PLANNING REPORT FOR THE COMPREHENSIVE APPRAISAL OF THE GROUND-WATER RESOURCES OF THE NORTH COAST LIMESTONE AREA OF PUERTO RICO

By Arturo Torres-González and Richard M. Wolansky

U.S. GEOLOGICAL SURVEY
OPEN-FILE DATA REPORT 84-427

Prepared in cooperation with the
PUERTO RICO DEPARTMENT OF NATURAL RESOURCES

San Juan, Puerto Rico
1984

UNITED STATES DEPARTMENT OF THE INTERIOR

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ABSTRACT

The north coast limestone aquifers are the most productive aquifers in Puerto Rico. The aquifers cover an area of about 600 square miles and are as much as 5600 feet thick at the coast. As of 1980 ground-water withdrawals for municipal, industrial and agricultural supply exceeded 50 million gallons per day. A variety of problems have developed with increasing development, principally water quality degradation and declining water levels.

In 1983, the U.S. Geological Survey began a 5-year comprehensive investigation of the ground-water resources of the north coast limestone aquifers. The investigation will include definition of the hydrogeologic framework, geochemistry, and regional flow system, and an assessment of water-quality degradation. The project will include: (1) synthesis of all existing data on regional hydrogeological and geochemical maps, (2) fill data voids with a well inventory, test well drilling and aquifer test program, and (3) design and calibration of a regional ground-water flow digital model of the aquifer system and detailed subregional models of problem areas. Computer simulation will be used to determine the best possible representation of the hydrologic system and to assess the effects of increasing ground-water withdrawals, sea-water intrusion and waste spills in the aquifers.

INTRODUCTION

The north-coast limestone aquifers are the most important ground-water reservoirs in Puerto Rico. The aquifers underlie the North Coast Province of Puerto Rico and extend from the west coast eastward to the San Juan Metropolitan area - a total area of about 600 square miles (mi^2) (fig. 1). As of 1980, ground-water withdrawals from the aquifers exceeded 50 million gallons per day (Mgal/d), and could double by the year 1990. Public water-supply wells account for about 50 percent of the withdrawals, followed by 30 percent for industrial use and 20 percent for agricultural use.

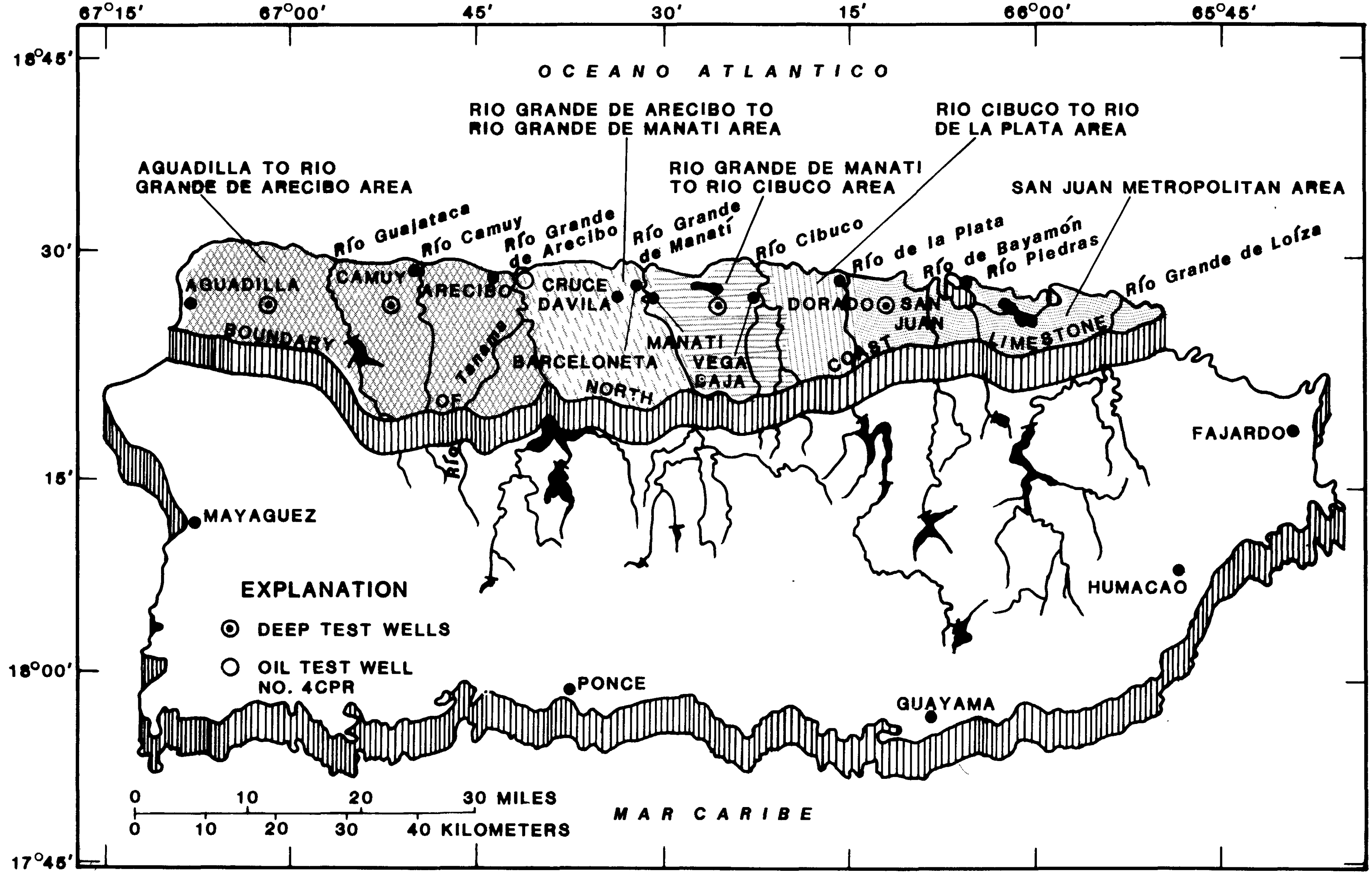


Figure 1.--The North-coast Limestone and modeled areas.

Hydrogeologic Setting

The north coast limestone aquifers are predominantly limestone but, contain minor amounts of gravel, sand, clay, chalk, and dolomite. The limestones are of middle Tertiary Age and crop out in a belt (fig. 1) approximately 625 mi^2, or one-fifth of the land area of Puerto Rico. The limestone belt extends 80 mi in length from Aguada to Loíza and as much as 13 mi in width near Arecibo. Thickness of the carbonate rocks varies from a feather edge at the outcrops to a maximum of about 5600 ft downdip at the northern coastline. The rocks dip northward or seaward at about 5° mi, and extend offshore approximately 15-20 mi. Overlying much of the coastal area are blanket sands and alluvium as much as 200-300 ft thick.

Two main aquifer systems occur in the north coast limestone area: the shallow water-table aquifer generally formed by the Aymamón Limestone and Aguada Limestone; and a deeper artesian system formed by the Montebello Limestone Member of the Cibao Formation and the Lares Limestone.

Problems

A variety of problems have developed in the aquifers of the north coast limestone area with increasing population, agricultural and industrial development. Declining water levels, salt-water intrusion in coastal areas, water-quality degradation, and the effects of past and future waste spills are the principal problems.

Declining water levels caused by an increase in pumpage have caused salt-water intrusion in several coastal areas. The definition of the fresh salt-water zone is necessary for management to plan location and pumpage of wells to minimize the effects of salt-water intrusion.

The lack of knowledge on water-quality degradation in the water-table limestone aquifers constitutes a very serious problem. Ground-water pollution by way of sinkholes is occurring in industrial, agricultural, and urbanized areas. Recent events have shown that several areas in the aquifer are contaminated with organic compounds, in effect limiting the water supply from those areas. High bacteria counts, trace-organic pollutants, and pesticides have been detected in samples from the water-table limestone aquifers. The recent spill of organic compounds in the Barceloneta area could be the "tip of the iceberg." The aquifer in this area, if contaminated as it appears, could be "lost" as a domestic water-supply source for many years.

PROBLEMS-Continued

Definition of the physical and hydraulic characteristics of the water-table limestone aquifers is spotty and limited. Only the area in the vicinity of Barceloneta has been studied in some detail and for which a digital ground-water flow model has been developed. In the western half of the study area, from Arecibo to Aguadilla, little data has been collected and knowledge of the aquifer characteristics is limited.

The artesian limestone aquifers have considerably a potential for further development. The knowledge of these aquifers, however, is also limited. Aquifers under artesian conditions were discovered near Barceloneta in the late 1960's. Pressures as high as 200 pounds per square inch (psi) have declined as a result of pumpage, and perhaps interaquifer water movement due to poor well construction. At present it is not known if the artesian aquifers extend east of the Río Grande de Manatí or west of Barrio Santana, in Arecibo. Water quality data of the artesian aquifer system is limited.

