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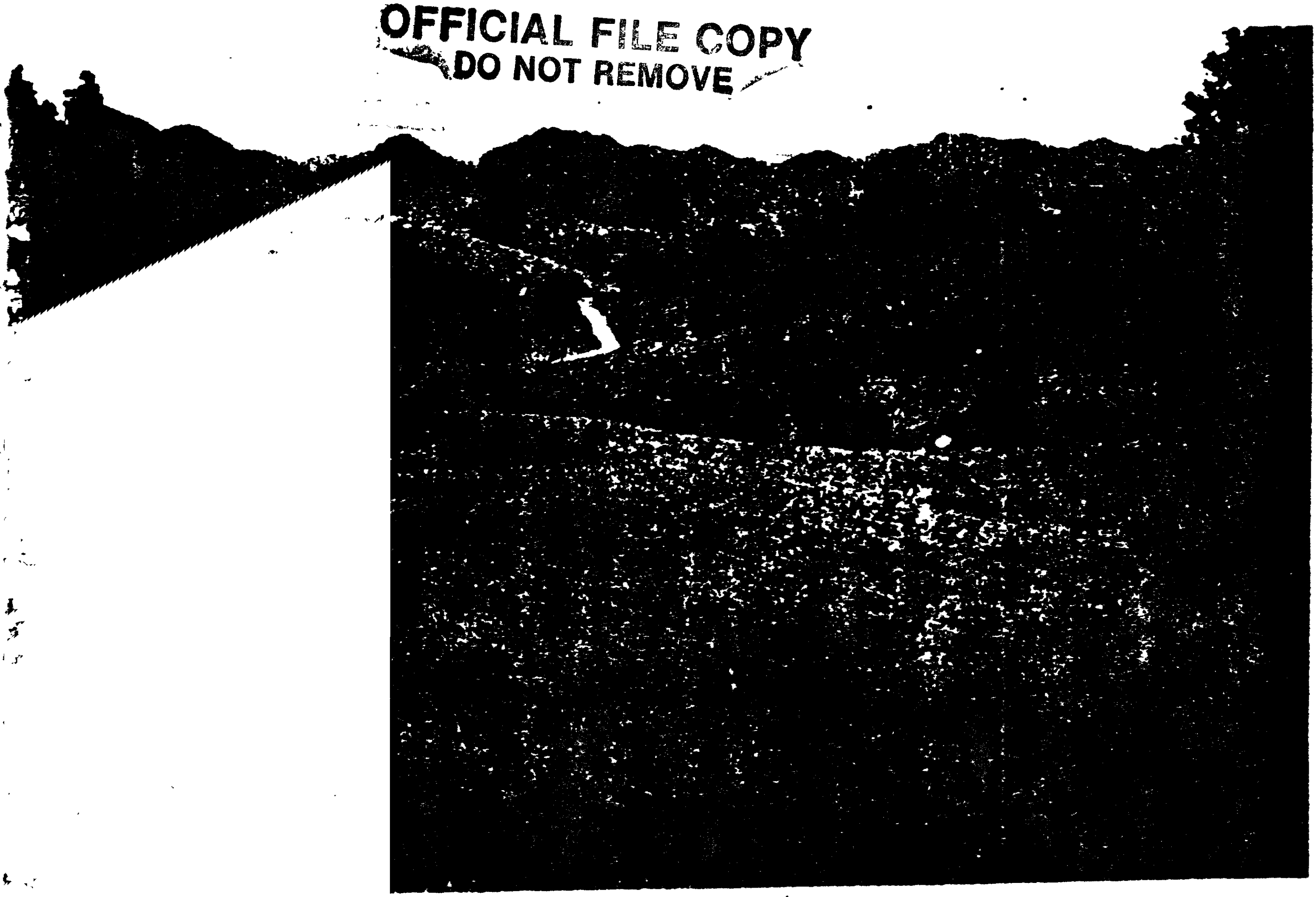
WATER RESOURCES OF THE NORTH COAST LIMESTONE AREA, PUERTO RICO

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 42-75



Prepared in cooperation with the COMMONWEALTH OF PUERTO RICO

WATER RESOURCES OF THE NORTH COAST LIMESTONE AREA, PUERTO RICO

By E.V. Giusti and G.D. Bennett

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February 1976

ABSTRACT

The North Coast Limestone study area covers about one-fifth of Puerto Rico, or an area of about 600 square miles. Four limestone aquifers are present; they are, from oldest to youngest: the Lares Limestone, the Cibao Formation, the Aguada Limestone, and the Aymamón Limestone. The hydraulic conductivity of these limestone aquifers decreases exponentially from a maximum of about 6,700 $ft^3/day/ft^2$ (cubic feet per day per square foot) in the upper Aymamón Limestone to a minimum of about 0.13 $ft^3/day/ft^2$ in the basal Lares Limestone. The water-table gradient is nearly flat--3 to 4 feet per mile--in the Aymamón and upper Aguada Limestones. It increases through the lower Aguada Limestone and decreases again--to 15-20 feet per mile--in the outcrop areas of the Cibao Formation and Lares Limestone. The impure Cibao Formation and layers of massive limestone provide, locally, artesian conditions.

At the time of this report (1971) only in the area between Arecibo and Barceloneta have artesian aquifers (the Montebello Limestone Member of the Cibao Formation, and the upper Lares Limestone) been found. Wells tapping the artesian aquifer of the Montebello Limestone Member along Highway 2 can be expected to yield as much as 2,000 gpm (gallons per minute). Wells tapping the upper Lares Limestone are reported to yield less; approximately 1 gpm per foot of penetration into the aquifer. West of Arecibo and east of Barceloneta, no wells have tapped artesian aquifers. But, if such aquifers exist, the long-term yield to wells cannot be expected to be as large as in the area between Arecibo and Barceloneta because the recharge areas are not as large.

Wells drilled in the water-table aquifers can be expected to yield 1,000 gpm in the upper Aymamón Limestone. Yield to wells in the lower Aymamón and the Aguada Limestones may range locally from 100 to 800 gpm, and in the Cibao Formation and Lares Limestone the average yield may range from 100 to 200 gpm.

A streamflow budget study was made in which the discharges of streams entering and leaving the limestone belt were measured, along with the discharges of streams draining the volcanic terrane immediately south of the limestone belt. In addition to these measurements of streams, measurements were made of the outflows of two coastal discharge features, the Caño Tiburones area and Laguna Tortuguero. These features are swampy depressions parallel and adjacent to the coast, and drain much of the coastward ground-water flow in their respective areas.

The quality of water is generally good except that the hardness is somewhat high, as might be expected in a limestone region, and for some industrial applications the water would have to be treated. Near the coast, the limestone contains fresh water at shallow depths and sea water deeper in the section. In this area quality problems caused by sea-water intrusion may accompany development of the aquifer unless care is taken in the management of the supply.

The North Coast Limestone area, outside of the San Juan area, is one of the few sparsely populated areas in Puerto Rico, and it possesses unique esthetic and geologic qualities in addition to being the last large and underdeveloped source of ground water on the island.

CONTENTS

Page

ILLUSTRATIONS

Figure | Page

Figure | ILLUSTRATIONS | Page

TABLES

Table | Page

WATER RESOURCES OF THE NORTH COAST LIMESTONE AREA, PUERTO RICO

by Ennio V. Giusti and Gordon D. Bennett

INTRODUCTION

The North Coast Limestone area is one of the two most important ground-water provinces of Puerto Rico--the other being the South Coast Alluvial aquifer. The investigation of the water resources of the South Coast has progressed to the point that at this time (mid-1971) an electric-analog model of the area is being prepared. The hydrology of the North Coast Limestones, however, was never investigated as a whole before this investigation, and, therefore, this study was designed to assess the most important hydrologic features of the area. The approach used to evaluate the water resources of the limestone area was mainly that of a surface-water budget supplemented by ground-water data from wells in the area.

The study was made through the cooperative water resources investigation program and conducted by the following Commonwealth Agencies: P.R. Environmental Quality Board, P.R. Aqueduct & Sewer Authority, P.R. Water Resources Authority, P.R. Industrial Development Company, P.R. Department of Natural Resources, and the U.S. Geological Survey--Water Resources Division.

DESCRIPTION OF THE AREA

Location and Extent

The study area of the North Coast Limestones of Puerto Rico is about 60 miles long and averages 9.5 miles wide. This 600-square mile area comprises nearly one-fifth of Puerto Rico. The location of the study area is shown in figure 1 as is the full extent of the limestone belt.

Geology

The central core of the island is formed of volcanic rocks, mostly of Cretaceous Age. In the Tertiary period, limestone beds were deposited along both the north and south coasts of this volcanic mass during periods of general subsidence. On the north coast, where deposition was most widespread, the total thickness of sedimentary material exceeds 4,000 feet. The sediments dip northward, or seaward, at about 5° and extend offshore an undetermined distance.

A formation of sand and clay, containing a few lenses of limestone, directly overlies the volcanic base. This sand-clay unit, known as the San Sebastián Formation, does not crop out in the central part of the area. The lowest formation of the limestone sequence, the Lares Limestone, overlies the San Sebastián Formation. The Cibao Formation overlies the Lares Limestone. West of Río Camuy, the Cibao Formation is typically chalk and limestone with interbedded marl and some sand and clay beds. The typical Cibao Formation is replaced by the predominantly fine-grained Montebello Limestone Member of the Cibao Formation from about midway between Río Camuy and Río Grande de Arecibo to just east of Río Grande de Manatí. East of Río Grande de Manatí the Montebello Limestone Member pinches out and the Cibao Formation is similar to that of the western area, although there is an apparent increase in the amount of sand and clay in the section. Above the Cibao Formation and cropping out in sequence from south to north are the Aguada Limestone and the Aymamón Limestone. Overlying the Aymamón Limestone in the western part of the area but disappearing toward the east, is the Camuy Formation. The general disposition of these formations is shown in figure 2. The limestone formations are described below, following the discussion of Briggs and Akers (1965).

Lares Limestone

Massive, dense limestone and calcarenite; thickness ranges from 0 to 1,650 feet; Oligocene Age.

Cibao Formation

Interbedded marl, chalk and limestone, some thin sand and clay beds; Montebello Limestone Member in central part of outcrop area is predominantly a fine-grained, nearly pure limestone; thickness ranges from 0 to 1,000 feet; late Oligocene and early Miocene Age.

Aguada Limestone

Hard, thick-bedded to massive calcarenite and dense limestone interbedded with chalky limestone and marl; thickness ranges from 100 to possibly 580 feet; early Miocene Age.

Aymamón Limestone

Thick-bedded and massive dense limestone and calcarenite, some dolomite beds. Rocks are commonly hard on surface and soft and chalky in excavation; thickness ranges from about 630 to possibly 1,100 feet; early Miocene Age.

