (2)	05-13-94	-7.8	-2.35
Mackovic (2)	10-31-94	-6.4	-2.32
La Poza (3)	08-23-94	-6.4	-2.23
Don Vicente Morales (4)	08-23-94	-7.9	-2.27
Ojo de Agua in Vega Baja (5)	11-05-92	-7.5	-2.40
Ojo de Agua in Vega Baja (5)	06-17-93	-7.7	-2.41
Ojo de Agua in Vega Baja (5)	09-01-93	-8.4	-2.58
Ojo de Agua in Vega Baja (5)	11-16-93	-7.3	-2.38
Ojo de Agua in Vega Baja (5)	11-19-93	-8.9	-2.45
Ojo de Agua in Vega Baja (5)	12-20-93	-8.5	-2.37
Ojo de Agua in Vega Baja (5)	01-28-94	-9.2	-2.40
Ojo de Agua in Vega Baja (5)	03-02-94	-9.1	-2.38
Ojo de Agua in Vega Baja (5)	06-06-94	-8.3	-2.36
Ojo de Agua in Vega Baja (5)	06-07-94	-7.7	-2.39
Ojo de Agua in Vega Baja (5)	08-19-94	-8.1	-2.40
Ojo de Agua in Vega Baja (5)	09-16-94	-7.2	-2.33
Ojo de Agua in Vega Baja (5)	09-26-94	-7.7	-2.36
Ojo de Agua in Vega Baja (5)	11-04-94	-8.9	-2.48
Ojo de Agua in Vega Baja (5)	11-09-94	-8.0	-2.37
Ojo de Agua in Vega Baja (5)	01-12-95	-7.7	-2.39
Ojo de Agua in Vega Baja (5)	03-14-95	-7.0	-2.40
Ojo de Agua in Vega Baja (5)	05-16-95	-7.6	-2.38
Ojo de Agua in Vega Baja (5)	06-05-95	-6.9	-2.38
Ojo de Agua in Vega Baja (5)	08-24-95	-8.3	-2.27
Ojo de Agua in Vega Baja (5)	09-07-95	-7.1	-2.41
Ojo de Agua in Vega Baja (5)	10-10-95	-6.8	-2.39
Ojo de Agua in Vega Baja (5)	02-06-96	-7.8	-2.44
Sonadora in Ciales (7)	10-17-96	-8.9	-2.56
Mamey (9)	08-26-93	-7.6	-2.63
Mamey (9)	01-20-95	-8.2	-2.53
Ojo de Guillo (10)	06-25-93	-9.3	-2.77
Ojo de Guillo (10)	07-20-93	-9.6	-2.84
Ojo de Guillo (10)	08-19-93	-9.0	-2.81
Ojo de Guillo (10)	09-01-93	-10.3	-2.79
Ojo de Guillo (10)	11-16-93	-10.7.	-2.69
Ojo de Guillo (10)	11-19-93	-16.3	-3.45
Ojo de Guillo (10)	12-20-93	-10.1	-2.60
Ojo de Guillo (10)	01-28-94	-9.1	-2.63
Ojo de Guillo (10)	03-16-94	-11.8	-2.61
Ojo de Guillo (10)	05-19-94	-7.9	-2.14
Ojo de Guillo (10)	11-09-94	-9.3	-2.65
Ojo de Guillo (10)	11-16-94	-8.2	-2.31
Ojo de Guillo (10)	02-23-95	-8.0	-2.63
Ojo de Guillo (10)	06-29-95	-8.0	-2.55
Ojo de Guillo (10)	08-10-95	-8.7	-2.50
Ojo de Guillo (10)	10-10-95	-15.6	-3.81
Ojo de Guillo (10)	02-06-96	-7.6	-2.57
Zanja Fría (11)	08-03-93	-8.3	-2.34
Zanja Fría (11)	03-02-94	-9.5	-2.53
Zanja Fría (11)	04-25-94	-11.1	-2.55
Zanja Fría (11)	05-20-94	-7.8	-2.56
Zanja Fría (11)	06-09-94.	-7.5	-2.55
Zanja Fría (11)	07-14-94	-8.4	-2.52
Zanja Fría (11)	09-28-94	-9.3	-2.54
Zanja Fría (11)	01-31-95	-7.9	-2.54
Zanja Fría (11)	07-06-95	-7.5	-2.56
Zanja Fría (11)	07-25-95	-8.0	-2.53
La Pileta (12)	06-02-94	-7.4	-2.13
La Punta (13)	08-30-95	-7.0	-2.45
Opiola (15)	08-31-95	-7.1	-2.61
Opiola (15)	12-14-95	-7.3	-2.66
Los Chorros (16)	04-07-94	-9.1	-2.66
Los Chorros (16)	06-10-94	-9.8	-2.67
Los Chorros (16)	08-10-94	-9.3	-2.67
Los Chorros (16)	11-04-94	-8.4	-2.67
Los Chorros (16)	06-08-95	-1.3	-1.82
Los Chorros (16)	06-27-95	-8.9	-2.65
Los Chorros (16)	07-27-95	-7.6	-2.58
Los Chorros (16)	08-30-95	-6.0	-2.48
Los Chorros (16)	09-07-95	-12.7	-3.48
Los Chorros (16)	09-18-95	-12.3	-3.04
Los Chorros (16)	09-21-95	-11.9	-2.73
Los Chorros (16)	09-28-95	-11.4	-2.81
Los Chorros (16)	10-03-95	-7.5	-2.66

Table 7. Delta values of deuterium and oxygen-18 at various springs in the north coast limestone belt of Puerto Rico—Continued

Spring name and identification number	Date sampled	δD in per mil (‰)	$\delta^{18}O$ in per mil (‰)
Los Chorros (16)	02-06-96	-8.8	-2.70
Sumidero (17)	08-10-94	-7.3	-2.59
San Pedro (18)	09-01-93	-8.5	-2.62
San Pedro (18)	11-16-93	-8.9	-2.61
San Pedro (18)	11-19-93	-8.3	-2.57
San Pedro (18)	12-20-93	-8.6	-2.54
San Pedro (18)	01-28-94	-8.9	-2.56
San Pedro (18)	03-02-94	-7.4	-2.37
San Pedro (18)	05-13-94	-8.7	-2.48
San Pedro (18)	06-07-94	-6.7	-2.20
San Pedro (18)	06-16-94	-7.7	-2.37
San Pedro (18)	07-14-94	-8.6	-2.64
San Pedro (18)	08-10-94	-8.7	-2.44
San Pedro (18)	09-01-94	-7.7	-2.47
San Pedro (18)	09-19-94	-8.4	-2.43
San Pedro (18)	10-11-94	-7.8	-2.47
San Pedro (18)	11-09-94	-7.9	-2.46
San Pedro (18)	01-23-95	-7.8	-2.47
San Pedro (18)	03-07-95	-5.3	-2.25
San Pedro (18)	05-16-95	-1.1	-1.98
San Pedro (18)	05-17-95	-3.1	-2.14
San Pedro (18)	05-18-95	-4.3	-2.10
San Pedro (18)	05-19-95	-4.5	-2.14
San Pedro (18)	05-23-95	-6.7	-2.26
San Pedro (18)	05-25-95	-5.5	-2.27
San Pedro (18)	06-06-95	-0.4	-1.60
San Pedro (18)	09-07-95	-18.5	-3.94
San Pedro (18)	09-16-95	-15.4	-3.38
San Pedro (18)	09-21-95	-6.7	-2.57
San Pedro (18)	09-28-95	-12.8	-2.99
San Pedro (18)	10-11-95	-8.7	-2.63
San Pedro (18)	02-06-96	-8.6	-2.41
Obrero #2 (19)	05-13-94	-8.9	-2.53
Obrero #2 (19)	06-01-94	-9.2	-2.47
Bambú #2 (21)	08-11-94	-8.8	-2.64
Bambú #2 (21)	11-04-94	-8.3	-2.62
Bambú #1 (22)	05-13-94	-8.8	-2.51
Bambú #1 (22)	06-01-94	-8.3	-2.62
Bambú #1 (22)	08-11-94	-8.1	-2.57
Bambú #1 (22)	11-04-94	-8.4	-2.60
Bambú #1 (22)	06-07-95	-9.9	-2.68
[1] Río Tanamá Dam (23)	05-13-94	-7.5	-2.51
[1] Río Tanamá Dam (23)	06-01-94	-7.8	-2.38
[1] Río Tanamá Dam (23)	08-11-94	-5.5	-2.28
[1] Río Tanamá Dam (23)	11-04-94	-8.9	-2.48
[1] Río Tanamá Dam (23)	06-07-95	-3.3	-2.22
[1] Río Tanamá Dam (23)	08-30-95	-5.4	-2.49
[1] Río Tanamá Dam (23)	09-18-95	-13.2	-3.34
[1] Río Tanamá Dam (23)	09-21-95	-11.9	-2.84
[1] Río Tanamá Dam (23)	09-28-95	-16.4	-3.52
[1] Río Tanamá Dam (23)	02-06-96	-6.8	-2.55
PVC (24)	08-15-94	-6.5	-2.29
Odilio Jiménez (25)	08-15-94	-6.5	-2.26
Cambijas (27)	08-12-94	-8.1	-2.43
Avispa (28)	08-15-94	-8.4	-2.32
Luis Pérez #2 (29)	08-11-94	-6.7	-2.26
Luis Pérez #1 (30)	06-02-94	-8.6	-2.34
Luis Pérez #1 (30)	08-11-94	-8.0	-2.28
Sonadora (34)	10-27-93	-8.7	-2.57
Aserradero (35)	03-31-94	-10.9	-2.56
Aserradero (35)	11-15-94	-9.2	-2.51
Aserradero (35)	04-04-95	-7.5	-2.46
Márquez (43)	03-17-94	-9.5	-2.46
Cortez (45)	11-16-94	-8.2	-2.31
Ojo Claro (47)	04-07-94	-9.3	-2.57
Zumbadora (50)	03-22-94	-6.0	-2.02
Zumbadora (50)	10-27-94	-7.8	-2.16
Zumbadora (50)	11-08-94	-8.0	-2.13
Zumbadora (50)	04-05-95	-5.0	-2.15
Medina (55)	11-08-94	-7.3	-2.30
Medina (55)	04-21-95	-5.1	-2.25
Río #2 (56)	03-18-94	-9.5	-2.53
Río #2 (56)	04-21-95	-8.6	-2.48
Soto Quintín (59)	03-15-94	-6.3	-2.18
Soto Quintín (59)	03-15-95	-6.3	-2.18
Soto Quintín (59)	04-20-95	-5.1	-2.16
Municipio (60)	03-15-94	-6.0	-2.13
Ferrer (62)	03-10-94	-7.8	-2.16
La Salle (63)	03-10-94	-10.3	-2.34
Victoria (65)	10-25-94	-6.9	-2.04
Ojo de Agua in Aguadilla (67)	03-04-94	-10.4	-2.4
Ojo de Agua in Aguadilla (67)	10-25-94	-16.0	-3.27
Alers (68)	03-08-94	-6.6	-1.91

