POTENTIOMETRIC SURFACES OF THE UPPER AND LOWER AQUIFERS, NORTH COAST LIMESTONE AQUIFER SYSTEM, PUERTO RICO

by Robert A. Renken and Fernando Gómez-Gómez

U.S. GEOLOGICAL SURVEY

Open File Report 93-499

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Norcross, Georgia
1994

U.S. DEPARTMENT OF THE INTERIOR
Bruce Babbitt, *Secretary*

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, *Director*

For additional information
write to:

Regional Hydrologist
U.S. Geological Survey
3850 Holcomb Bridge Road
Suite 160
Norcross, GA 30092

Copies of this report can be
purchased from:

U.S. Geological Survey
Earth Science Information Center
Federal Center, Box 25286
Mail Stop 517
Denver, CO 80225

CONTENTS

LIST OF ILLUSTRATIONS
(Plates are in pocket in back of report)

TABLE

CONVERSION FACTORS

Multiply	*by*	*to obtain*
Length		
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Area		
square mile (mi^2)	2.590	square kilometer
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
Flow		
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.0006309	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

POTENTIOMETRIC SURFACES OF THE UPPER AND LOWER AQUIFERS, NORTH COAST LIMESTONE AQUIFER SYSTEM, PUERTO RICO

By

R.A. Renken and Fernando Gómez-Gómez

Abstract

Potentiometric-surface data of the karstic North Coast limestone aquifer system indicate that precipitation recharges the upper and lower aquifers in topographically elevated interstream areas. Ground-water recharge infiltrates through soil cover and surficial deposits or enters as direct runoff into sinkholes, dry valleys, and fracture-controlled solution trenches. Ground water naturally discharges to large rivers, cave systems, springs, wetlands, and the Atlantic Ocean. Ground water also discharges to agricultural drainage canals and wells in the area.

Water that enters the unconfined flow system of the upper aquifer flows northward toward the Atlantic Ocean and discharges to wetlands along the coast; coastal, nearshore, and offshore springs; or the ocean as seabed seepage. The upper aquifer also discharges water to rivers in their headwater reaches and commonly receives recharge from the same rivers near the coast. A large potentiometric low at Caño Tiburones, which is a former brackish water lagoon, is caused by agricultural drainage. Ground-water withdrawals also have locally lowered water levels at some pumping centers.

The lower aquifer is recharged from precipitation where the aquifer crops out and by downward leakage in shallow subsurface areas. Recharge water then flows either downgradient toward the coast into confined parts of the lower aquifer, or upward along a circuitous path to discharge to major rivers and some second-order springs. Some water also flows eastward toward an area of upward discharge in metropolitan San Juan. Cave systems and major river valleys of the North Coast are the principal drains. Large rivers are characterized by an entrenched alluvial valley, low potentiometric surfaces, and second- to third-order springs. It is postulated that a fluvially breached part of the confining unit overlying the lower aquifer lies buried in the middip reach of major alluvial river valleys. Extensive downcutting by north-flowing rivers during periods of low Pleistocene sea levels resulted in the incision of deep channels in the confining unit. The entrenched river valleys were subsequently filled by aggradation and alluvial infilling during periods of higher sea level. The lower aquifer has been developed for industrial and municipal water supplies, primarily in the central part of the North Coast ground-water province. Ground-water withdrawals from the lower aquifer in 1987 totaled an estimated 13 million gallons per day (Mgal/d). Ground-water withdrawals and some leakage from poorly grouted or corroded well casings have locally lowered water levels in the lower aquifer as much as 150 feet.

INTRODUCTION

This report, which has been prepared as part of the U.S. Geological Survey (USGS), Regional Aquifer System-Analysis (RASA) Program, describes potentiometric surfaces of the North Coast limestone aquifer system and is one in a series of reports that describes aquifers in the U.S. Caribbean Islands. The North Coast ground-water province (McGuinness, 1948) represents one of the most prolific sources of ground water in Puerto Rico and the U.S. Caribbean Island region. In 1987, the North Coast ground-water province supplied about 40 percent of the total ground-water withdrawals on the island. Total 1987 ground-water withdrawals from the North Coast limestone aquifer system are estimated to be 60 million gallons per day (Mgal/d).

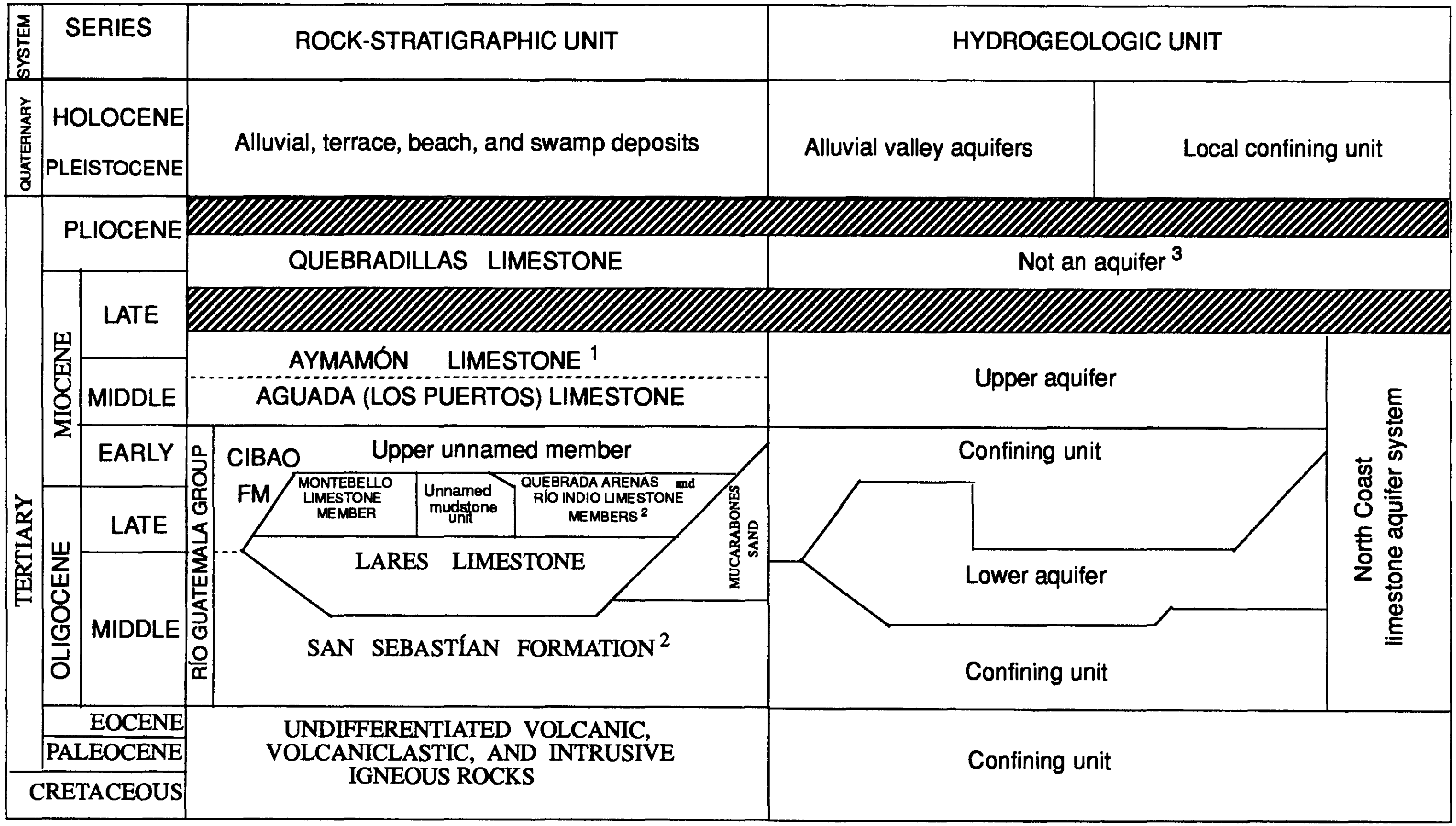
The North Coast ground-water province extends nearly 50 miles (mi) eastward from Aguadilla near Puerto Rico's western coast to Loiza and has an area of about 700 square miles (mi^2). The North Coast ground-water province is underlain by a seaward-thickening homoclinal wedge (more than 5,600 ft) of platform carbonate and lesser siliciclastic rocks that range in age from Oligocene to Pliocene (Briggs, 1961; Monroe, 1980; Meyerhoff and others, 1983; Seiglie and Moussa,1984; Ward and others, 1990). These rocks collectively form the North Coast limestone aquifer system.

