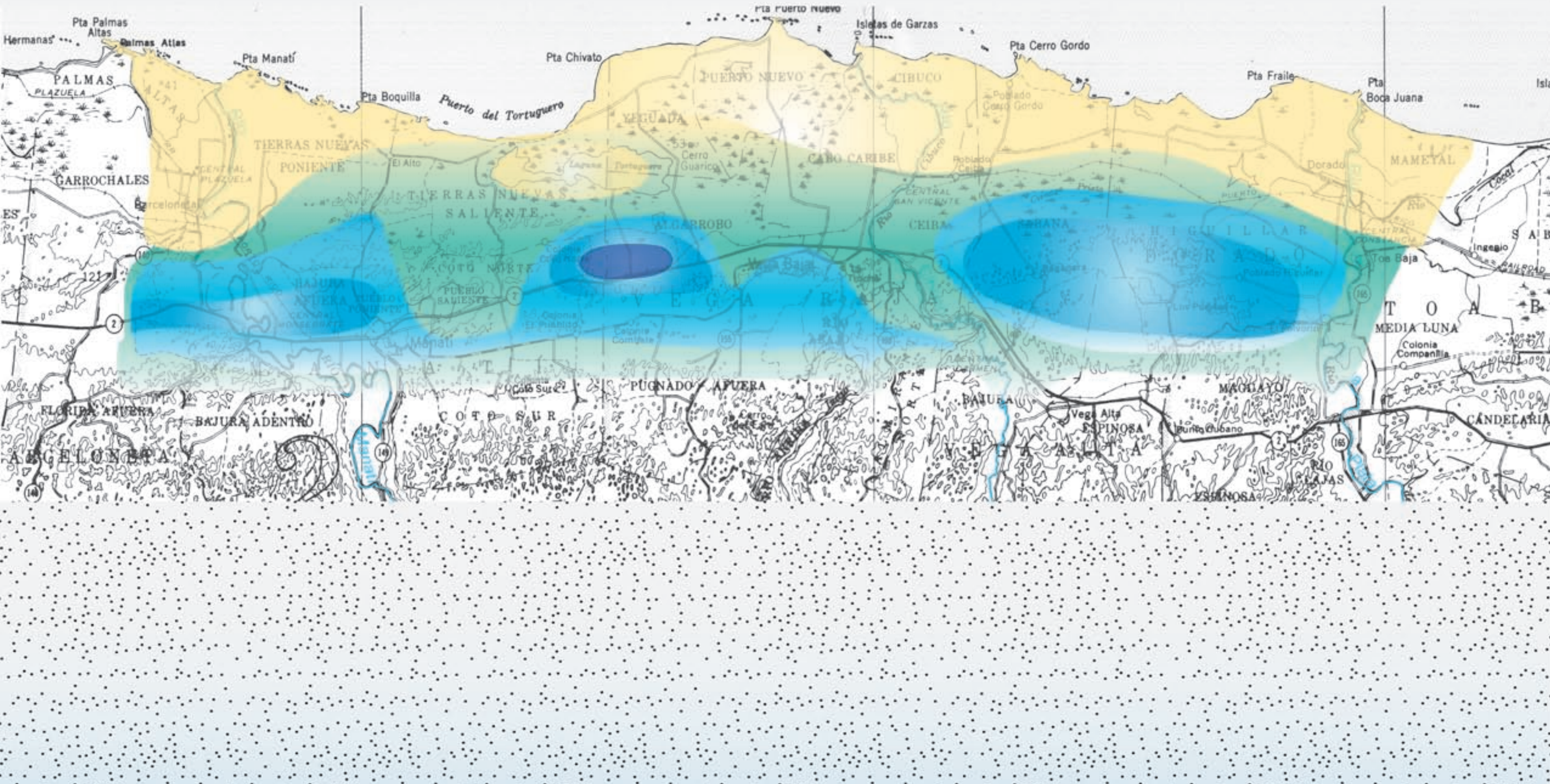
U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
U.S. Environmental Protection Agency

Estimation of the Change in Freshwater Volume in the North Coast Limestone Upper Aquifer of Puerto Rico in the Río Grande de Manatí-Río de la Plata Area between 1960 and 1990 and Implications on Public-Supply Water Availability

Scientific Investigations Report 2007-5194



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Estimation of the Change in Freshwater Volume in the North Coast Limestone Upper Aquifer of Puerto Rico in the Río Grande de Manatí-Río de la Plata Area between 1960 and 1990 and Implications on Public-Supply Water Availability

By Fernando Gómez-Gómez

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Density values are shown in kilograms per cubic meter (kg/m^3), dissolved-solids concentrations are shown in milligrams per liter (mg/L), and specific conductance values are shown in microsiemens per centimeter at 25 °C (µS/cm).

Estimation of the Change in Freshwater Volume in the North Coast Limestone Upper Aquifer of Puerto Rico in the Río Grande de Manatí-Río de la Plata Area between 1960 and 1990 and Implications on Public-Supply Water Availability

By Fernando Gómez-Gómez

Abstract

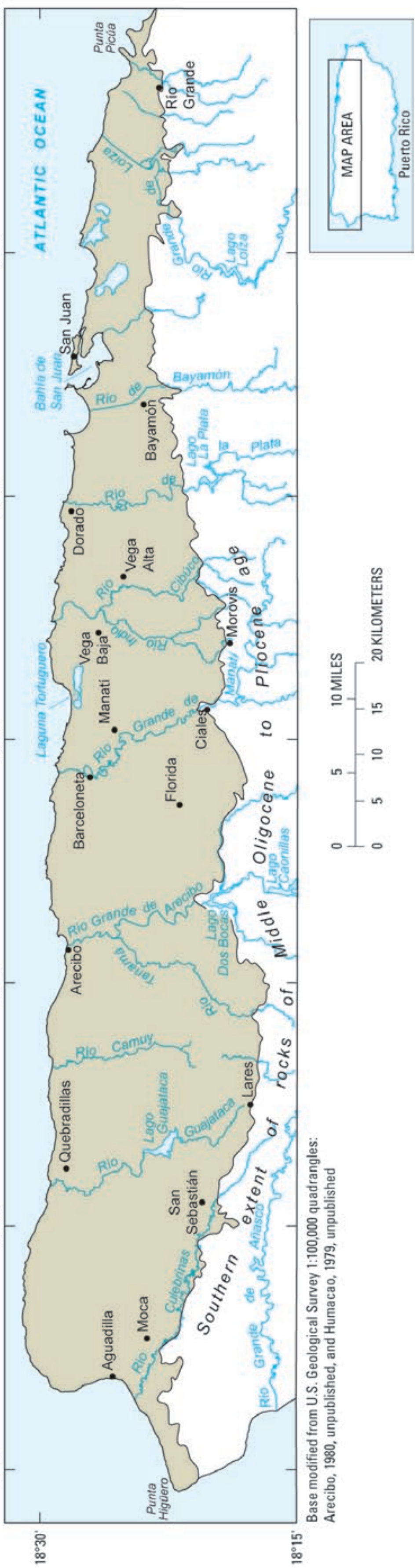
Ground water in the upper aquifer of the North Coast Limestone aquifer system historically has been the principal source of public-supply and self-supplied industrial water use in north-central Puerto Rico. Development of the aquifer for these two major water-use categories began in about 1930; however, withdrawals did not become an important water-supply source for sustaining local development until the 1960s. Ground-water withdrawals averaged about 6 million gallons per day from 1948 to the mid-1960s and peaked at about 33 million gallons per day in the 1980s. Withdrawals have since declined, averaging about 11.5 million gallons per day in 2002. Aquifer contamination by industrial chemical spills and by nitrates from agricultural and domestic sources initially reduced pumpage for public-supply use within localized areas, leading eventually to increased withdrawals at unaffected well fields.

The long-term effect of unconstrained ground-water withdrawals has been a regional thinning of the freshwater lens in an area encompassing 50,600 acres between the Río Grande de Manatí and Río de la Plata, generally north of latitude 18º25’. The effects of aquifer overdraft have been documented in the regional thinning of the freshwater lens, with an increase in dissolved-solids concentration in ground-water wells. Dissolved-solids concentration in public-supply wells were generally between 250 and 350 milligrams per liter during the 1960s, but increased to greater than 500 milligrams per liter in virtually all of the wells by 2000.

Depletion of fresh ground water was estimated at 282,000 acre-feet: 103,000 acre-feet in the Río Grande de Manatí to Río Cibuco area between 1960 and 1995, and 179,000 acre-feet in the Río Cibuco to Río de la Plata area between 1960 and 1992. Thus, aquifer freshwater volume depletion below mean sea level datum may have contributed as much as 38 percent (7.5 million gallons per day) of the 20-million gallons per day average withdrawal rate during the stated time periods. The calculated depletion of aquifer freshwater volume is equivalent to an average long-term rate of 8,400 acre-feet per year. Aquifer withdrawals can be anticipated to decline to about 10 million gallons per day by 2010 at the projected trend of well closures. The lost supply would have to be compensated from surface-water sources because the part of the North Coast Limestone aquifer system south of latitude 18º25’, although less vulnerable to saline-water encroachment, is not as productive.

Introduction

The North Coast Limestone aquifer system is one of the most productive sources of ground water in Puerto Rico and consists of the upper aquifer, a confining unit, and the lower aquifer. The upper aquifer is the principal source of fresh ground water in the five communities of Barceloneta, Manatí, Vega Baja, Vega Alta, and Dorado in north-central Puerto Rico (fig. 1). Over the past century, the upper aquifer has been negatively impacted by large-scale reclamation and construction of drainage projects throughout the region. This problem has been further worsened by aquifer overdraft and increased ground-water withdrawals that have caused degradation of water quality, saline-water encroachment from the coast, and thinning of the freshwater lens.



Base modified from U.S. Geological Survey 1:100,000 quadrangles:
Arecibo, 1980, unpublished, and Humacao, 1979, unpublished

Figure 1. Extent of the North Coast Limestone aquifer system in northern Puerto Rico (modified from Renken and others, 2002).