[1] Surface-water site

Table 8. Delta values of oxygen-18 and deuterium of monthly rainfall composite samples at various rainfall stations in the north coast limestone belt of Puerto Rico

[Delta values are expressed in per mil differences relative to VSMOW (Vienna Standard Mean Ocean Water)]

Name of rainfall station	Month and year of sample collection	δD in per mil (‰)	$\delta^{18}O$ in per mil (‰)
[1]Valparaíso	May 1993	-13.6	-2.79
[1]Valparaíso	June 1993	-5.6	-1.83
[1]Valparaíso	July 1993	-10.6	-2.40
[1]Valparaíso	August 1993	-2.1	-1.49
[1]Valparaíso	September 1993	-6.8	-2.1
[1]Valparaíso	October 1993	0.8	-1.18
[1]Valparaíso	November 1993	-5.3	-1.96
[1]Valparaíso	December 1993	-6.6	-2.34
[1]Valparaíso	January 1994	4.7	-0.93
[1]Valparaíso	February 1994	13.7	0.78
[1]Valparaíso	April 1994	-1.7	-1.7
[1]Valparaíso	May 1994	0.1	-1.08
[1]Valparaíso	June 1994	3.7	-0.77
[1]Valparaíso	July 1994	3.8	-0.72
[1]Valparaíso	August 1994	1.0	-1.14
[1]Valparaíso	September 1994	-4.6	-1.95
[1]Valparaíso	October 1994	-16.5	-3.17
[1]Valparaíso	November 1994	-6.4	-2.17
[1]Valparaíso	December 1994	-0.5	-1.37
[1]Valparaíso	January 1995	8.3	-1.26
[1]Valparaíso	February 1995	8.6	-0.78
[1]Valparaíso	Mar 1995	5.9	-0.69
[1]Valparaíso	April 1995	9.3	-0.09
[1]Valparaíso	May 1995	3.2	-1.46
[1]Valparaíso	June 1995	6.0	-0.54
[1]Valparaíso	July 1995	-5.0	-1.69
[1]Valparaíso	August 1995	-3.0	-1.62
[1]Valparaíso	September 1995	-24.9	-4.37
[1]Valparaíso	October 1995	-3.3	-1.84
[1]Valparaíso	November 1995	4.3	-1.10
[1]Valparaíso	December 1995	4.7	-1.24
Pugnado Afuera	May 1993	-1.5	-1.53
Pugnado Afuera	June 1993	-5.2	-1.83
Pugnado Afuera	August 1993	-3.5	-0.43
Pugnado Afuera	November 1993	-7.1	-2.12
Pugnado Afuera	December 1993	-12.8	-3.15
Pugnado Afuera	January 1994	-21.2	-3.15
San Agustín	May 1993	-7.6	-1.86
San Agustín	August 1993	-15.4	-3.29
San Agustín	September 1993	-7.6	-2.04
San Agustín	October 1993	0.0	-1.38
San Agustín	December 1993	-1.6	-1.35
San Agustín	January 1994	-3.1	-1.05
San Agustín	April 1994	3.9	0.23
San Agustín	August 1994	-5.7	-1.14
San Agustín	October 1994	-23.4	-4.08
San Agustín	November 1994	-10.9	-2.28
San Agustín	December 1994	1.5	-0.88
San Agustín	February 1995	15.5	0.78
San Agustín	April 1995	9.7	-0.18
San Agustín	May 1995	5.8	-0.10
San Agustín	June 1995	5.1	-0.47
San Agustín	July 1995	0.9	-0.58
San Agustín	August 1995	7.7	0.61
San Agustín	September 1995	-37.1	-5.36
San Agustín	October 1995	14.8	2.70
San Agustín	November 1995	14.8	2.72
San Agustín	December 1995	3.4	-1.73
Hato Viejo	May 1993	-0.4	-1.86
Hato Viejo	June 1993	-17.0	-2.15
Hato Viejo	August 1993	-28.9	-4.69
Hato Viejo	September 1993	-14.5	-2.94
Hato Viejo	October 1993	-7.3	-0.44
Hato Viejo	November 1993	-8.8	-2.14
Hato Viejo	January 1994	-4.3	-1.11

[1] F. Gómez-Gómez, USGS, written commun., 1996.

Table 9. Delta values of oxygen-18 and deuterium at various wells in the north coast limestone belt of Puerto Rico

[Delta values are expressed in per mil differences relative to VSMOW (Vienna Standard Mean Ocean Water)]

Well name (location shown on figure 1)	Date sampled	δD in per mil (‰)	$\delta^{18}O$ in per mil (‰)
Vivoni	02-13-95	-4.7	-2.17
Pámpano	02-13-95	-5.9	-2.31
Santa Ana	02-13-94	-8.2	-2.74
Coto Sur	02-13-95	-9.3	-2.56
Río Arriba	02-13-95	-9.5	-2.43
Boquillas	02-13-95	-9.9	-2.56
Parcha	02-14-95	-11.9	-2.97
Fortuna	02-13-95	-10.8	-2.64
Pajonal #2	02-13-95	-9.4	-2.81
Pajonal #1	02-13-95	-8.6	-2.82
Florida #7	02-13-95	-9.0	-2.73
Garrochales # 33	02-13-95	-9.7	-2.69
Sabana Hoyos #1	02-13-95	-10	-2.62
Sabana Hoyos #2	02-13-95	-10.4	-2.76
Jovales #2	02-15-95	-7.7	-2.77
Jovales #1	02-15-95	-8.0	-2.71
Jovales #3	02-14-95	-9.5	-2.65
Miraflores #1	02-14-95	-7.8	-2.53
Miraflores #2	02-14-95	-7.3	-2.36
Arecibo #6	02-14-95	-8.9	-2.58
Esperanza #2	02-15-95	-8.2	-2.44
Bayaney #2	02-15-95	-7.5	-2.36
Pajuil #1	02-15-95	-8.3	-2.39
Piedra Gorda #1	02-15-95	-8.6	-2.52
El Rey #1	02-15-95	-10	-2.6
El Rey #2	02-15-95	-8.9	-2.57
Rocha #1	02-14-95	-6.9	-2.26

The isotopic data also revealed that mixing and dispersion in the upper aquifer tends to attenuate or average the variable isotopic composition of the recharging waters. A regional northward gradient in ^{18}O and ^{2}H is apparent in the upper aquifer, with water farther north having enriched (less negative deltas) concentrations of both isotopes. Comparison of the isotopic data collected for this study with the limited pre-existing isotopic data indicate that, with minor exceptions, changes have not occurred in the isotopic composition of most of the springs and wells since 1986 (F. Gómez-Gómez, USGS, written commun., 1996).

Comparison of Spring Waters with Modern Precipitation

The $\delta^{18}O$ and δD of precipitation are controlled by a variety of factors, including temperature (altitude and latitude effect), distance from the vapor source, and evaporation processes (Craig and others, 1963). According to Craig and others (1963), the $\delta^{18}O$ and δD of ground water (including spring waters) will be a function of these factors in the recharge area, with additional modification due to subsurface processes such as mixing. The $\delta^{18}O$ and δD relation for precipitation in the study area was based on a linear regression with the equation $\delta D=8.23\ (\delta^{18}O)+11.6$ (fig. 12). This regression is based on 80 monthly composite samples obtained from May 1993 to December 1995 at Pugnado Afuera in Vega Baja, San Agustín in Barceloneta, Hato Viejo in Arecibo, and Valparaíso in Cataño (fig. 1). This relation will be referred in this report as the Local Meteoric Water Line (LMWL) for the north coast of Puerto Rico. Plots of δD versus $\delta^{18}O$ and the equation for the best fit line at each rainfall station together with the LMWL and GMWL are shown in figure 12.