Camuy Formation

Fragmental limestone and marl containing some

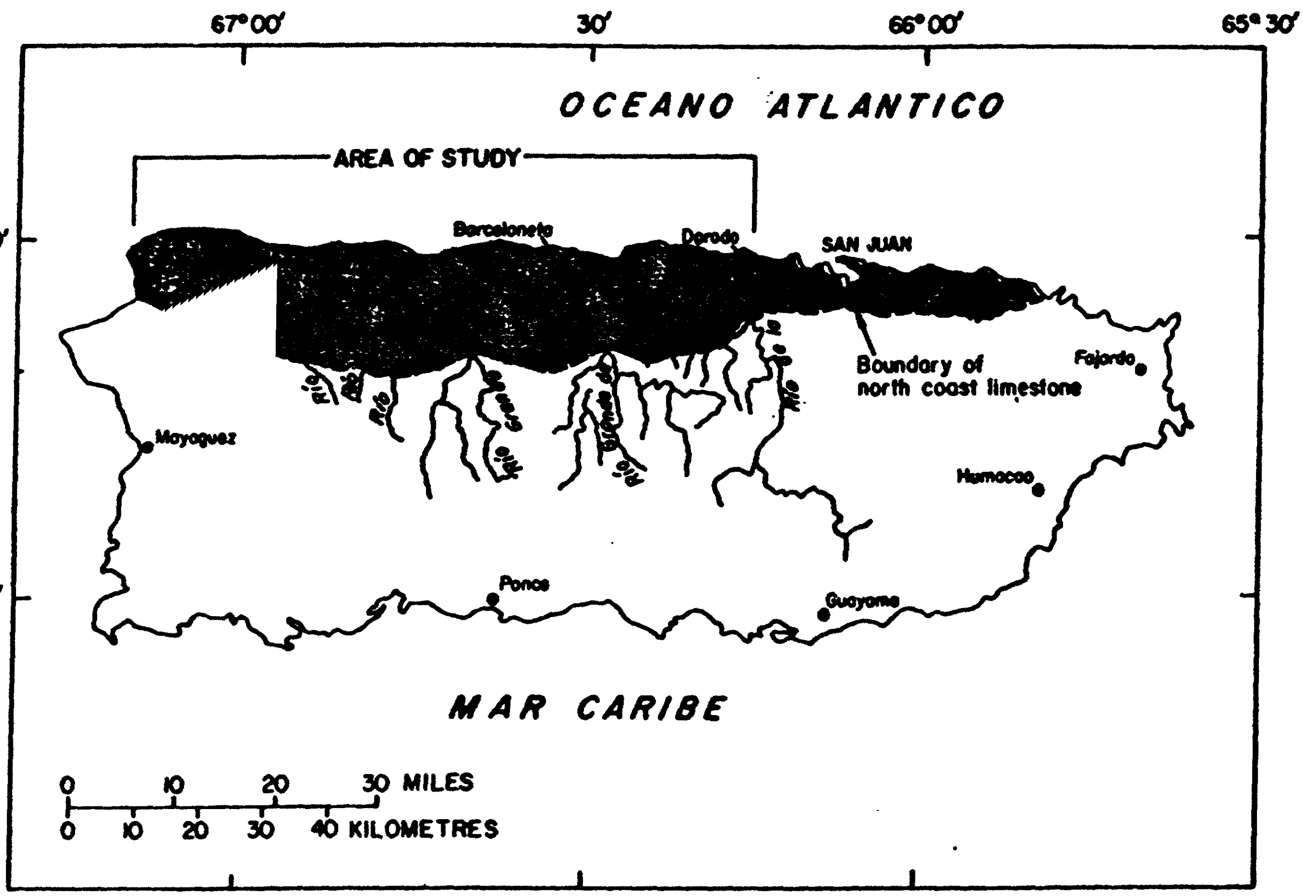
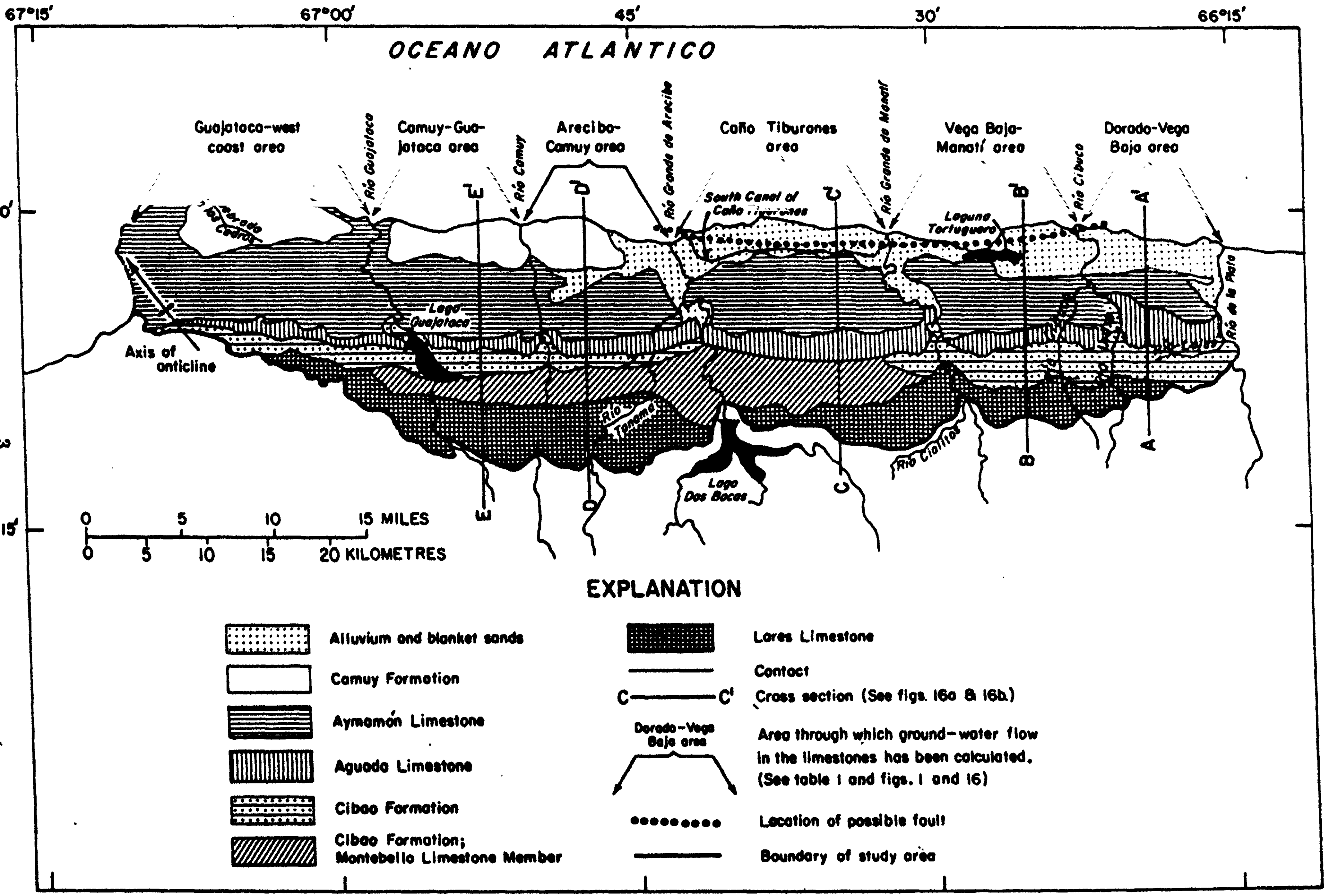


Figure 1.--North Coast Limestone belt of Puerto Rico showing study area and selected streams



Geology after Monroe and Pease, 1962.

Figure 2.--Geology of the study area.

sandstone and hard limestone beds; some discontinuous dolomite beds; maximum thickness about 600 feet; Miocene Age (Pliocene Age, according to paleontologic work by Dr. G. A. Seiglie of Univ. of Puerto Rico, oral comm., 1970).

The separation of the North Coast Limestone into five units is based in a large part on paleontological differences. The appearance of the rocks is uniform, and one cannot tell one formation from another without an analysis of hand specimens, with the exception of the typical Cibao Formation.

In addition to the five limestones described, the area of investigation contains other rocks. Of these the most important are the blanket sands and alluvium. The blanket sands are a surficial reddish-brown sandy clay as thick as 50-60 feet. The formation is younger than the limestone, but its age as well as its origin is still debated. Briggs (1966) believed it to be of Tertiary and Quaternary Age and partly derived from residues from dissolved limestone. Most flat areas between limestone hills are covered with the blanket sands.

The alluvium, of Quaternary to Holocene Age, is a mixture of sand, gravel, and clay, as thick as 200 feet, found chiefly in the alluvial valleys of the major rivers.

The general attitude of the limestone sequence is that of homocline gently inclined to the north. Figure 3 shows the distribution and orientation of 135 angles of dip. Using average values, the limestones dip 5° N. 0° 47'E. The uniformity of the structure is remarkable, especially if compared with the intense deformation of the interior core of the island. There is, however, a northwest-plunging anticline near the west end of the limestone area (Monroe, 1969) as shown in figure 2. This anticline is possibly an expression of tectonic activity of the Puerto Rico trench, which, in turn, is probably responsible for the raised shoreline of the western part of the limestone belt.

Physiography

The land forms, developed on the North Coast Limestones of Puerto Rico, constitute one of the finest examples of tropical karst in the world.

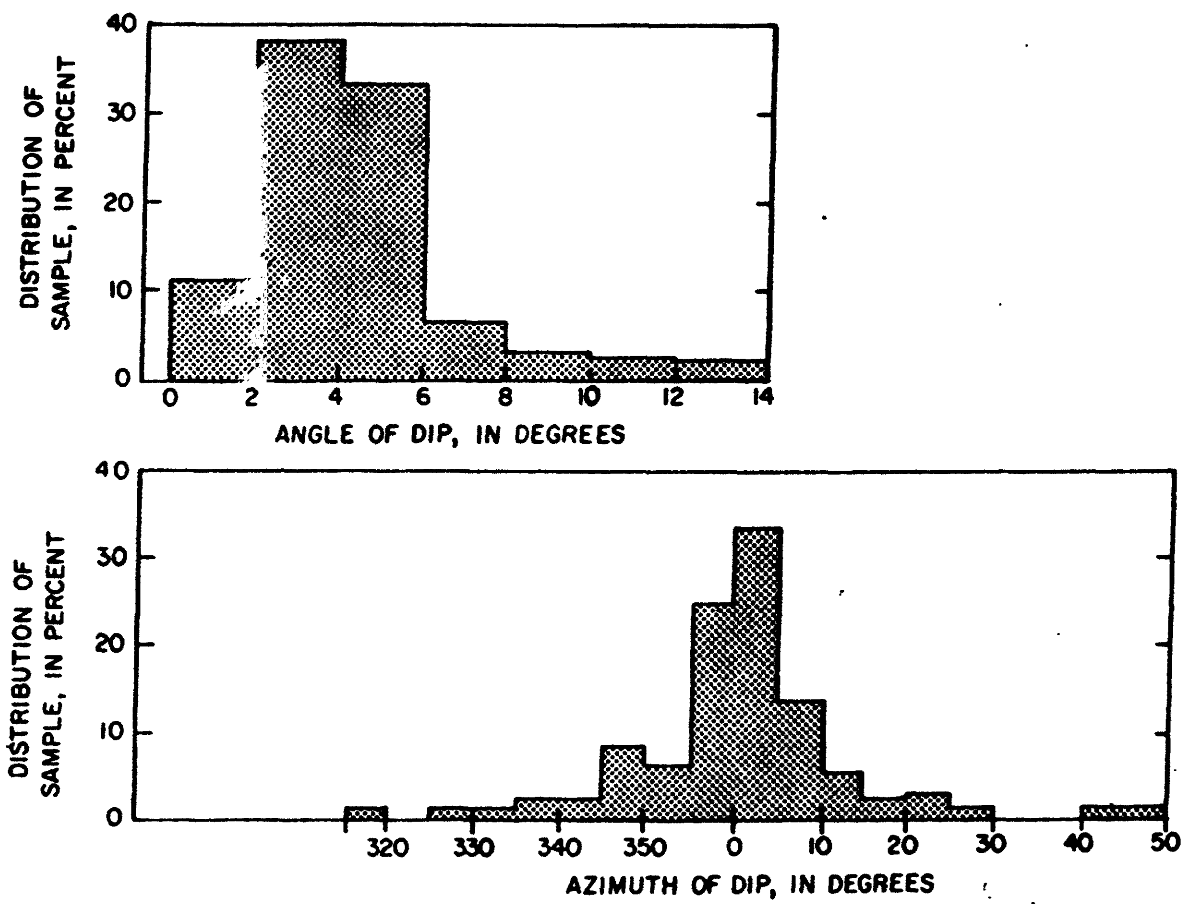


Figure 3.--Histograms of orientation and dip of limestone strata.

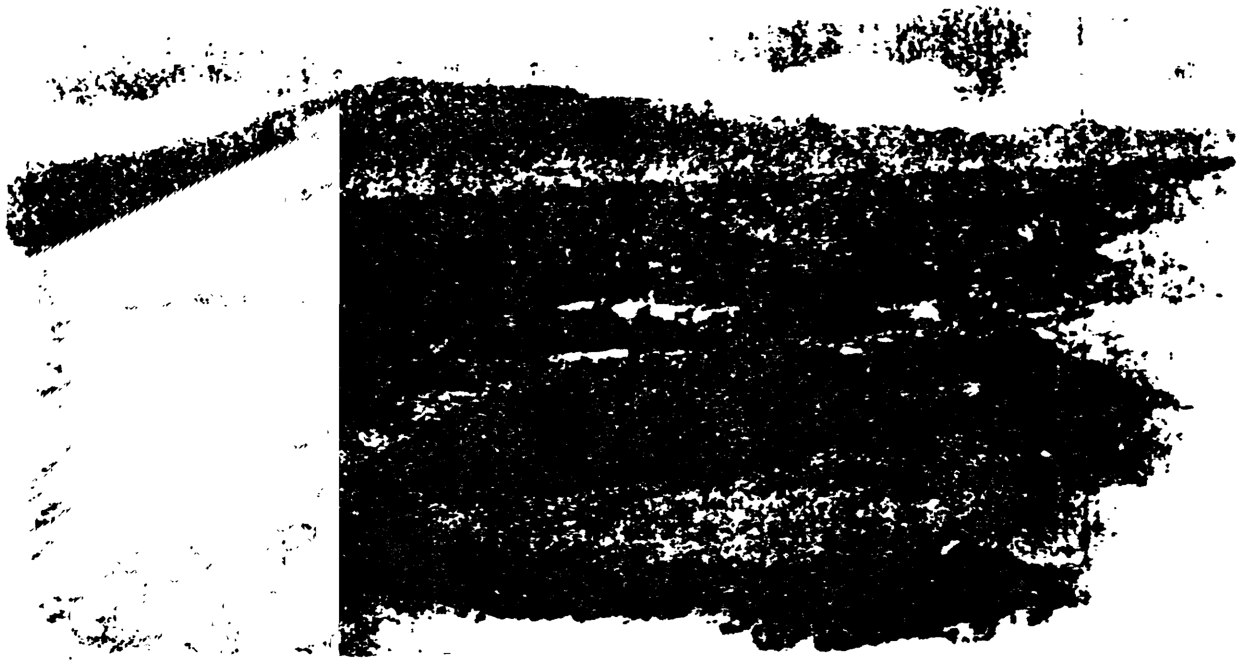


Figure 4.--Aerial view showing the karst which appears as a generally flat surface which is highly pitted, and almost entirely covered by vegetation.

Figure 5.--Haystack hills and rounded depressions of the karst terrane.

This karst appears from the air as a generally flat surface deeply pitted and almost entirely covered with vegetation (fig. 4). No evidence of major surface drainage is present except for the six main rivers that cross from south to north. From a closer viewpoint, the terrane appears as clusters of haystack hills separated from one another by rounded depressions (fig. 5). On a topographic map altitude contours are often shown as concentric closed lines with hachures for the depressions between the hills. This type of terrane is uniquely developed on carbonate rocks because the limestone is dissolved by the weak acids that are formed by the combining of rain water with carbon dioxide in the air or soil.

In addition, the development of karst requires only enough permeability so that water can percolate and dissolve the rock. Almost all the limestones of the study area have developed a karst. The notable exception is the slightly permeable Cibao Formation, where, instead of karst, a normal fluvial drainage has formed. The streams disappear underground where the Cibao Formation comes in contact with the next limestone downslope--the Aguada Limestone. The areal development of karst terrane is shown in figure 6, by percentage of area covered by sinkholes. The area of maximum development is just north of the Cibao Formation; from there development decreases in a seaward direction. South of the Cibao Formation on the Lares Limestone, other areas of sinkholes are found and their development is maximum near the contact of the Lares Limestone with the San Sebastián Formation. However, the sinkholes are not nearly as continuous as just north of the Cibao Formation. Both areas of well-developed sinkholes seem to coincide with areas where the ground-water level fluctuates the most.