Development of the upper aquifer as a source of public-supply and self-supplied industrial water use began in about 1930. During the 1940s, withdrawals for these two major water-use categories were estimated at less than 2.5 million gallons per day (Mgal/d), with about 1.5 Mgal/d accounting for public-supply use and 1.0 Mgal/d accounting for self-supplied industrial use. Ground-water withdrawals increased rapidly after the 1960s, reaching a maximum of about 33 Mgal/d during the 1980s. Since that time, withdrawals from the upper aquifer have been declining. Consequently, degradation of ground-water quality from industrial chemical spills (U.S. Environmental Protection Agency, 2004a; 2004b) and nitrate contamination from agricultural and domestic sources (Conde-Costas and Gómez-Gómez, 1999) have reduced the capacity of the upper aquifer to meet the water-supply demands of the five communities in north-central Puerto Rico. Near Barceloneta, the lost production at public-supply wells has been primarily compensated by the construction of new wells (greater than 1,000 feet deep) that penetrate the lower aquifer (also locally referred to as the “artesian aquifer” near the coast). East of Barceloneta, public-supply ground-water production has been compensated primarily by increasing ground-water withdrawals from the upper aquifer at unaffected wells because the lower aquifer is substantially less productive and wells must penetrate the aquifer at depths greater than 2,000 feet.

East of the Río Grande de Manatí, increased pumping at existing wells in the upper aquifer has caused saline-water encroachment, which principally is evidenced by the increases in dissolved-solids, hardness, and chloride concentrations. The increases generally are subtle, and probably a result of upconing of saline water near the freshwater/seawater interface. However, these subtle increases can be discerned by domestic users of the public-supply system in the formation of scale in plumbing fixtures, greater use of detergents, the unpalatable taste of drinking water, stain marks on washed vehicles, and the need to install household water softening units to address the degraded water quality.

Ground-water depletion as a result of sustained pumping has been a major concern in Puerto Rico for many years. To address this concern, the U.S. Geological Survey, in cooperation with the U.S. Environmental Protection Agency, conducted a study to evaluate ground-water withdrawals and the effects on depletion of storage in the upper aquifer in Puerto Rico from predevelopment time to the present. The regional assessment was made for an area in north-central Puerto Rico that encompasses about 50,600 acres, where ground-water withdrawals have been the major source of public-supply water use to an estimated population of about 178,000 people (Molina-Rivera, 2005). The results of the study will provide water managers and others with the necessary information to improve knowledge on ground-water flow in the upper aquifer, especially the relative importance of aquifer recharge, streamflow infiltration, and reduced ground-water flow to natural discharge features.

Purpose and Scope

The purpose of this report is to evaluate the availability of public-supply water in the upper aquifer in north-central Puerto Rico and the changes that have taken place as a result of ground-water withdrawals over the last century. Specifically, this report describes the occurrence of ground water in the upper aquifer, estimates the water balance and spatial thickness of the freshwater lens in the aquifer, documents historical regional changes in ground-water quality in public-supply wells and its relation to the spatial thinning of the freshwater lens, and describes the implications of unconstrained ground-water withdrawals. The water balance of the upper aquifer was estimated by development of numerical models that simulate conditions in the areas between the Río Grande de Manatí and Río Cibuco and between the Río Cibuco and Río de la Plata. The historical record was evaluated at an observation well to determine ground-water level trends in the aquifer over time. Average ground-water withdrawal rates from the upper aquifer were determined for the area between the Río Grande de Manatí and the Río de la Plata by decade from the 1940s to 1990s (and estimated for 2002). Maps were constructed using various sources of literature and data to estimate the regional spatial thickness of the freshwater lens in the upper aquifer for pre-development and post-development assuming static equilibrium will be reached. Finally, to evaluate trends in water quality, dissolved-solids concentrations were determined in samples collected from 1950 to 2005 in selected wells that penetrate the upper aquifer.

Acknowledgments

The author is grateful to Ms. Claudia Gutierrez of the U.S. Environmental Protection Agency, Region II, New York, for her interest on this effort as part of the Regional Geographic Initiative Program. Special thanks also is extended to René García formerly of the U.S. Geological Survey, New Mexico Water Science Center, and Sigfredo Torres-González of the U.S. Geological Survey, Caribbean Water Science Center, for their initiative in the development of a ground-water/source-water-protection program in Puerto Rico.

Hydrogeology of the Upper Aquifer

The North Coast Limestone aquifer system consists of a thick sequence of carbonate rocks of Miocene to Oligocene age (fig. 2). This aquifer system, which extends about 90 miles (mi) along the northern coast of Puerto Rico and encompasses an area of almost 700 square miles (mi^2), consists of two aquifers separated by a confining unit (Renken and others, 2002). The confining unit in the middle of the aquifer system is formed primarily by the upper unnamed member of the Cibao Formation (undivided), and a mudstone unit that seems to be present only in the subsurface near Manatí. The mostly unconfined upper aquifer (the focus of this report) primarily consists of the Aymamón and Aguada (Los Puertos) Limestones. The lower aquifer is composed primarily of the Montebello Limestone Member of the Cibao Formation and the Lares Limestone.

Occurrence of Ground Water and Hydraulic Characteristics

The upper aquifer encompasses an area of about 430 mi^2 in northern Puerto Rico, but is most productive between Barceloneta and Toa Baja (fig. 2). In this region, the upper aquifer underlies the coastal area generally northward of latitude 18º24’ and is extensive throughout the alluvial valleys of the lower Río Grande de Manatí, Río Indio, Río Cibuco, and Río de la Plata (fig. 2). Generally, northward of about latitude 18º26’, the upper aquifer exists primarily as a lens of freshwater “floating” above saltwater with aquifer heads varying from about 10 ft to near sea level at the coast (Torres-Sierra, 1985; Conde-Costas and Rodríguez, 1997; Sepúlveda, 1999). Inland from about latitude 18º24’30”, the Aguada Limestone is mostly unsaturated and ground-water flow exists primarily as conduit or thin “sheet-like” flow above the underlying Cibao Formation, which constitutes the relatively impermeable base of the upper aquifer (Bennett and Guisti, 1972). An exception to this condition is to the east of the Río Cibuco, where the Aguada Limestone is saturated and is in hydraulic connection with the underlying Cibao Formation and older carbonate units. The transmissivity of the upper aquifer east of the Río Cibuco in areas inland from latitude 18º25’, however, is less than 200 feet squared per day (ft^2/d) with wells typically yielding less than 50,000 gallons per day (gal/d). Northward from latitude 18º25’, the transmissivity in the freshwater part of the upper aquifer throughout the region ranges from 10,000 to 150,000 ft^2/d with public supply well yields ranging from 300,000 to 1,500,000 gal/d. In the alluvial valleys, alluvium consists predominately of fine-grained deposits with a low to moderate hydraulic conductivity (less than 30 feet per day (ft/d)), and wells must penetrate the underlying limestone units to obtain yields greater than 150,000 gal/d.

Water Balance of the Upper Aquifer

The water balance of the upper aquifer has been estimated by development of finite-difference digital ground-water flow models tested under transient conditions between the Río Grande de Manatí and Río Cibuco area (Cherry, 2001) and between the Río Cibuco and Río de la Plata area (Gómez-Gómez and Torres-Sierra, 1988; Sepúlveda, 1999). These two sub-areas will be referred to throughout the report as the “western area” for the part of the upper aquifer between the Río Grande de Manatí and Río Cibuco, and the “eastern area” for the part of the aquifer between the Río Cibuco and Río de la Plata. The aquifer models were used to improve estimates of ground-water recharge rates and discharge sinks. The ground-water recharge rates were derived from spatial rainfall runoff infiltration and streamflow seepage. Discharge sinks are represented as aquifer flow to: (1) natural discharge features such as wetlands, streams, and the seabed near the coastline; and (2) man-made modifications to the flow system, such as withdrawals from wells and coastal drainage works. The aquifer flow models were calibrated for near-present conditions, using data that included the spatial distribution of aquifer water levels and water budgets such as discharge rates from wells, outflow from the relatively freshwater Laguna Tortuguero (fig. 1) to the sea, and stream baseflow measurements. Adequate data sets used to develop the digital ground-water flow models were available for the eastern area in 1983 and 1992 and for the western area in 1995. These aquifer models were used to simulate the historical changes of the water table and the effects that ground-water withdrawals for public-supply and self-supplied industrial uses have had on the ground-water flow system (table 1).

Although the developed aquifer models have contributed to improving the knowledge on the occurrence and movement of ground water, the constructed digital flow models had two major assumptions that limit their use to anticipate future changes. Among the most important assumptions used in the digital models developed to date are: (1) a static freshwater-saltwater interface was assumed to be present beneath the freshwater lens for the calibration period used and also throughout the historical simulation periods, which averaged 60 years; and (2) aquifer recharge was assumed to be constant throughout the entire simulation period, although recharge may vary substantially from average, especially during excessively wet years and during years with rainfall deficiency at or