The North Coast limestone aquifer system includes two principal aquifers--an upper and a lower (pl. 1; Guisti, 1978; Torres-González and Wolansky, 1984; Rodríguez-Martínez, 1990; Ward and others, 1990). The upper aquifer consists of carbonate rocks of the Aymamón Limestone and the Aguada (Los Puertos) Limestone (fig. 1). The Lares Limestone, Montebello Limestone Member, and Mucarabones Sand make-up the lower aquifer.

Aguada Limestone" (Zapp and others, 1948) is essentially the same section previously named "Los Puertos Limestone" by Hubbard (1920), although the type locality of the Aguada (Zapp and others, 1948) is within the Cibao outcrop. Monroe (1968) established a reference section for the Aguada Limestone to deal with this problem. However, Moussa and Seiglie (1975) found Monroe's procedure to be contrary to the Code of Stratigraphic Nomenclature. Although the name "Los Puertos Limestone" has priority over "Aguada Limestone" (Moussa and Seiglie, 1975; Meyerhoff, 1975), "Aguada (Los Puertos) Limestone" is used here to be consistent with U.S. Geological Survey usage. Nomenclatural problems associated with the geologic name "Los Puertos" are further complicated because the same terminology is used to describe rocks of Paleocene age located in the leeward central interior of the island (Glover and Mattson, 1967; MacLachlan and others, 1992).

The upper aquifer contains ground water mostly under unconfined conditions, except near the coast where surficial and some alluvial deposits of Pleistocene to Holocene age may form a local confining unit. Other surficial and alluvial deposits that overlie the upper aquifer are permeable and function as local surficial aquifers that either discharge water to or receive water from the upper aquifer.

A confining unit of clay, marl, and mudstone of the Cibao Formation and some of its subsurface units—the Quebrada Arenas Limestone Member, Río Indio Limestone Member, and the unnamed mudstone unit (Seiglie and Moussa, 1984)—separate the upper aquifer from the lower aquifer.



1 Seiglie and Moussa (1984) considered the Aymamón to be middle or late Miocene in age.
2 Functions as part of the lower aqufier where it crops out or lies in the shallow subsurface and as part of a confining unit in the deeper subsurface.
3 Largely lies about the water table and is unsaturated.

Figure 1. Chart showing relations among the geologic and hydrogeologic units of the North Coast limestone aquifer system (Stratigraphic column modified from W.C. Ward, University of New Orleans, written communication, 1994).

The lower aquifer contains water under confined conditions where it lies buried in the deeper subsurface and under unconfined conditions where it crops out along the southern margin of the North Coast ground-water province. In the deeper subsurface, the lower aquifer is composed of rocks of the Montebello Limestone Member of the Cibao Formation, the Lares Limestone, and the Mucarabones Sand. Where the lower aquifer is near land surface, it also can include more permeable rocks of the Quebrada Arenas and the Río Indio Limestone Members of the Cibao Formation, as well as the sandy conglomeratic San Sebastían Formation. In northwestern Puerto Rico, the coastward extent of the lower aquifer is uncertain because permeable limestone of the Montebello Limestone Member and the Lares Limestone grade by facies change to poorly permeable marl, calcareous mudstone, and clayey wackestone (W.C. Ward, University of New Orleans, written commun., 1993). The lower aquifer is underlain by a confining unit of lithified volcaniclastic and minor igneous rocks of Cretaceous and early Tertiary age that form the core of the island and a confining unit of mudstone, siltstone, marl, and poorly permeable limestone equivalent to the San Sebastían Formation.

The purpose of this report is to present the potentiometric surface of the upper aquifer based on data collected between 1980 and 1990 and the estimated potentiometric surface of the lower aquifer for predevelopment and 1987 conditions. A secondary purpose is to qualitatively describe the pattern of regional ground-water flow within the upper and lower aquifers.

A synoptic measurement of water levels in the upper and lower aquifers has never been done on a ground-water province wide scale. A potentiometric surface map of the North Coast ground-water province that shows the ground-water conditions in the late 1960's was presented by Guisti (1978). However, Guisti's map did not separate the flow system into the upper and lower aquifers.

The reader should be cautioned to interpret potentiometric maps in this report with care because some of the maps are based on water-level measurements made over a long period of time and, in some instances, in some wells installed in different stratigraphic horizons within the aquifer. Despite these limitations, the maps are considered to be reasonable estimates of regional predevelopment hydrologic conditions for the lower regional aquifer and postdevelopment hydrologic conditions for the upper and lower aquifers. Seasonal water-level fluctuations are small (Torres-González, 1991) in many wells that are cased in the aquifer system, and stress on the system due to pumping is largely restricted to certain areas of the North Coast. More importantly, these maps provide insight to regional flow patterns and show which areas need to be examined more closely to better understand hydrologic conditions in the North Coast ground-water province.