The study area is traversed by six rivers which head in the volcanic terrane to the south. Figure 7 shows the surface-water features of the area as well as the average altitude of the terrane. The topography slopes N.5°E., whereas the rocks dip due north (fig. 3). The flow direction of the main rivers is generally west of north, and major tributaries enter the main streams from the west within the limestone area. The short segments of rivers shown in about the middle of the limestone area reflect the fluvial development formed on the Cibao Formation. Ríos Camuy and Tanamá have underground reaches; in fact, Río Camuy flows underground for a straight-line distance of about 4 miles. These facts provide clues to possible developments in the geologic past that have led to the present physiography of the limestone area.

During the deposition of the Camuy Formation in shallow seas of the Miocene time, the island of Puerto Rico had a slight topographic and geologic dip just west of north. After (or perhaps during) this deposition, the island emerged farther, exposing part of the Camuy Formation. At this stage (middle-late Pliocene?) karst began to form, and drainage (at first subterranean, at least in the western half) began to develop, following a general course slightly west of north. At some time in the Pleistocene, the entire Puerto Rico platform tilted to the east (Meyerhoff, 1933). The major stream drainages, which had developed up to this time in the limestone, continued to be slightly west of north; but the lateral drainage, most of which was and still is subterranean, took a slightly eastward course.

Since these Pleistocene events, weathering of the limestone region has continued without major tectonic activity. At present, different parts of the area exhibit different stages of the karst erosional cycle. In the outcrop area of the impure marly Cibao Formation, some relatively conventional stream drainage has developed. In the outcrop areas of the relatively pure Lares, Aguada, and Aymamón Limestones, dendritic stream drainage has not developed. Except for the six major rivers, which rise in the volcanic region and cross these formations, the drainage is largely subsurface as commonly occurs in limestone terrane. The Lares, the oldest major limestone of the north coast, must have had a sinkhole topography even before Pleistocene time; subsequent erosion may have acted to reduce this sinkhole expression in some parts of the Lares outcrop area.

Hydrologically, the most interesting feature of the karst erosional cycle is perhaps the transition from sinkhole topography, with associated subterranean drainage, to some form of stream-drained topography. On a topographic map sinkholes are indicated by hachured contours enclosing the depression; this suggests the possibility of measuring the extent of sinkhole development in

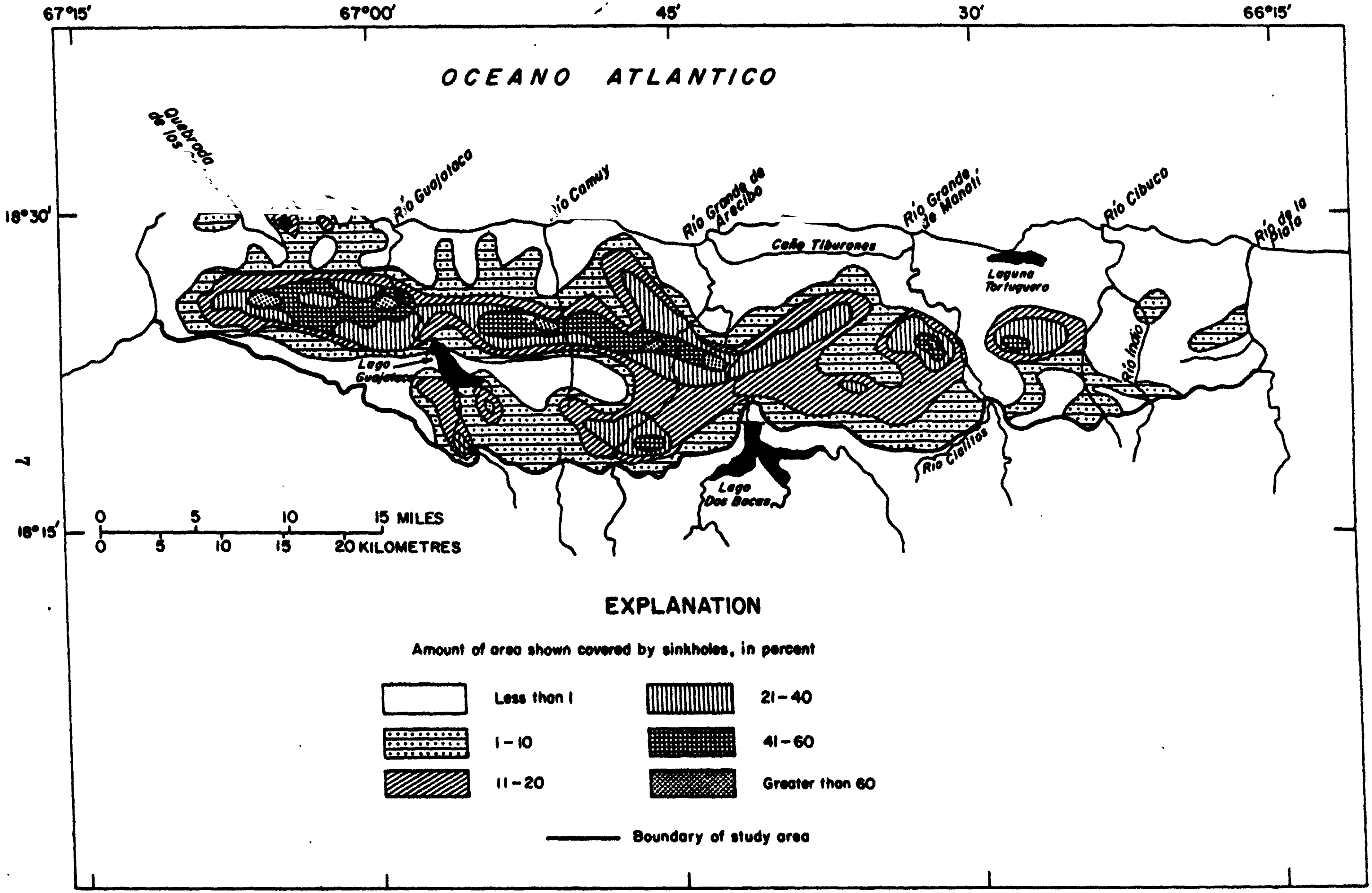


Figure 6.--Karst development by percent of land area covered by sinkholes.

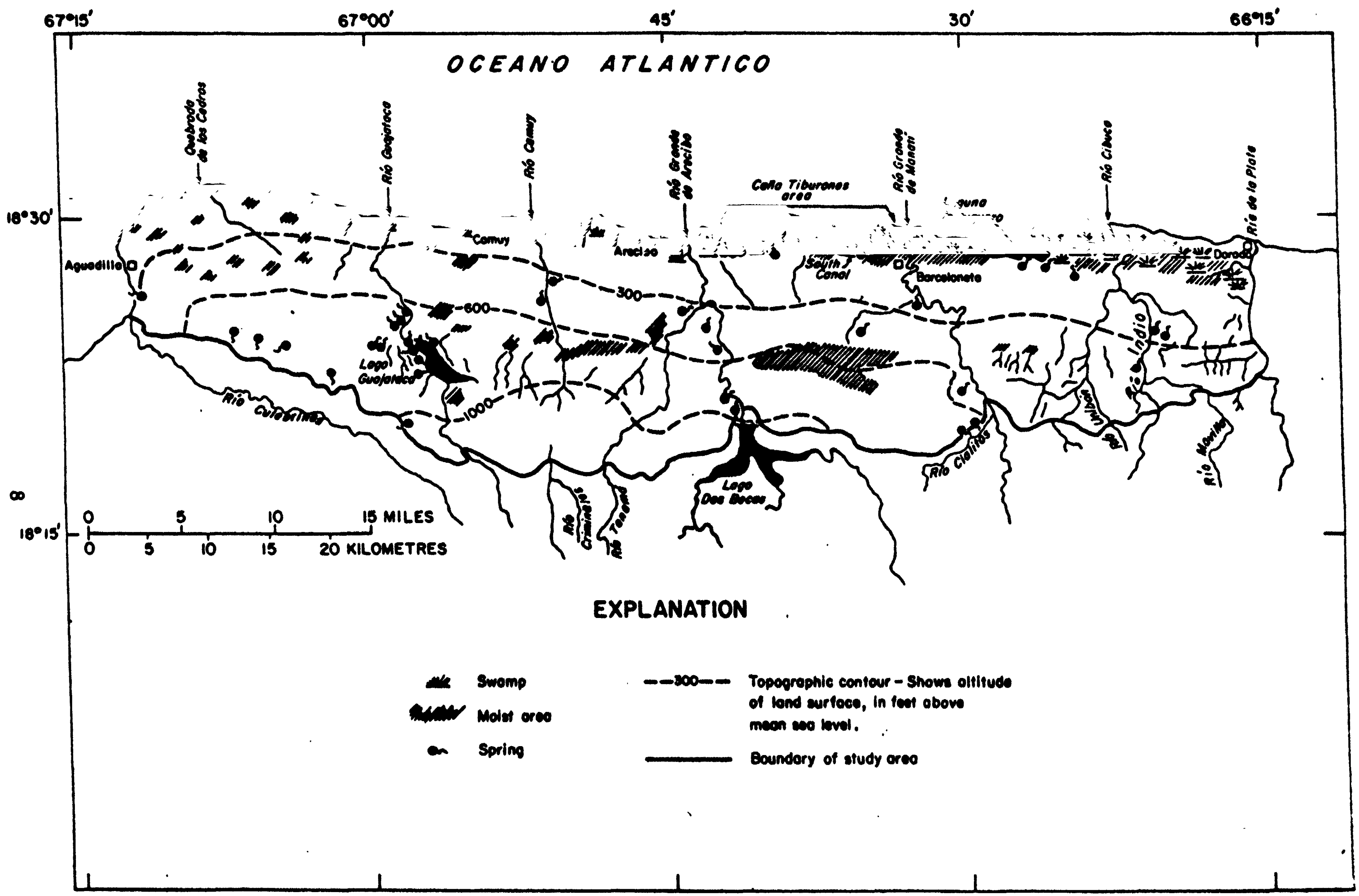


Figure 7.--Study area showing selected surface-water features and and contours of land-surface altitude.

an area by noting the percentage of the area that falls within closed hachures. The intensity of sinkhole development in the North Coast Limestone area was studied in this way. A topographic map of the limestone outcrop area was divided into rectangles of 1 minute latitude by 1 minute longitude. The percentage of the area of each rectangle falling within closed hachured contours was estimated by using a grid. Results ranged from zero to nearly 50 percent; the latter probably represents the maximum possible sinkhole development--that is, half the land is occupied by sinkholes and half by intervening high areas.

Sinkholes are a surface expression of one stage of the karst erosional process, whereas topographic relief provides some measure of the stage of any form of erosion. In figure 8, the extent of sinkhole development, expressed in percentage of area of each 1-minute rectangle of the limestone area, is plotted against the maximum topographic relief in that rectangle. The distribution shows that for a sinkhole intensity of more than 20 percent maximum local relief ranges from about 120 to 560 feet. For a sinkhole intensity of more than 30 percent, maximum local relief ranges from 130 to 460 feet, and for a sinkhole intensity greater than 40 percent, maximum relief ranges from about 160 to 360 feet. Thus, there seems to be a fairly wide range of maximum relief figures associated with large-scale sinkhole development.

Lower values of relief are associated with early stages of the karst cycle, when sinkholes just start to form, or with late stages, when high areas between sinkholes have been destroyed and the sinkholes have been filled. The higher values of relief associated with the intermediate stages, for example, are found along Río Guajataca, where collapse of caves and tunnels has left an exposed channel through a deep gorge. Remnants of former caves on Río Guajataca are, in fact, clearly evident (fig. 9), and the streambed is scattered with limestone blocks. During this stage, the sinkhole topography is actually being changed by stream erosion. The high areas between sinkholes are destroyed by collapse, opening the way to surface drainage rather than the subterranean drainage. In contrast to Río Guajataca, Río Camuy flows underground for long

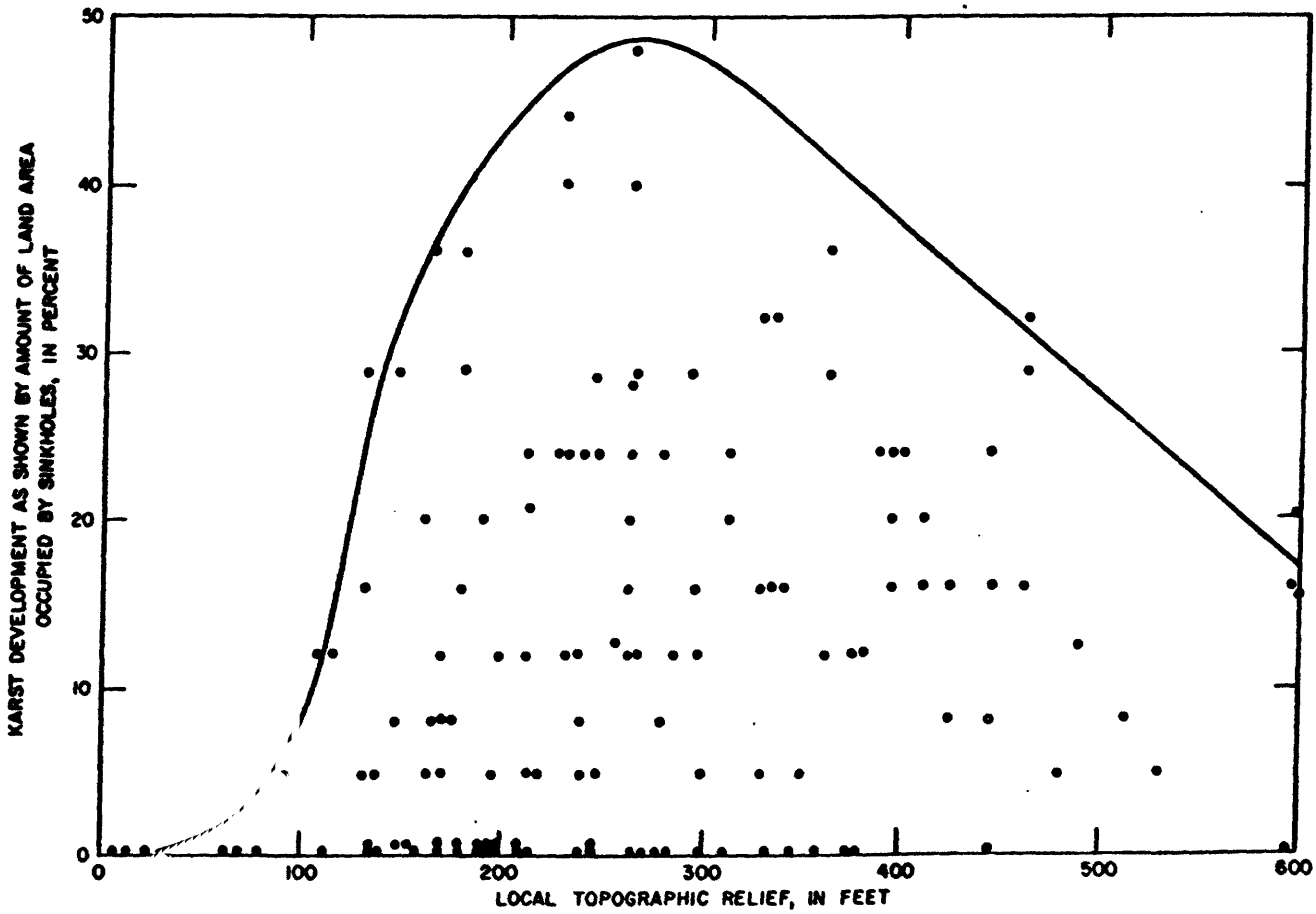


Figure 8.--Relation of karst development to topographic relief.