The temporal and spatial variations in the $\delta^{18}O$ and δD of precipitation in the study area are significantly larger than those from springs and wells in the same area (figs. 13a, 13b); however, springs such as San Pedro (18), with a significant conduit flow component may exhibit short-term variations in their isotopic signatures with significant increases in flow. During high flow periods, isotopic concentrations of the conduit-type springs look more like modern precipitation (fig. 13d). This can be observed during the rainy months of August, September, and October when the flow of these springs were dominated by rapid response to rainfall.

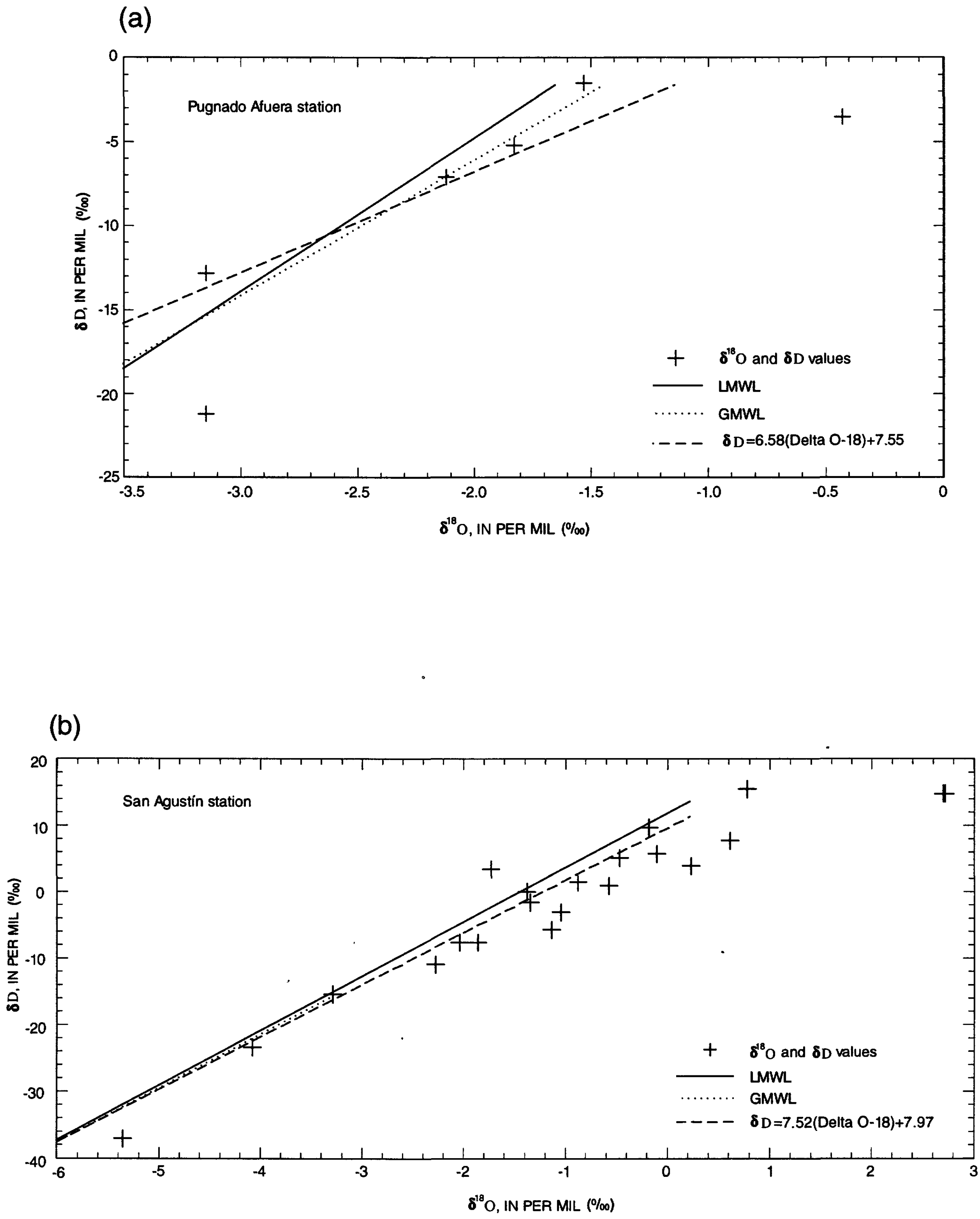
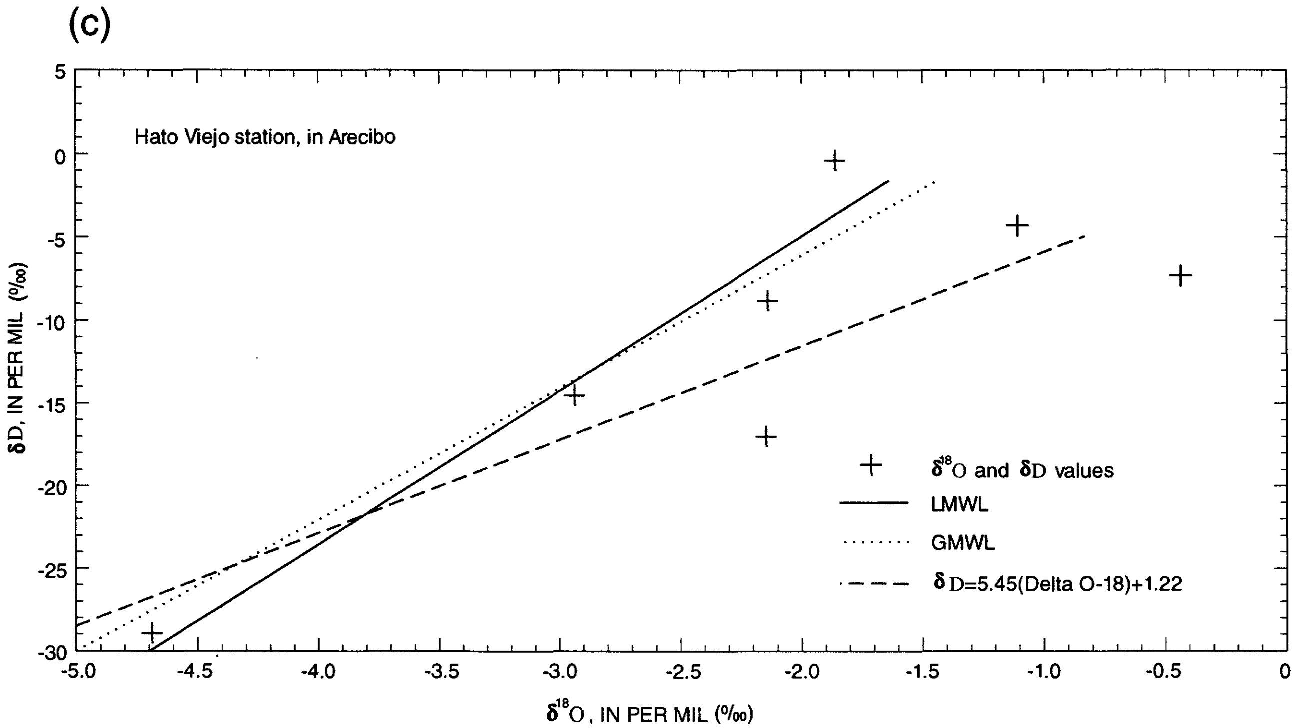


Figure 12. Relation between oxygen-18 and deuterium of the monthly rainfall composite samples at (a) the Pugnado Afuera station in Vega Baja, (b) the San Agustín station in Barceloneta, (c) the Hato Viejo station in Arecibo, and (d) the Valparaíso station in Cataño, Puerto Rico.