Water-level measurements used to draw the development potentiometric-surface map for the upper aquifer (pl. 2) were collected between 1980 and 1990 and are considered to be a reasonable representation of conditions during 1987, when most of the measurements were collected for the lower aquifer. Much of the upper aquifer water level information shown herein also is available in reports that describe local hydrologic conditions (Gómez-Gómez, 1984; Torres-González and Díaz, 1984; Zack and Class-Cacho, 1984; Quiñones-Aponte, 1986; Gómez-Gómez and Torres-Sierra, 1988). Additional water-level information were made available from studies currently in progress (U.S. Geological Survey, unpub. data, 1993). The configuration of lines of equal hydraulic head on potentiometric surface maps in this report are, for the most part, similar to the configuration of contours shown in the reports listed above. Stream-stage altitudes were estimated from USGS 1:20,000 topographic maps and used as additional control in mapping ground-water levels along the major rivers that traverse the outcrop area. Other water-level data were obtained from the files of the USGS. Data were not available in USGS files to construct a regionwide predevelopment map of the upper aquifer because development of the upper aquifer preceded hydrologic data collection efforts in Puerto Rico by the USGS. In some areas, agricultural dewatering and pumping of wells caused change in upper aquifer water levels as early as 1909 (Zack and Class-Cacho, 1984).

Water-level measurements of wells completed in the lower aquifer were used to construct potentiometric-surface maps that show predevelopment (pl. 3) and 1987 (pl. 4) hydrologic conditions. Additional information regarding predevelopment conditions, mostly within a small subbasin in the upper reach of the Río Tanamá Basin, is presented by Jordan (1970, 1977). The occurrence of a lower aquifer that contains freshwater under artesian conditions was confirmed in 1968 by exploratory drilling near Barceloneta (Guisti, 1978). Other wells have been completed in the lower aquifer, primarily to provide water for industries in the Barceloneta/Manatí area of Puerto Rico. By 1987, 12 industrial and 3 public-supply wells were withdrawing water from the artesian system. In the shallower updip, unconfined parts of the lower aquifer near the town of Florida and barrio of Montebello, 21 public-supply wells were withdrawing water from equivalent rocks within the Ríos Grande de Arecibo/Grande de Manatí area. In areas to the west and east of the Ríos Grande de Arecibo/Grande de Manatí area, water from the lower aquifer also is being withdrawn from 23 wells.

SALIENT FEATURES OF THE NORTH COAST LIMESTONE AQUIFER SYSTEM

Topographic relief and incision of carbonate Coastal Plain rocks by streams are the principal factors that control the direction of ground-water flow in areas of outcrop of the upper and lower aquifers. Areas that have a high potentiometric surface generally correspond to areas of elevated topography and function as principal sites for ground-water recharge. Areas that have a low potentiometric surface generally correspond to areas of low topography and commonly are sites of ground-water discharge. Puerto Rico's North Coast ground-water province is characterized by a well-developed cuesta karst topography (Monroe, 1976) in which differential erosion has created a belted series of northward-dipping cuestas with steep, south-facing cuesta escarpments. Heights of escarpment crests from the valley floor commonly range from 150 to 1,100 ft. Northern cuesta slopes conform to the gentle northward dip of beds and have been greatly modified by processes of karstification. Dissolution along a poorly defined fracture system and mass transport have contributed to the wide variety of positive (cone and tower karst) and negative (fracture-controlled solution trenches or zanjones, closed sinkhole depressions or dolines, and dry valleys) karst relief features. Cave collapse locally reveals an extensive subterranean river system.

Under predevelopment conditions, large rivers, subterranean-cave systems, springs, and coastal wetland areas were the principal areas of ground-water discharge. Ground-water withdrawals and agricultural dewatering have greatly affected the present-day (1980-90) ground-water flow system. Major rivers of Puerto Rico's North Coast ground-water province that gain streamflow due to regional ground-water discharge include, from west to east, the Ríos Culebrinas, Gúajataca, Camuy, Tanamá, Grande de Arecibo, Grande de Manatí, Indio, Cibuco, and de la Plata.

Well-completion records and geologic data indicate that the northward-flowing rivers were deeply incised in response to eustatic sea level decline during the Pleistocene. Mechanical erosion of the coastal plain by fluvial processes may have been extensive enough to have breached middip parts of the middle confining unit. These deeply incised areas were covered subsequently by thick alluvial deposits deposited by channel aggradation in response to interglacial sea-level rise (fig. 2). The occurrence of large springs and a low potentiometric surface in the entrenched river valleys that incise the lower aquifer (pls. 3, 4) indicates that ground water is probably discharged from the lower aquifer upward into overlying alluvium that covers the breached part of the middle confining unit (fig. 3).