Figure 9.--Collapsed caves on Río Guajataca.

Figure 10.--Mogotes--subconical hills rising from the surrounding terrane, representing the final phase of karst expression.

stretches, and represents a much earlier stage in the process of stream development. In some thousands of years its channel will probably develop to the present condition of Río Guajataca. Río Tanamá is at a stage of development somewhere between that of Río Camuy and Río Guajataca. It flows underground only for short reaches, with the stage of cave and tunnel collapse almost complete.

The coastal region between Arecibo and Dorado is characterized by a chain of swampy ground-water discharge areas (fig. 7). The most important features are the Caño Tiburones area, a swampy depression extending along the coast from Río Grande de Arecibo to Río Grande de Manatí, and Laguna Tortuguero, a fresh-water lagoon between Río Grande de Manatí and Río Cibuco. The discharge to these features occurs both as springflow and as areal seepage. Immediately to the south of these flat swampy areas lie remnants of karst as isolated hills standing above a gently seaward-sloping layer of blanket sands. These are the mogotes described in the literature (Monroe, 1968) and shown in figure 10. The mogotes are the last phase of karst expression before complete denundation and are the equivalent in limestone of "monadnocks."

The coastline from Aguadilla to Arecibo is composed of a limestone cliff with a narrow sandy beach at its foot (Kaye, 1959). East of Arecibo the coastline marks the edge of the swampy coastal plain containing the Caño Tiburones area and Laguna Tortuguero. Unconsolidated and cemented sand dunes and isolated limestone outcrops are found in places along this part of the coast, and beach rock occurs at various places.

CLIMATE

Rainfall

The North Coast Limestone area has an average annual rainfall of about 70 inches. The uniformity of the annual rainfall, which ranges only from 60 to 80 inches, reflects the small range of relief in the study area. The monthly variation follows the trend of the rest of the island: a relatively dry period from December to March, a spring rainy period in April and May, another dry period in June and July, and a wet season in August, September, October, and November. September is usually the rainiest month. The hurricane season lasts from June through October, and in any one year can produce a very wet June or July, which normally are considered part of the dry season.

Temperature

The range of air temperature is small--the annual average being about 24°C (Celsius). Only a few degrees Celsius separate the coldest winter from the hottest summer.

Evapotranspiration

The water-budget analyses described in subsequent sections of this report required evaluation of the evapotranspiration (ET) from the study area. These evaluations were made by empirical relationships developed among ET, pan evaporation, and precipitation.

Figure 11 shows a plot of ET against rainfall for several basins in various parts of Puerto Rico. The ET was computed as rainfall minus runoff; the basins used in this exercise were chosen so that ground-water outflow could be considered negligible. The fact that the data plot as a well-defined function of rainfall does not imply that rainfall is the major cause or controlling factor for ET, but rather that both processes are related to the same climatic factors, such as humidity, solar radiation, cloud cover, and temperature. However, rainfall does have direct influence as the source of water for ET. If rainfall is zero ET would also be zero, whereas, if rainfall is sufficient to keep the water table within reach of plant roots ET would increase. Figure 11 shows that ET increases with rainfall up to an annual precipitation of 80 to 90 inches. ET then begins to decrease, probably reflecting the greater humidity, lower temperature, and more prevalent cloud cover associated with areas of high rainfall.

Figure 11 also shows a plot of pan evaporation against precipitation for various stations on the island. The two curves appear to merge for precipitation greater than 80 or 90 inches per year.

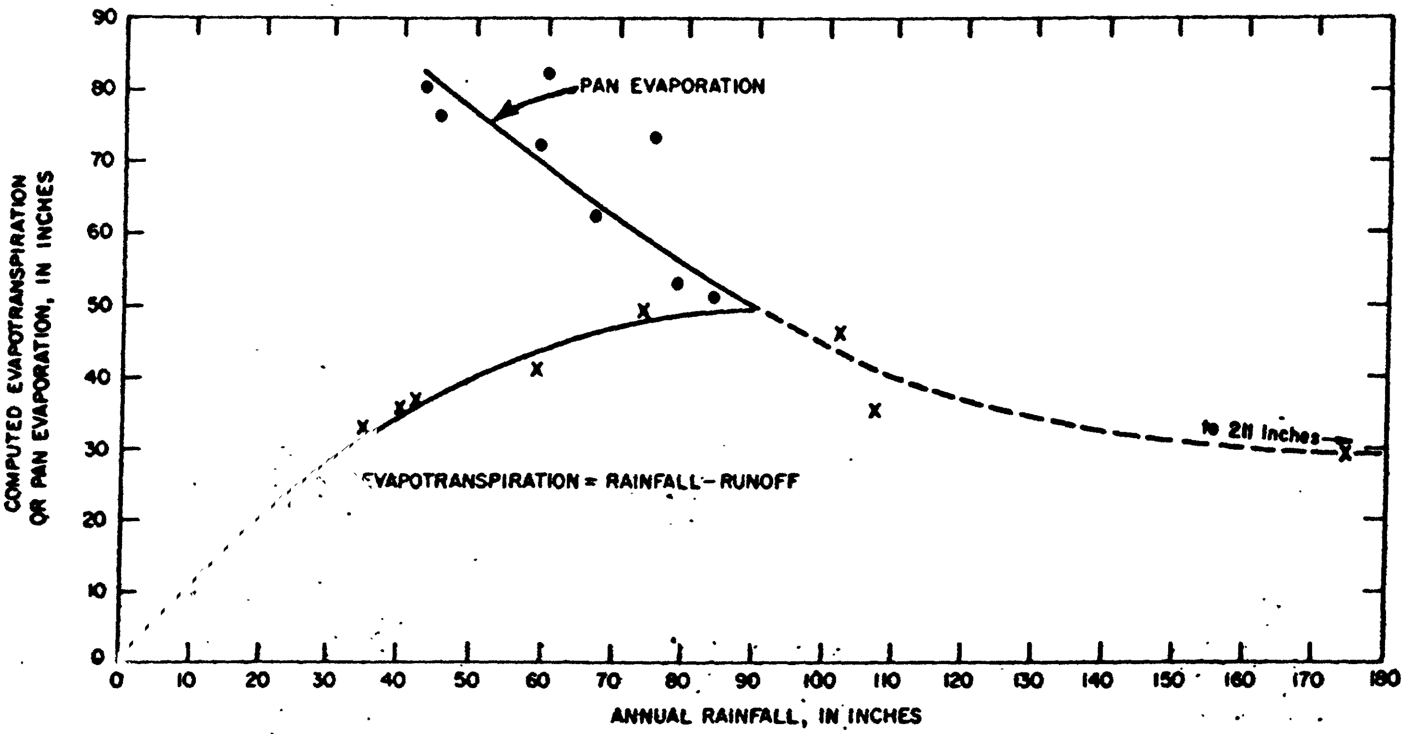


Figure 11.--Relation of computed evapotranspiration and pan evaporation to annual rainfall.

Using the data summarized in figure 11, it was possible to develop relationships between ET and pan evaporation. These relationships were later used in computing ET from pan evaporation data for the limestone area. (In the limestone area ET could not simply be taken as the difference between rainfall and runoff, as ground-water flow could not be neglected.) As a first approximation, however, the data of figure 11 indicate that an ET of about 45 inches, corresponding to a rainfall of 70 inches or a pan evaporation of 60 inches, can be used as an average for the study area.

HYDROLOGY

It was evident, from the beginning of the project, that the most practical approach to the study of the area was to determine a water balance for the limestone area. The basic equation for any given time period is:

Inflow minus Outflow = Change in Storage

The inflow (I) includes:
Rainfall (P), streamflow from the volcanic terrane (Q_v), and ground-water inflow from volcanic terrane (Q_{gv}).

The outflow (O) comprises:
Evapotranspiration (ET), including evaporation from the unsaturated zone, transpiration by plants, evaporation from wet surfaces, and evaporation from the ground water rising through the capillary fringe; ground-water outflow to the sea (Q_g); and streamflow to the sea (Q).

Change in storage ($\pm\Delta S$) is increase or decrease of volume of ground water, the change in the volume of ground water, the change in the volume of water in surface storage being negligible over the time periods used in the study. In terms of an equation:

$$P + Q_v + Q_{gv} - ET - Q_g - Q = \pm\Delta S$$

The term Q_{gv}, the ground-water inflow from the volcanic terrane, can be neglected as a first approximation because it is very small, and of the other terms, rainfall and streamflow can be gaged and quantities calculated. Using parentheses to identify the directly measurable quantities:

$$(P) + (Q_v - Q) = ET + Q_g \pm \Delta S.$$

For a time period with ground-water levels the same at the beginning as at the end, the term ΔS approaches zero, and

$$(P) + (Q_v - Q) = ET + Q_g.$$

A fair estimate of ET can be made by computing ET from a water budget in the volcanic terrane, where the ground-water terms can be neglected, and by adjusting this computed value to the climatologic conditions of the limestone area. Therefore, the ground-water outflow from the limestone can be estimated. The greatest effort went into the assessment of surface inflows and outflows. In brief, all the stream inflows from the volcanic terrane were gaged continuously where they entered the limestone area, and all the stream outflows from the limestone were gaged as far downstream as possible. The difference between the discharges of the upstream and downstream sites constitutes the contribution to streamflow from the limestone area. Rainfall and pan evaporation were obtained from the available data published by the National Weather Service, supplemented by data from a few sites maintained by the U.S. Geological Survey. Figure 12 shows the location of data collection sites.

After the selection of streamflow measurement sites, the problem arose of delineating basin divides to compute the drainage areas in the karst terrane. The topographic divides gave numerous alternatives because many of the intersink spilling routes (the lowest path through the hills around a sinkhole, which determines where water would spill if the sink area were flooded to that altitude) lay at the same altitude, insofar as could be determined from contour lines on the maps.

The two criteria were used to select drainage divides:

(1) Sinkholes would drain to the neighboring sinkhole of lowest altitude.

(2) Where neighboring sinkholes lay at the same altitude, a preferential path was chosen according to the general orientation of drainage lines. An example from a part of a topographic map is shown in figure 13. Use of these criteria lead to a fairly rapid delineation of drainage divides and, hence, to computation of drainage areas. Several indeterminate areas, which did not clearly drain to any stream basin, were found; their probable drainage paths are discussed subsequently with the streamflow data.

Ground Water

Water Table

The water table is contoured in figure 14. The contours are based on water levels in wells and sinkholes; riverbed altitudes were used as control points in the stream valleys. The resulting water-level pattern indicates that the streams act as ground-water drains. Within the most seaward part of the Aymamón Limestone, the altitude of the water table is just above mean sea level with an average slope of 0.0007, expressed in consistent units such as feet per foot. Southward the gradient steepens to 0.045 within a geologic interval that varies locally but in general includes the lower Aymamón and the Aguada Limestones; the gradient flattens again to 0.003 within the Cibao Formation and is assumed to be about the same in the Lares Limestone.

The steep gradient is generally associated with a relatively thin sheetlike flow through the Aguada Limestone for which the upper part of the Cibao Formation forms a low-permeability base. The low gradient of the water table in the lower part of the Cibao Formation and the Lares Limestone reflects an area of input in which the dominant direction of ground-water movement, at least near the surface, is downward.