Objectives and Approach

The objectives of the study are as follows: (1) to describe the hydrogeologic framework and geochemistry of the north coast limestone aquifers, (2) to define the regional flow system, and, (3) to assess the effects of large withdrawals of ground water and waste spills upon the aquifers. Computer simulations will be used to evaluate the regional and subregional flow models.

A regional approach to investigating the north coast limestone aquifers is proposed that will include the following activities:

1. Assembly, evaluation, and mapping of all existing information which includes a literature search and preparing existing ground-water data for the USGS Ground Water Site Inventory (GWSI) computerized file.

2. A well and water-use inventory for the north coast limestone area will be conducted. Data collected will be translated into the GWSI and State Water Use Data System (SWUDS) files. The collection of data will include test drilling and aquifer testing in critical areas.

3. Preparation of a series of regional hydrogeologic and geochemical maps of the north coast aquifers. The initial phase will include rough mapping of the various parameters (hydraulic conductivity, transmissivity, thickness of the aquifers, recharge, specific yield, and storage coefficient). These will be refined as additional data is made available.

Objectives and Approach-Continued

4. Design, construction, and calibration of a regional ground-water flow digital model (covering approximately 600 square miles) to understand the ground water flow system in the water-table aquifer and the deep artesian aquifer.

5. Design, construction, and calibration of subregional areal and cross-sectional flow models which can be used for assessing water-management alternatives. Where required, solute-transport models will be used to predict water-quality degradation.

6. Definition of the fresh-saltwater transition zone in both water table and artesian aquifers, and preparation of maps that can be used to plan location and pumpage of wells while minimizing the potential for salt-water intrusion.

PLAN OF STUDY

The comprehensive appraisal of the ground-water resources of the north coast limestone aquifers will be a 5-year effort beginning in fiscal year 1984. A schedule of project activities and their relationship to proposed funding and personnel requirements are shown in figure 2. In the first year of the study, an intensive program of well inventory and geochemical sampling will be initiated. Most of the emphasis during the first year will be on the compilation and analysis of existing data, and design of computer models. Efforts during the following 2 years will be concentrated in test drilling, water sampling, borehole and surface geophysical studies, aquifer tests, and refinement of models. The fourth and fifth year will consist of an intensive modeling effort designed to produce state of the art models that will enable water managers to monitor the response of the aquifers to different stresses. Quarterly progress reports will be prepared for DNR and other cooperating agencies. Annually a seminar-briefing on progress activities will be conducted. Written reports will be prepared according to the projects timetable (fig. 2).

	1984	1985	1986	1987	1988
Data acquisition and interpretation	Assembly and interpretation of existing geologic and hydrologic data	Acquisition of new data with exploratory drilling, aquifer testing, geophysical surveys, and so forth		Data analysis	
Digital computer models	Preliminary model design and trial runs	Revision, "tuning," and final calibration of model (s)		Predictive model runs	
Report preparation	Preliminary reports (WRI or Open-File) and yearly progress reports			Journal articles	Professional Paper Series
	FUNDING AND PERSONNEL				
Budget	300,000	400,000	300,000	300,000	250,000
Hydrologists (man years)	3	3½	3	3	3

Figure 2.--Principal project activities for calendar years 1984-1988, as related to funding and personnel requirements.

Definition of the Aquifer System

Proposed Hydrogeologic Framework

The following is a proposed hydrogeologic framework for the north coast limestone area that will be revised and refined as the study advances. Aquifers in the study area occur in various geologic formations. The water-table aquifers occurs in the alluvial deposits that border the major rivers and in the Aymamón and Aguada limestones which are hydraulically connected throughout most of the study area. The Cibao and Lares formations contain artesian aquifers which are separated from the water-table aquifer by confining or semi-confining beds. Below the lowest most formation (Lares Limestone) is the lower confining bed (San Sebastián Formation) which represents the base of the system. Stratigraphic and lithologic descriptions of the hydrogeologic units and their estimated hydraulic characteristics are summarized in table 1. Figure 3 is a hydrogeologic section through the Cruce Davila area and shows the location of selected deep artesian wells.

The alluvial aquifer is predominantly medium to fine sand and gravel with varying amount of clay, the percentage of which generally increases with depth. Thickness of the aquifer ranges from about 0 to 300 ft. Ground water in the alluvial aquifer is unconfined, and the water table fluctuates seasonally, generally less than 5 ft. Other surficial deposits of importance are blanket sands, terrace, swamp, beach, and dune deposits. Although these deposits do not contain aquifers as such, they do contribute recharge to the underlying limestones.

The Aymamón and Aguada limestones, and the Camuy Formation are predominantly limestone with some dolomite and clastic rocks. These limestones vary in thickness from about 700 to 2300 ft. For modeling purposes, the bottom of the water-table limestone aquifer will be considered either (1) the top of the fresh-saltwater mixing zone (chlorides greater than 500 mg/l) near the coastline or (2) the top of a persistent zone of clayey sediment in the Cibao Formation.

The Cibao aquifer is predominantly carbonate rock and clastic sediments. The aquifer includes all limestone members of the Cibao Formation: Guajataca Member, Montebello Limestone Member (the most productive artesian system), Río Indio Limestone Member, Almirante Sur Sand Lentil, Quebrada Arenas Limestone Member, and Miranda Sand Member. The Cibao ranges in thickness from 0 to about 1000 ft. The top of the formation consists of limestone whereas the lower part of the unit consists of clayey sediment, limiting the ground-water development potential from the lower Cibao. Ground water in the Cibao aquifer occurs under artesian conditions in the area from Arecibo to Manatí and its artesian head is higher than the water table of the upper aquifers.

Table 1.--Hydrogeologic framework of the North-coast Limestone area.

Stratigraphic unit	General lithology	Major lithological unit	Hydrologic unit	Thickness feet	Estimated aquifer Characteristics
Surficial	Sand, gravel	Sand & clay	Surficial aquifer water table	0-200	T=1000-50,000 ft^2/d, S=0.05-0.2
Camuy Formation	Fragmental limestone, marl & sandstone	Carbonate & clastic	Water-table limestone aquifer (unconfined to semiconfined	0-600	T=1000-3000 ft^2/d, K'/b' - 1x10^{-3} (ft/d)/ft S=2x10^{-4}-0.1
Aymamón Limestone	Massive dense limestone & dolomite, (locally carbonate	Carbonate		600-1100	T=5000-50,000 ft^2/d, K'/b'=1x10^{-3} (ft/d)/ft S=0.1-3x10^{-4}
Aguada Limestone	Calcarenite	Carbonate		100-600	T-2000-20,000 ft^2/d, K'/b'=1x10^{-3} (ft/d)/ft S=0.1-2x10^{-4}
Cibao Formation	Marl, chalk & sand	Carbonate & clastic	Cibao aquifer (confined)	0-1000	T=3000 ft^2/d K'/b'=1x10^{-4} (ft/d)/ft S=5x10^{-4}
Lares Limestone	Calcarenite	Carbonate	Lares aquifer (confined)	0-1650	T=10,000 ft^2/d K'/b'=1x10^{-4} (ft/d)/ft S=1x10^{-3}
San Sebastián Formation	Sand & silt stone	Clastic & carbonate	Lower confining bed Bottom of fresh-water flow	0-900	