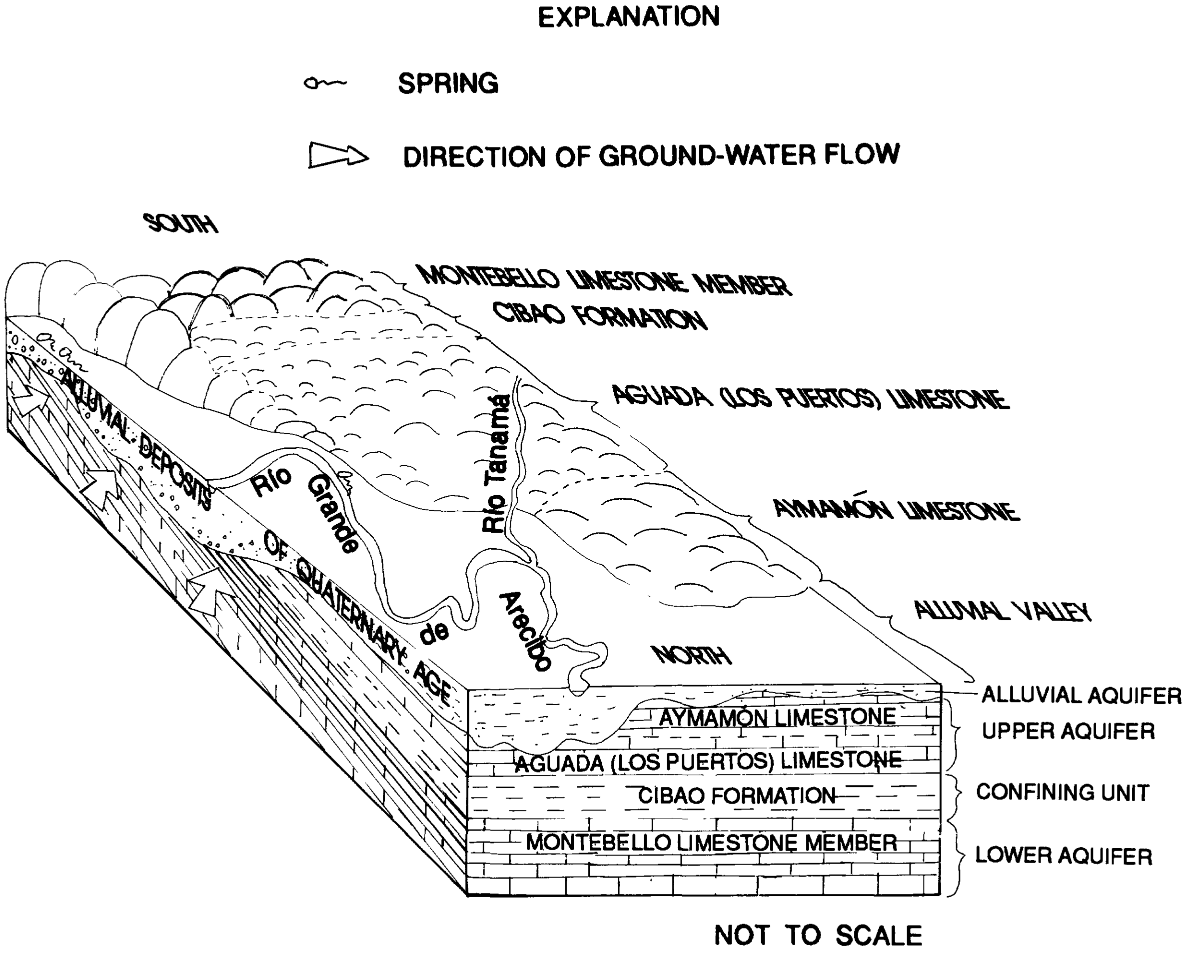


FIGURE 2. — **Area of probable ground-water discharge from lower aquifer to the alluvial aquifer in the Río Grande de Arecibo valley.**

Large cave systems of the North Coast ground-water province represent major ground-water drains, especially in areas where the lower aquifer crops out. This is evident in the Río Camuy cave system where potentiometric-surface contours show a characteristic upstream V-contour pattern indicative of ground-water discharge (pl. 3). Ground water also discharges to the Río Encantado cave system located in the Florida-Montebello area (pls. 3, 4). The large number of water-level measurements in this area help constrain the position of the lines of equal hydraulic head (water-level contours) and help define the probable extent of the subterranean passageway. Potentiometric surface data also indicate the possible presence of another major cavernous drainage feature that lies to the north and appears to parallel the Río Encantado cave system (pl. 3). However, further study is needed to confirm the presence of this possible subterranean drainage feature.

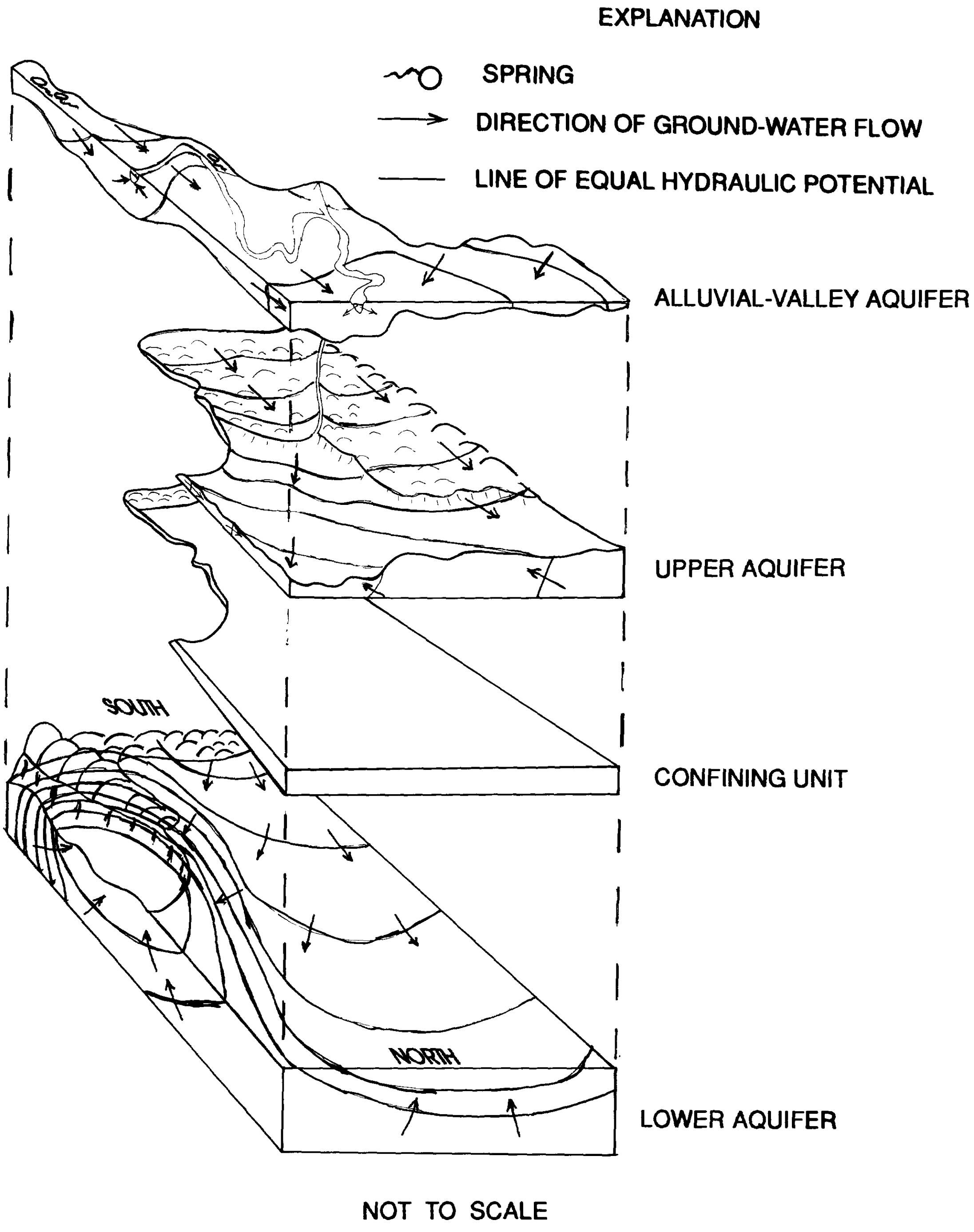


FIGURE 3. — Exploded view of aquifers in the Río Grande de Arecibo valley and pattern of ground-water flow.