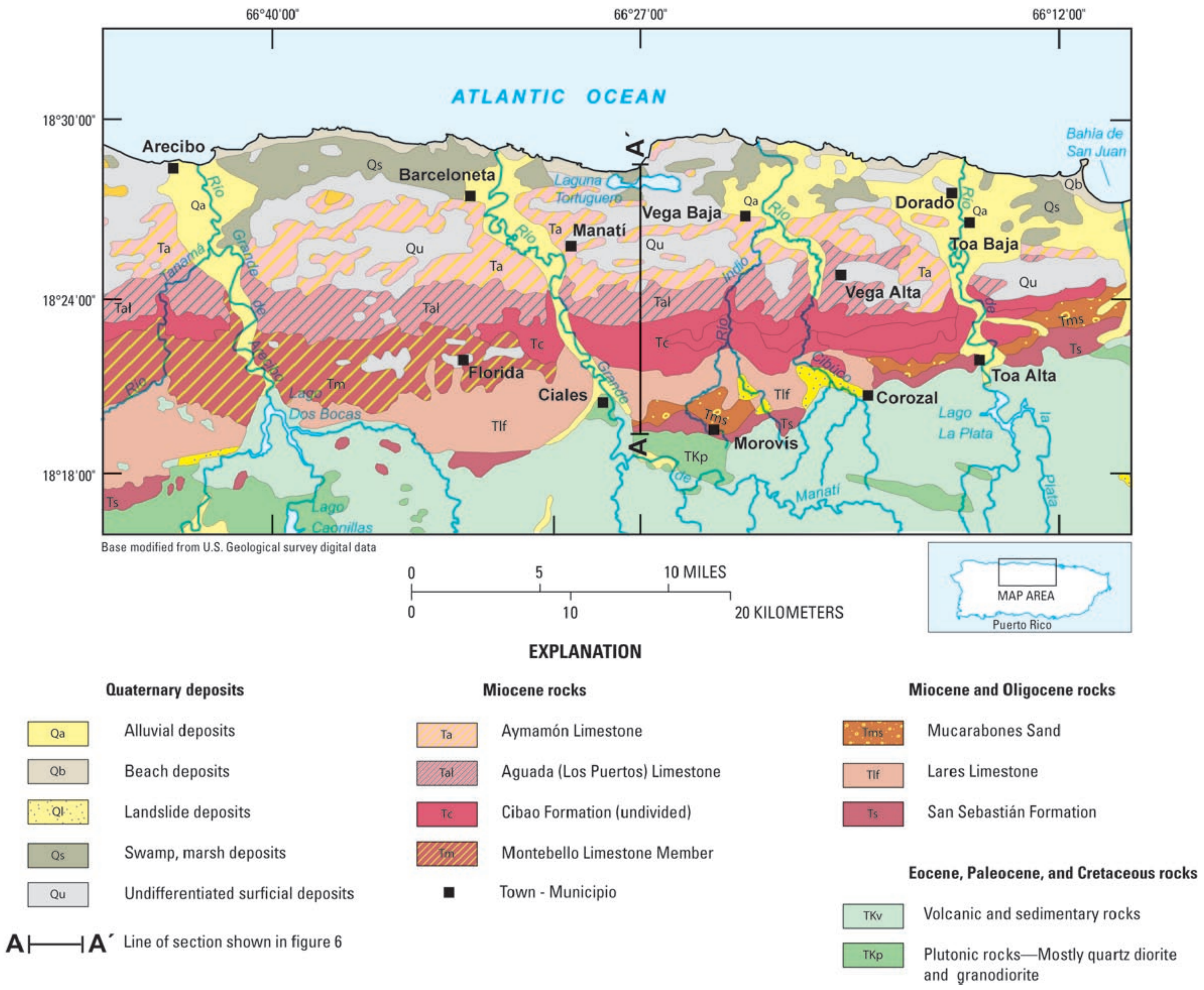


Figure 2. Surficial geology of the North Coast Limestone aquifer system in north-central Puerto Rico and area of study between Barceloneta and Toa Baja, Puerto Rico (modified from Renken and others, 2002).

Table 1. Generalized water budget for the upper aquifer in the area between the Río Grande de Manatí and the Río de la Plata.

[Pre-development water budgets from digital ground-water flow models by Gómez-Gómez and Torres-Sierra (1988) for the eastern area and Cherry (2001) for the western area; budget terms rounded to nearest 0.5 cubic feet per second (ft^3/s); acre-ft/yr, budget terms expressed in acre feet per year. Budget terms for the end of simulation of transient models: 1983 for the eastern area and 1995 for the western area; for the eastern area budget terms at end of 1983 assumed valid also for early 1990s. Budget terms at end of transient simulations were at new steady-state conditions, no significant change in storage.]

Recharge to aquifer from:	**Pre-development (prior to about 1940), in ft^3/s (acre-ft/yr)**	**Post-development (estimate for conditions in early 1990s), in ft^3/s (acre-ft/yr)**
Rainfall/runoff from inland of latitude 18° 25'	1.5 (1085)	1.5 (1085)
River infiltration		
Río Grande de Manatí	2.5 (1810)	7.5 (5430)
Río Cibuco and Río Indio	1 (725)	6 (4340)
Río de la Plata	0	0
Areal rainfall/runoff infiltration	55 (39,800)	55 (39,800)
Total recharge to aquifer	60 (43,420)	70 (50,670)
Discharge from aquifer to:		
Wetlands		
Laguna Tortuguero	4 (2890)	3 (2170)
Cienaga Prieta	15 (10,860)	3 (2170)
Caño Las Pozas & Cabo Caribe	5 (3620)	3 (2170)
Coastal springs	16 (11,580)	7 (5070)
Streams		
Río Grande de Manatí	7.5 (5430)	5 (3620)
Río Cibuco and Río Indio	6.5 (4700)	2 (1450)
Río de la Plata	3 (2170)	1 (725)
Atlantic Ocean	3 (2170)	1 (725)
Ground-water withdrawals	0	45 (32,570)
Total discharge from aquifer	60 (43,420)	70 (50,670)

greater than 20 percent of the 30-year normal rainfall. Drought years in this region typically have had rainfall deficits from 20 to 34 percent below the 30-year normal (fig. 3).

The consequence of using a constant-density transient freshwater model with a static freshwater-seawater interface is that the final change in freshwater volume of the aquifer after development and a new static equilibrium is achieved would show change in storage from water-level decline, but would not show the change in volume of freshwater in the aquifer. It is important to note that it may take 100 years for the new static equilibrium to be achieved; however, deteriorating water-quality conditions may occur well before the freshwater-seawater interface reaches a new static equilibrium as evidenced from the total dissolved solids data. The consequence of assuming a constant aquifer recharge rate is that aquifer recharge equal to or greater than that occurring during an average rainfall year can take place within short time periods. Examples of intense rainfall that occurred in north-central Puerto Rico include: a stalled cold front during December 11-15, 1981, and the passage of Hurricane Hortense during September 9-10, 1996. The cold front contributed between 14 and 26 inches (in.) of rainfall —equivalent to 20 and 40 percent, respectively, of the mean annual rainfall— along the part of the upper aquifer under consideration in this study, causing ground-water levels to rise by as much as 8 ft. The hurricane contributed from 8 to 12 in. of rainfall, causing ground-water levels to rise by as much as 3 ft (Gómez-Gómez, 1997). During above-average rainfall years (rainfall greater than 60 in. along the coast and 70 in. at inland parts of the upper aquifer), aquifer discharge to natural discharge features, such as wetlands, and to wells is more than compensated by recharge, and loss of aquifer storage is either insignificant or reversed.

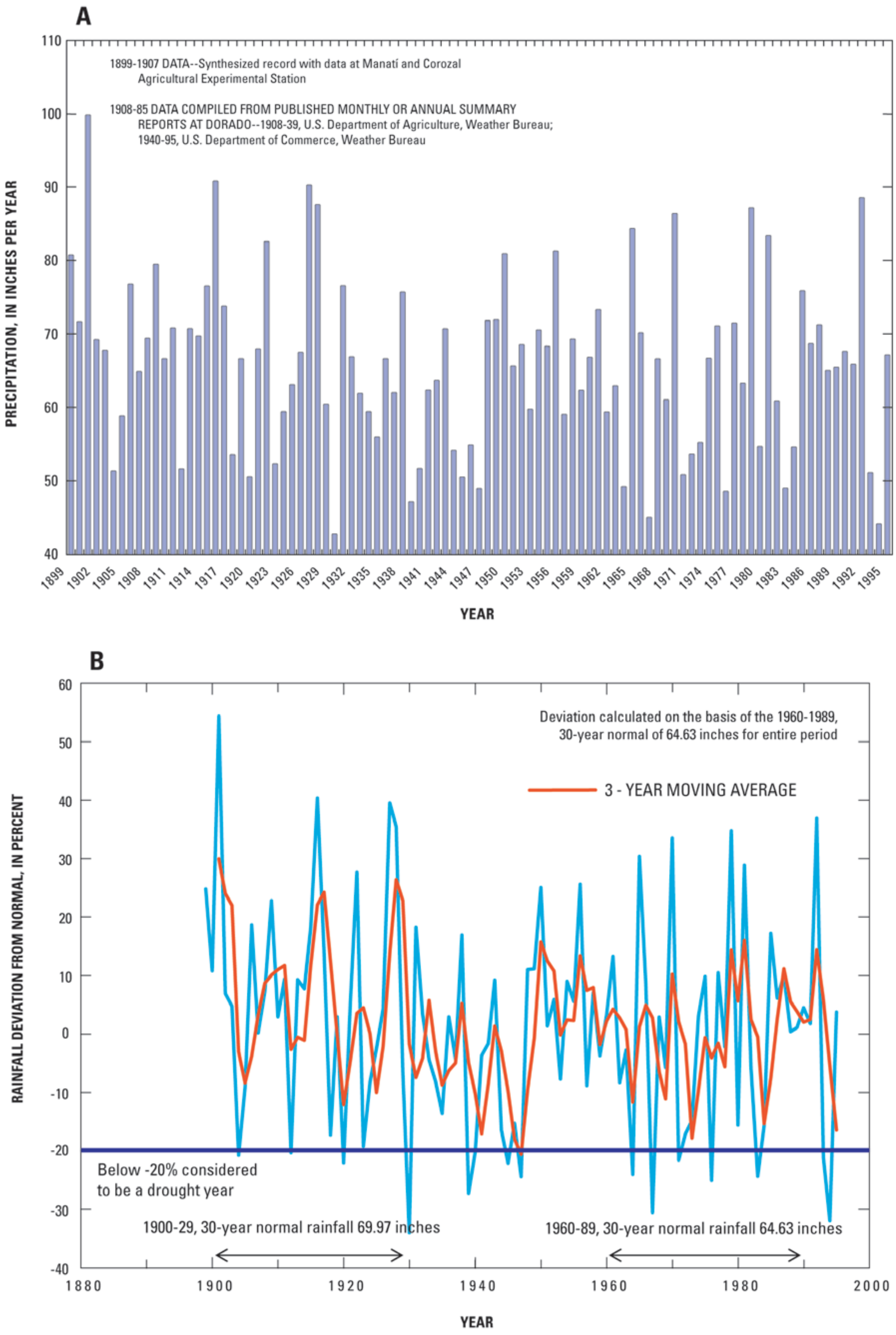


Figure 3. (A) Long-term annual rainfall, and (B) annual rainfall deviation at Dorado, Puerto Rico, from the 64.63 inches per year normal for the 1960-89 period.