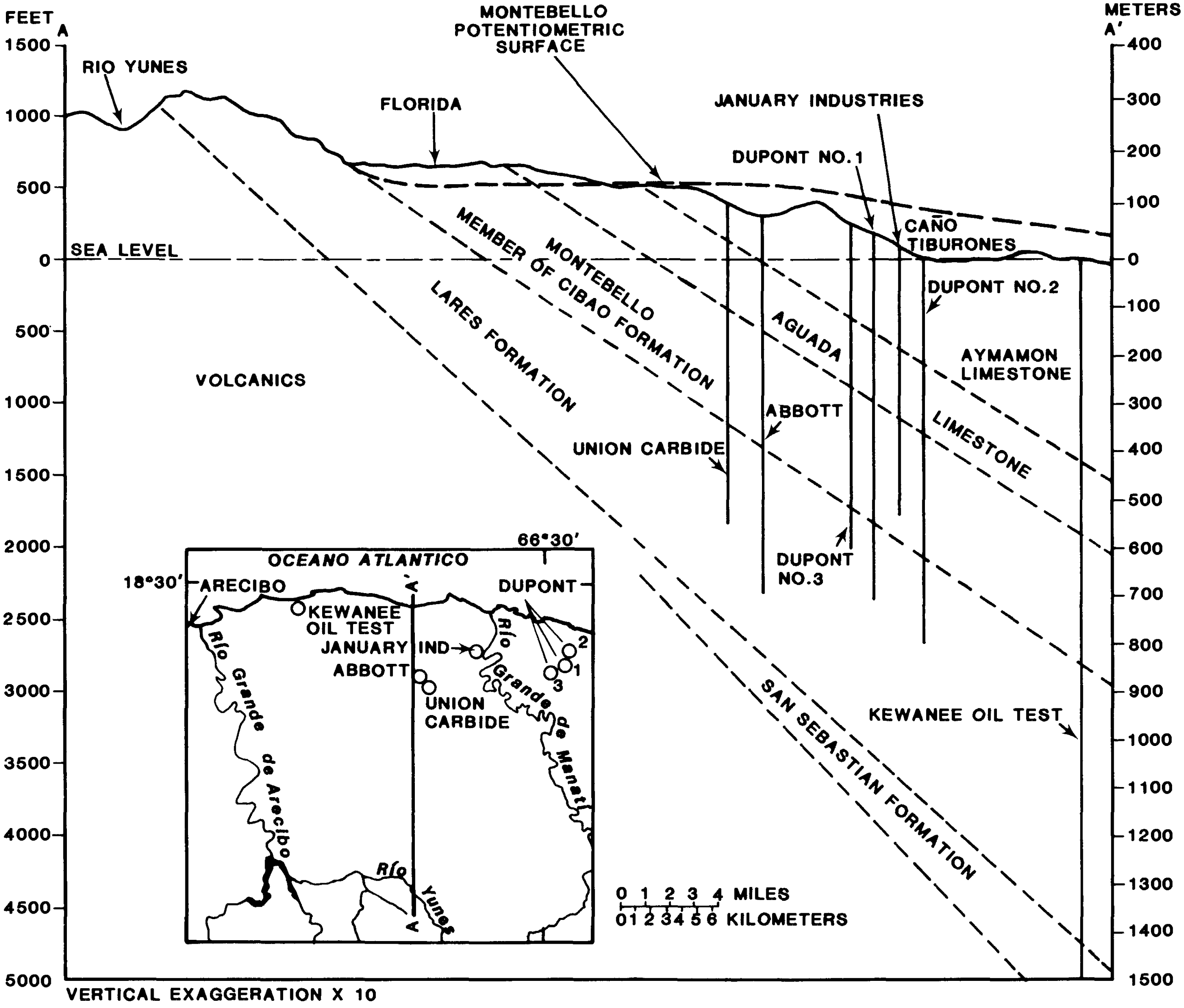


Figure 3.--Hydrogeologic section through Cruce Dávila area and location of selected deep artesian wells.

Proposed Hydrogeologic Framework-Continued

The Lares Limestone is composed of relatively pure limestone which ranges in thickness from 0 to about 1650 ft. The top of the formation consists of limestone whereas the lower part concurs with the first occurrence of clayey sediments at the top of the San Sebastián Formation. Ground water is known to be confined in the Lares aquifer in the Arecibo to Manatí area and its artesian head is higher than the overlying aquifer because its area of recharge is at a higher elevation. Only in this central part of the limestone belt has drilling shown that water flows under artesian head within the Montebello Limestone Member and the Lares Limestone.

Preparation of Hydrogeologic and Geochemical Maps

The preparation of regional hydrogeologic and geochemical maps of the north coast limestone aquifers will be the culmination of the initial data collection and analyses steps. The maps will serve to describe the geologic, hydraulic, and geochemical characteristics of the north coast aquifers. Detailed maps of subregional stressed areas, and cross sections or fence diagrams will be generated as needed. An important aspect of map preparation for modeling, will be a description of the regional boundaries of the aquifers, and identification of boundaries with the aquifers that affect lateral flow (such as faults, facies changes and fractured zones) and vertical flow (solution enlargement along vertical joints, faults, and breaching, and discontinuity of confining beds).

This mapping effort will require compilation and analysis of all existing data, and published reports on the hydraulic properties of the aquifers. As new data is generated by the well inventory, test drilling, and aquifer testing programs, it will be used to improve the maps.

Regional hydrogeological maps will be prepared at 1:140,000 scale to include the following:

1. Areal extent and thickness of the alluvial aquifers.

2. Areal extent and thickness of the water-table limestone aquifer.

3. Structure contour maps showing base and top of the water-table limestone aquifer.

Preparation of Hydrogeologic and Geochemical Maps-Continued

4. Areal extent and thickness of the Cibao aquifer.

5. Structure contour maps showing base and top of the Cibao aquifer.

6. Transmissivity and leakage map (where confined) of the Cibao aquifer.

7. Areal extent and thickness of the Lares aquifer.

8. Structure contour map showing base and top of the Lares aquifer.

9. Transmissivity and leakage map (where confined) of the Lares aquifer.

10. Areal extent and depth of the fresh-saltwater transition zone in both water table and artesian systems.

11. Map showing internal boundaries and inhomogeneities (lithofacies, structural, and hydraulic boundaries, etc.).

Regional geochemical maps will be prepared at 1:140,000 scale to include the following:

1. Maps showing the distribution of dissolved solids, chloride, sulfate, calcium plus magnesium (hardness), and hydrochemical facies distributions in water from the alluvial, water-table limestone, Cibao, and Lares aquifers.

2. In addition to regional maps, mass transfer geochemical modeling will be applied to selected ground-water flow paths. This effort will serve to better understand aquifer-water interactions which affect the observed chemical variations in the limestone aquifers. Mass transfer models of the aquifers can provide independent tests of hydrogeologic model concepts.

Regional water level maps will be prepared at 1:140,000 scale to include the following:

1. Maps showing the semi-annual high and low-water levels of the alluvial and water-table limestone aquifers, and of the potentiometric surface of the Cibao and Lares aquifers.

2. Maps showing water levels of the alluvial and water-table limestone aquifers, and the potentiometric surface of the Cibao and Lares aquifers under predevelopment conditions.

Description of the Flow System

The water-table limestone aquifer (Aymamón Limestone and Aguada Limestone) and the artesian aquifers (Montebello Limestone Member of the Cibao Formation and Lares Limestone) are the most productive aquifers of the north coast area.

The areal distribution of heads in the water table or upper limestone aquifer is fairly well documented in the eastern two-thirds of the study area (east of Arecibo). Water-table maps are not available, however, for the area west of Arecibo. The artesian system is largely unknown, with scarce information obtained from well drillers. The potentiometric surface of the artesian aquifers has not been mapped regionally and the position of the fresh-saltwater mixing zone has not been defined. As the well inventory and the test drilling programs provide new data, the potentiometric surface of the artesian aquifers and the water table of the upper limestone aquifer, particularly west of Arecibo, will be mapped. An observation-well network will be established for the aquifers and water-level measurements will be made twice a year to document seasonal changes in the water table and potentiometric surfaces. All water level data will be evaluated to determine whether a reported head is a composite for more than one aquifer or if it is representative of the aquifer to be mapped.

The upper limestone aquifer is generally unconfined and therefore is treated as a water-table aquifer. The aquifer has varying hydraulic connection to the overlying alluvium associated with streams and with blanket sands along the coast. Recharge to the aquifer occurs primarily by direct infiltration of rainfall over the outcrop areas of the Aguada and Aymamón, as well as the fluvial drainage in the blanket sands. Recharge also probably occurs from leakage from the underlying artesian aquifers and perhaps from interaquifer water movement due to poor well construction.

Water entering the aquifer in the recharge areas of the Aguada generally moves north under hydraulic gradients steeper than those in the Aymamón. The steep gradient reflects the lower hydraulic conductivity of the saturated Aguada. It is also generally associated with a relatively thin sheetlike flow through the Aguada for which the upper part of the Cibao forms a low-permeability base. Gradients gradually flatten out as ground water moves from the Aguada into the Aymamón. Here the higher hydraulic conductivity of the Aymamón contributes to flatter hydraulic gradients.

Natural ground-water discharge occurs near the coast, either as fresh-water springs or as diffuse flow that mixes with seawater. The downdip limit of freshwater for the aquifer closely approximates the coast. As of 1980, water production from the water-table limestone aquifer was about 60 Mgal/d.

Description of the Flow System-Continued

Knowledge of the deep artesian aquifers is very limited. At present it is unknown if the aquifers extend east of the Manatí area or west of Barrio Santana, in Arecibo. The upper artesian zone, found in the Barceloneta area, occurs within the Montebello Limestone Member of the Cibao Formation, which in the outcrop area is relatively pure limestone. Drillers' reports indicate that a massive limestone layer was penetrated before the crumbly limestone of the artesian aquifer. The massive limestone seemingly serves as a confining layer in this area, although the stratified clay and marl of the Cibao could also be expected to provide confinement. The lower artesian zone lies in the Lares Limestone.

The Cibao and Lares artesian aquifers are recharged in their outcrop areas, but downdip recharge is minimal as the head of the aquifer is greater than the water table in the upper limestone aquifer. The downdip limit of fresh-water flow is undefined, however, the extrapolation of head gradient, as of 1976, and dip of the artesian aquifers show that discharge could probably be occuring approximately 15 to 20 mi offshore. Figure 4 shows a cross section through the central study area in which possible patterns of ground-water flow and estimated hydraulic conductivities are illustrated.