Major springs that produce water from the North Coast limestone aquifer system are listed by Guzmán-Ríos (1988). These and other North Coast springs are listed in table 1; however, this table is not considered a complete list of all North Coast springs. Other springs could be present, but are difficult to locate as a result of extensive vegetative cover and limited access. No first-order springs (discharge more than 100 ft^3/s) are in the North Coast limestone aquifer system, but numerous second- (10-100 ft^3/s) and third- order (1-10 ft^3/s) springs are. One of the two largest springs that produce from the lower aquifer, the Aguas Fría, is the point where discharge from the Río Encantado cave system surfaces. Between December 1982 and January 1984, instantaneous discharge measurements at this spring ranged from 5.3 to 11 ft^3/s. The other large spring, the San Pedro, is a second- to third-order spring along the Río Grande de Arecibo. Discharge measurements at this spring ranged from 4.8 to 54 ft^3/s between June 1983 and June 1984 (Guzmán-Ríos, 1988). The San Pedro spring probably discharges from the Montebello Limestone Member, which is the most permeable part of the lower aquifer. A dye-trace study in the Río Tanamá basin area indicates there is loss of the water from that river to the aquifer with subsurface movement of the water to the San Pedro spring located on Río Grande de Arecibo (Jordan, 1970, p. 17). Two large springs (la Cambija and Zanja Fría) that discharge from the upper aquifer are located in the Caño Tiburones area. These two springs are considered to be second- to third-order springs with discharge from la Cambija reported to be as much as 20 ft^3/s (Zack and Class-Cacho, 1984). However, most springs that discharge water from the upper aquifer are third- (1-10 ft^3/s) or fourth- (100 to about 449 gal/min) order springs. Similarly, most freshwater and saltwater springs and seeps located in the Caño Tiburones, which is an area of upper aquifer ground-water discharge, are classified as third- or fourth-order springs.

Table 1: Principal springs within the North Coast limestone aquifer system

[Data from Percious (1971), Gómez-Gómez (1984), Quiñones-Aponte (1986), Gómez-Gómez and Torres-Sierra (1988), and Guzman-Ríos (1988). Spring order (Meinzer, 1927) refers to discharge; 2d order, 10 to 100 ft^3/s; 3d order, 1 to 10 ft^3/s; 4th order, 100 to 449 gal/min; 5th order, 10 to 100 gal/min]

Spring number	Spring name	Spring order
	Upper aquifer	
1	Maguayo spring near Dorado	3d-4th.
2	Ojo de Agua spring at Vega Baja	Do.
3	Ojo de Agua Guillo spring near Manatí	3d.
4	Palo de Pana and Mamey spring	4th.
5	Isadora spring	Do.
6	La Cambija spring at Caño Tiburones	2d.
7	Zanja Fría spring at Caño Tiburones	2d-3d.
8	El Dique spring near Río Tanamá	4th.
9	Sonadora spring near Camuy	4th-5th.
10	Tiburón spring near Camuy	4th.
11	Sumbadora spring at Los Puertos near Camuy	Do.
12	Ojo de Agua spring at Aguadilla	3d.
13	Nearshore, offshore, and shoreline springs	Do.
a	Borinquen Beach	
b	U.S. Coast Guard lighthouse	
c	Colonel B. Smith's house	
14	Unnamed spring near Río Cibuco	No information.
15	Ojo de Valencia near Municipio de Moca	Do.
16	Unnamed spring near Río Cibuco	Do.
	Lower aquifer	
1	Ojo de Agua at Torrecillas near Morovis	5th.
2	Repressa Sonadora de Ciales at Ciales	3d-4th.
3	Aguas Frías spring near Ciales resurgence of Río Encantado	2d-3d.
4	San Pedro spring near Río Arecibo	Do.
5	Hato Viejo spring near Río Arecibo	4th.
6	Zanja spring	No information.
7	Los Chorros spring near Dos Bocas dam	3d-4th.
8	Unnamed springs along Río Tanamá	Do.
a		3d.
b		Do.
9	Salto Collazo spring near San Sebastián	Do.

POTENTIOMETRIC SURFACE AND REGIONAL GROUND-WATER FLOW PATTERNS

The potentiometric surface of an aquifer is defined as the altitude to which water would rise in fully penetrating wells cased to the top of the aquifer. The potentiometric- surface maps in this report were prepared by contouring water-level data with lines of equal hydraulic head (water level). Assuming that hydraulic properties of the aquifer are uniformly distributed, lateral movement of water within the aquifer (direction of ground-water flow) is downgradient and perpendicular to the lines of equal hydraulic head. Study of these flow lines provides insight to regional patterns of ground-water flow.

Upper aquifer

Precipitation, which is the ultimate source of water to the North Coast limestone aquifer system, enters the upper aquifer by infiltrating through the overlying surficial deposits or as runoff that enters the system directly through karstic conduits (sinkholes, dolines, zanjones). With the exception of some coastal areas and lower reaches of some major alluvial valleys where the upper aquifer is confined by poorly permeable clay, silt, and mud, the upper aquifer is capable of being recharged throughout its extent.

The potentiometric-surface map of the upper aquifer, which is based on water-level measurements made between 1980 and 1990, shows that principal recharge areas are in topographically elevated, inland parts of the aquifer (pl. 2). In general, ground water flows northward and is discharged to coastal wetlands, nearshore and offshore springs, and the ocean floor as seabed seepage. Ground water also is discharged along the inland reach of north-flowing rivers. Data for the southernmost areas underlain by the upper aquifer are limited, which create some uncertainty regarding the altitude of the potentiometric surface in these areas (pl. 2). East of the Río Grande de Arecibo, the landwardmost contour shown is 100 ft above sea level. Ground water within the upper aquifer at altitudes of about 100 ft or somewhat higher probably is a thin freshwater lens or saturated zone at the base of the aquifer. Additional data are needed to assess more accurately the occurrence of water in the upper aquifer within these upgradient areas.

Only limited water-level data are available for the upper aquifer in areas east of the Río Bayamón. Two factors have restricted development of the aquifer in the Metropolitan San Juan area. In some areas, the upper aquifer is reported to mostly contain brackish or saline water. In other areas, the upper aquifer is thin or may be entirely absent (pl. 1).

Marl, mudstone, and clayey wackestone of the middle confining unit that separates the upper and lower aquifers grades by facies change to terrigenous sediments in the Metropolitan San Juan area. These sediments, which include sandstone and sandy limestone, are more permeable and permit greater hydraulic interconnection between the two aquifers. Given the sparse hydrologic and geologic control in the San Juan area, the authors assumed that the configuration of the lower and upper potentiometric surfaces in this area were similar and that there is a potential for upward discharge from the lower aquifer to the upper aquifer (compare pls. 2 and 3).

East of the Río Grande de Arecibo, the upper aquifer discharges ground water mainly to springs and coastal wetland areas. West of the Río Grande de Arecibo, the aquifer discharges to wetland areas near the shoreline; nearshore, offshore, and shoreline springs such as those located along the northwest coast of the island (Percious,1971); or to the ocean as seabed seepage. Future investigations could focus on identifying other coastal freshwater springs that may lie offshore. Percious (1971) suggested the possibility of offshore spring discharge at three sites—one near the western end of Punta Peñón, one near the inlet at Hatillo, one near and off the point near the Río Gúajataca (known locally as El tunel).