The opposite condition of little to no aquifer recharge also occurs during drought years. Over the course of the 20th century, 12 drought years were identified in the climatological data records (1899-95) from the U.S. Department of Agriculture and the U.S. Department of Commerce weather bureaus near Dorado (fig. 3). The precipitation data also indicate two periods when the annual rainfall amount was substantially below average during 3 consecutive years: a 3-year period ending in 1946 and another 3-year period ending in 1973. The moving average for both 3-year periods indicates an average rainfall deficit of 18 percent below the 1960–89 normal rainfall amounts of 64.63 in. Because aquifer discharge is not compensated by recharge during drought years, aquifer discharge to natural systems (primarily wetlands) and to wells in this region is mostly derived from depletion of aquifer storage. The loss of aquifer storage that sometimes occurs may be replenished by wetter-than-average years, as can be inferred from the long-term trend of rainfall near Dorado and the annual minimum ground-water levels in the Sabana Hoyos observation well between 1960 and 2000. This well provides the longest continuous historical record of change in aquifer ground-water levels in the Dorado-Vega Alta area (fig. 1), with levels declining from about 12.5 ft above mean sea level in 1960 to about 7 ft above mean sea level in 2001 (fig. 4).

The water-level record in the Sabana Hoyos observation well indicates that the water table had been relatively unchanged between 1948 (earliest water-level measurements at this station) to about the mid-1960s, when ground-water withdrawals in the eastern area averaged about 4 Mgal/d (fig. 5). After the mid-1960s, total withdrawals increased to about 33 Mgal/d in the 1980s and declined to about 27.5 Mgal/d during the 1990s. Although, coastal dewatering works may have been the initial cause of a lowering of the water table in coastal areas such as in the vicinity of Laguna Tortuguero prior to the 1960s (Bennet and Giusti, 1972) and in the coastal wetlands in the Dorado-Vega Alta area in the early 1960s (Gómez-Gómez and Torres-Sierra, 1988) in general, most of the decline can be ascribed to regional aquifer overdraft (Conde-Costas and Rodríguez, 1997; Cherry, 2001; and Gómez-Gómez and Torres-Sierra, 1988).

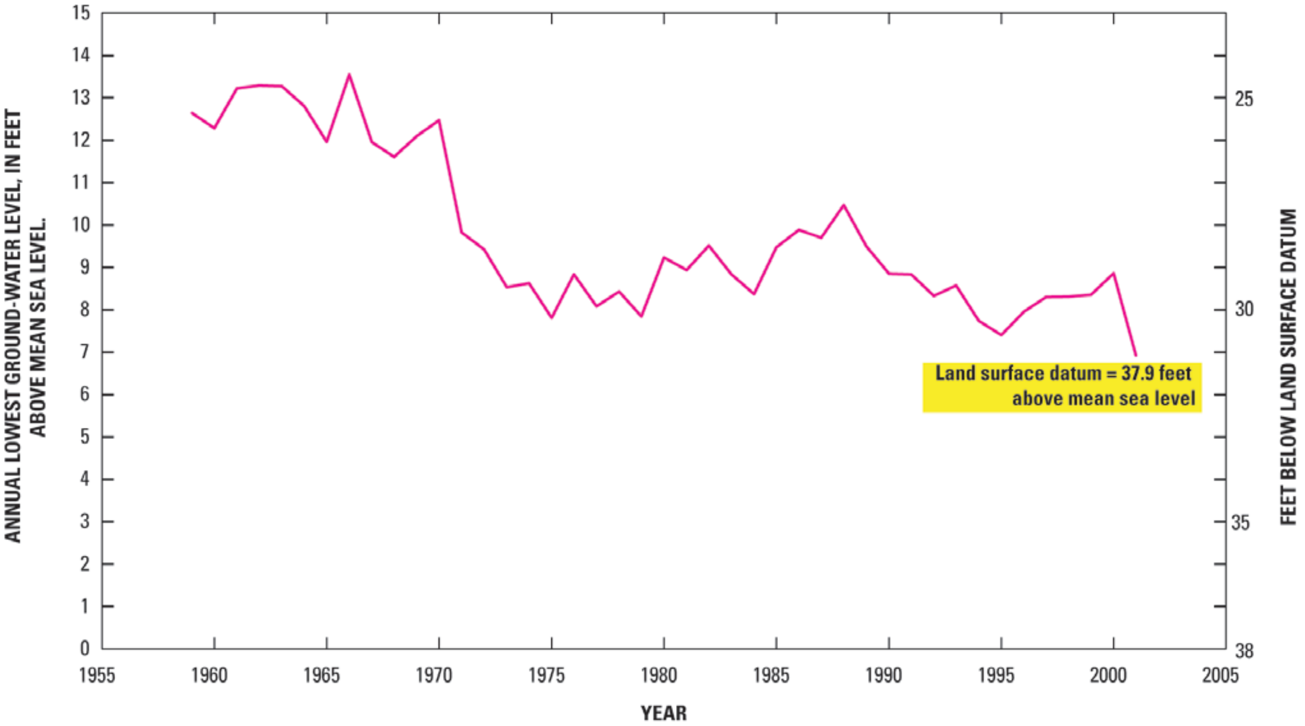


Figure 4. Annual minimum ground-water levels and trend at the Sabana Hoyos 2, Vega Alta, observation well. This well is considered representative of the ground-water level trend in part of the upper aquifer between the Río Cibuco and Río de la Plata area.

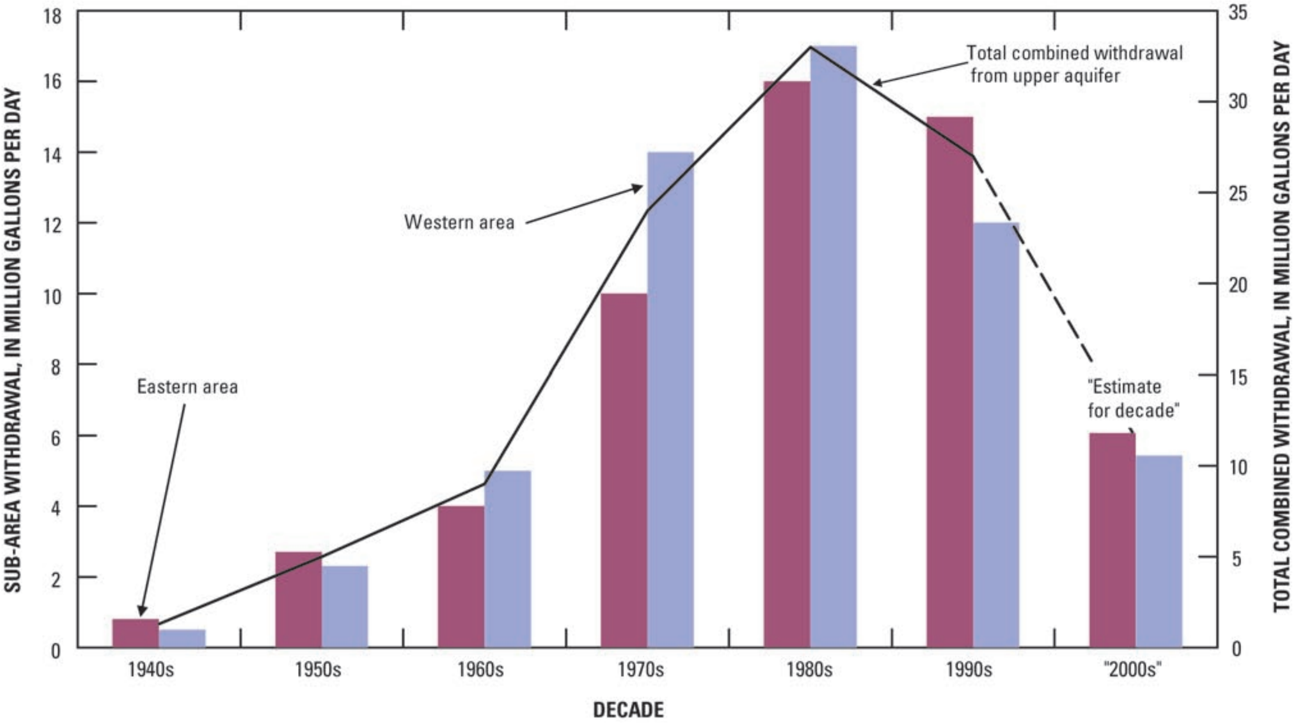


Figure 5. Ground-water withdrawal rates from the upper aquifer between the Río Grande de Manatí and Río Cibuco (western area) and between the Río Cibuco and Río de la Plata (eastern area). Average by decades from the 1940s to 1990s and estimated for 2000s.