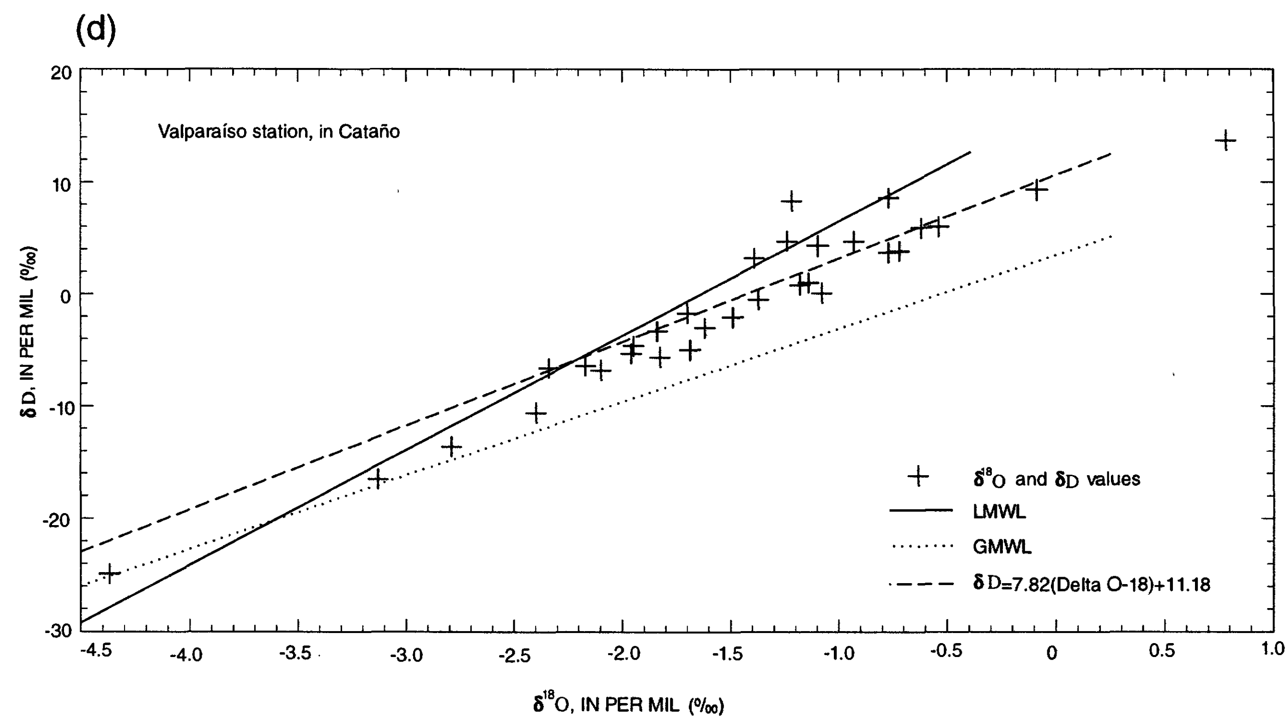


Figure 12. Relation between oxygen-18 and deuterium of the monthly rainfall composite samples at (a) the Pugnado Afuera station in Vega Baja, (b) the San Agustín station in Barceloneta, (c) the Hato Viejo station in Arecibo, and (d) the Valparaíso station in Cataño, Puerto Rico—Continued

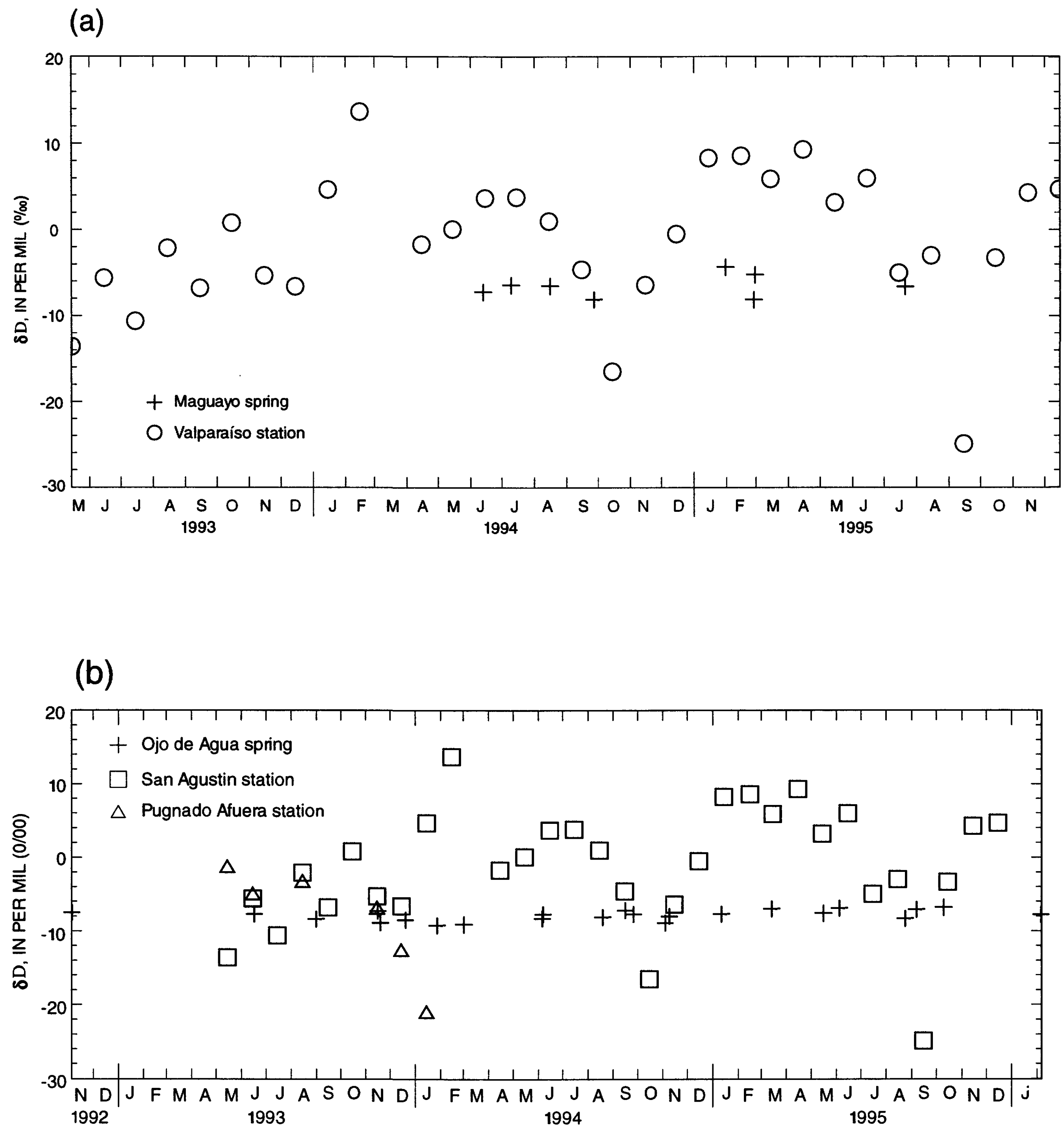


Figure 13. Temporal variations in the deuterium of water samples from (a) the Maguayo spring and monthly rainfall composites at the Valparaíso station, (b) the Ojo de Agua spring in Vega Baja and monthly rainfall composite samples at the Pugnado Afuera and San Agustín stations, (c) the Ojo de Guillo spring and rainfall composite sample at the San Agustín station, and (d) the San Pedro spring and the monthly rainfall composite samples at the Hato Viejo and San Agustín stations.

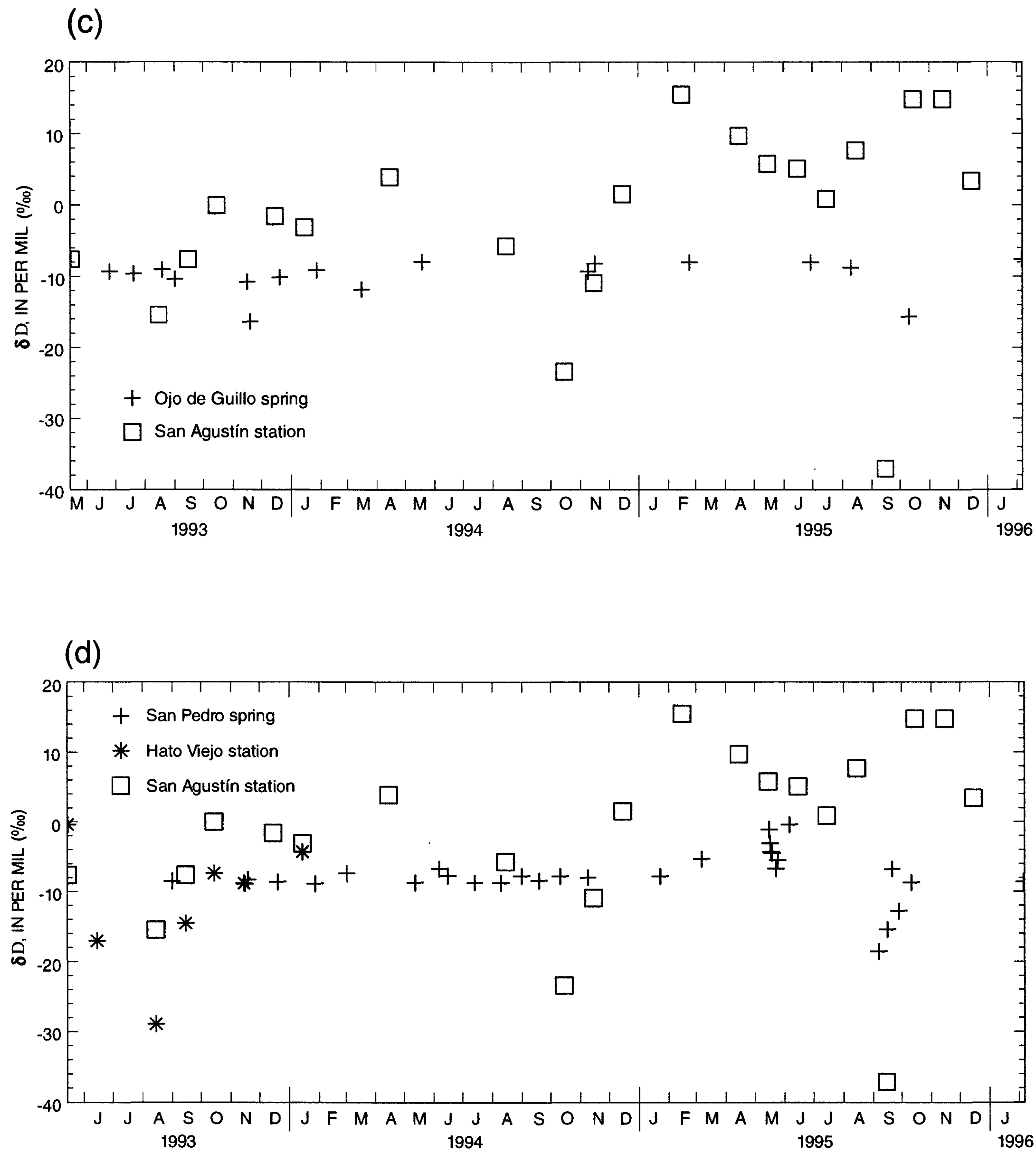


Figure 13. Temporal variations in the deuterium of water samples from (a) the Maguayo spring and monthly rainfall composites at the Valparaíso station, (b) the Ojo de Agua spring in Vega Baja and monthly rainfall composite samples at Pugnado Afuera and San Agustín stations, (c) the Ojo de Guillo spring and rainfall composite sample at the San Agustín station, and (d) the San Pedro spring and the monthly rainfall composite samples at the Hato Viejo and San Agustín stations—Continued.