Contours on the potentiometric-surface maps in this report curve upstream in many interstream areas of the upper aquifer; this indicates that ground water discharges along inland reaches of many rivers and streams. These maps show that ground water discharges from the upper aquifer to upstream reaches of the Ríos Gúajataca, Camuy, Tanamá, Grande de Arecibo, Grande de Manatí, Cibuco, and de la Plata. Near the coast, however, some of these rivers lose streamflow to the upper aquifer by streambed seepage. Streamflow data indicate that the coastal reaches of the Ríos Grande de Arecibo and Tanamá lose water to the upper aquifer during most of the year (Quiñones-Aponte, 1986, p. 26). Simulation of ground-water movement in the lower Río Grande de Arecibo valley indicates that ground water discharges from the upper aquifer along the western limestone channel bank and moves across a highly stratified alluvial aquifer containing water-bearing zones and confining beds. Ground water reenters the upper aquifer along the eastern margin of the alluvial valley (Quiñones-Aponte, 1986, p. 24). Stratification of the alluvial aquifer by clay and silt in the lower reach of the Río Grande de Arecibo valley has resulted in local confinement of the upper limestone aquifer. The movement of water from the aquifer to the river and back into the aquifer and the northward and northeastward direction of regional ground-water flow toward Caño Tiburones are shown in plate 2. The local confinement of alluvium and the underlying upper aquifer also helps explain why lines of equal hydraulic head on the potentiometric-surface maps do not show strong hydraulic interconnection between the upper aquifer and the river. Simulation of ground-water flow near the Río Cibuco indicates that the river could contribute as much as 15 percent of the water that enters the aquifer in that area (Gómez-Gómez and Torres Sierra, 1988).

Ground water does not discharge to the upper reaches of all major rivers that traverse the upper aquifer. For example, water-level measurements and streambed altitude data indicate that discharge is limited along a reach of the Río Camuy. Similar hydrologic conditions could exist along the Río Gúajataca. The Quebrada de los Cedros, which is in the northwestern part of the study area, is an ephemeral stream. The water table in the basin lies below the streambed much of the year. In areas drained by such streams, regional ground-water discharge from the upper aquifer in northwestern Puerto Rico probably is to the ocean or springs, rather than to streams (Guisti and Bennett, 1976, p. 27).

The potentiometric surface of the upper aquifer has one large and one small potentiometric depression (pl. 2). The large depression, which extends over an area of about 14 mi^2, is in the swampy coastal area at Caño Tiburones, which is located between the Ríos Grande de Arecibo and Grande de Manatí. Caño Tiburones is the site of a former shallow brackish water coastal lagoon that accumulated freshwater from adjacent springs and rivers. Under natural conditions, Caño Tiburones drained to the ocean by subterranean caverns and conduits. Before agricultural development of the area (1909), saltwater entered the lagoon during high tides or by up-stream migration during periods of low flow. The large present-day (1980-90) potentiometric low at Caño Tiburones is attributed to agricultural dewatering. Drainage of the area for agriculture contributed to soil shrinkage and land subsidence and gradually lowered the water table to sea level. By 1949, gravity drainage became less effective and a drainage system of canals, laterals, tidal gates, and coastal pump stations had been installed to lower water levels to below sea level. Spring-head levels of 2 ft below sea level in this area have been reported by Zack and Class-Cacho (1984). One major side-effect of lowering the water levels to below sea level was that it reversed the local hydraulic gradient and caused intrusion of seawater into Caño Tiburones. Much of this seawater intrusion was the result of seawater moving into the aquifer through caverns that had previously drained freshwater to the sea. The smaller, but locally significant potentiometric depression (shown in plate 2) is in the Colonia Combate/Colonia Coto Sur area, which is located about 3.8 mi south of Laguna Tortuguero. In 1987, ground-water withdrawals of nearly 2 Mgal/d concentrated in a 2-mi^2 area at this location locally lowered the potentiometric surface below sea level (U.S. Geological Survey, unpub. data, 1993). Three pumped wells in this area were abandoned in 1989 because they yielded water with a nitrate-nitrogen concentration that exceeded 10 milligrams per liter. Before 1989, the depression in the potentiometric surface at this site may have been as much as 10 ft below sea level.

Hydraulic conductivity is a measure of the ability of an aquifer to transmit a unit volume of water through a unit area in a unit of time under a unit hydraulic gradient. By definition, hydraulic conductivity is inversely proportional to hydraulic gradient, assuming that the aquifer has isotropic properties and that areal differences in recharge are negligible. Permeability is another way of measuring the ability of an aquifer to transmit water and is equal to the hydraulic conductivity multiplied by the gravitational constant and divided by the density and dynamic viscosity of the water. The steeper the hydraulic gradient, the lower the permeability. Accordingly, the spacing of lines of equal hydraulic head on potentiometric-surface maps may provide some insight to the change in permeability within an aquifer. However, this type of analysis needs to be further qualified. The effect of streams on the potentiometric surface can mimic the effect caused by a reduction in hydraulic conductivity. Similarly, the effect of high rates of recharge on the potentiometric surface can resemble the effect caused by an increase in vertical anisotropy. Therefore, knowledge of local hydrologic conditions is required before one can infer areal variations in permeability from the spacing of lines of equal hydraulic head.

Potentiometric-surface contours for the upper aquifer in interstream areas of the upper reaches of river basins are closely spaced and the hydraulic gradient is steep. This might indicate a lower permeability within the aquifer in these areas. In coastward areas east of Río Grande de Arecibo, potentiometric-surface contours are widely spaced, the hydraulic gradient is low, and the potentiometric surface is nearly flat. This might indicate that the permeability of the aquifer in this area is high. Also, the potentiometric surface of the upper aquifer has a steeper hydraulic gradient in middip and coastward areas to the west of the Río Grande de Arecibo than in similar areas to the east. This may indicate that permeability of the upper aquifer is lower to the west of the river than in similar areas to the east.

Lower aquifer

The lower aquifer is exposed as a 2- to 7-mi-wide band along the southern one-third of the North Coast ground-water province. The lower aquifer is recharged by infiltration of precipitation through soil cover or as runoff that enters the aquifer through numerous sinkholes, solution trenches (zanjones), and dry streambeds in the outcrop areas. The predevelopment and 1987 potentiometric-surface maps for the lower aquifer shown in this report indicate that the principal areas of recharge are in topographically elevated interstream areas where the aquifer crops out. Much of the water that enters the shallow part of the flow system moves to the principal north-flowing rivers and some water enters deeper confined parts of the flow system. Many areas where the potentiometric surface is elevated are located along the northern boundary of the outcrop belt. Other areas where the potentiometric surface is elevated are located downdip in areas where the lower aquifer is in the shallow subsurface (pls. 3, 4). The elevated potentiometric surface in these areas indicates that the lower aquifer is probably recharged by the downward leakage of water from the upper aquifer through a leaky confining unit.