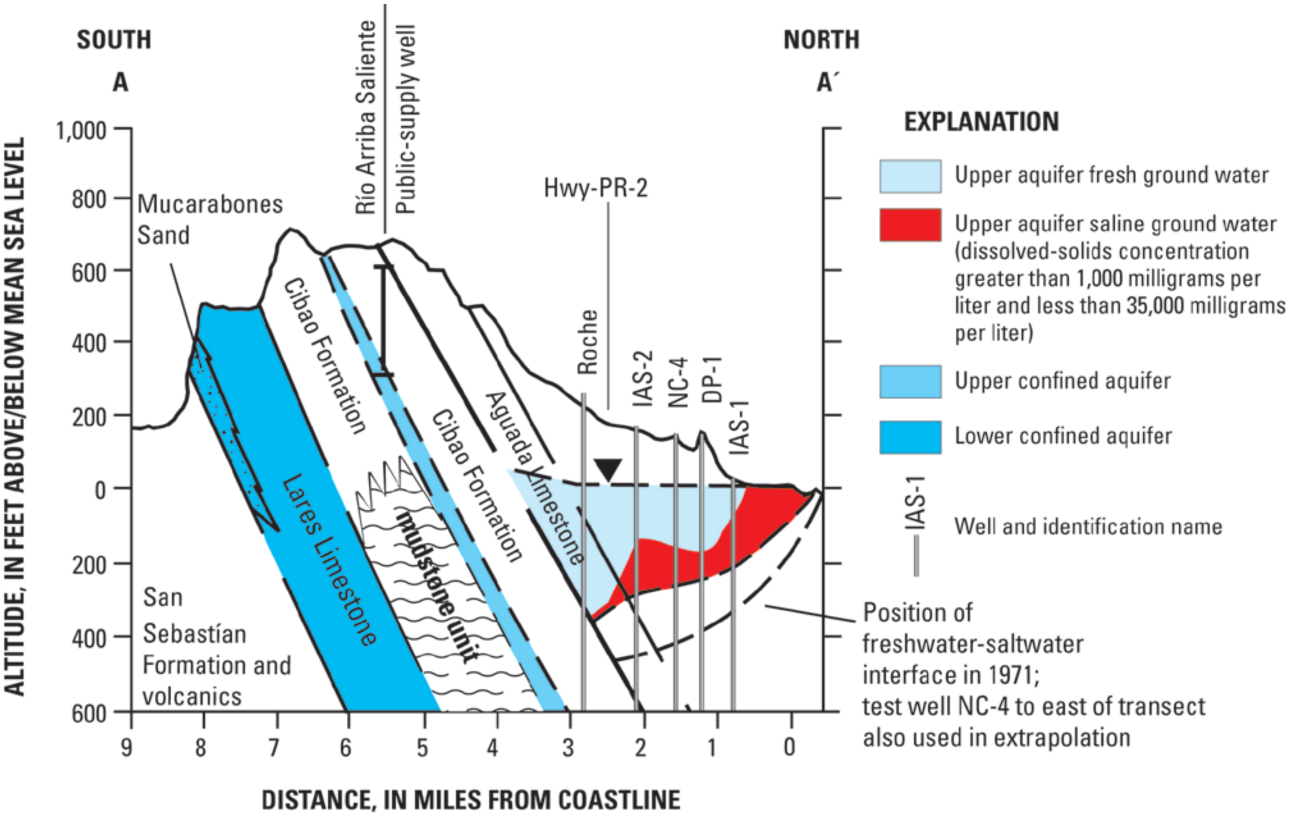


Figure 6. Change in the thickness of the freshwater lens in the upper aquifer near Manatí along longitude 66°27′ from 1971 to 1987 (modified from Conde-Costas and Gómez-Gómez, 1999). The test wells are located in the vicinity of Laguna Tortuguero near Manatí. Location of the line of section is shown in figure 2.

Because most of the potable water in the upper aquifer exists as a lens of freshwater “floating” above saltwater, the thickness of the lens has diminished in an amount that can be estimated by the Ghyben-Herzberg relation (described in the next section), which is used to predict the thickness of a freshwater lens in a homogeneous (isotropic) porous media (Fetter, 1980). In the vicinity of Laguna Tortuguero, the freshwater lens was found to be as much as 400 ft thick in 1971, when wells were first drilled to tap confined aquifers at depth, but was only 165 ft thick in 1987 when the U.S. Geological Survey conducted test drilling in the area (Rodríguez-Martínez and others, 1992) (fig. 6).

Estimated Spatial Thickness of the Freshwater Lens Pre- and Post-Development

The regional thickness of the freshwater lens in the upper aquifer can be estimated at specific locations by use of the Ghyben-Herzberg relation (Fetter, 1980):

$$b = h + z$$

$$z = \left(\frac{e_f}{e_s - e_f} \right)$$

where,

b is the thickness of the freshwater lens, in feet;

h is the altitude of the water table above mean sea level, in feet;

z is the depth to the saltwater interface below mean sea level, in feet;

e_f is the density of freshwater, in kilograms per cubic meter; and

e_s is the density of saltwater, in kilograms per cubic meter.

The Ghyben-Herzberg relation is valid for systems in static-equilibrium. It may take hundreds of years for the freshwater-seawater interface to reach equilibrium after a water-level change. For the purposes of estimating the thickness of the freshwater lens in 1960 and 1990, static equilibrium is assumed. The 1960 map was considered to represent the estimated thickness of the freshwater lens for pre-development conditions and the 1990 map to represent post-development conditions.

The assumption is made that water levels will remain lower at post-development for a long enough period, so that a new static equilibrium of the freshwater-seawater interface is achieved. In cross-sectional variable density simulation of the high permeability, carbonate Biscayne aquifer in south Florida, it took 50 years for the freshwater-seawater interface to move inland and reach a new static equilibrium given a 1-ft lowering in canal stage boundary and 90 years for the freshwater-seawater interface to move out and reach a new equilibrium after a 1-ft rise in canal stage boundary (Dausman and Langevin, 2004).

Although the Ghyben-Herzberg relation assumes that the change in water level has occurred for a long enough period of time that a new static-equilibrium has been achieved, 30 years may not be enough time for a new static equilibrium in the area of study. However, this equation provides a good approximation of the thickness of the freshwater lens ground water with dissolved-solids concentrations less than 1,000 milligrams per liter (mg/L)–by assuming density values of 1,000 kilogram per cubic meter (kg/m^3) for e_f, and 1,025 kg/m^3 for e_s or that typical of seawater. Potentiometric-surface and specific conductance data obtained during drilling of test wells, which penetrated the freshwater-saltwater transition zone in the upper aquifer in 1986-87 (A. Torres-González and others, U.S. Geological Survey, written commun., 1987), 1993-95 (Troester, 1999; Sepúlveda, 1999), and U.S. Geological Survey, Caribbean Water Science Center records (fig. 7), indicated the following:

(1) The fresh-to-saline transition zone was only tens of feet thick;

(2) Although aquifer development in 1960-86 caused a substantial upward displacement of the interface in the coastal area to the south of the Laguna Tortuguero, the transition zone in saline ground water with dissolved-solids concentrations ranging between 1,000 and 5,000 mg/L was also only tens of feet thick; and

(3) The depth at which the specific conductance in ground water was about 1,800 microsiemens per centimeter at 25 °C (µS/cm) (or equivalent to a dissolved-solids concentration of about 1,000 mg/L in the upper aquifer) could be predicted by assuming values as indicated for e_f and e_s.

The absence of a substantially thick freshwater-saltwater transition zone in the study area indicates that possibly, as a result of the high transmissivity in the upper aquifer and withdrawals never exceeding the mean annual recharge rate for an extended period of time (decades), the ground-water flow pattern has not been greatly modified in the horizontal plane to cause a diffuse freshwater-to-saltwater transition zone in the vertical axis in the order of hundreds of feet. Diffuse transition zones in the order of hundreds of feet were observed at several of the test wells and only where dissolved solids concentrations exceeded 5,000 mg/L as shown in figure 7.

Various sources of data were used to construct a map and estimate the thickness of the freshwater lens for aquifer conditions in the western area (Río Grande de Manatí to Río Cibuco) and in the eastern area (Río Cibuco to Río de la Plata) prior to large-scale development in the 1960s (about 1960) (fig. 8A). These

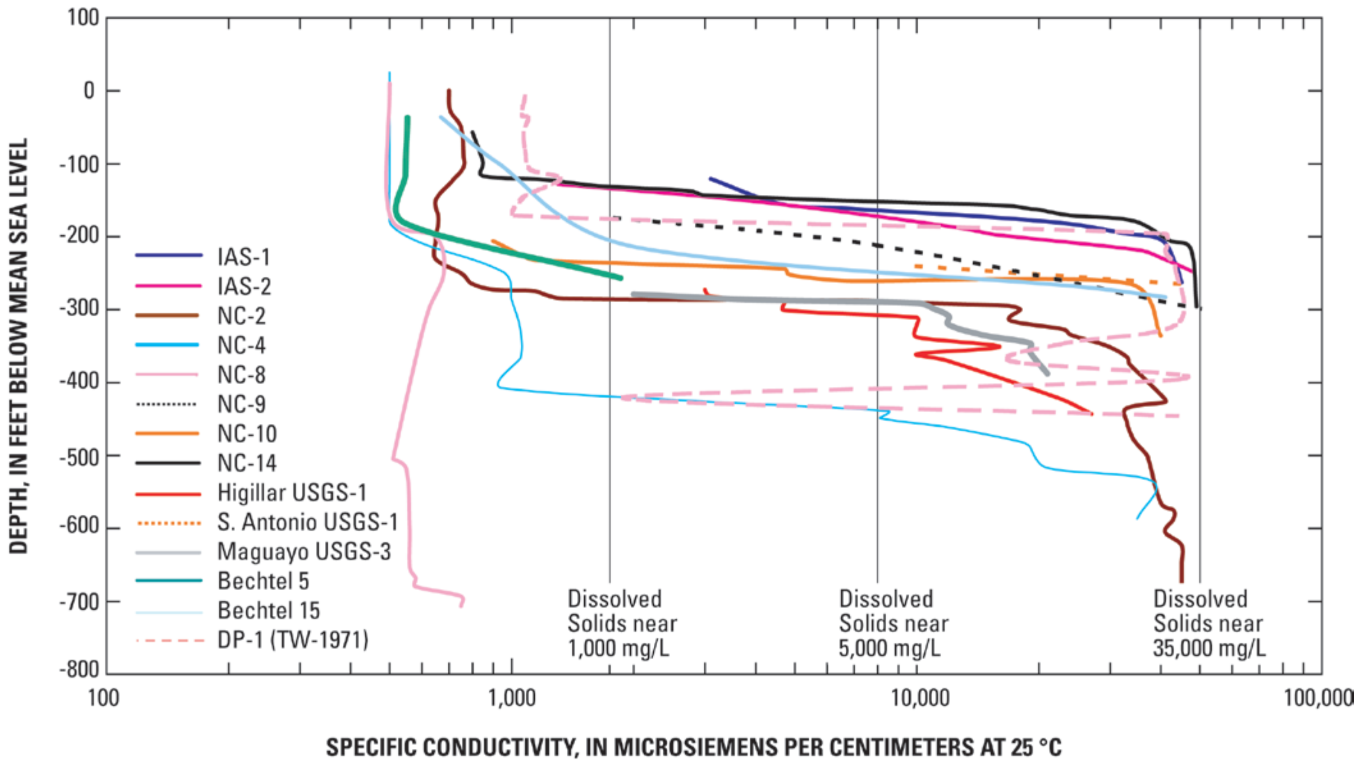


Figure 7. Specific conductivity variation with depth during test well drilling in upper aquifer (refer to table 2a and 2b and figure 2A and 2B for site locations).

sources include: direct-current surface resistivity surveys in the Río Grande de Manatí lower valley (Gómez-Gómez, 1984), water levels from well completion reports provided by drillers (in U.S. Geological Survey, Caribbean Water Science Center files), and surface-water altitude in coastal wetlands (from the 1:30,000 scale U.S. Geological Survey quadrangles originally developed at a scale of 1:10,000) (table 2A). A second and similar map (fig. 8B) representing conditions in the 1990s (about 1990) was developed from: (a) available potentiometric-surface maps, prepared with third-order leveling to wells in the western area for conditions in 1995 (Conde-Costas and Rodríguez, 1997), and the eastern area for conditions in 1992 (Sepúlveda, 1999) (table 2B); and (b), drilling logs documenting the change of specific conductivity with depth for test wells drilled to depths beneath freshwater (specific conductivity greater than 1,800 µS/cm at 25°C; fig. 7). Since the historical variation of water levels in the study area has only been documented from stage changes in Laguna Tortuguero in the western area and at a well (USGS Sabana Hoyos 2 observation well) in the eastern area no effort was made to estimate the storage change in the aquifer caused by water-level lowering between pre- and post-development conditions.