In springs of the diffuse type, such as Ojo de Agua in Vega Baja (5), changes in isotopic composition do not parallel changes in the isotopic composition of modern precipitation (fig. 13; tables 7, 8). The isotopic variations at this spring follow seasonal trends that seem to be representative of the isotopic trend in the mostly diffuse ground-water flow. The predominance of the seasonal trends seems also to reflect an extraordinary capacity of this spring to regulate and "average-out" the highly variable isotopic signature of precipitation. This averaging process of the isotopic signatures probably results from the mixing and hydrodynamic dispersion that takes place along the flow paths that tend to dampen the temporal and spatial isotopic variations in present precipitation (recharge). The effects of the drought that occurred during the study period can be observed in the temporal changes in δD at various springs (fig. 14; hereafter only the δD will be used considering that although the fluctuations of both the δD and $\delta^{18}O$ are in the same direction, the fluctuations of δD are more evident). The convergence in the δD at San Pedro (18), Ojo de Agua in Vega Baja (5), and Ojo de Guillo (10) springs from about August 1994 to January 1995 indicates that only diffuse flow or base flow occurred as recharge derived from rainfall-runoff infiltration practically ceased.. Note that the δD values for the conduit-type San Pedro (18) and Ojo de Guillo (10) springs follow those of the diffusive-type Ojo de Agua spring in Vega Baja (5) during this period. This almost total convergence in the isotopic composition at springs occurred some time after the onset of the drought discussed in the section on climate. This delay might be indicative of the time required to achieve a nearly steady-state ground-water flow pattern after rainfall for recharge to the upper aquifer ceases.

The δD values during high flow at conduit-type springs such as Aserradero (35) and Márquez (43) springs in Hatillo, San Pedro spring in Arecibo (18), and Ojo de Guillo spring in Manatí (10), closely represent those of recent recharge (monthly rainfall composites). This occurs because the discharges of these springs during high flow represent rainfall-runoff infiltration from slopes above the springs and indicates the existence of an integrated conduit network strongly coupled with the land surface. These two factors favor a short residence time for the water, which in turn, inhibits mixing and consequent averaging of the isotopic composition observed for the steady-state regional flow pattern (as explained above).

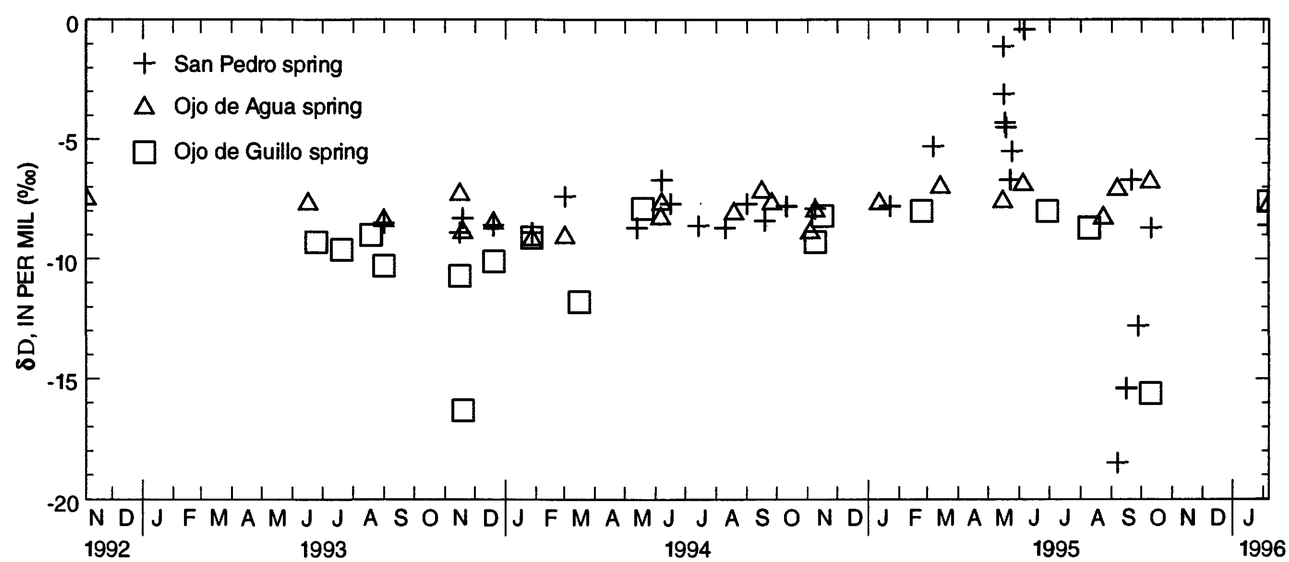


Figure 14. Temporal and spatial variation in the deuterium at selected springs in the study area.

Comparison of Springflow with Regional Ground-Water Flow

A preliminary regional characterization of the δD signature of ground water in the upper aquifer of the north coast of Puerto Rico was made based on data collected during the study at both springs and wells (fig. 1; tables 1, 2). This first attempt at describing the regional deuterium variability in the upper aquifer was limited by its short time span (about 2 years). Longer time periods of data collection (7 to 10 years) have allowed a fairly accurate definition of short, seasonal, and long-term changes in the isotopic composition of the end members of the hydrologic system under study (Smith and others, 1992).

Despite the limitations of the data, the range of values known to represent the seasonal changes in deuterium composition of some wells and of the diffuse flow component in several perennial springs (tables 7, 8) were used in the regional characterization shown in figure 15 (in pocket at end of report). These ranges in the δD of these springs and wells are assumed to represent the seasonal changes in the deuterium composition of the regional flow in the upper aquifer and result from the mixing and averaging capability of the regional ground-water system. Those δD values, in both springs and wells, that deviate from these ranges can be assumed to represent a mixture of ground water with that derived from local flow systems or water sources separated from the regional flow of the upper aquifer. Examples of these local flow systems (or water sources) are intensive rainfall-runoff recharge events in conduit-type springs (fast-response springs), recharge in the upper slopes of ephemeral springs, natural or induced local recharge through sinkholes and from rivers, ground water from the overlying saturated alluvium, and possible discharge from the lower aquifer.

As shown in figure 15, a northward gradient in the δD exists in the regional flow of the upper aquifer. A generalized enrichment in the deuterium content (the δD becomes less negative) occurs away from the inland zones (southern boundary) of the upper aquifer. This progressive northward enrichment in deuterium might result from the increasingly longer and deeper flow paths that would allow the interaction of flow zones representative of different depths and areas of the upper aquifer. This in turn would tend to damp, by hydrodynamic dispersion and mixing, the differences in isotopic composition of the recharging waters (Carillo-Rivera and others, 1992). West of the Río Grande de Arecibo the zone of deuterium depletion, with a δD ranging from -8.5 to -10.5, shifts northward. The causes for this northward shift are unknown. Information on the isotopic composition of precipitation in this area is lacking, although the cooler mean annual temperature in this region may cause a depletion of deuterium in precipitation toward the northwestern part of Puerto Rico (F. Gómez-Gómez, USGS, written commun., 1996). Another plausible explanation for this northward shift of water depleted in deuterium could be the increasing importance of conduit-springflow in the area west of the Río Grande de Arecibo. Conceptually, the increasing importance of conduit flow combined with a reduction in the width of the limestone belt could reduce both the mixing and attenuation of the short term and seasonal variations in the isotopic composition of recharge (precipitation) compared to the area east of the Río Grande de Arecibo.