Figure 15 shows a graph of depths to water, as measured in wells, against land-surface altitude. In the Aymamón and Aguada Limestones, the water table rises more slowly than the land surface causing an increase in depth to water with altitude. In the Cibao Formation and Lares Limestone there is no clear relationship between depth to water and altitude--depth to water depends on the presence of artesian conditions

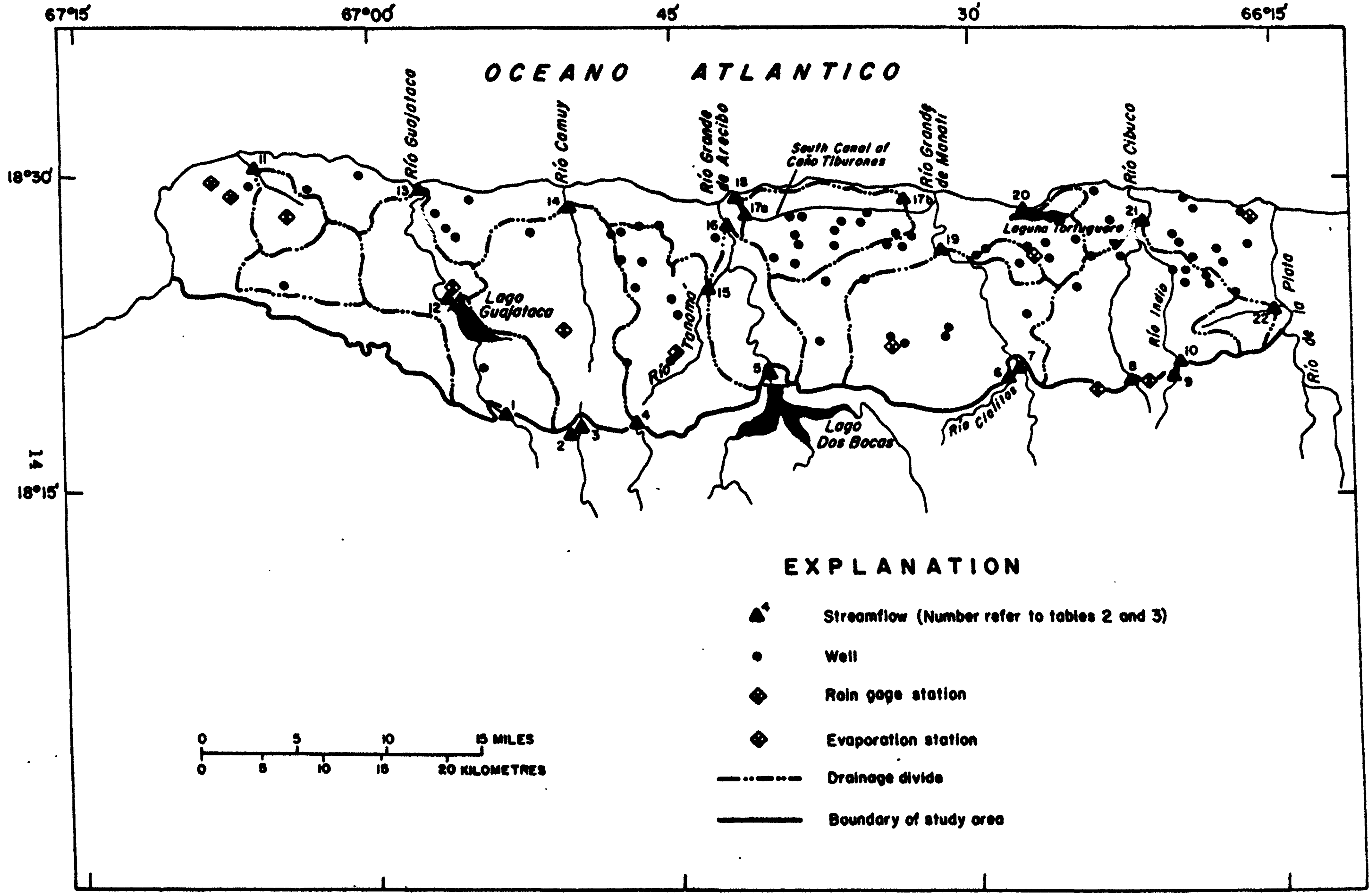


Figure 12.--Location of hydrologic data-collection sites.

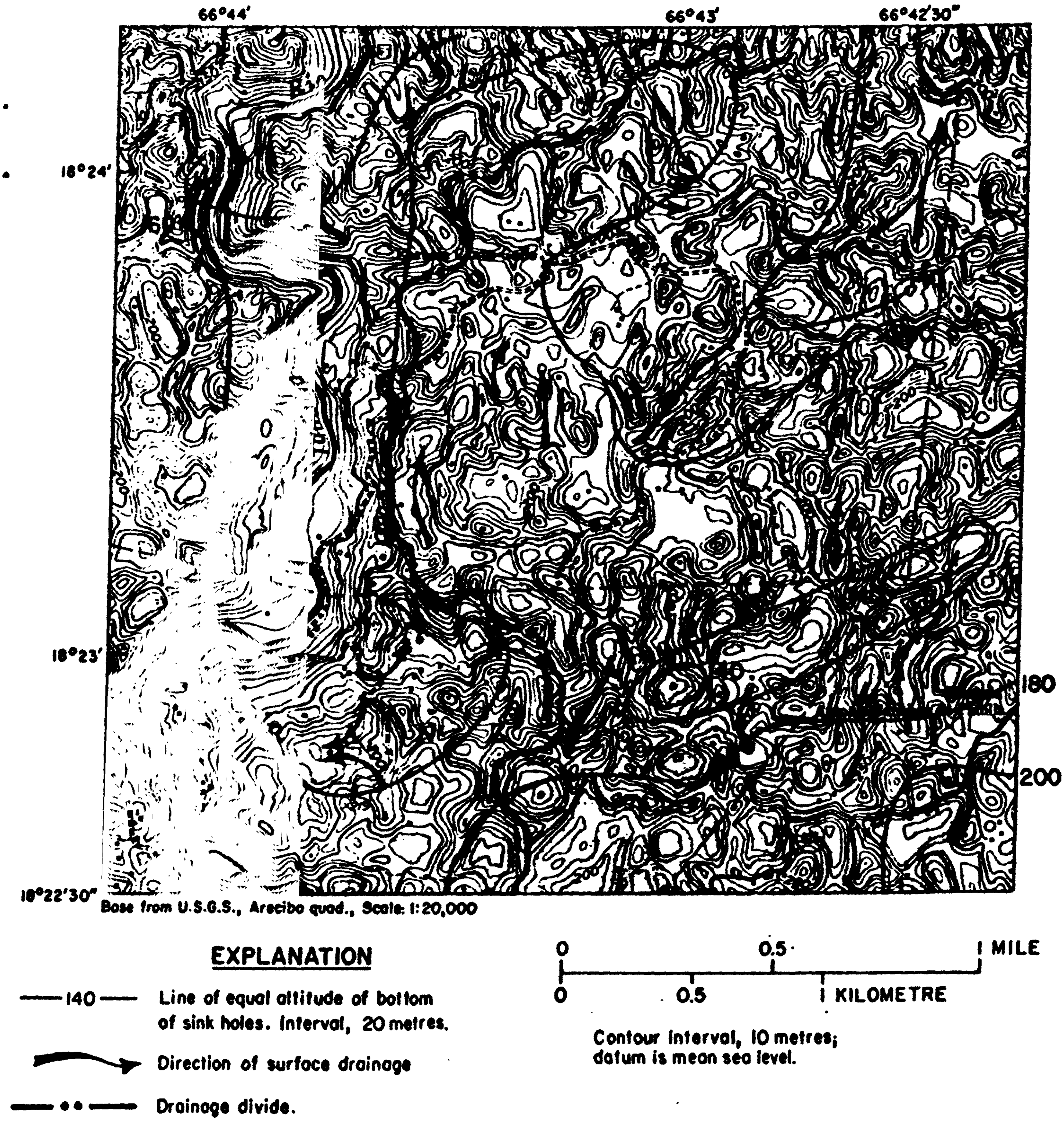


Figure 13.--Example of the method used to determine drainage divides in karst terrane.

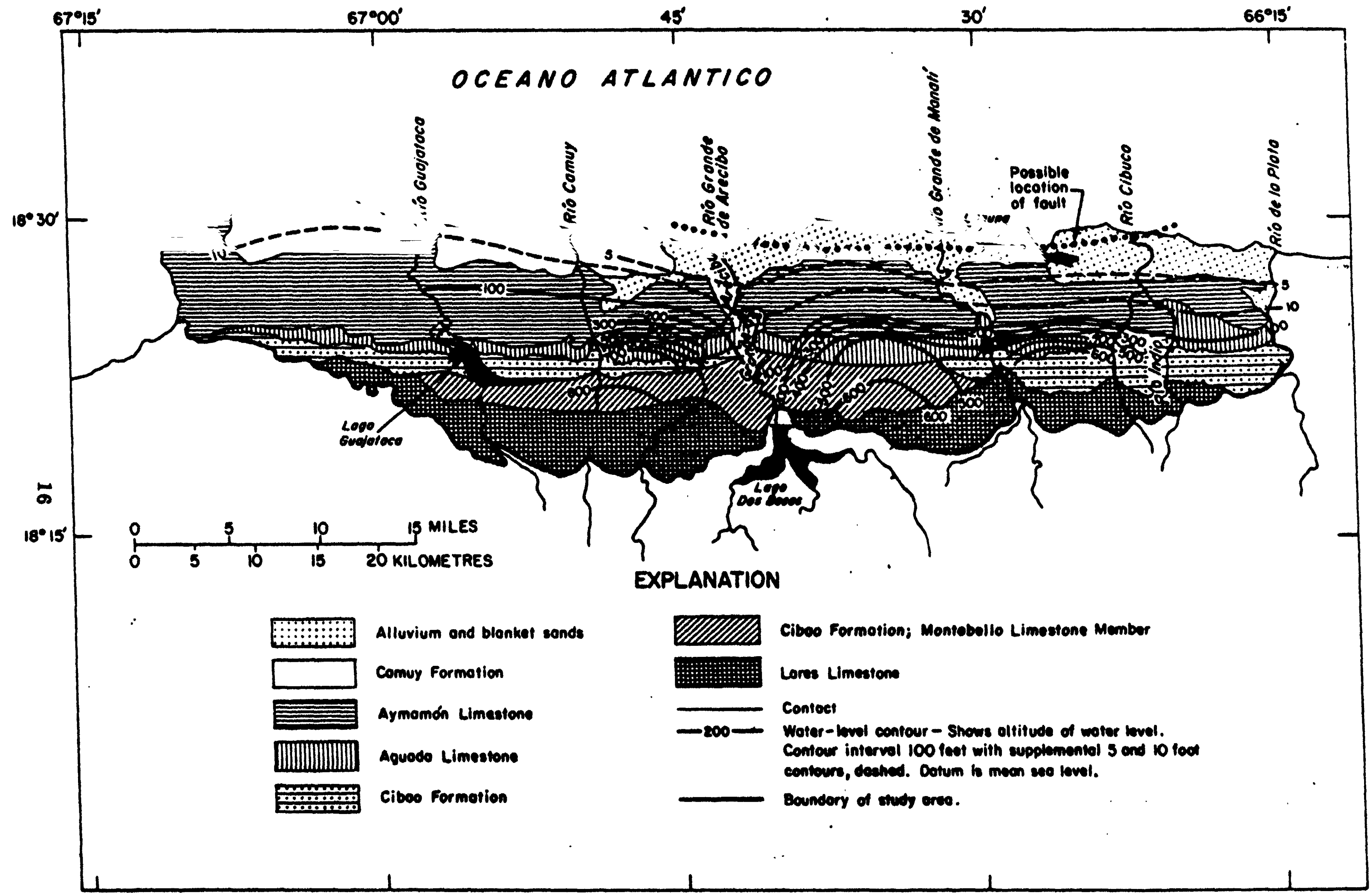


Figure 14.--Representative ground-water levels in the North Coast Limestones.

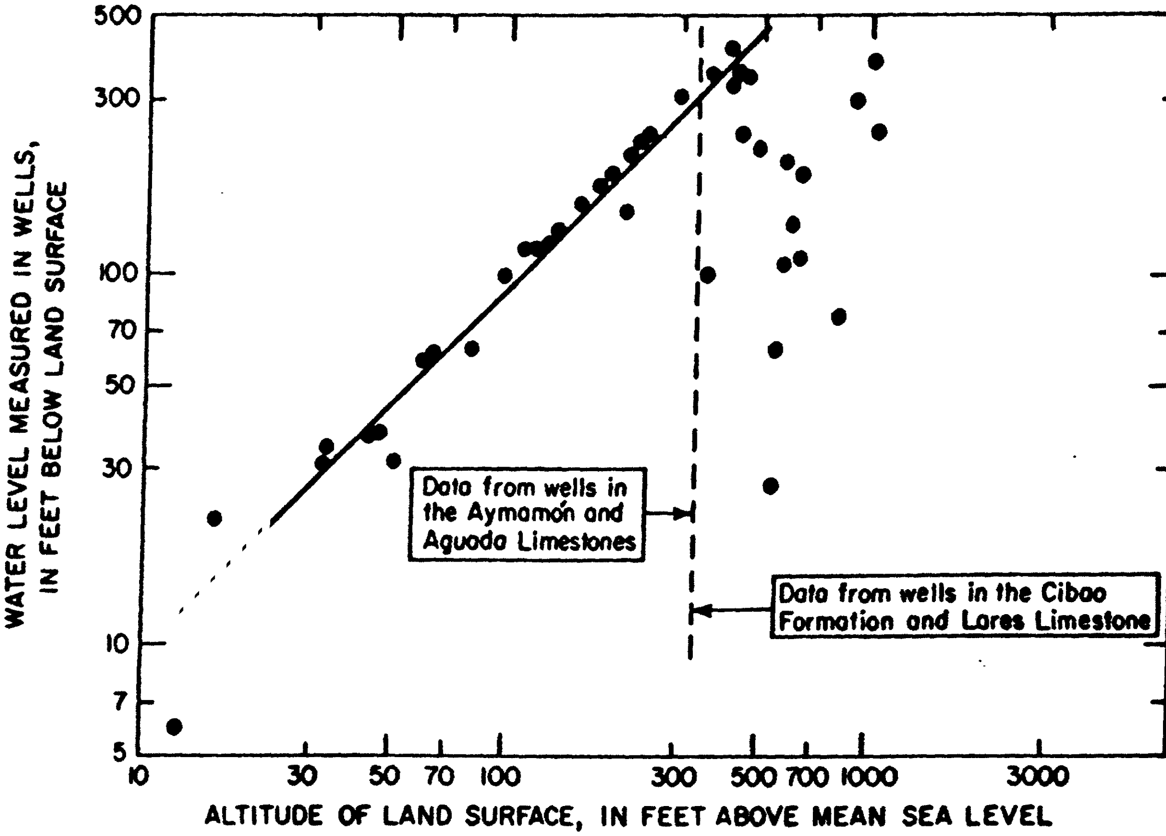


Figure 15.--Relation of ground-water levels to altitude of land surface.

and on local sources of recharge.