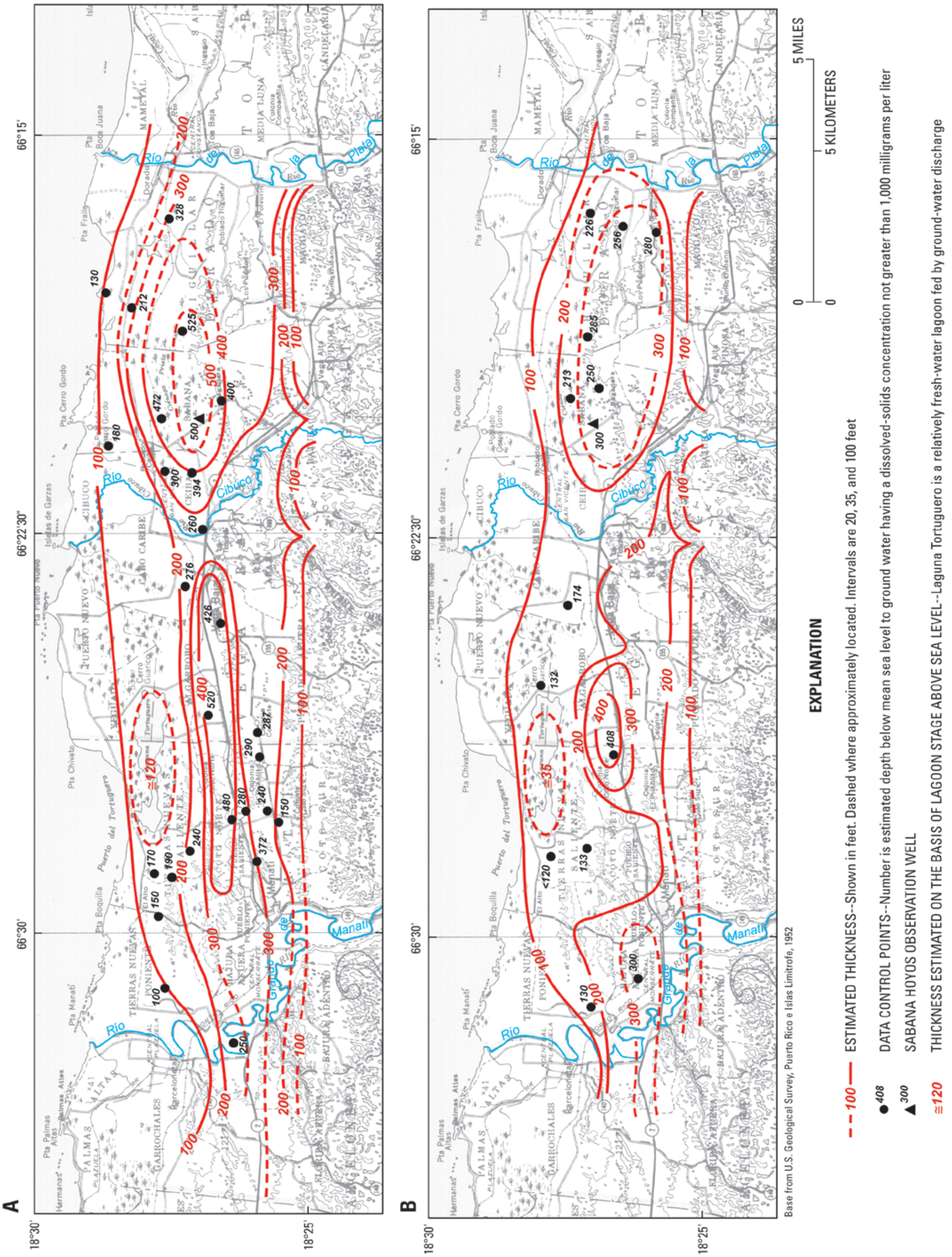
A calculation of the amount of fresh ground water available in the aquifer below sea level datum was made using a porosity of 0.10 (Ward and others, 1991; Gómez-Gómez, 1997). Freshwater volume depletion was calculated using a Geographic Information System (GIS) from a triangular irregular network (TIM) prepared at a scale of 1:20,000 showing the estimated thickness of the freshwater lens for pre- and post-development conditions. For comparison purposes the volumes were also estimated using the frustum pyramid formula given below:

$$V = 1/3\ [A_1 + A_2 + (A_1A_2)^{1/2}](h),$$

where,

V is the volume
A_1, A_2 are surface areas of upper and lower boundaries of prism, and
h is the difference in height (depth) between layers

Volume calculations using the frustum pyramid formula for pre-development conditions were higher than that obtained by use of a GIS. In the western area volume calculations were 10.3 percent higher [574,000 acre-feet (acre-ft) by frustum pyramid formula versus 515,000 acre-ft by GIS] and 6.6 percent higher in the eastern area [498,000 acre-ft by frustum pyramid formula versus 466,000 acre-ft by GIS]. The estimated total volume of freshwater in the aquifer contained below mean sea level datum for post- development conditions in the western area was 412,000 acre-ft by GIS and 460,000 acre-ft by the frustum pyramid formula (10.4



Base from U.S. Geological Survey, Puerto Rico e Islas Limitrofe, 1952

Figure 8. Estimated thickness of the freshwater lens in the upper aquifer between Río Grande de Manatí and Río de la Plata area in about (A) 1960 and (B) 1990.

Table 2a. Locations used in development of the estimated thickness map of the freshwater lens for pre-development conditions.

[m/d/yr, month/day/year; land surface datum and water level values to one decimal point of significance does not necessarily indicate precision of site altitude; altitudes from topographic maps;---, for site locations refer to figure 2A in conjunction with saline water depth and coordinates given in table.]

Well name or location	Latitude	Longitude	Land surface datum, feet NGVD29	Water level, in feet below land surface datum	Water level date m/d/yr	Water level, in feet mean sea level	Saline water depth, below mean sea level feet	Comment
	NAD 27							
Estación Dorado	182720	661626	8.2	---	---	8.2	328	Altitude of marsh in 1:30,000 topographic map, maximum 2.5 meters, revision 1953
Dorado Airport	182804	661735	62.3	57	10/28/1941	5.3	212	
Marsh to north of Forestal	182714	661805	13.1	---	---	13	525	Maximum altitude in marsh 4 meter, 1:30,000 topographic map, revision 1953
Dorado Beach pool well	182838	661815	---	---	1958	---	130	Log of well saltwater reported at given depth
Regadera	182623	661951	197	187	2/28/1978	10	400	
Sabana Hoyos well	182647	662019	37.9	25.4	1960	12.5	500	
Cienega Prieta marsh	182738	662023	11.8	11.8	---	11.8	472	Map altitude control point on 1:30,000 topographic map, 3.6 meters, revision 1953
Pennock Garden 1	182751	662045	39.5	35	---	4.5	180	
Marsh at locality of Ceiba	182716	662126	9.8	---	---	9.8	394	Maximum altitude 1:30,000 topographic map in marsh 3 meters, revision 1953
Ceiba 1	182656	662216	23	16.5	1931	6.5	260	
Kirk Wink	182704	662311	23	16.1	9/13/1962	6.9	276	
Vega Baja 3 (Criollo)	182644	662404	86.6	76	12/6/1969	10.6	426	
Tortuguero 2	182715	662458	70	57	11/2/1940	13	520	
Pugnado Afuera 3	182555	662618	259.2	252	7/1/1980	7.2	287	
Coto Sur Warehouse	182546	662730	260	254	9/1945	6	240	
Coto Norte 1	182623	662732	165	153	5/1947	12	480	
Alvarez	182732	662828	49	43	1945	6	240	
Vocacional	182605	662833	139.3	130	8/27/1984	9.3	372	
Boquillas	182752	662937	49	---	1980	---	150	Surface resistivity survey; Gómez-Gómez (1984)
Tierras Nuevas	182739	663103	6.7	---	1980		100	Surface resistivity survey; Gómez-Gómez (1984)
Río Grande de Manatí valley	182624	663202	6.7	---	1980		250	Surface resistivity survey; Gómez-Gómez (1984)
Laguna Tortuguero stage	---	---	---	---	1967	3	120	Lagoon stage in 1:20,000 topographic map, revision 1967; stage in lagoon prior to dredging an ocean outlet in 1940 estimated at 5 feet above sea level (Bennett and Giusti, 1972); stage March 1995 at 0.9 foot (Conde-Costas and Rodríguez, 1997)
DP-1 (TW-1971)	182740	662856	92		1971		170	Aquifer impacted since 1940s by dredging of ocean outlet at Laguna Tortuguero and aquifer withdrawals for public-supply water post 1960; saltwater wedge between -200 and -400 feet, freshwater between -400 and -410 feet, saltwater below -410 feet.

Table 2b. Locations used in development of the estimated thickness map of the fresh-water lens for post-development conditions.

[< 120, less than 120 feet, see comments; land surface datum values to one decimal point of significance do not necessarily indicate precision of site altitude; altitudes from topographic maps; ---, for site locations refer to figure 2b in conjunction with saline water depth and coordinates given in table.]