Significant deviations from the regional isotopic characterization of the upper aquifer occur in water samples collected from various wells. In general, the sources of water responsible for the deviation from the expected δD are not rigorously known. Deviations are observed in a series of wells in the Río Grande de Manatí alluvial valley where the water was more depleted in deuterium (δD more negative) than the regional trend (fig. 15). Two possible causes for this deviation or anomaly in the δD of these wells are: (1) seepage induced from the overlying alluvium or from the nearby Río Grande de Manatí, or both, or (2) these wells withdraw water from a specific flow zone with a different δD from that of the prevalent regional flow in the upper aquifer. Similar deviations or anomalies are observed elsewhere in the north coast limestone upper aquifer. For example, the δD of the Maguayo spring in Dorado (1), and the Opiola spring in Arecibo (15) are different from those expected from the regional flow as shown in figure 15. A possible explanation for these deviations could be that these two springs discharge from the lower aquifer and have a different δD from those springs discharging from the upper aquifer

(F. Gómez-Gómez, USGS, written commun., 1996). Similarly, a few springs in the area west of the Río Grande de Arecibo exhibit a different δD from the regionalized values of figure 15. This difference can be attributed to a probable hydraulic connection with rivers or, in the case of the Salto Collazo spring (57), to discharge from the lower aquifer. Distribution of δD with depth in the upper aquifer is limited to four water samples collected during November and December 1986 at the NC–8 well in the municipality of Vega Alta (figs. 1, 15). Data of δD versus depth at well NC–8 depart significantly from the expected regional values (F. Gómez-Gómez, USGS, written commun., 1996). The δD in the upper aquifer at this well changed from -6.50 ‰ at a depth of 116 ft to -5.50 ‰ at a depth of 356 ft and in the lower aquifer changed from -4.00 ‰ at a depth of 517 ft to -1.50 ‰ at a depth of 1,277 ft. The vertical distribution of δD indicates that water enriched in deuterium is moving from the lower aquifer to the upper aquifer. As a result, the δD at the uppermost parts of the NC–8 well can be interpreted as resulting from the mixing of water from the lower aquifer, that has δD values usually -4.00 ‰ and higher, with water of the upper aquifer with δD between -7.50 ‰ and -8.50 ‰ as expected from the regional δD characterization. The hydrologic and lithologic data available indicate that in the Vega Alta area the head gradient is toward the upper aquifer and the confining unit is leaky (Renken and Gómez-Gómez, 1995). Consequently, this will favor upward movement of water enriched in deuterium from the lower aquifer to the upper aquifer.

Only minor seasonal variations in the isotopic composition of the wells and springs used to develop the regional δD map were observed. Limited stable isotope data were available prior to this study to evaluate long-term changes in the regional isotopic characterization of the upper aquifer (^{18}O and ^{2}H). The only previous data available were collected between 1984 and 1989 (F. Gómez-Gómez, USGS, written commun., 1996). No changes have occurred in the isotopic composition of the upper aquifer of the north coast between 1984 and 1995. In only two of the wells sampled during this study, Pámpano (2) and Santa Ana (3) in Dorado, did the δD change significantly since 1984 and 1986, respectively (F. Gómez-Gómez, USGS, written commun., 1996). At the Pámpano well, the δD changed from -9.50 ‰ on May 1, 1984, to -5.90 ‰ on February 13, 1995. At the Santa Ana well the δD changed from -5.00 ‰ on April 14, 1986, to -8.2 ‰ on February 13, 1995. The causes for these changes are not known, but in the case of the Santa Ana well it is suspected that the well completely drained a perched water zone that was relatively enriched in deuterium, and proceeded to capture ground water from the regional flow.

Isotopic Data and the Preliminary Delineation of Spring Drainage Basins

Drainage basins of karst springs are not fixed features and may vary in extent and shape as the hydrologic regime changes. However, a preliminary delineation of a drainage basin of a diffuse-type spring is possible if data are available on springflow, recharge, potentiometric head distribution, pumpage, and the δD and $\delta^{18}O$ composition of the recharge and the spring. This preliminary delineation, although approximate, can provide insights into water resources-management issues in the area. These issues may include determining the proper placement of wells with the goal of either maximizing the water yield or minimizing unwanted flow reductions at the spring, determining the probable path and point of discharge of contaminants that may have entered into the aquifer, and determining the degree of anisotropy in that part of the aquifer the spring is draining.

To illustrate the potential use of isotopic and hydrologic data, a preliminary drainage basin of the Ojo de Agua spring in Vega Baja (5) (a diffuse ground-water flow-type spring) was delineated (fig. 16). Using a discharge of 2 ft^3/s as the base flow, a base flow δD between -7.6 ‰ and -8.2‰, an areal recharge of about 20 inches (Giusti, 1978; Gómez-Gómez and Torres-Sierra, 1988), and data on the head distribution from wells south of the spring, a minimum drainage basin for this spring of 3.90 mi^2 was delineated (fig. 16). The PRASA withdraws about 4.9 Mgal/d from the upper aquifer in this area. This probable drainage area for a base flow of 2 ft^3/s extends southward from the spring to about a latitude of 18°25'00". Increases in flow above 2 ft^3/s are presumed to be derived from an undetermined area inland of 18°25'00". Using a mass balance calculation based on the isotopic data, it was estimated that 75 percent of the water flowing to the spring comes from a subarea that extends south from the spring to just north of latitude 18°25'00". This area has a regional δD that fluctuates between -7.8 ‰ and -8.4 ‰. The remaining 25 percent of the water input probably comes from the remaining portion of the drainage area, with a regional δD of about -9.0 ‰, that extends southward to the latitude of 18°25'00" and is characterized by numerous sinkholes.

In a conduit-type spring, the delineation of a drainage basin is more complex. In this type of spring the boundaries of the drainage area are highly responsive to changes in hydrologic conditions (head distribution) and more frequent data collection during different flow conditions as well as dye-tracing tests (Quinlan, 1986) are required for an accurate delineation. The San Pedro spring (18) appears to be a typical case. During high springflow conditions a hydraulic connection may exist between the Río Tanamá and San Pedro spring (18) as indicated by the results of a dye test conducted by Jordan (1970). Results of that study were inconclusive. Most likely, high-water conditions after a significant rainfall event eliminate or minimize the ground-water divide between the Río Tanamá and Río Grande de Arecibo and establishes a transient hydraulic gradient from the Río Tanamá toward the San Pedro spring (18). This inversion of the hydraulic gradient will induce a fraction of the flow of the Río Tanamá to move toward San Pedro spring (18). The isotopic data collected at the Río Tanamá and at San Pedro spring (18) (fig. 17) indicate that both the Río Tanamá and San Pedro spring (18) appear to drain the unconfined part of the lower aquifer during low-flow conditions and are recipients of shallow-subsurface transitional flow (conduit flow) when high water conditions prevail. This, and their physical proximity to one another, could account for the general similarity in both the magnitude and direction of change in their δD as observed in figure 17. However, differences between the δD values measured during the rainfall event from September 21 to September 28, 1995, which included the collection of samples well into a recession after a peak flow (fig. 17), and during February 6, 1996, during low-flow conditions, favor the hypothesis of the probable establishment of a hydraulic connection to San Pedro spring (18) from the Río Tanamá after a certain water stage is reached. When the water level in the Río Tanamá falls below this stage, the hydraulic connection ceases. Therefore, the areal extent and configuration of the drainage basin of San Pedro spring (18) likely depends on the hydrologic conditions prevailing in the area and probably reflects both short-term and seasonal variations. A preliminary drainage basin of the San Pedro spring (18), with an areal extent of about 1.56 mi^2, is shown in figure 18. This preliminary drainage basin does not assume a hydraulic connection with the Río Tanamá, and best fits the low water conditions during the drought period when base flow at the spring decreased to 2 ft^3/s, the lowest on record. The delineation of this preliminary drainage basin, based on stream low-flow discharge data, requires a subregional recharge rate of about 12 in/yr (F. Gómez-Gómez, USGS, written commun., 1996). Conduits open to rainfall recharge become the main suppliers of water to the spring as indicated by the rapid response of the stable isotopes of oxygen and hydrogen to storm events (fig. 19). After the rainfall ceases, the δD changes rapidly as the flow recedes and approaches the value existing prior the recharge event (fig. 19). This variation in the isotopic composition indicates a change in the water source of the spring as the flow decreases which in turn implies cessation of inflow into the spring's conduit network from the Río Tanamá or overland runoff. However, until additional data are available in the form of dye-tracing tests, hourly rainfall data from several sites, and additional isotopic data from both the Río Tanamá and the San Pedro spring (18), the dynamic nature of the conduit drainage network of the latter will not be fully understood.