Test Drilling and Aquifer Tests

Drillings of test wells and aquifer tests will be programmed on the basis of the well inventory, reasonable completion of hydrogeologic data compilation, and initiation of modeling effort. A major priority will be drilling test wells and subsequent testing to define (1) the hydraulic properties of the water-table limestone aquifer west of Arecibo, and (2) the areal extent of the artesian aquifers and their properties. The areal extent of the artesian aquifers is the major data void. Drilling of test wells in these aquifers will require perforations to depths of as much as 2000 ft. Four deep test wells are planned for the study area (fig. 1). In addition to these, about fifty shallow test wells (300 to 500 ft deep) will be drilled where needed in the study area.

Priorities for test drilling and for aquifer test will be the following:

1. Obtaining data on the hydraulic properties of the water-table limestone aquifer west of Arecibo.

2. Obtaining data on the extent of the artesian aquifers and their properties.

3. Obtaining transmissivity and leakage values from aquifer tests in areas where little or no information is available.

4. An improvement in the areal coverage of the piezometer network for water-level mapping.

5. Collection of salinity data to improve knowledge of the fresh-saltwater transition zone in the water-table aquifer.

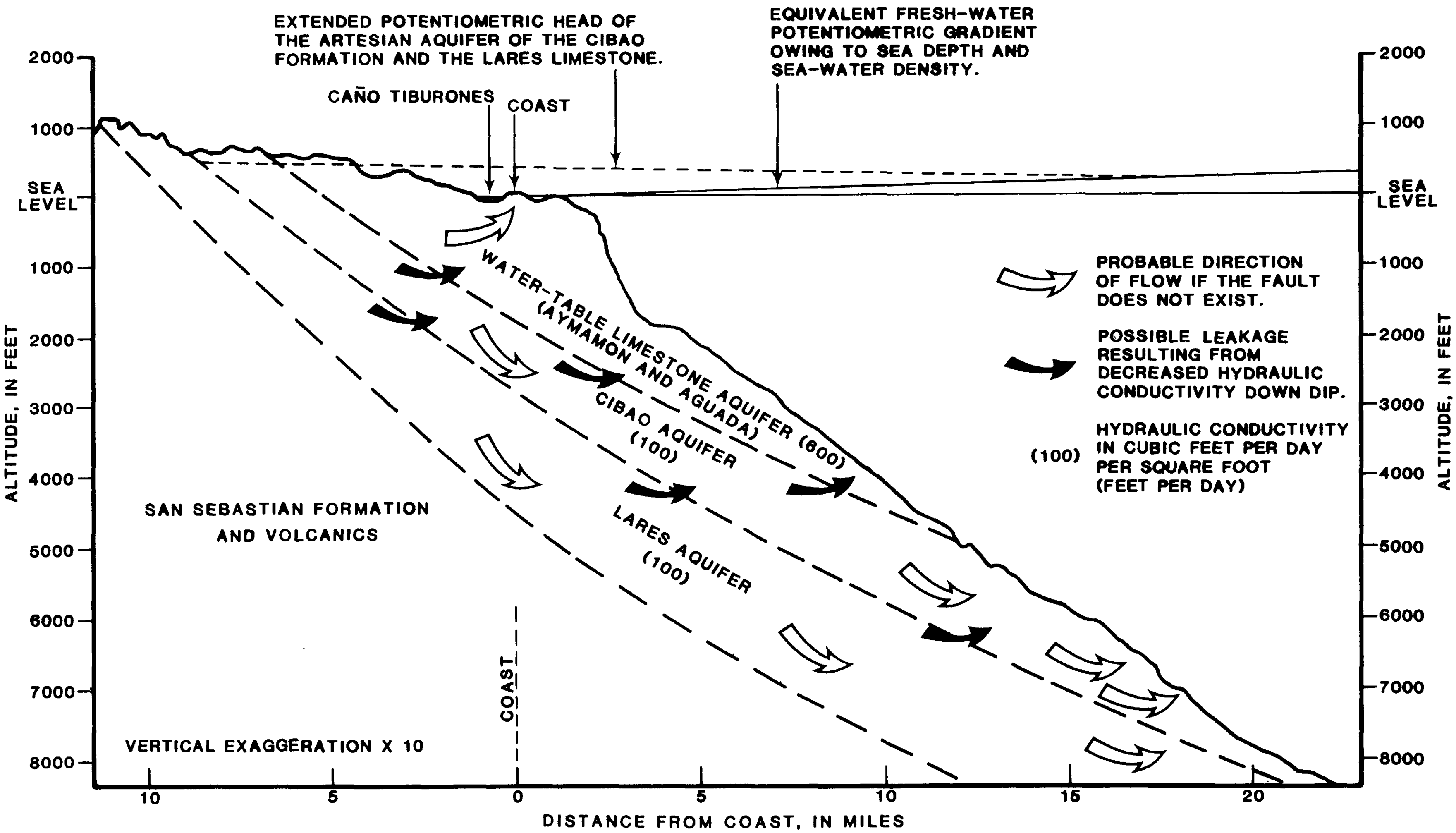


Figure 4.--Schematic diagram of possible patterns of ground-water flow and estimated hydraulic conductivities in the central section of the study area.

Regional Model

A regional digital model of the north coast limestone aquifers will be designed early in the study. The purpose of the model will be:

1. to define the flow of ground water in the system.

2. to assess the importance of hydrologic boundaries separating the five subregional model areas.

3. to investigate very large stresses located near subregional boundaries and whose effects may extend beyond the boundaries.

In calibrating the model, simple trial calculation and sensitivity analyses will be used early in the study. As new data is made available the simulation of the regional system will be refined progressively and more sophisticated parameter identification techniques will be attempted.

The limestone aquifers of the north coast area (water-table and artesian aquifers) may be treated either:

1) as independent aquifers with very little leakage between, or

2) as hydraulically connected aquifers with significant interaquifer leakage.

If treated as independent aquifers, areal two-dimensional flow analyses are required. Each layer could be modelled separately with an areal model covering the entire hydraulic unit from west to east and from southern outcrop northward to the submarine discharge area. The McDonald-Harbaugh Model (finite difference code, USGS, 1983) is recommended.

If the aquifers are treated as hydraulically connected units, a three-dimensional flow analysis is warranted. An obvious all encompassing approach would be to develop a three-dimensional ground-water flow model (using the McDonald-Harbaugh 3-D finite difference code) for the entire vertical sequence of the north coast limestones from Aymamón down to the Lares. The model will consist of four layers that corresponds to the following hydrogeologic units:

Layer 1 - alluvial aquifer

Layer 2 - water-table limestone aquifer (Aymamón and Aguada).

Layer 3 - Cibao artesian aquifer

Layer 4 - Lares artesian aquifer

Such a model must extend from the inland outcrops of the Lares where recharge takes place to discharge areas between 10 and 20 mi offshore. The model considers storage changes in the aquifers but not in the confining beds. The underlying confining bed (San Sebastián Formation) is the base of the system. Preliminary plans are to construct a coarse-mesh grid system (nodes will be about 0.4 meters (m) in area) with about 5,000 active nodes. The grid will encompass an area of about 1650 m^2.

Regional Model-Continued

A three-dimensional approach will only be considered upon completion of cross-sectional studies of the north coast aquifer system. Cross-sectional studies of an aquifer often are preferred over the areal regional analysis because they constitute simpler representations of the hydrology. In a 3-D model, for example, there are too many unknowns involved which must first be studied separately: (1) upstream recharge to each layer, (2) vertical and horizontal hydraulic conductivity of each layer, (3) leakage between more permeable layers through semi-confining sequences, (4) offshore heads in artesian layers, (5) offshore positions of seawater interface in artesian layers, and (6) distribution of discharge from each layer. All the above unknowns necessary for a complete understanding of the system may be clearly addressed in a series of cross-sectional studies. A minimum of three cross sections will be analysed as part of the north coast limestone study.

Subregional Studies

To appraise important water problems in the north coast limestone area, the study has been broken down into five subregions (fig. 1):

1. Aguadilla to Río Grande de Arecibo Area.
2. Río Grande de Arecibo to Río Grande de Manatí Area.
3. Río Grande de Manatí to Río Cibuco Area.
4. Río Cibuco to Río de la Plata Area.
5. San Juan Metropolitan Area.

Subregional models will be designed to assess the effects of increased pumpage, sea-water intrusion, wate spills, and other developments upon the aquifers.