The leaky character of the confining unit at the outcrop and in shallow subsurface areas is possibly due to two geologic factors. Poorly permeable clay, marl, and mudstone of the Cibao Formation that comprise the downdip confining unit are interbedded with permeable sand, conglomerate, and limestone in updip areas. The second geologic factor relates to the poorly defined fracture system mentioned above. In areas where the lower aquifer is near the subsurface, fractures enhanced by dissolution tend to increase the hydraulic conductivity. These features are less numerous and generally smaller where the aquifer is more deeply buried. The confining unit is entirely absent at outcrop between the Ríos Grande de Arecibo and Grande de Manatí due to facies change. Here, the clay, marl, and mudstone confining unit grades to the Montebello Limestone Member that forms part of the lower aquifer. However, the effectiveness of the confining unit can be readily demonstrated in middip and downdip areas where the difference between potentiometric heads of the upper and lower aquifers locally exceeds 300 ft.

Areas where the potentiometric surface of the lower aquifer is low generally coincide with principal stream valleys and north-flowing rivers. The upstream V-contour pattern of potentiometric-surface contours in both predevelopment and 1987 potentiometric-surface maps (pls. 3, 4) indicates that the lower aquifer discharges water upward to shallower units in the major river valleys. Large potentiometric lows associated with major river valleys probably coincide with areas where the middle confining unit was breached by deep channel incision during Pleistocene sea-level lowstands. Two of Puerto Rico's largest springs (San Pedro and Aguas Fría) are located within the Ríos Grande de Arecibo and Grande de Manatí potentiometric lows. Southwestward movement of ground water to the Río Culebrinas indicates that this river is a major area of discharge from the lower aquifer in the outcrop belt (pl. 3). Ground water from the lower aquifer also discharges to the Ríos Limon, Cialitos, Manvilla, and Mucarabones in the outcrop belt. Although these rivers receive discharge from the lower aquifer, the amount of ground water discharged is not considered to be significant in terms of the total ground-water budget.

In the Ríos Grande de Arecibo/Grande de Manatí area, ground-water movement in the deeper confined parts of the flow system is coastward along a circuitous path to the principal river drains. East of the Río Grande de Manatí some ground-water flows eastward toward the Levittown and Metropolitan San Juan area. Recent test drilling indicates that the upper aquifer is thin or absent in the Metropolitan San Juan area and that the confining unit (Cibao Formation) overlying the lower aquifer is leaky (pl. 1). The pattern of regional ground-water flow indicates that the San Juan area may be a site of regional discharge from the lower aquifer. However, surficial deposits in the San Juan area form a local confining unit that tends to impede upward leakage. West of the Río Grande de Arecibo, ground-water flow is largely coastward within the lower aquifer; however, some upward ground-water discharge to north-flowing streams is possible. In the westernmost part of the island, ground-water flow is locally westward. Ground-water flow in deep confined parts of the lower aquifer in the northwestern part of the island is poorly understood because of a lack of data. Test drilling near Camuy and Isabella indicates that the stratigraphic and hydraulic nature of the lower aquifer is increasingly complex, and ground water is contained under fragmented, heterogeneous artesian conditions made up of different water-bearing and confining zones that are probably limited in physical extent. Freshwater was encountered at depth in this western area, but facies relations within the Lares Limestone and Cibao Formation suggest strata equivalent to the lower aquifer are poorly permeable.

Ground-water development within confined parts of the lower aquifer is limited to the north-central part of the coastal plain, which extends eastward from the Río Grande Arecibo to the Laguna Tortuguero and southward to Florida and Montebello. This area corresponds to the area where water-level declines in the lower aquifer have been greatest. Generally, little has changed in water levels within the lower aquifer elsewhere, although ground-water withdrawals and possible leakage from wells southwest of the Laguna Tortuguero have locally lowered water levels as much as 125 ft in some wells. The greatest decline in the potentiometric surface was in the area between the Ríos Grande de Arecibo and Grande de Manatí. In 1987, the potentiometric surface in this area was as much as 150 ft lower than estimated predevelopment levels in some wells. This is largely attributed to industrial ground-water withdrawals, mainly from the Montebello Limestone Member near Barceloneta, and the pumping of public water supply wells from equivalent strata near Florida. Upward leakage of water from the lower aquifer around poorly constructed wells in the Barceloneta area have also contributed to a decline in heads (Conde-Costas and Torres-González, written commun.,1990; Conde-Costas, written commun., 1991; Hydro Geo Chem, Inc., 1991).

The hydraulic gradient of the potentiometric surface of the lower aquifer west of the Río Grande Arecibo is relatively steep when compared to the gradient between the Ríos Grande de Arecibo and the Grande de Manatí. This might indicate that the permeability of the lower aquifer is lower to the west of the Río Grande de Arecibo than to the east of the river. The hydraulic gradient between the Ríos Grande de Manatí and Cibuco also is steep which indicates lower permeability within the lower aquifer in this area. Such an interpretation seems to be supported by the facies changes described above and shown in plate 1. Permeable strata that form the lower aquifer (Montebello Limestone Member) grade westward to a less permeable clay and marl of the Cibao Formation lithology and eastward to the poorly permeable unnamed mudstone unit. The hydraulic gradient within the lower aquifer gradually decreases eastward from Río Cibuco to the metropolitan San Juan area; this indicates an increase in permeability as the lower aquifer grades by facies change to the sandier strata of the Mucarabones Sand.

SUMMARY

Potentiometric-surface data of the karstic North Coast limestone aquifer system of Puerto Rico indicate that precipitation recharges the upper and lower aquifers in topographically elevated interstream areas by infiltrating soil cover and surficial deposits or entering as direct runoff into sinkholes, dry valleys, and fracture-controlled solution trenches. Ground water naturally discharges to large rivers, cave systems, springs, wetlands, and the Atlantic Ocean. Ground water also discharges to agricultural drainage canals and wells in the area.

Water that enters the unconfined flow system of the upper aquifer flows northward toward the Atlantic Ocean and discharges to wetlands along the coast; coastal, nearshore, and offshore springs; or the ocean as seabed seepage. The upper aquifer also discharges water to rivers in their headwater reaches and commonly receives recharge from the rivers in its coastal reach. The potentiometric surface of the upper aquifer at Caño Tiburones has been lowered by agricultural drainage of this former brackish water lagoon. Ground-water withdrawals also have locally lowered water levels at some pumping centers.