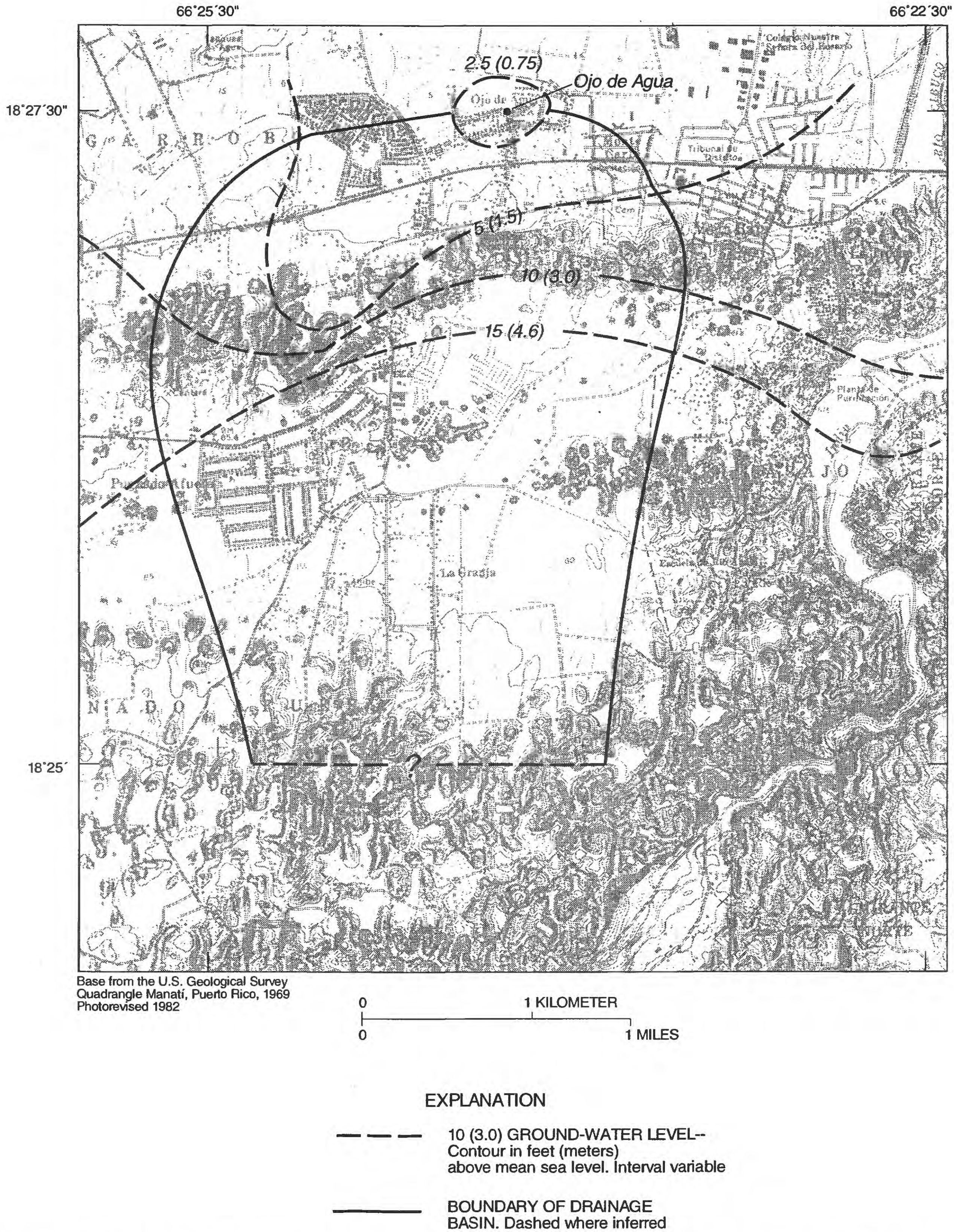


Figure 16. Preliminary drainage basin for base flow conditions at the Ojo de Agua spring in Vega Baja, Puerto Rico.

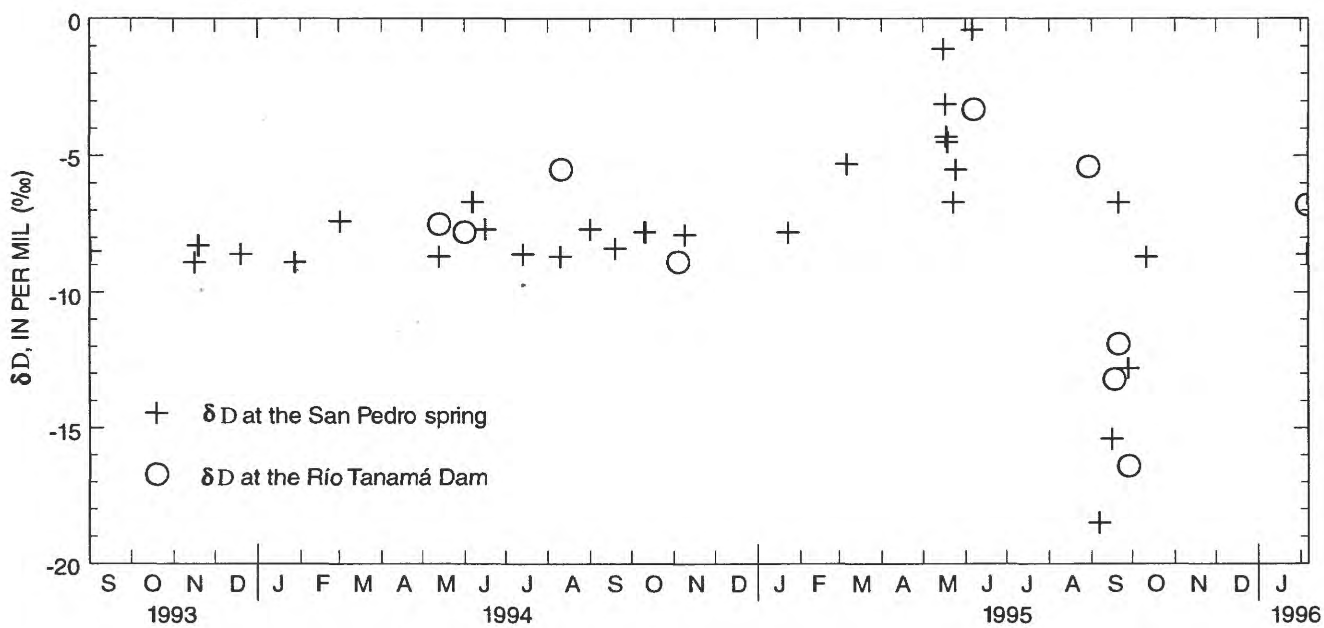
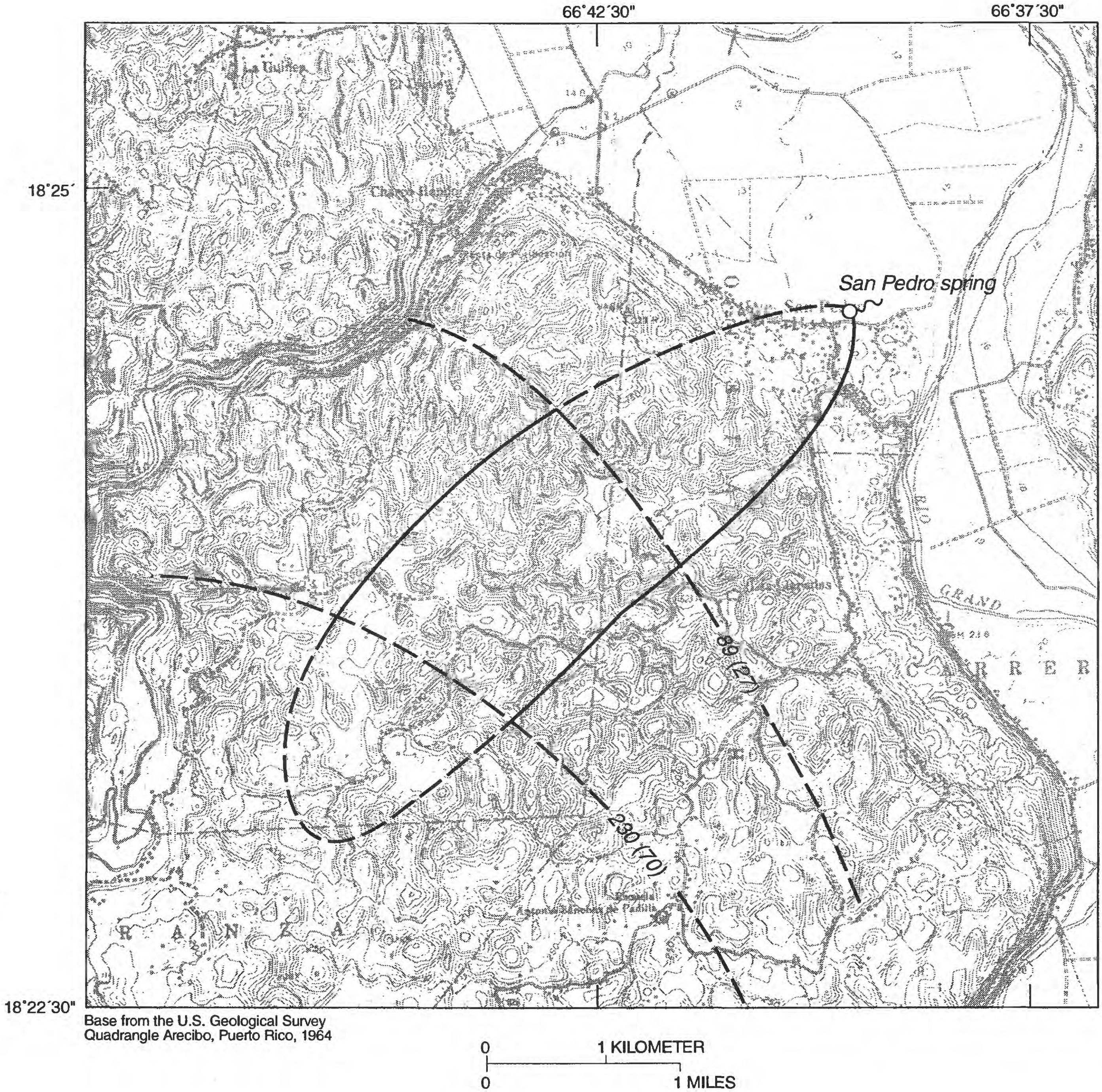


Figure 17. Temporal variation in the deuterium at the Río Tanamá and the San Pedro spring in Arecibo, Puerto Rico.