Aguadilla to Río Grande de Arecibo Area

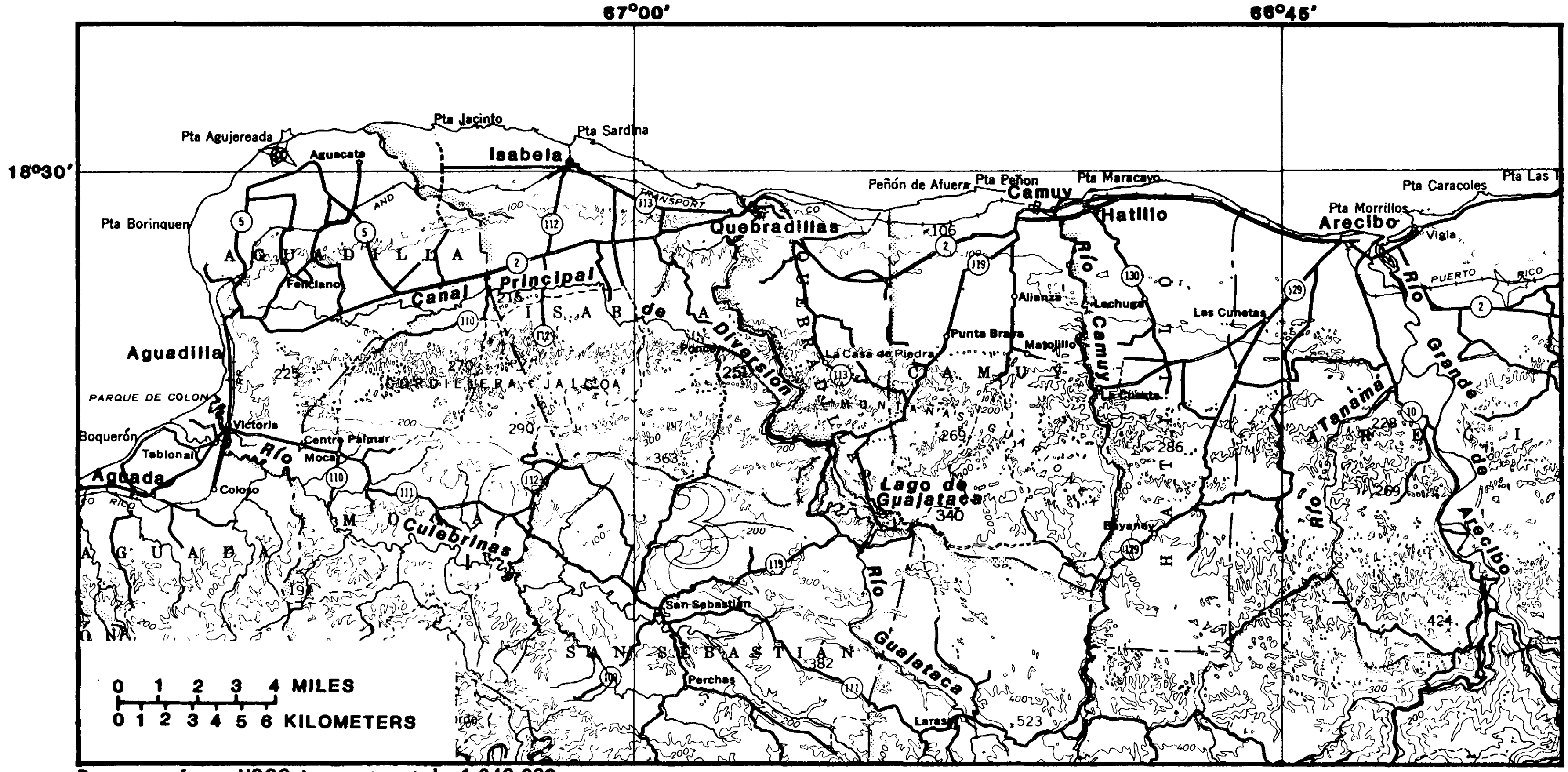
West of Arecibo in the Aguadilla to Río Grande de Arecibo area (fig. 5), the knowledge of the physical and hydraulic characteristics of the water-table limestone aquifers is extremely limited. Little ground-water data has been collected. The pattern of ground-water outflow in the Río Guajataca - Río Grande de Arecibo area is rather speculative. Ríos Tanamá, Camuy, and Guajataca appear to be efficient ground-water drains and therefore, a small part of the regional ground-water flow is expected to be discharged through coastal swamps or the sea bottom.

Ground-water outflow in the Río Guajataca - west coast area remains essentially unknown. In the southernmost part of this area the Lares Limestone is drained southward by streams tributary to Río Culebrinas, and the Cibao Formation here is a nearly impermeable clayey marl. These conditions are not favorable for development of artesian zones such as those found in the Arecibo to Manatí area. The water-table limestone aquifers in the area (Aguada and Aymamón) however, seems to be favored by an advance karst development in the outcrops which maximizes the potential of aquifer recharge from rainfall. It is estimated that in this westernmost area a large direct discharge of ground water occurs through the sea bottom.

Ground-water withdrawals west of Río Grande de Arecibo are relatively small (about 6 Mgal/d) because of economic reasons (deep wells are required to reach the water table) and abundance of surface-water supplies.

Potential ground-water problems are quality related rather than due to water-level declines. Pollution problems in sinkhole areas from domestic, municipal (landfills), and industrial sources occur locally.

Data collection on geology, water heads, aquifer characteristics, and water quality is the highest priority in the Aguadilla to Arecibo area. A two-dimensional areal flow model (using the McDonald-Harbaugh finite difference code) of the water-table limestone aquifer in this subregion will be developed to help define the ground-water flow system.



Base map from USGS topo map scale 1:240,000

Figure 5.--The Aguadilla to Río Grande de Arecibo area.

Río Grande de Arecibo to Río Grande de Manatí Area

Ground-water withdrawals in the area (fig. 6) have increased dramatically since the early 1970's. Pumpage for industrial, agricultural, and municipal supplies from the alluvial and water-table limestone aquifers has increased from about 8 Mgal/d in 1970 to about 20 Mgal/d in 1982. Artesian limestone aquifers underlying the shallow aquifers supply about 5 Mgal/d.

The area probably has more potential problems than any of the other subregions to be investigated. Competition for ground water supplies between industry, municipalities, and agriculture is a very serious water problem in the area. Declining water levels, salt-water intrusion, and local water-quality degradation have resulted from increased pumping. Industrial, agricultural, and municipal wastes have been discharged to aquifers through sinkholes and disposal wells or have entered the aquifers from accidental waste spillages. Wastes disposed in sinkholes include sewage, oil, neutralized acid, organic compounds, pineapple-cannery wastes, and others.

The existance of deep artesian aquifers (Montebello Limestone Member of the Cibao Formation and Lares Limestone) in the Río Grande de Arecibo to Río Grande de Manatí area was first noted in 1968 during the drilling of a deep well in the Cruce Davila area of Barceloneta. Subsequently, more deep wells were drilled for industrial purposes, and by 1979, there were 15 deep artesian wells in an area approximately 25 mi^2. Pressure heads have declined in both aquifers as a result of pumpage, and perhaps interaquifer water movement through poorly constructed and/or improperly abandoned water wells. There has been a dramatic shift in interest to the artesian aquifers, particularly as a source for municipal water supply, because of the recent toxic industrial spills that have locally contaminated the water-table limestone aquifer.

Digital modeling of the water-table limestone aquifer has been done in the Barceloneta area. A 2-D model (McDonald-Harbaugh finite difference code) was used to simulate varied conditions of recharge from precipitation, infiltration from streams, withdrawals from wells, and the effects of these stresses on the current water levels.

The major activities of the aquifers study in the Río Grande de Arecibo to Río Grande de Manatí area will be:

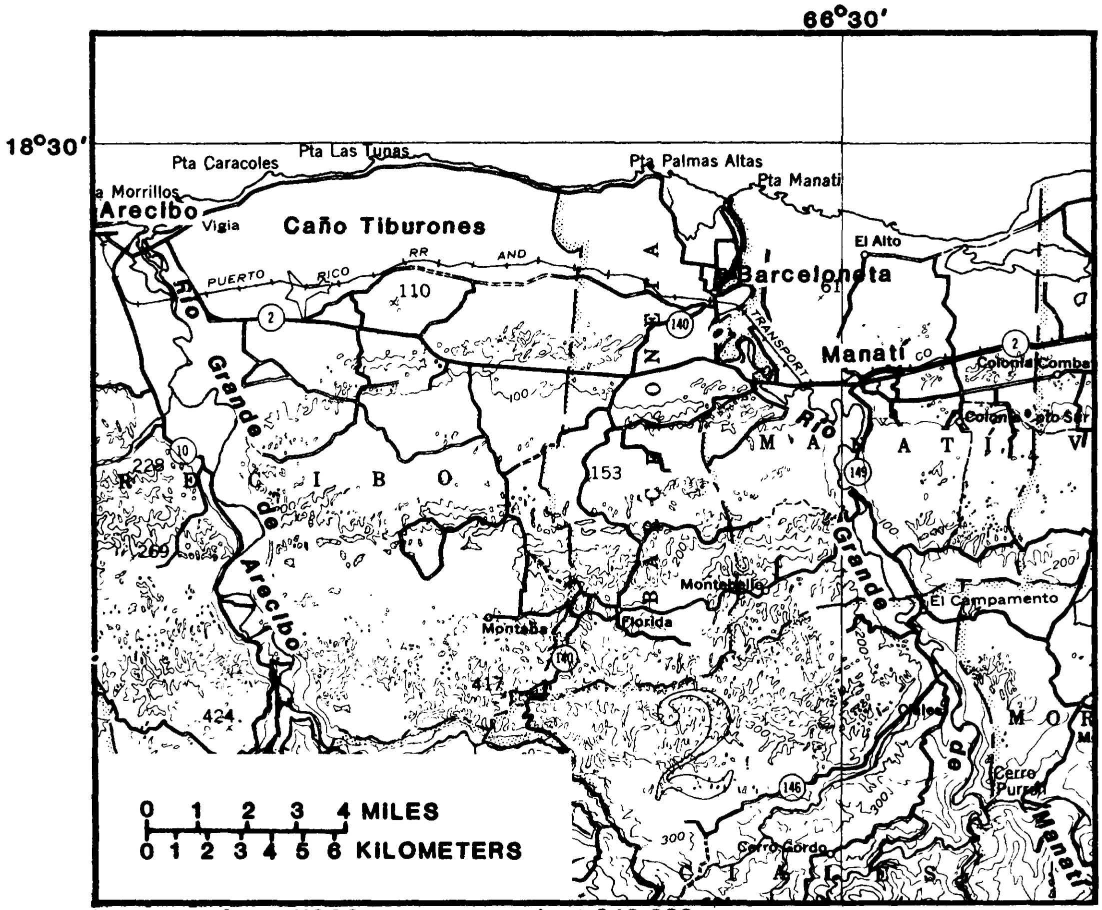
1) Enlargement of the existing areal 2-D model of the water-table aquifer in the Barceloneta area to include the Río Grande de Arecibo as a natural hydrologic boundary.