The lower aquifer is recharged primarily by infiltration of precipitation where the aquifer crops out; it also is recharged by downward leakage in shallow subsurface areas where the aquifer is overlain by a leaky confining unit. Ground water in the lower aquifer flows downgradient toward the coast into confined parts of the system or flows upward along a circuitous path to discharge to major rivers and some second-order springs. Some water also flows eastward toward an area of upward discharge in Metropolitan San Juan. Areas that have a low potentiometric surface in the lower aquifer generally correspond to the large entrenched, alluvial-filled river valleys. Extensive downcutting by north-flowing rivers during Pleistocene sea-level lowstands probably resulted in the incision of deep channels that breached the middle confining unit in some areas. These deep channels were subsequently filled by processes of fluvial aggradation, largely in response to the eustatic rise in sea level. The lower aquifer has been developed for industrial and municipal supplies, primarily in the central part of the North Coast ground-water province. In 1987, ground-water withdrawals from the lower aquifer were estimated to be 13 Mgal/d. Ground-water withdrawals and some leakage from poorly grouted or corroded well casings has locally lowered water levels in the lower aquifer by as much as 150 ft.

REFERENCES

Briggs, R.P., 1961, Geology of Kewannee Interamerican Oil Company test well number CPR-4, *in* Oil and gas possibilities of northern Puerto Rico: Puerto Rico Mining Commission, p. 1-26.

Glover III, Lynn, and Mattson, P.H., 1967, The Jacaguas Group in central-southern Puerto Rico, *in* Cohee, G.V., West, W.S., and Wilke, L.C., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1966: U.S. Geological Survey Bulletin 1254-A, p. 29-38.

Gómez-Gómez, Fernando, 1984, Water resources of the lower Río Grande de Manatí Valley, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 83-4199, 42 p.

Gómez-Gómez, Fernando, and Torres-Sierra, Heriberto, 1988, Hydrology and effects of development on the water-table aquifer in the Vega Alta quadrangle, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 87-4105, 54 p.

Guisti, E.V., 1978, Hydrogeology of the karst of Puerto Rico: U.S. Geological Survey Professional Paper 1012, 68 p.

Guisti, E.V., and Bennett, G.D., 1976, Water resources of the North Coast limestone area: U.S. Geological Survey Water-Resources Investigations Report 42-75, 42 p.

Guzmán-Ríos, Senén, 1988, Hydrology and water quality of the principal springs in Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 85-4269, 30 p.

Hubbard, Bela, 1920, The Tertiary formations of Puerto Rico: Science, new ser., v. 51, p. 395-396.

Hydro Geo Chem, Inc., 1991, Artesian wells in the North Coast Limestone aquifers of Puerto Rico—Observations regarding well leakage and repair: Prepared for General Electric, 32 p.

Jordan, D.G., 1970, Water and copper-mine tailings in karst terrane of Río Tanamá basin, Puerto Rico: U.S. Geological Survey Caribbean District Open-File report, 24 p.

___1977, Drainage pattern and subsurface flow of an isolated karst basin in the Río Tanamá drainage, Puerto Rico, *in* Tolson, J.S., and Doyle, F.L., *eds.*, Karst hydrogeology: International Association of Hydrogeologists Memoirs, v. 7, p. 177-192.

MacLachlan, M.E., Koozmin, E.D., Orndoroff, R.C., Hubert, M.L., and Murdock, C.R., 1992, Stratigraphic nomenclature data bases for the United States, its possessions, and territories: U.S. Geological Survey Digital Data Series DDS-6.

McGuinness, C.L.,1948, Ground-water resources of Puerto Rico: Puerto Rico Aqueduct and Sewer Service, 613 p.

Meinzer, O.E., 1927, Large springs in the United States: U.S. Geological Survey Water-Supply Paper 557, 94 p.

Meyerhoff, H.A., 1975, Stratigraphy and petroleum possibilities of middle Tertiary rocks Puerto Rico--Discussion: American Association of Petroleum Geologists, v. 59, p. 169-172.

Meyerhoff, A.A., Krieg, E.A., Closs, J.D., Taner Irfan, 1983, Petroleum potential in Puerto Rico: San Juan, Puerto Rico, Departamento de Recursos Naturales, 174 p.

Monroe, W.H., 1968, The Aguada Limestone of northwestern Puerto Rico: U.S. Geological Survey Bulletin 1274-G, p. G1-G12.

___1976, The karst landforms of Puerto Rico: U.S. Geological Survey Professional Paper 899, 69 p.

___1980, Geology of the middle Tertiary formations of Puerto Rico: U.S. Geological Survey Professional Paper 953, 93 p.

Moussa, M.T., and Seiglie, G.A., 1975, Stratigraphy and petroleum possibilities of middle Tertiary rocks in Puerto Rico--Discussion: American Association of Petroleum Geologists Bulletin, v. 59, no. 1, p. 163-168.

REFERENCES--Continued

Quiñones-Aponte, Vicente, 1986, Water resources of the low Río Grande de Arecibo Valley: U.S. Geological Survey Water-Resources Investigations Report 85-4160, 38 p.

Percious, D.J., 1971, Submarine spring explorations: northwest coast of Puerto Rico: Mayaguez, Puerto Rico, Water Resources Research Institute, School of Engineering, PR-71-29-1, 48 p.

Rodríguez-Martínez, Jesús, 1990, The hydrogeologic framework of the northern coastal province aquifer system of Puerto Rico, *in* Gómez-Gómez, Fernando, Quiñones-Aponte, Vicente, and Johnson, A.I., *eds.*, Regional aquifer systems of the United States--Aquifers of the Caribbean Islands: American Water-Resources Association Monograph Series 15, p. 5-16.

Seiglie, G.A., and Moussa, M.T., 1984, Late Oligocene-Pliocene transgressive-regressive cycles of sedimentation in northwestern Puerto Rico *in* Schlee, J.S., *ed.*, Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Memoir 36, p. 89-95.

Torres-González, Arturo, and Díaz, J.R., 1984, Water resources of the Sabana Seca to Vega Baja area, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 82-4115, 53 p.

Torres-González, Arturo, and Wolansky, R.M.,1984, Planning report for the comprehensive appraisal of the ground-water resources of the north coast limestone area of Puerto Rico: U.S. Geological Survey Open-File Report 84-427, 32 p.

Torres-González, Sigfredo, 1991, Compilation of ground-water level measurements obtained by the United States Geological Survey in Puerto Rico, 1958-1985: U.S. Geological Survey Open-File Data Report 88-701, p. 163.

Ward, W.C., Scharlach, R.A., and Hartley, J.R., 1990, Controls on porosity and permeability in subsurface Tertiary carbonate rocks of northern Puerto Rico, *in* Gómez-Gómez, Fernando, Quiñones-Aponte, Vicente, and Johnson, A.I., *eds.*, Regional aquifer systems of the United States--Aquifers of the Caribbean Islands: American Water-Resources Association Monograph Series 15, p. 5-16.

Zack, A. L., and Class-Cacho, Angel, 1984, Restoration of freshwater in the Caño Tiburones area, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 83-4071, 33 p.

Zapp A.D., Bergquist, H.R., and Thomas, C.R., 1948, Tertiary geology of the coastal plains of Puerto Rico: U.S. Geological Survey Oil and Gas Inventory Preliminary Map OM-85, scale 1:60,000, *reprinted 1950.*