Well name or location	Latitude	Longitude	Land surface datum, feet NGVD29	Drill date	Saline water depth, below mean sea level, feet	Comments
	NAD 27					
IAS-1	182732	662813	33	August 1988	< 120	Ground water near top had dissolved solids of about 1,800 milligrams per liter
IAS-2	182624	662814	148	February 1989	133	
NC-14	182743	662522	18	November 1987	132	
NC-4	182633	662626	108	June-July 1986	408	Land surface datum as 94 feet in Ground Water Site Inventory
NC-2	182701	661822	25	May-June 1986	285	Land surface datum as 29.5 feet in Ground Water Site Inventory
Pieziometer Higuillar USGS 1	182620	661634	39	September 1994	256	
Pieziometer San Antonio USGS 1	182657	661627	19.7	December 1993	226	
Piezometer Maguayo USGS 3	182548	661644	39	February 1995	280	
NC-8	182517	661941	89	November-December 1986	---	No saline water in the upper aquifer
NC-9	182731	662342	12	December 1986	174	
Bechtel 5	182640	661931	153	January 1990	250	
Bechtel 15	182717	661944	32.3	January 1990	213	
Río Grande de Manatí valley	182610	663045	29	1980	300	Surface resistivity survey; Gómez-Gomez (1984)
Río Grande de Manatí valley test well	182652	663117	16.4	1980	130	Gómez-Gómez (1984)

percent difference); and, for the eastern area, 287,000 acre-ft by GIS and 313,000 acre-ft by the frustum pyramid formula (8.3 percent difference). For purposes of this analysis, the GIS volumes are considered more precise. Freshwater volume change for each of the subareas was as follows: from 515,000 to 412,000 acre-ft in the western area, and from 466,000 to 287,000 acre-ft in the eastern area. In summary, the overall freshwater volume depletion below mean sea level datum was from 981,000 acre-ft in 1960 to 699,000 acre-ft in 1990.

Thus, the combined freshwater volume depleted below sea level datum in the aquifer may have constituted the source of about 7.5 Mgal/d (8,400 acre-feet per year (acre-ft/yr)) of the estimated average ground-water withdrawal rate of 20 Mgal/d (22,000 acre-ft/yr) between pre-development and post-development conditions.

Effects of Fresh Ground-Water Volume Depletion in the Upper Aquifer

Deterioration of water quality and unconstrained ground-water withdrawals have detrimentally affected areas of north-central Puerto Rico from Río Grande de Manatí to Río de la Plata (fig. 1). These major effects of ground-water storage depletion in the upper aquifer and the implications on public-water availability are discussed in the subsequent sections of this report.

Deterioration of Ground-Water Quality

Prior to large-scale development of ground-water resources in the upper aquifer, the available historical data on the quality of ground water indicate that it is reasonable to assume dissolved-solids concentrations generally ranged from 250 to 350 mg/L in wells drilled during the 1960s (Román-Más and Ramos-Ginés, 1988). As ground-water development lowered the water table, the freshwater lens thinned, leading to the upward and landward displacement of the freshwater-saltwater interface. Of the two conditions leading to an increase in dissolved-solids concentrations, the regional upward displacement of the freshwater-saltwater interface possibly has been the primary cause of most of the change in dissolved-solids concentrations documented at many wells and at Ojo de Agua spring in Vega Baja (fig. 9). An increase in dissolved-solids concentrations can be inferred from specific-conductance measurements obtained at public-supply wells and Ojo de Agua throughout the years. Specific conductance is directly related to dissolved-solids concentrations. In the upper aquifer, dissolved-solids concentration in ground water can be estimated on the basis of specific conductance as follows:

$$DSS = SC \times 0.58,$$

where

DSS is dissolved-solids sum of constituents, in milligrams per liter; and SC is specific conductance, in microsiemens per centimeter at 25 degrees Celsius.

Based on the historical specific conductance data, dissolved-solids concentrations increased to greater than 500 mg/L in virtually all of the public-supply wells north of latitude 18º26’ in the Río Grande de Manatí to Río de la Plata area by the year 2000 (fig. 9). The closure of some wells used as a potable water source may have been a result of these high dissolved-solids concentrations.

Implications of Unconstrained Ground-Water Withdrawals

Ground-water withdrawals from the upper aquifer in the Río Grande de Manatí to Río de la Plata study area historically have been the principal source of water for public-supply and self-supplied industrial uses. Ground-water withdrawals from the aquifer declined from a peak withdrawal rate of 33 Mgal/d in the 1980s to an average of 11.5 Mgal/d in 2002. After the 1980s, the declines were attributed, in part, to contamination of ground water by organic solvents and nitrates, and encroachment of saline water. Saline-water encroachment caused by aquifer overdraft constitutes a major threat on future use of the aquifer as a source of potable-water supply. Aquifer overdraft has resulted in a decline of the water table by as much as 15 ft and a regionally substantial upward displacement of the freshwater-saltwater interface of as much as 250 ft between about 1960 and 1990. The amount of freshwater removed from aquifer storage below sea level datum within the approximately 50,600 acres of land surface overlying the aquifer north of latitude 18º25’ is estimated at 282,000 acre-ft, assuming an aquifer porosity of 0.10. For comparative purposes this volume is equivalent to almost 10 times the large available storage capacity (28,750 acre-ft) of Lago La Plata in 1998 (Soler-López and others, 2000). Thinning of the freshwater lens below sea level datum contributed an estimated 7.5 Mgal/d of the approximate 20-Mgal/d average long-term mean annual withdrawal rate from the upper aquifer in the study area between about 1960 and 1990. Because most of the withdrawals have been used for public supply, the lost yield will have to be substituted by surface-water sources or expensive, alternative treatment of the ground water to achieve drinking-water standards (U.S. Environmental Protection

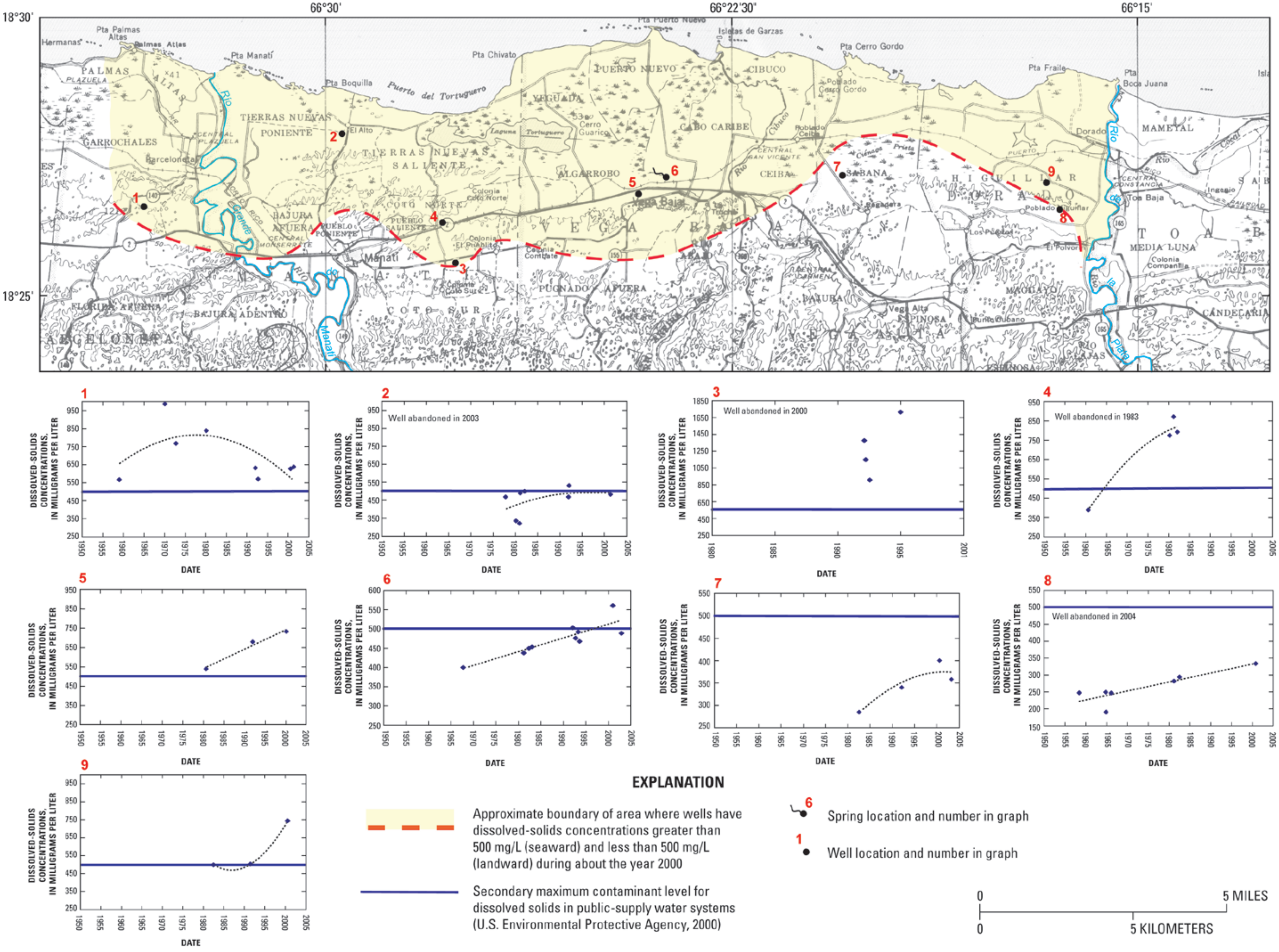


Figure 9. Trend in dissolved-solids concentrations at selected wells and at Ojo de Agua spring in the Barceloneta to Toa Baja area of the North Coast Limestone upper aquifer (from U.S. Geological Survey files, unpublished data).

Agency, 2000). At the estimated rate of freshwater depletion in the aquifer, many of the remaining large-capacity production wells yielding ground water with dissolved-solids concentrations equal to or greater than 500 mg/L probably will be abandoned by 2010, with total withdrawals declining to less than 10 Mgal/d.