2) Design of a finite element areal model of the water-table aquifer (using AQUISALT - Voss, 1984) to simulate the moving freshwater-saltwater interface at Ghyben-Herzberg depth.

Rio Grande de Arecibo to Rio Grande de Manati Area-Continued

3) Design of a finite element cross-sectional model (using FEMOD-Cooley and Torak, 1984) of the entire vertical sequence of the north coast limestone aquifers. This model will help determine if in the regional north coast flow model, the limestone aquifers (water table and artesian aquifers) may be divided into effectively independent aquifers with very little leakage (2-D approach) or if there is significant flow connection between them (3-D approach).

4) To conduct additional runs of the solute-transport model (SATRA finite element code - Voss, 1983) already designed for the Upjohn carbon tetra-chloride spill in the Barceloneta area. The Upjohn site is an excellent candidate for a transport model study as there is both good information about the contaminant source and good measurements of plume extent. The preliminary SATRA model of the area is an excellent tool with which to test hypothesis of the mechanisms of contaminant dispersion at the site, and the origin and shape of the plume.



Base map from USGS topo map scale 1:240,000

Figure 6.--The Río Grande de Arecibo to Río Grande de Manatí area.

Río Grande de Manatí to Río Cibuco Area

Knowledge of the hydraulic characteristics of the shallow aquifer is limited. Ground-water withdrawals from the water-table aquifer in the Río Grande de Manatí to Río Cibuco area (fig. 7) are approximately 11 Mgal/d (1982). The artesian aquifers, in addition, are only known to exist in the westernmost tip of the area. If artesian zones extend eastward, these might probably occur in the Lares Limestone and perhaps in any of the other members of the Cibao Formation (Quebrada Arenas Limestone Member and Río Indio Limestone Member). The Montebello Limestone Member, the most productive artesian aquifer in the north coast, no longer exist in the area as it pinches out near Manatí.

The Aymamón Limestone, like in the rest of the north coast, is the most productive unit of the water-table aquifer in the area. Its transmissivity is on the order of 120,000 ft^2/d. Specific capacities of wells tapping the Aymamón can be expected to range from 100 to 1,000 gal/m/ft of drawdown.

The fresh-water saturated thickness of the Aymamón (at Hwy 2) is somewhere between 200 and 300 ft. A published report of the Tortuguero area indicates that approximately 15 percent of the ground-water flow discharges directly to the sea, 20 to 30 percent discharges south of Laguna Tortuguero through springs and areal discharge, and the remainder discharge into the lagoon or north of it, also through springs and areal discharge.

Critical water problems in the area have not been thoroughly documented. However, water-quality degradation from landfill sites and industrial waste injections and spills are known to exist in localized area. Water-use projections suggest that ground-water withdrawals will increase to satisfy the needs of an increasing population, agricultural and industrial development. Pumpage increases will probably cause significant declines in aquifer water levels and salt-water intrusion in coastal areas.

Some exploratory drilling and aquifer tests are needed to support the modeling in this area. Modeling efforts in the Río Grande de Manatí to Río Cibuco area will include:

1. Design of a finite-difference 2-D areal model (McDonald-Harbaugh model) of the water-table aquifer to evaluate (a) the effects of additional ground-water withdrawals on aquifer water levels, particularly in the area of Laguna Tortuguero, and (b) the availability of fresh ground water in the aquifer.

2. Design of a finite element 2-D areal model (AQUI-SALT - Voss, 1984) to simulate the moving freshwater-saltwater interface in the coastal area.

3. Design of a finite element cross-sectional model (FEMOD - Cooley and Torak, 1984) of the entire vertical limestone sequence in the area. If artesian aquifers exist, the model will evaluate if significant flow connection exist between the water table and artesian aquifers.

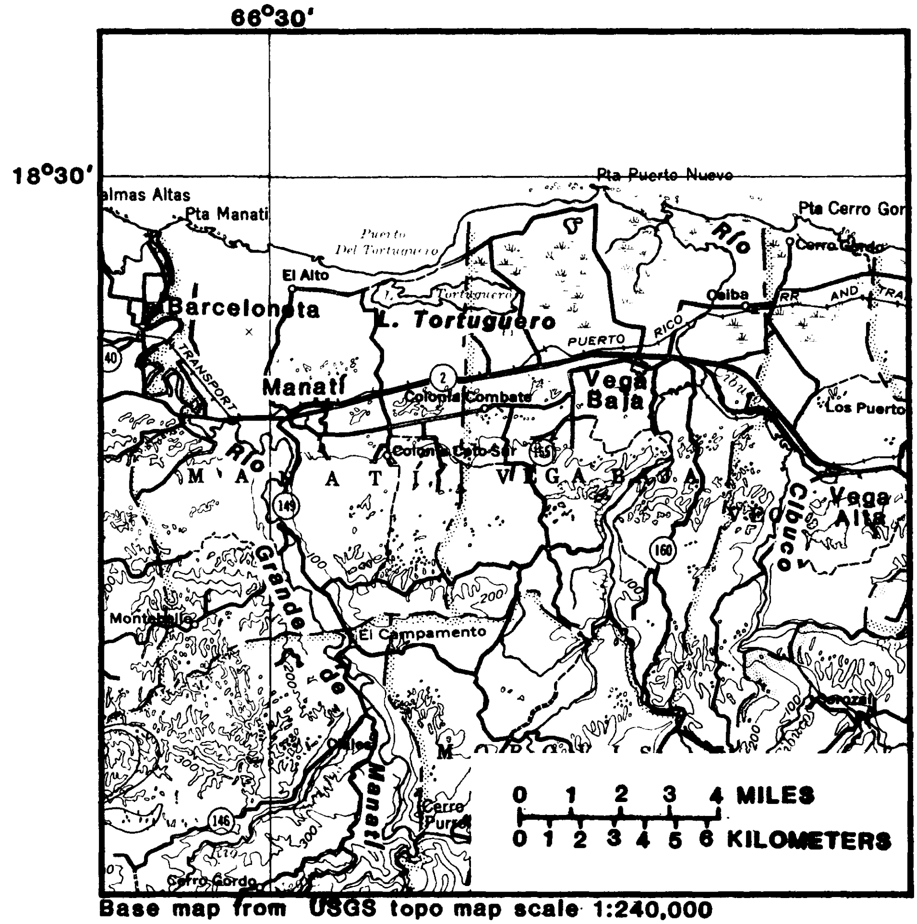


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Figure 7.--The Río Grande de Manatí to Río Cibuco area.

Río Cibuco to Río de la Plata Area

The municipalities of Dorado, Vega Alta, and Vega Baja depend almost entirely on the ground-water resources of the Río Cibuco to Río de la Plata area (fig. 8) to satisfy domestic, commercial, industrial, and irrigation needs. Present ground-water withdrawals from the water-table aquifer are approximately 12 Mgal/d. Previous areal appraisals indicate withdrawals may be near the threshold point where demand is approaching the available supply in the aquifer. The growth of all the sectors of the economy will be delayed if increasing water demand cannot be met from ground-water sources. Surface water supplies of both Río Cibuco and Río de la Plata are already appropriated. Conflict between water users is likely to occur unless the ground-water resource is adequately assessed.