Artesian Head

Until July 1968 only ground water under water-table conditions was known in the area, although, the water in some wells was reported by drillers to have risen several feet above certain intervals tapped during drilling. No high-capacity flowing well had ever been developed in the area, but no well had ever been drilled deeper than 800 feet. In July 1968, a well for waste disposal was drilled in the Cruce Dávila area near Barceloneta. In order to obtain permission to use the well for disposal of certain industrial effluents, the law required the well be finished in salty water. Therefore, the well was drilled deeper than any other water well in Puerto Rico. At a depth of about 1,200 feet below land surface, the drill penetrated a "crumbly limestone layer" from which water flowed at a rate of 2,500 gpm (gallons per minute). The static head of the artesian zone was about 200 feet above land surface and about 450 feet above the water table in the Aymamón aquifer at that point. The water was fresh.

A second artesian zone was found about 1,600 feet below the land surface, and the water was reported to be highly mineralized. Since 1968, several more deep wells have been drilled in the same vicinity. All have tapped the upper artesian zone and two tapped the upper part of the lower artesian zone--these two latter wells produced water of good quality from both artesian zones. Yield from the lower zone is approximately 1 gpm per foot of penetration into the aquifer.

The pressure heads measured at the top of the wells and converted into units of altitude correlate well with extrapolation of the water-table altitude of the Cibao Formation and Lares Limestone. This is shown in the cross section of the Caño Tiburones area in figure 16; the line representing potentiometric head in the Cibao Formation and the Lares Limestone was constructed by extrapolating from the water table in the outcrop area through the artesian water levels in the Cruce Dávila area where the head is about 440 feet above mean sea level. At the coastline, the projected head is about 350 feet above mean sea level, indicating a loss of head of about 45 feet per mile.

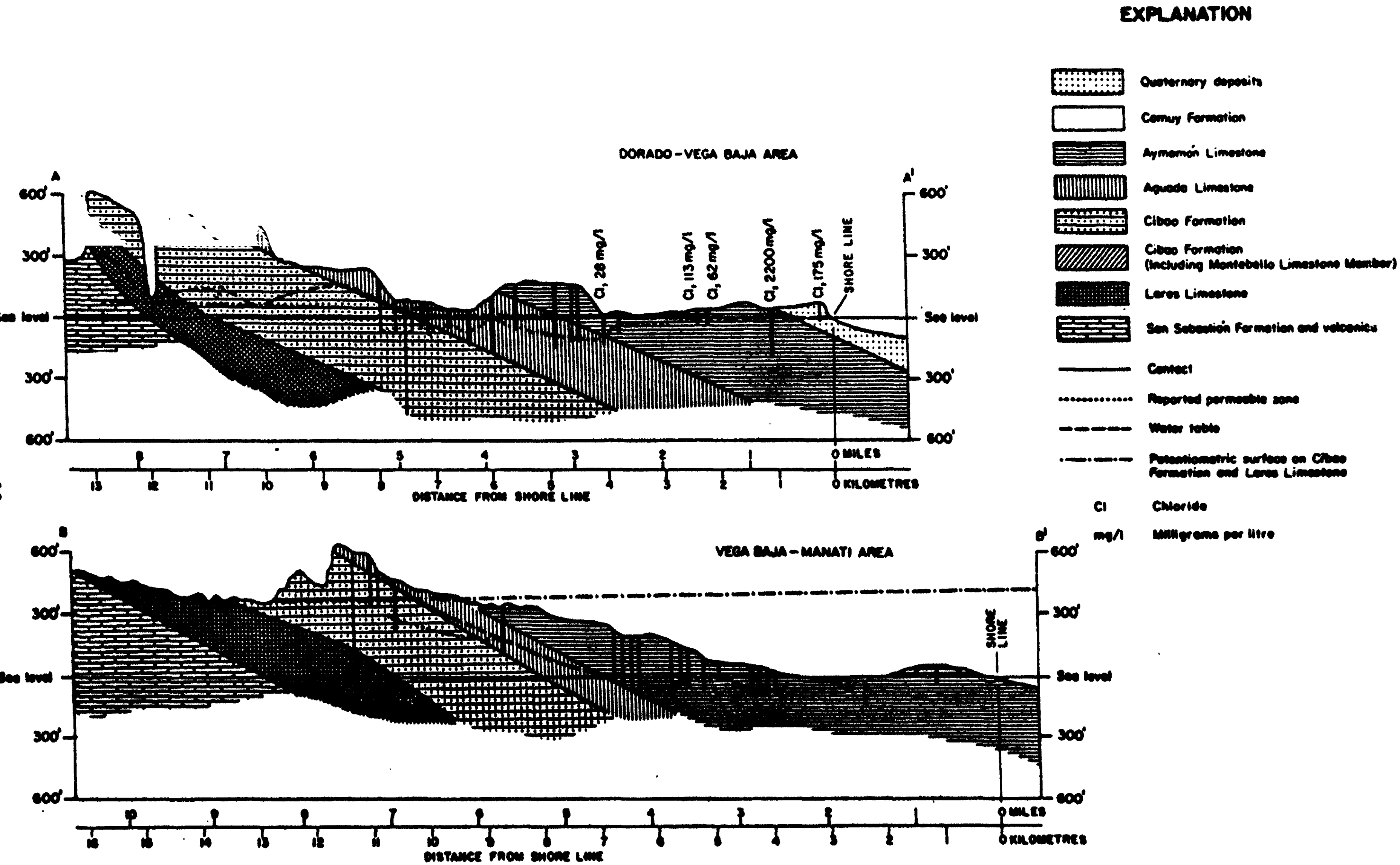


Figure 16.--Cross sections of the North Coast Limestones.
(See fig. 2 for location of cross sections.)

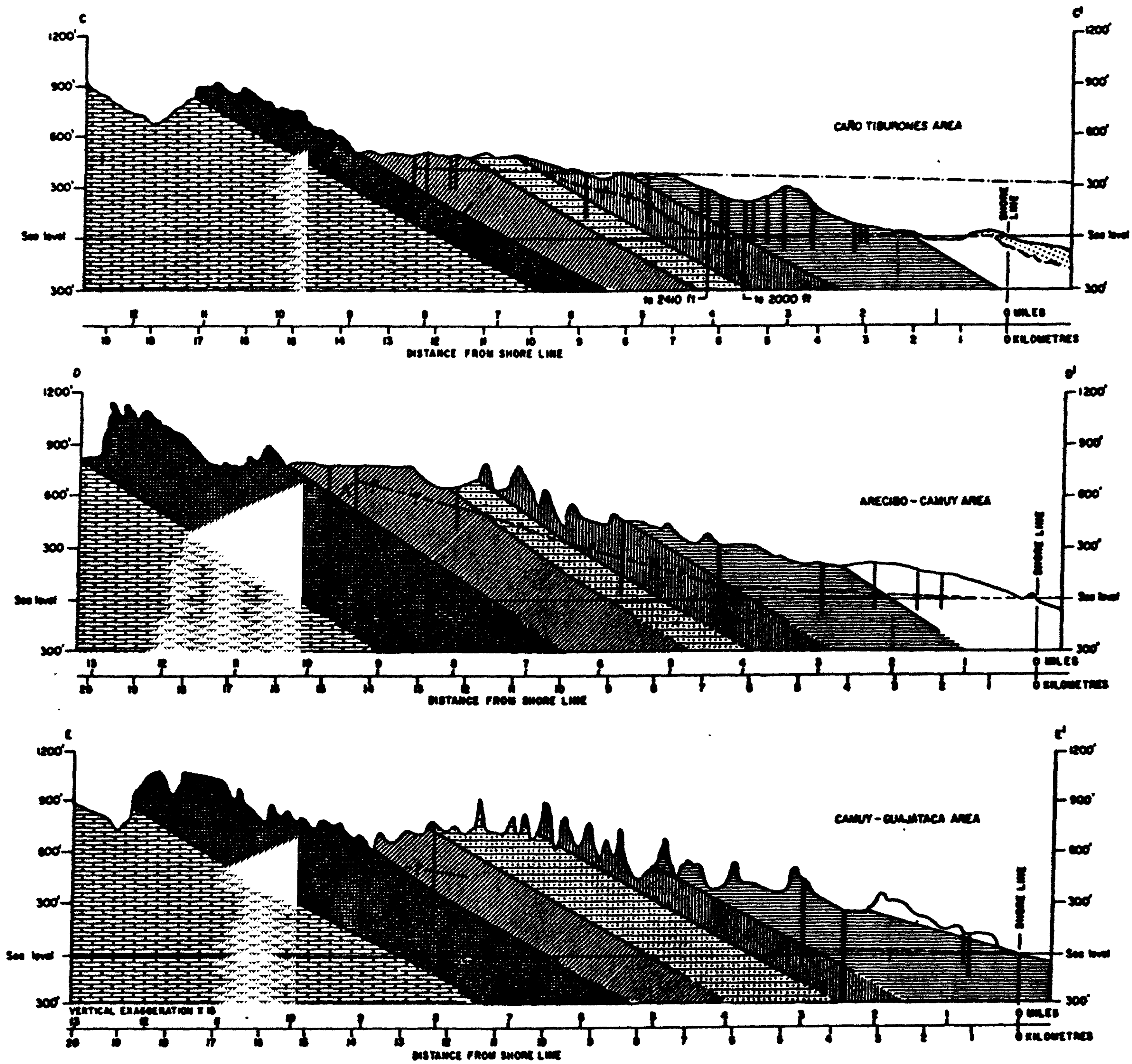


Figure 16.--Cross sections of the North Coast Limestones.
(See fig. 2 for location of cross sections.)

The upper artesian zone occurs within the Montebello Limestone Member of the Cibao Formation, which in the outcrop area is a relatively pure limestone. The driller's report indicates that a massive limestone layer was penetrated before the crumbly limestone of the artesian aquifer. This 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. Only in the central part of the limestone belt, between Río Grande de Arecibo and Río Grande de Manatí, has drilling shown that water flows under artesian head within the Montebello Limestone Member and the Lares Limestone. Elsewhere, only indirect evidence is available to indicate paths of flow. This evidence is discussed subsequently in the report.

Hydraulic Conductivity Distribution and Ground-Water Flow

Estimating ground-water flow by Darcy's law requires a knowledge of the hydraulic conductivity[1] of the aquifer in addition to the head gradient and the area of flow. For the limestone belt the assumption must be made that the flow is, on the average, uniform saturated flow through a porous medium. There is the possibility that at places the flow may be concentrated in "pipes," along the bedding planes, or through fractures. In such areas of concentrated flow, Darcy's law may not be applicable locally. Regionally, however, the networks of solution pipes, bedding planes, and fractures are probably interconnected sufficiently and so spaced as to simulate a uniform porous medium. The extent to which results from the application of Darcy's law agree with the results of the water-budget evaluation indicate the validity of the assumption of regional uniformity.

Hydraulic conductivity calculations, based on data from wells in the North Coast Limestone, were made using the following equation:

$$K = 530 \frac{Q}{sM} \text{Log} \frac{r_e}{r_w}$$

where K = hydraulic conductivity, in cubic feet per day per square foot, or the equivalent, feet per day;

Q = well discharge, in cubic feet per minute;

s = drawdown, in feet;

M = screened interval in the casing, in feet;

r_e = the radius of influence of the well, in feet; and

r_w = radius of casing, in feet.

In applying this equation, r_e was arbitrarily assumed to be 500 feet for all wells. The term r_e appears only in the logarithmic term and large errors in the ratio r_e/r_w, therefore, produce relatively small errors in K.

The hydraulic conductivity values computed by this method range from less than 0.1 ft/day (feet per day) to about 6,700 ft/day. The estimated average hydraulic conductivity distribution in a vertical section near the line through the Caño Tiburones area (figs. 2 and 16) is shown in figure 17. The figure shows that hydraulic conductivity decreases with depth from a high in the Aymamón Limestone to a low in the Lares Limestone. Because hydraulic conductivity was calculated from well-performance data, the values shown in figure 17 apply only to those zones in the section that are sufficiently permeable to yield water to wells. Thus, the decrease in hydraulic conductivity actually refers to the water-yielding zones, or aquifers, and should not be interpreted as a linear decrease in hydraulic conductivity with depth through the section because of lithology. Data show that the hydraulic conductivity of each aquifer varies from place to place in the area.

In figure 18 the hydraulic conductivity values obtained from the various wells in the limestone area are plotted against the stratigraphic depth of the water-yielding zone, which is here defined as the depth of the water-yielding zone beneath the projected top of the Aymamón Limestone. This figure suggests that the hydraulic conductivity of water-yielding zones decreases logarithmically with stratigraphic depth. The artesian wells fit this pattern as do the water-table wells; the large discharge of the artesian wells owes more to the fact that they operate at a drawdown of 200 feet, when opened at land surface, than to high hydraulic conductivity.

[1] The term "hydraulic conductivity" replaces the term "coefficient of permeability" formerly used by the U.S. Geological Survey.

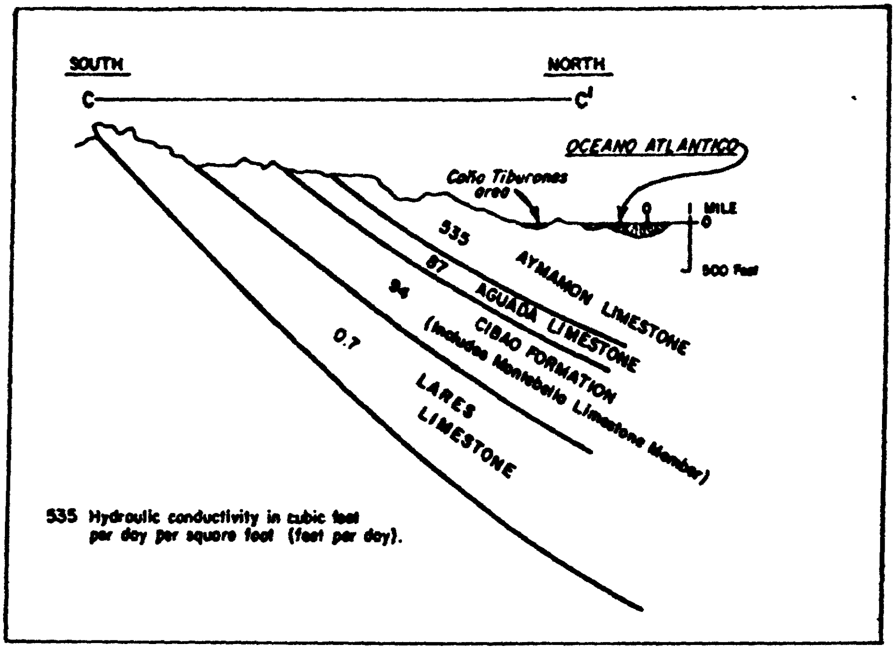


Figure 17.--Estimated average hydraulic conductivity distribution with depth in a cross section through the Caño Tiburones area. (See figs. 2 and 16 for cross section C-C'.)