EXPLANATION

— — — 230 (70) GROUND-WATER LEVEL--Contour in feet (meters) above mean sea level

——— BOUNDARY OF DRAINAGE BASIN--Dashed where inferred

Figure 18. Preliminary drainage basin for low-flow conditions at the San Pedro spring in Arecibo, Puerto Rico.

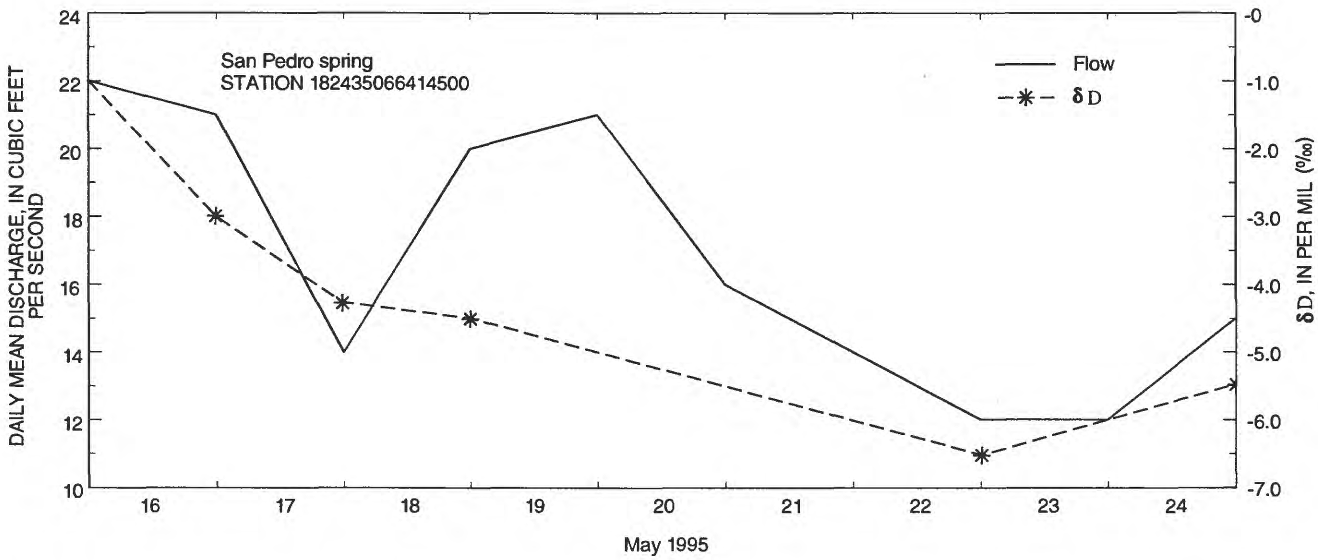


Figure 19. The relation between discharge and deuterium at the San Pedro spring in Arecibo, Puerto Rico.

SUMMARY AND CONCLUSIONS

The middle Tertiary age carbonate sequence of the north coast of Puerto Rico is characterized by numerous springs in the coastal areas, along the banks of the rivers, and in the alluvial valleys of the major streams. Prior to this investigation, the hydrologic and chemical characteristics of these springs were largely unknown. In order to advance the understanding of the hydrologic role of the springs in the north coast limestone aquifer system of Puerto Rico, a 4-year study was conducted by the USGS in cooperation with the PRASA. As part of this study, instantaneous discharge, chemical, physical, bacteriological, and stable isotope ($\delta^{18}O$ and δD) data were obtained from springs, wells, and surface water sites. $\delta^{18}O$ and δD were also determined for monthly rainfall composites collected at a series of sites in the study area.

Springs are associated with all the carbonate units of the middle-Tertiary sequence of the northern karst belt, except the Camuy and San Sebastián Formations, and mostly drain the water-table parts of the upper and lower aquifers.The permeability contrast between successive geologic units or between strata of the same geologic unit appears to be highly favorable for the occurrence of springs in the north coast.

Ground-water flow in the outcrop areas of the upper and lower aquifers seems to be highly controlled by fractures. Consequently, most of the springs in these areas are of the conduit type. Ground-water flow in the mid-valleys and coastal areas of the upper aquifer appears to occur largely along vertically and laterally discontinuous permeable zones that may be connected by fractures and, therefore, most of the springflow is of the diffuse type. Springs in the north coast limestone belt discharge preferentially toward the east, although a significant number also discharge toward the west. These discharging orientations can be explained by the preference of phreatic flow to follow passages of greater width or diameter that normally occur along the strike of the strata. An anticlinal structure seems to control the orientation of springs in the Camuy to Aguadilla area. Similarly, a structural flexure is responsible for a ground-water divide that diverges springflow between the Río Grande de Arecibo and the Río Tanamá.

Springs are classified according to the system developed by Meinzer (1923), which ranks springs by their discharge. Within the north coast limestone belt there are no first and second order springs. Fifth-and sixth-order springs with flows from 0.022 to 0.22 ft^3/s are the most numerous. Springflow in the north coast belt exhibits both a seasonal and short-term variation in discharge and water quality in direct response to rainfall. Springs that have seasonal fluctuations with no or minimum short-term responses to rainfall are Ojo de Agua (5) in Vega Baja, Mamey spring in Manatí (9), Mackovic in Vega Alta (2), and Ojo Claro in Camuy (47). These springs are referred to as diffuse-type springs. Other springs such as Maguayo (1), Ojo de Guillo (10), San Pedro (18), Los Chorros (16), Aguas Frías (8), and Ojo de Agua in Aguadilla (67) exhibit a strong short-term response to rainfall superimposed on a broader seasonal response and are referred to as conduit-type springs.

The temperature variations at all springs were minor and, in general, follow the seasonal changes in the air temperature. Measured temperatures ranged from 22.5 °C at Los Chorros spring (16) to 28 °C at Zanja Fría spring (11).The specific conductance of the springs ranged from 289 µS/cm at the Río #2 (56) spring in Quebradillas to 4,000 µS/cm at La Poza spring in Vega Baja (3). In "fast response" (conduit flow) springs such as the San Pedro (18) and Ojo de Guillo (10) springs, significant short-duration (hours and days) reductions in specific conductance were noted superimposed on the longer-trend seasonal changes. The pH of the water from the springs ranged from 6.9 to 7.8.

Limited water-quality data indicate that calcium, bicarbonate, sodium, and chloride are the main ionic species among the springs sampled during the study. Springs near the coast exhibit an increase in sodium and chloride indicative of a freshwater-seawater mixture.The historical water-quality data available prior to this study indicate that no significant change has occurred in the chemical or bacteriological character of the water of the springs since 1988. An exception may be the Ojo de Guillo spring (10) where the concentration of fecal bacteria showed an increase since 1988. Nutrients concentrations showed only minor fluctuations and only one sample from Ojo de Guillo spring (10) had a total phosphorus and total ammonia plus organic nitrogen considered to be high.

A seasonal and short-term, transient relation exists, particularly in conduit-type springs, between discharge, the physical properties, and the water quality. The sampling done during this study was sufficient to characterize the seasonal relation at the Ojo de Agua spring in Vega Baja (5), Ojo de Guillo spring in Manatí (10), and San Pedro spring in Arecibo (18); however, in order to completely record the transient and short-term variations in chemical and physical properties with flow longer-term monitoring is required. A determination of these more complex transient relations at karst springs is essential when evaluating their potential as water supply sources, impact of contaminants, or change in discharge as a result of ground-water development.

Temporal and spatial variations in the oxygen-18 and deuterium composition of modern precipitation in the study area are significantly larger than those of springs and water wells in the same area. This can be explained by the capacity of the regional flow of the upper aquifer to attenuate or average either the temporal or spatial variations in isotopic composition of modern recharge, or both. The δD values of the high-flow components of conduit-type springs such as the Aserradero (35) and Márquez (34) springs in Camuy and the San Pedro and the Ojo de Guillo (10) springs in Arecibo and Manatí, respectively, closely resemble that of modern rainfall. This indicates a relatively short residence time of the rainfall recharge in the conduit network.

Isotopic data collected during this study at both springs and wells revealed the existence of a regional northward gradient in the δD of the regional flow in the upper aquifer. A generalized enrichment in the δD occurs toward the northern boundary of the upper aquifer. West of the Río Grande de Arecibo the zone of deuterium depletion shifts northward. This shift can be explained by deuterium depletion in rainfall due to cooler temperatures. Another cause for this northward shift could be a reduced mixing capability of the aquifer as a result of the increasing importance of conduit flow and a decrease in the width of the limestone belt west of the Río Grande de Arecibo. Deviations from the regional isotopic pattern in the upper aquifer can be explained by the occurrence of local sources of recharged water with different isotopic composition.

Preliminary drainage basins for the San Pedro spring in Arecibo (18) and Ojo de Agua spring in Vega Baja (5) were delineated, using existing knowledge of the potentiometric surface distribution, hydrologic framework, and areal estimates for rainfall recharge combined with δD data.These preliminary basins may be used to establish a program with more detailed hydrologic analysis.

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