Pumpage increases in coastal areas are expected to cause significant water-level declines and salt-water intrusion in the aquifer. Another critical problem related to water-quality degradation exists in the area of Vega Alta. Organic contaminants, primarily Trichloroethylene (TCE), have been detected in the well field that supplies the town of Vega Alta. As a result of the contamination the well field was partially closed by the State Health Department severely limiting the water supply in the area. A monitoring well program is at present been established to determine the extent, movement, and dispersion of the contaminants.

Exploratory drilling, particularly a deep test hole (2,000 ft), and some aquifer tests will be required to support the proposed modeling program. The principal activities of the aquifer study in the Río Cibuco to Río de la Plata will be:

1. To evaluate and modify, if needed, the existing finite difference 2-D model (McDonald-Harbaugh model) of the water-table aquifer. The model will be used to evaluate the effects of additional pumpage on aquifer water levels, particularly in critical zones like the Vega Alta area.

2. Design of a finite element cross-sectional model of all the existing limestone formations. The model will evaluate the vertical hydraulic connection between the aquifers, particularly between the water table and artesian aquifer if the latter is found to exist. FEMOD, a finite element model by Cooley and Torak, will be used.

3. Design of a finite element 2-D areal model to simulate the moving freshwater-saltwater interface in the coastal area. AQUISALT, a finite element model by Voss, (1983), will be used.

4. Design a simple preliminary solute-transport model of the Vega Alta area to test various hypothesis of contaminant dispersion at the site, and the origin and shape of the plume. More data collection is needed however, to define the local flow system, plume extent, concentrations near possible sources, and the effect of the clay layer in the area. SATRA, a finite element model by Voss, (1983) will be used.

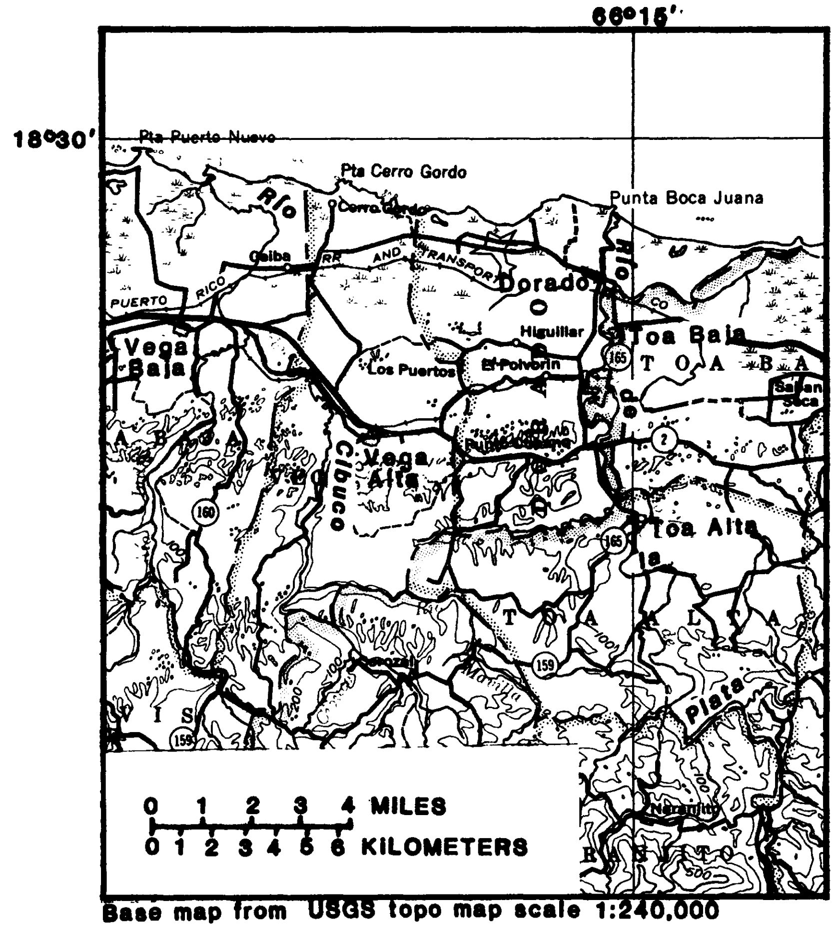


Figure 8.--The Río Cibuco to Río de la Plata area.

San Juan Metropolitan Area

The San Juan Metropolitan area (fig. 9) includes the capital city of San Juan and all or parts of the municipalities of Toa Baja, Toa Alta, Bayamón, Cataño, Guaynabo, Río Piedras, Carolina, and Canovanas. The study area extends from the Río Grande de Loíza on the east to the Río de la Plata on the west. For reference purposes, the metropolitan area has been arbitrarily divided into three units - Bayamón, San Juan, and Carolina (fig. 9).

Ground water in the San Juan Metropolitan area has played a declining role in water supply since the completion of the Loíza reservoir in the early 1950's and La Plata reservoir in the mid 1970's. Ground-water yield in the easternmost two-thirds of the area is limited because the aquifers are small and succeptible to sea-water intrusion.

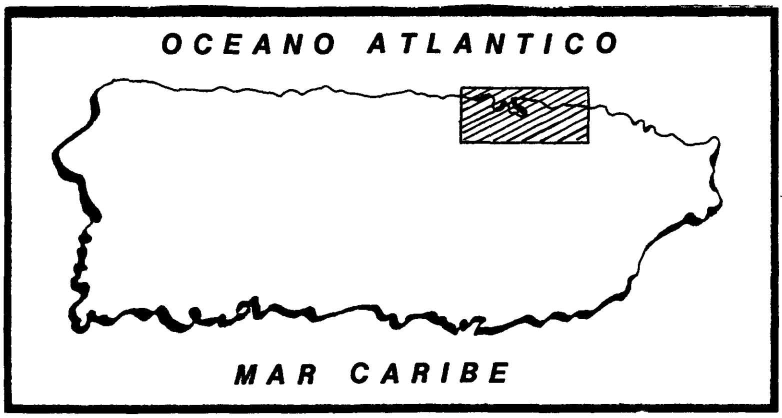
A published report of the metropolitan area (Anderson, 1976) indicates that artesian and water-table aquifers exist in the area. The artesian aquifer, composed of the San Sebastián Formation and basal part of the Cibao Formation, exist in much of the metropolitan area, particularly in the Bayamón and San Juan area. The transmissivity of the aquifer is reported to vary from less than 150 to 2,000 ft^2/d. Wells in areas that tap the artesian aquifer often flow. Known flowing wells occur in the lower valleys of the Río Bayamón and the Río Piedras and the coastal plain south of San José Lagoon. The largest of these has been reported to flow at 275 gal/min with a potentiometric head of 15 ft above the land surface.

The water-table aquifer is composed of the Cibao Formation, the Aguada Limestone, and Aymamón Limestone. The greatest production potential of the aquifer is in the Bayamón area where the fresh-water zone of the aquifer not only has its greatest extent, but the recharge area is extensive in comparison with the areas to the east. Two major well fields operated by the Puerto Rico Aqueduct and Sewer Authority are located in the Bayamón area: the Campanilla and the Sabana Seca well fields. Wells in the Campanilla area tap the Aguada Limestone and their yields are as much as 1,000 gal/min. Wells in the Sabana Seca field tap the Aymamón Limestone and the upper part of the Aguada Limestone. Yields range from 500 to 1,000 gal/min. Water quality in both fields, however, is being affected by salt-water encroachment.