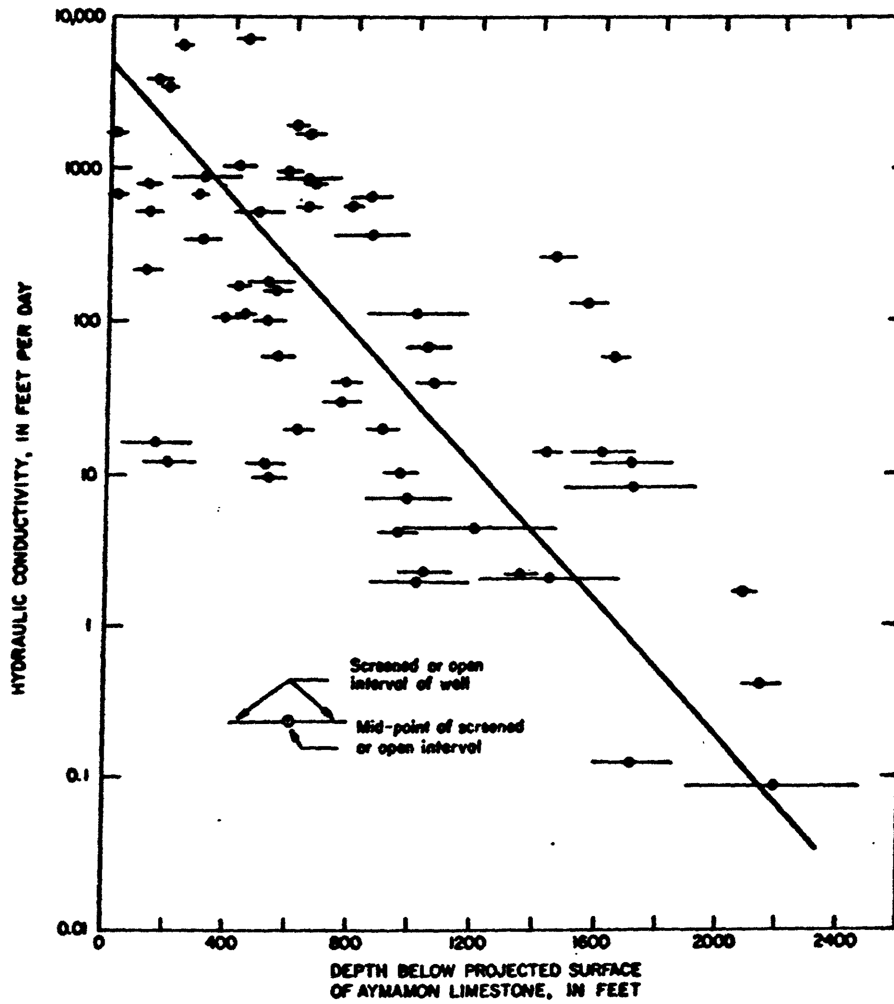


Figure 18.--Hydraulic conductivity of limestone relative to stratigraphic depth.

The ground-water flow through the Caño Tiburones area can be estimated from Darcy's law, by using the gradients of figure 16 and estimates of average hydraulic conductivity derived from computations for wells in that area. For a 1-mile width of aquifer:

$$Q = 5{,}280\,K\,I\,b$$

where Q = discharge, in ft^3/day (cubic feet per day);
K = hydraulic conductivity, in ft^3/day per square foot;
I = head gradient, dimensionless;
b = thickness of aquifer, in feet.

The discharges for the various aquifers are as follows:

Aymamón Limestone

$Q = 5{,}280 \times 535 \times 0.00095 \times 200 = 535{,}000$ ft^3/day (4.00 mgd--million gallons per day) per mile width of aquifer

Aguada Limestone

$Q = 5{,}280 \times 87 \times 0.00095 \times 400 = 174{,}000$ ft^3/day (1.30 mgd) per mile

Cibao Formation including the Montebello Limestone Member

$Q = 5{,}280 \times 9.4 \times 0.0021 \times 800 = 84{,}000$ ft^3/day (0.62 mgd) per mile

Lares Limestone

$Q = 5{,}280 \times 0.7 \times 0.0021 \times 1{,}500 = 12{,}000$ ft^3/day (0.09 mgd) per mile.

Thus, ground-water flow in the limestone of this area through a section 1-mile wide would be 805,000 ft^3/day, or 6.0 mgd. Total ground-water flow in the 11-mile wide Caño Tiburones area, therefore, would be 8,855,000 ft^3/day, or 66 mgd.

Similar computation for the other areas shown in figure 2 are summarized in table 1. The computations for the Guajataca-west coast area are based on data extrapolated from the other areas because no other information is available. The estimates of ground-water flow in that area, therefore, should be considered as rough approximations.

Figure 19 shows the distribution of estimated maximum hydraulic conductivity of the limestone in each of the five cross sections of figures 2 and 16. For section C-C' in the Caño Tiburones area where the highest hydraulic conductivities are found, the average hydraulic conductivity of each limestone is also shown. Although the figure shows information only at the cross sections, it is evident that the maximum hydraulic conductivity of each aquifer varies considerably from place to place through the area. For example, the estimated maximum hydraulic conductivity of the upper Aymamón Limestone ranges from about 6,700 ft/day in cross section C-C' to about 20 ft/day in cross section E-E'.

Ground-Water Flow Pattern

The caves in the karst of the north coast area are almost invariably like tunnels produced by the dissolving of limestone along bedding planes. The implication of the tunnel configuration, as it affects the regional ground-water flow, is that the flow lines follow the bedding of the limestone layers downdip, presumably along preferential paths of higher permeability. The graph in figure 18, however, indicates that hydraulic conductivity decreases with stratigraphic depth; thus, hydraulic conductivity should generally decrease downdip along the path of flow in the artesian zones. Such a decrease in hydraulic conductivity could be expected to cause a natural upward discharge through the overlying sediments, rather than a continued downdip flow toward a submarine discharge face. Vertical fracturing could increase such an upward flow by several orders of magnitude.

Figure 20 shows a cross section through the Caño Tiburones area, in which three possible patterns of ground-water outflow from the artesian zones are illustrated. The simplest pattern is direct discharge to sea at a submarine outflow face, and is illustrated by the large arrows. In such submarine outflow, the ground water must discharge against the static head exerted by the column of sea water above the outflow face. This head can be measured in terms of an equivalent fresh-water potentiometric head, defined as the height above sea level to which fresh water would

Table 1.--Ground-water flow in the North Coast Limestones (See figs. 2 and 16.)

Aquifer	Thickness, feet	Gradient, feet per foot	Hydraulic conductivity, feet per day	Discharge per mile of width		Discharge by area	
				cubic feet per day	million gallons per day	cubic feet per day	million gallons per day
			Dorado-Vega Baja Area (width 8 miles)				
Aymamón	200	0.00076	270	217,000	1.62		
Aguada	250	.00076	67	67,000	.50		
Cibao	500	.0028	4.0	30,000	.22		
Lares	400	.0028	1.3	8,000	.06		
			Total	322,000	2.40	2,576,000	19.2
			Vega Baja-Manatí Area (width 10 miles)				
Aymamón	300	0.00057	270	244,000	1.82		
Aguada	300	.00057	13.4	12,000	.09		
Cibao	550	.0028 (?)	1.3	11,000	.08		
Lares	650	.0028 (?)	.7	7,000	.05		
			Total	274,000	2.04	2,740,000	20.4
			Caño Tiburones Area (width 11 miles)				
Aymamón	200	0.00095	535	535,000	4.00		
Aguada	400	.00095	87	174,000	1.30		
Cibao	800	.0021	9.4	84,000	.62		
Lares	1,500	.0021	.7	12,000	.09		
			Total	805,000	6.01	8,855,000	66.1
			Arecibo-Camuy Area (width 8 miles)				
Aymamón	300	0.00075 (?)	80	95,000	0.71		
Aguada	300	.00075 (?)	5.4	6,000	.05		
Cibao	650	.003 (?)	2.7	28,000	.21		
Lares	1,000	.003 (?)	.7	11,000	.08		
			Total	140,000	1.05	1,120,000	8.4
			Camuy-Guajataca Area (width 8 miles)				
Aymamón	200	0.00075 (?)	54	43,000	0.32		
Aguada	300	.00075 (?)	4.0	5,000	.04		
Cibao	650	.003 (?)	1.3	13,000	.10		
Lares	600	.003 (?)	.7	7,000	.05		
			Total	68,000	0.51	544,000	4.1
			Guajataca-West Coast Area (width 12 miles)				
Aymamón	200	0.00075	67	53,000	0.40		
Aguada	400	.00075	6.7	11,000	.08		
Cibao	550	.00075	1.3	3,000	.02		
			Total	67,000	0.50	804,000	6.0
			Grand Total			16,639,000	124.2

23

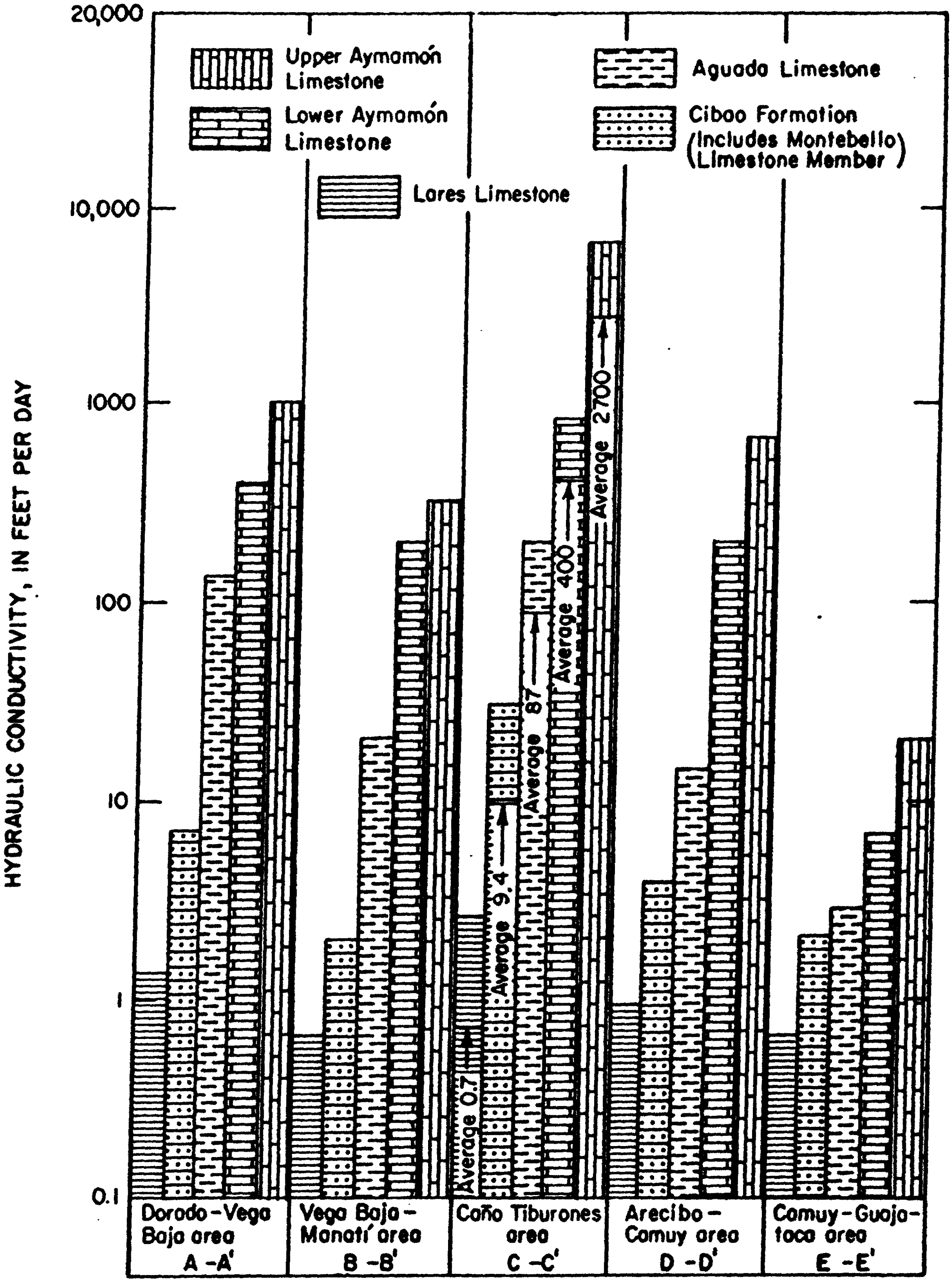


Figure 19.--Estimated maximum hydraulic conductivity in selected cross sections of the North Coast Limestones. (See figs. 2 and 16.)