Summary

An evaluation was made to determine the effects that ground-water withdrawals have had on the upper aquifer in north-central Puerto Rico (from Río Grande de Manatí to Río de la Plata) during the 20th century and beyond. The upper aquifer, which is part of the more extensive North Coast Limestone aquifer system has historically been the principal source of the public-supply and self-supplied industrial water uses. Ground-water withdrawals for theses two major categories were estimated at less than 2.5 million gallons per day during the 1940s and reached a maximum of about 33 million gallons per day during the1980s. Withdrawals from the upper aquifer have been subsequently declining and can be attributed to aquifer contamination from industrial chemical spills and nitrate contamination from agricultural and domestic sources.

Digital, transient ground-water flow models have been developed to estimate the water balance of the upper aquifer between the Río Grande de Manatí and Río Cibuco (western area) and between the Río Cibuco and Río de la Plata (eastern area). The models helped to achieve improved knowledge on the occurrence and movement of ground water in the region. Two limitations of these flow models to anticipate future changes have been the assumption that: (1) a static freshwater-saltwater interface lies beneath the freshwater lens, and (2) aquifer recharge rate is constant. The consequence of using a constant-density freshwater model with a static freshwater-seawater interface is that the final change in freshwater volume of the aquifer after development and a new static equilibrium is achieved, cannot be estimated, since it would show only the change in volume from water-level decline.

Various sources of data were used to estimate the change in thickness of the freshwater lens below sea level datum for pre- and post-development (between about 1960 and 1990). These data were obtained from published literature, automated data bases, and files of the U.S. Geological Survey, Caribbean Water Science Center, relative to ground-water levels, test drilling, ground-water quality, and ground-water withdrawals. Dissolved-solids concentrations ranged from 250 to 350 milligrams per liter in wells penetrating the upper aquifer during the 1960s and increased to greater than 500 milligrams per liter in virtually all of the public-supply wells by 2000. During the 1960s as ground-water development lowered the water table, the freshwater lens thinned and led to the upconing and landward movement of the freshwater-saltwater interface. The increase in dissolved-solids concentrations may have contributed to the closure of some wells used as a potable-water source. Ground-water withdrawals began on a large scale in the 1960s, peaking to about 33 million gallons per day in the 1980s and declining to about 11.5 million gallons per day in 2002. After the 1980s, the decline in withdrawals was attributed, in part, to contamination of ground water by organic solvents and nitrates and to saltwater encroachment. The depletion of fresh ground water from the freshwater lens below sea level datum may have contributed an estimated 282,000 acre-feet or about 7.5 million gallons per day of the mean annual withdrawal of 20 million gallons per day between pre- and post-development (between about 1960 and early 1990s). The anticipation is that many of the remaining large-capacity production wells yielding dissolved-solids concentrations equal to or less than 500 milligrams per liter will be abandoned by 2010, with total withdrawals declining to less than 10 million gallons per day.

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APPENDIX

Appendix 1. Specific conductivity variation with depth of penetration during test well drilling in upper aquifer.

[Land surface datum from 1:20,000 scale U.S. Geological Survey topographic maps; Specific conductivity in microsiemens per centimeter at 25 degrees Celsius; FW, freshwater (specific conductivity less than 1,800)]

Site identification	Latitude	Longitude	Land surface datum, in feet	Depth below land surface datum, in feet	Specific conductivity	Depth below mean sea level datum, in feet
IAS-1	182732	662813	33	154	3100	-154
				188	4600	-188
				195	7000	-195
				206	15000	-206
				216	24000	-216
				228	32000	-228
				237	40000	-237
				271	43500	-271
				296	45000	-296
IAS-2	182624	662814	148	276	1300	-276
				296	3400	-296
				316	7000	-316
				337	13000	-337
				346	16000	-346
				366	35000	-366
				377	40000	-377
				396	48000	-396
				397	48500	-397
NC-2	182701	661822	25	25	700	-25
				52	705	-52
				75	750	-75
				112	760	-112
				130	760	-130
				150	710	-150
				175	650	-175
				200	660	-200
				230	650	-230
				256	650	-256
				275	750	-275
				290	800	-290
				298	910	-298
				300	1150	-300
				310	1350	-310
				312	7000	-312
				315	9000	-315
				320	16800	-320
				325	18000	-325
				340	17000	-340
				352	23000	-352
				360	24000	-360
				375	29500	-375
				390	33000	-390
				400	33500	-400
				420	36500	-420

Appendix 1. Specific conductivity variation with depth of penetration during test well drilling in upper aquifer.—Continued

[Land surface datum from 1:20,000 scale U.S. Geological Survey topographic maps; Specific conductivity in microsiemens per centimeter at 25 degrees Celsius; FW, freshwater (specific conductivity less than 1,800)]

Site identification	Latitude	Longitude	Land surface datum, in feet	Depth below land surface datum, in feet	Specific conductivity	Depth below mean sea level datum, in feet
				448	41000	-448
				452	41000	-452
				460	33000	-460
				480	33000	-480
				500	34000	-500
				510	35000	-510
				525	37000	-525
				535	37500	-535
				590	40000	-590
				600	43000	-600
				612	43000	-612
				630	41000	-630
				648	45000	-648
				675	45000	-675
				700	45000	-700
NC-4	182633	662626	108	83	500	25
				121	500	-13
				150	500	-42
				215	500	-107
				234	500	-126
				276	500	-168
				295	510	-187
				317	600	-209
				356	950	-248
				395	1000	-287
				435	1050	-327
				475	1050	-367
				516	950	-408
				547	8500	-439
				557	8100	-449
				570	12100	-462
				589	18000	-481
				596	19000	-488
				625	21000	-517
				643	38000	-535
				695	35000	-587
NC-8	182517	661941	89	79	500	10
				170	500	-170
				200	650	-200
				250	680	-250
				300	625	-300
				358	585	-358
				504	510	-504
				505	510	-505

Appendix 1. Specific conductivity variation with depth of penetration during test well drilling in upper aquifer.—Continued

[Land surface datum from 1:20,000 scale U.S. Geological Survey topographic maps; Specific conductivity in microsiemens per centimeter at 25 degrees Celsius; FW, freshwater (specific conductivity less than 1,800)]

Site identification	Latitude	Longitude	Land surface datum, in feet	Depth below land surface datum, in feet	Specific conductivity	Depth below mean sea level datum, in feet
				520	550	-520
				601	560	-601
				653	560	-653
				668	580	-668
				680	580	-680
				693	750	-693
				707	750	-707
				714	750	-714
				731	760	-731
				742	760	-742
				780	760	-780
				805	700	-805
				1225	700	-1225
NC-9	182731	662342	12	186	1800	12
			12	224	8000	-212
			12	311	50000	-299
NC-10	182605	663445	280	486	900	-486
				510	1100	-510
				513	1200	-513
				517	1950	-517
				524	4700	-524
				531	4800	-531
				535	5200	-535
				541	7000	-541
				544	33000	-544
				616	40000	-616
NC-14	182743	662522	18	75	800	-57
				116	850	-98
				135	850	-117
				140	1200	-122
				148	1600	-130
				151	2000	-133
				153	2400	-135
				156	2800	-138
				161	3000	-143
				168	6000	-150
				171	9000	-153
				174	14000	-156
				176	17000	-158
				180	19000	-162
				181	20000	-163
				189	24000	-171
				196	34000	-178

Appendix 1. Specific conductivity variation with depth of penetration during test well drilling in upper aquifer.—Continued

[Land surface datum from 1:20,000 scale U.S. Geological Survey topographic maps; Specific conductivity in microsiemens per centimeter at 25 degrees Celsius; FW, freshwater (specific conductivity less than 1,800)]

Site identification	Latitude	Longitude	Land surface datum, in feet	Depth below land surface datum, in feet	Specific conductivity	Depth below mean sea level datum, in feet
				223	42000	-205
				236	47500	-218
				314	49000	-296
Higuillar 1 test well	182620	661634	39	295	FW	-256
				312	3000	-273
				321	3100	-282
				328	4700	-289
				340	4700	-301
				350	10000	-311
				360	10000	-321
				377	10000	-338
				390	16000	-351
				400	10000	-361
				410	12000	-371
				459	22000	-420
				482	27000	-443
San Antonio 1 test well	182657	661627	19.7	246	FW	-226.3
				260	10000	-240.3
				285	45000	-265.3
Maguayo 3 test well	182548	661644	39	13	FW	26
				279	FW	-240
				318	2000	-279
				325	3800	-286
				330	10000	-291
				338	11000	-299
				348	12000	-309
				360	12000	-321
				374	14500	-335
				385	19000	-346
				397	19000	-358
				427	21000	-388
Bechtel Multiport well 5	182640	661931	153	116.2	554	-36.8
				-116.8	546	-116.8
				-181.8	546	-181.8
				-256.8	1856	-256.8
Bechtel Multiport well 15	182717	661944	32.3	-3.9	669	-36.2
				-101.2	937	-101.2
				-213.2	1972	-213.2
				-268.2	24736	-268.2
				-283.2	41093	-283.2

Note: Specific conductivity calculated from chloride data using relation for ground-water samples in the Puerto Rico Aqueduct and Sewer Authority wells between Dorado and Manatí for chloride-specific conductivity relation at both Bechtel wells.

Appendix 1. Specific conductivity variation with depth of penetration during test well drilling in upper aquifer.—Continued

[Land surface datum from 1:20,000 scale U.S. Geological Survey topographic maps; Specific conductivity in microsiemens per centimeter at 25 degrees Celsius; FW, freshwater (specific conductivity less than 1,800)]

Site identification	Latitude	Longitude	Land surface datum, in feet	Depth below land surface datum, in feet	Specific conductivity	Depth below mean sea level datum, in feet
DP-1 (TW-1971)	182740	662856	92	100	1080	-100
				125	1060	-125
				129	1100	-129
				150	1070	-150
				175	1080	-175
				200	1110	-200
				213	1320	-213
				238	1070	-238
				263	1020	-263
				288	40600	-288
				313	41000	-313
				338	43500	-338
				413	43600	-413
				438	23300	-438
				463	17100	-463
				488	43700	-488
				513	1880	-513
				538	43900	-538
NC-13	182630	661223	3.3		FW to 100 feet below land surface	-96.7