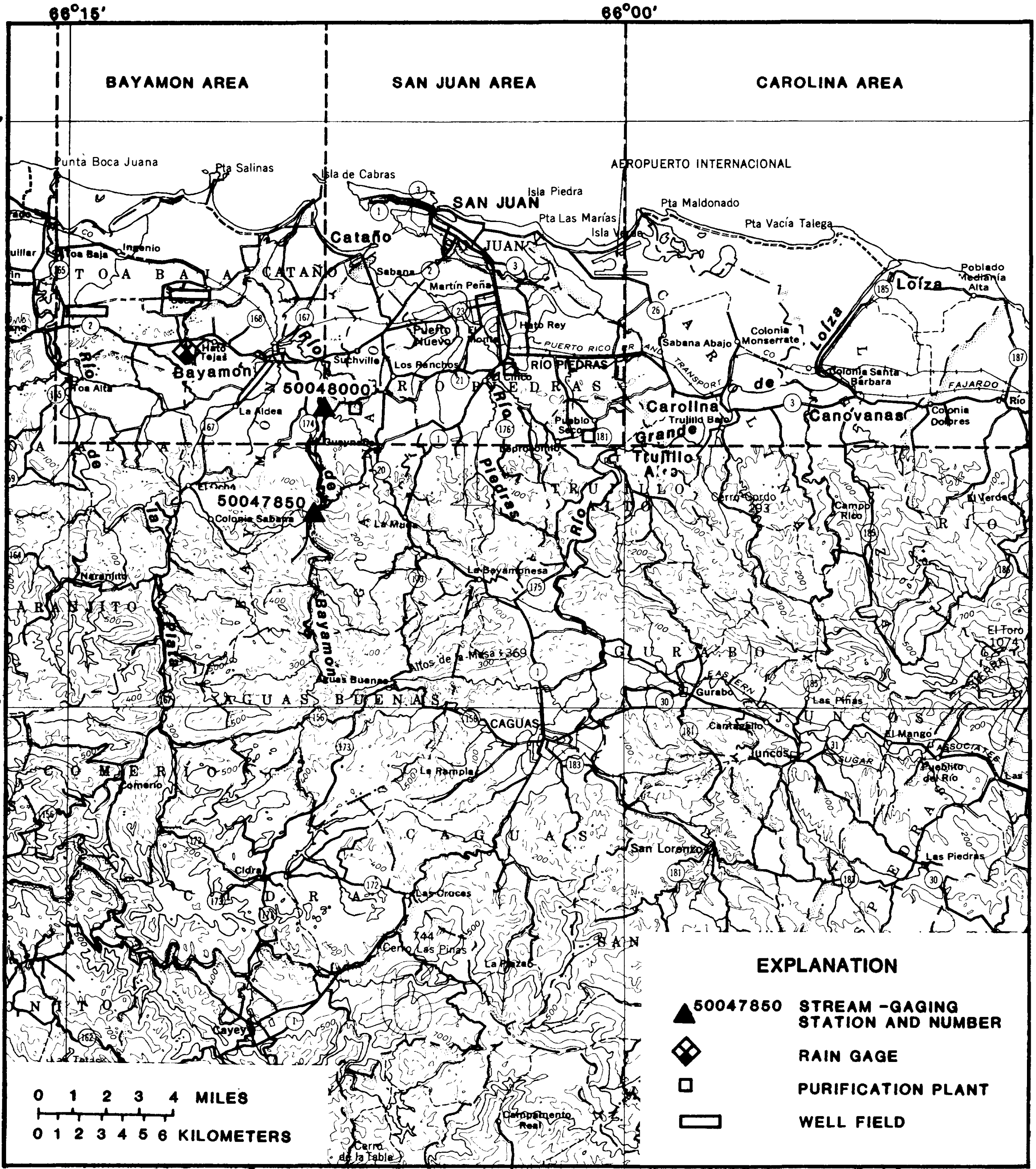
San Juan Metropolitan Area-Continued

In the San Juan-Carolina area, freshwater in the water-table aquifer is found only in the upper part of the Cibao Formation and the Aguada Limestone. Well yields are restricted , however, to less than 200 gal/min because of the potential for sea-water intrusion. The Aymamón Limestone in almost all the area contains mostly saltwater.

Since 1976 there has been relatively no impetus to conduct investigations specifically designed to yield a more complete regional analysis of the water table and artesian aquifers in the San Juan Metropolitan area. Exploratory drilling, geophysical logging, and aquifer tests are highly desirable in some areas where no subsurface data exists. An attempt will be made to design and calibrate an areal ground-water flow model which can be interfaced with models of the fresh-water system to the west. A localized cross-sectional model in the San Juan area will also be attempted to determine the flow connection between the water-table aquifer and known artesian system.



THE METROPOLITAN AREA
(See figure 9)



Base map from USGS topo map scale 1:240,000

Figure 9.--The San Juan Metropolitan area.

Reports

The results of the study will be presented in a professional paper prepared during the last year of the study. However, throughout the study, hydrogeologic, geochemical, salinity-intrusion maps, and preliminary model analyses will be presented in open-file reports. A non-technical report for planners and civic officials will be prepared. This report presents a summary of the principal features of the flow system and model simulation results with a minimum of hydrologic and geologic jargon.

The professional paper will tentatively consist of the following five chapters:

A. Summary Discussion of the North Coast Limestone Area of Puerto Rico and Water Management Alternatives.

B. Hydrogeologic Framework.

C. Geochemistry.

D. Regional Ground-Water Flow Model Analysis.

E. Subregional Studies.

Chapter A will be a summary report and will present principal features of the flow system and results of the regional model simulation. The report will highlight regional problems and the predicted effects of various water-management alternatives.

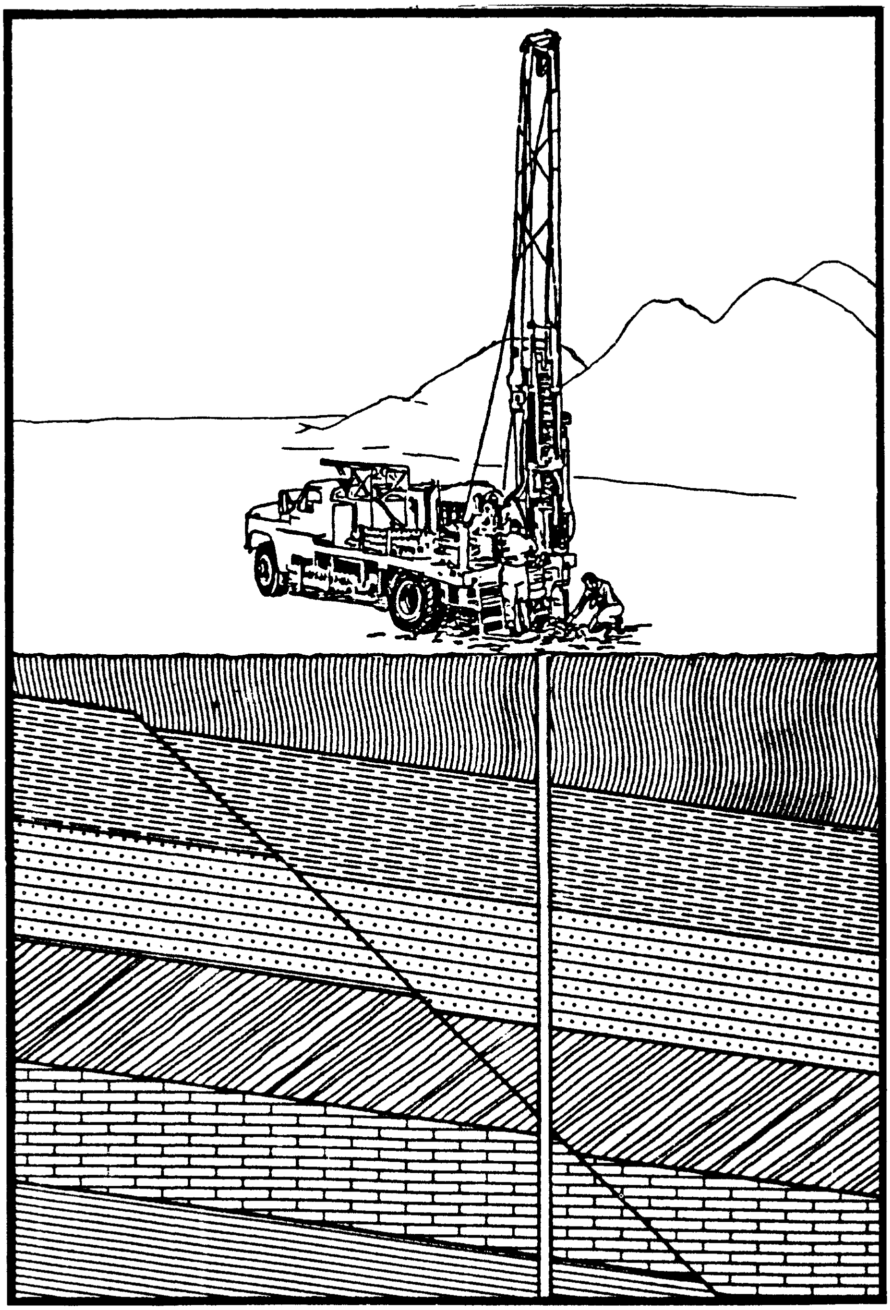
Chapter B will present a complete description of the geologic framework and hydraulic characteristics of the North Coast Limestone aquifers. Regional maps showing hydrogeologic and aquifer characteristic parameters will be presented. In addition to the maps, cross sections, and fence diagrams will be used to describe the subsurface framework.

Chapter C will describe the natural geochemical system and discuss the relationship between the flow system and natural changes in water chemistry. Geochemical changes brought about by pumping (such as salt-water intrusion) will be discussed.

Chapter D will present a complete description of the regional ground-water flow model analysis. The intensive use of computer simulations to determine the best possible representation of the hydrologic system will be described.

Chapter E will present hydrogeologic system descriptions and hydrologic analyses of the subregional studies. Emphasis will be placed on computer simulation of the subregions and local critical areas.

The project organization will consist of a core staff of four hydrologists and two hydrologic technicians. Specialists in ground-water modeling, solute-transport modeling, and geochemistry will be detailed to the San Juan office for various lengths of time as needed. In addition to the project chief which will be the modeling specialist, the staff will include a hydrogeologist, geologist, and a geochemist. Of the four hydrologists assigned to the project for its duration, the project chief will be fully committed to the study, while the other three hydrologist specialists will be committed for about half their time.



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