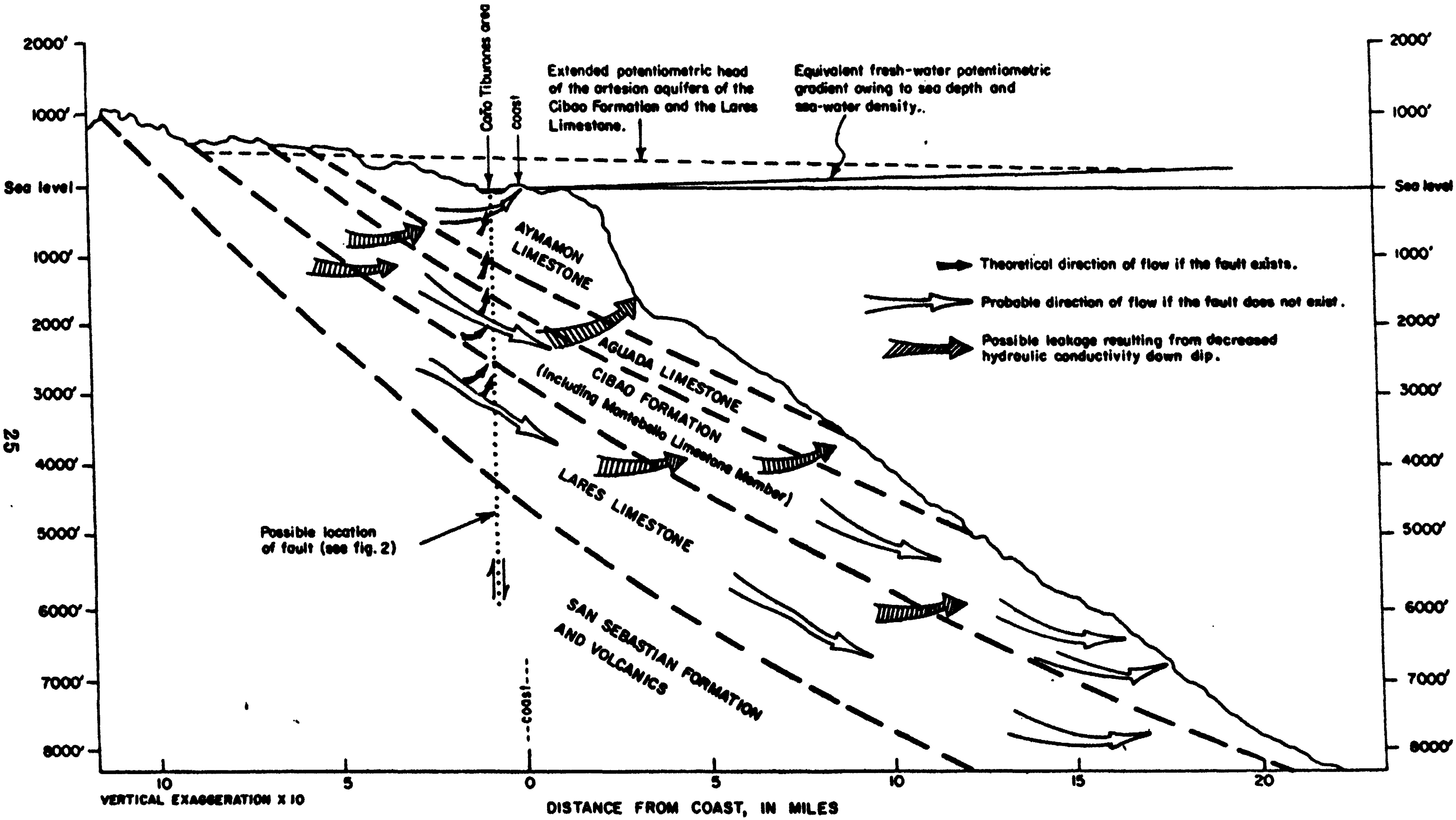


Figure 20.--Schematic diagram of possible patterns of ground-water flow in a cross section through the Caño Tiburones area. (See figs. 2 and 16.)

rise in a piezometer inserted to the seabed. This equivalent fresh-water head increases seaward as the depth of salt water increases. The solid line above the sea surface in figure 20 shows the trend of the equivalent fresh-water head.

The potentiometric head of the artesian zones to seaward can presumably be found by extending the artesian-head gradients measured on land. At the outflow face, the head obtained by such extrapolation should equal the equivalent fresh-water head for the column of sea water above the face. In figure 20, the extrapolated potentiometric head gradient of the artesian zones, indicated by the dashed line at the top of the figure, meets the solid line representing the equivalent fresh-water potentiometric head about 18 miles from shore.

Extending the potentiometric head of the artesian aquifer seaward assumes that there are no changes in hydraulic conductivity within the artesian zones and no gradual loss of flow from these zones. If the assumptions are valid, and if submarine outflow is the mechanism of discharge, the maximum distance that discharge could occur offshore is approximately 18 miles. This is in reasonable agreement with locations of the submarine outcrops of the artesian zones, as obtained by extrapolation of the dip seaward. However, the extrapolation of head gradients and geologic dips for tens of miles is questionable, and this agreement may be no more than fortuitous.

If the hydraulic conductivity of the artesian zones decreases seaward, the head gradient in the aquifer would not be linear, and the extrapolation would not be valid. The loss in head per mile would increase seaward, and the artesian head would be dissipated much closer to shore than 18 miles. If hydraulic conductivity decreases with the stratigraphic depth, the decrease in hydraulic conductivity of the artesian zones would likely be gradual and would probably cause an upward discharge of ground water over a large area through the confining beds (shown by the patterned arrows in fig. 20). Some of this upward seepage would probably escape through the sea floor and some through discharge areas on land.

Hydraulic conductivity might also be decreased by a fault postulated by Briggs (1961) in the Caño Tiburones area (figs. 2 and 20). Such a fault would presumably have thrown rock of low hydraulic conductivity against the artesian zones, thus blocking or impeding flow seaward, and forcing discharge upward. It is possible that fracturing associated with the theorized faulting could have produced a highly permeable vertical section along the fault trace, creating conditions favorable to vertical outflow. The pattern of ground-water flow that might result from these conditions is shown by the small solid arrows in figure 20.

Throughout the limestone area, but particularly east of Arecibo, ground water under water-table conditions discharges through springs and by areal seepage, either directly to sea or to the swampy areas along the coast (fig. 7). These swampy areas discharge, in turn, by evapotranspiration or by surface drainage to sea.

A two-dimensional steady-state electric analog model of the hydrologic system south of Laguna Tortuguero was made by G. D. Bennett (oral commun., 1971). The model, made of conducting paper of fixed resistance, was designed to simulate the water-table aquifer with a ratio of vertical to horizontal hydraulic conductivity of 1 to 10. The results of measuring the electric current at the boundaries of the model, analogous to measuring the ground-water flow, indicate that 75 percent of the outflow takes place inland from the coast and that 25 percent of the outflow takes place through the sea bottom in an area a few hundred yards wide. The inland seepage is discharged by evapotranspiration and by direct outflow from Laguna Tortuguero to sea. The Vega Baja-Manatí area, the Dorado-Vega Baja area, and possibly the Caño Tiburones area (fig. 2) are believed by the authors to have characteristics of ground-water flow similar to those of Bennett's model.

West of Arecibo in the Arecibo-Camuy and Camuy-Guajataca areas (fig.2), the pattern of ground-water outflow is more speculative. The water-budget data shown subsequently indicate that Ríos Tanamá, Camuy, and Guajataca are such highly efficient ground-water drains that only a small part of the regional ground-water flow is discharged through coastal swamps or the sea bottom. The coastline west of Arecibo is composed of cliffs several yards above the sea. During the study no springs were found to be issuing from these cliffs; a few ponds and swampy areas at the foot of the cliffs are the only evidence of ground-water outflow. There are no reports of large fresh-water springs at sea except one near Camuy. Thus, the evidence indicates that stream drainage (base flow) may be the primary mechanism of ground-water outflow in this area.

The pattern of ground-water outflow in the Guajataca-west coast area (fig. 2) 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 Caño Tiburones area.

The karst in this area, however, is well developed in the Aguada and lower Aymamón Limestones, which drop out as a flat surface where the karst topography is relatively young--conditions that facilitate infiltration to the water table. The ground-water outflow computed in table 1, even allowing for possible error, is much larger than the possible evapotranspiration from swampy areas at the foot of the sea cliffs. Quebrada de los Cedros, the only stream in the area, is usually dry. Thus, in this westernmost area, it seems that there may be a large direct discharge of ground water through the sea bottom from the Aymamón-Aguada system, in which the flow is essentially unconfined.

Surface Water

In this report surface water includes the streams, swamps, lakes, and springs of the area of study. Figure 7 is a generalized map of the location of these features. In addition to the moist areas near the coast, there are lakes in the central part of the area. These lakes are underlain by the slightly permeable Cibao Formation, which acts as a base for the sinkholes developed in the easily soluble Aguada and Aymamón Limestones.

There are thousands of springs within the study area. The major ones found in the field are shown in figure 7. Most of the springs discharging near the coast rise through the blanket sands or swamp deposits and feed into the Caño Tiburones area and Laguna Tortuguero. The springs discharging to rivers issue from cliffs or emerge through the alluvium, and most discharge on the west side of the river valleys. There are a few springs that flow only after heavy rain; otherwise they stand as nearly circular water-table pools.

Streamflow and Water Budget

As mentioned previously streamflow, rainfall, and pan-evaporation data were collected for water-budget calculations. Discharge of streams draining both volcanic and limestone terranes was recorded where the streams entered the limestone terranes and also as far downstream as possible. By difference in flow, therefore, the contribution from the limestone part of the basin could be assessed. Records were collected for about a year and a half but the data shown in table 2 are for November 1969 to October 1970 only. This is the period when data are most reliable, and streamflow at the beginning was nearly equal to that at the end.

Table 2 is arranged to show information for basins, or for parts of basins, in volcanic terrane and limestone terrane. The data are for that part of the basin in each respective terrane and are not cumulative values for the basin as a whole where the stream flows from the volcanic to the limestone. The numbers in column (1) represent rainfall, in inches, as obtained from Theissen averaging.

Column (2) lists ET, computed as a Theissen-averaged pan evaporation (shown in column 6) multiplied by a factor that varies with rainfall, as explained in the section of this report on climate (fig. 11). It would be more appropriate to compute ET as a constant fraction of pan evaporation for the permanently moist parts of the basins, such as flood-plain, swamp or lake areas, and as a variable fraction of pan evaporation elsewhere. However, because the method used led to reasonably satisfactory results--largest unexplainable error is about 30 percent--and because the period of record was about 20 percent wetter than normal

Table 2.--Water-budget calculations for the North Coast Limestone area, November 1969—October 1970 (See fig. 12 for location of sites

	Site number	Stream basin	(1) Rainfall (P), inches	(2) Evapotranspiration (ET), inches	(3) Discharge (Q)[3], inches	(4) $+\Delta S$, inches	(5) Drainage area, square mile	(6) Pan evaporation inches
Basins in volcanic terrane	1	Upper Río Guajataca	87	49	34	+4	3.2	55
	2	Upper Río Camuy	87	49	38	0	7.6	54
	3	Río Criminales	87	49	44	-6	4.5	54
	4	Upper Río Tanamá	88	49	36	+3	18.4	54
	5	Río Grande de Arecibo below Lago Dos Bocas	93	47	43	+3	169	54
	6	Río Cialitos	91	48	38	+5	17.0	54
	7	Upper Río Grande de Manatí	100	45	50	+5	128	52
	8	Río Unibón	88	49	47	-8	5.3	54
	9	Upper Río Cibuco	93	47	41	+5	15.1	54
	10	Río Mavilla	96	46	68	-18	9.5	54
Basins in limestone terrane[1]	11	Quebrada de los Cedros	68	46	1	+21	14.6	71
	12	Río Guajataca to Lago Guajataca	88	49	30	+9	30.4	71
	13	Río Guajataca to mouth	80	48	22	+10	29.5	65
	14	Lower Río Camuy	83	49	33	+1	65.6	60
	15	Lower Río Tanamá	82	49	22	+11	39.2	59
	16	Lower Río Grande de Arecibo	73	47	.6	+25	29.4	62
	17a&b	South Canal (two sites)	52	41	2	+9	20.6	71
	18	Caño Tiburones Outlet	52	41	83[2]	-72	17.9	71
	19	Lower Río Grande de Manatí	73	47	34	-8	67.0	52
	20	Laguna Tortuguero Outlet	68	46	20	+2	16.8	62
	21	Lower Río Cibuco	80	48	35	-3	65.7	59
	22	Río Lajas	82	48	43	-9	8.4	54

Notes

[1] For streams that rise in volcanic terrane, discharge is downstream flow minus upstream flow. Drainage area refers to that part of the basin that lies in limestone terrane.

[2] Represents only the fresh-water part of the discharge from the Caño Tiburones area.

[3] Discharge in cubic feet per second is given in table 3.

(precipitation was 85 inches against the average annual of 70 inches), no attempt was made to refine the calculations further.

The stream discharge per unit drainage area is listed in column (3), expressed in inches. In volcanic terrane, there is no logical reason to assume that drainage areas delineated from topographic divides may be in error; and, therefore, anomalies in the streamflow data probably cannot be ascribed to errors in drainage areas. The difficulty of computing drainage areas in the limestone basins, however, has already been discussed. The drainage areas of column (5) for the limestone basins represent estimates, the validity of which is discussed subsequently in this section.

The term $\pm\Delta S$ of column (4) is the residual from the budget equation:

$$\pm\Delta S = P - ET - Q$$

It represents net changes in water storage per unit surface area in the basin for the 1-year period of record. A plus sign indicates that water was taken into storage, whereas a minus sign indicates that water was taken out of storage.

A plot of the stream flow against the difference between rainfall and estimated ET is shown in figure 21. A line of unit slope has been drawn on this graph, showing the relationship that holds when the term ΔS of the budget equation is zero. The data of table 2 scatter randomly about this line primarily owing to data error. If the deviations were actually associated with changes in storage, they would most likely show a consistent bias, that is, that data would plot preferentially above or below the line.

Most of the points are within plus or minus 20 percent of the unit slope line; only one basin in volcanic terrane plots outside these limits--slightly over plus 30 percent. Four basins in the limestone terrane, however, depart considerably from the unit slope line. These are shown by points numbered 11, 16, 17 a and b, and 18 on the figure.

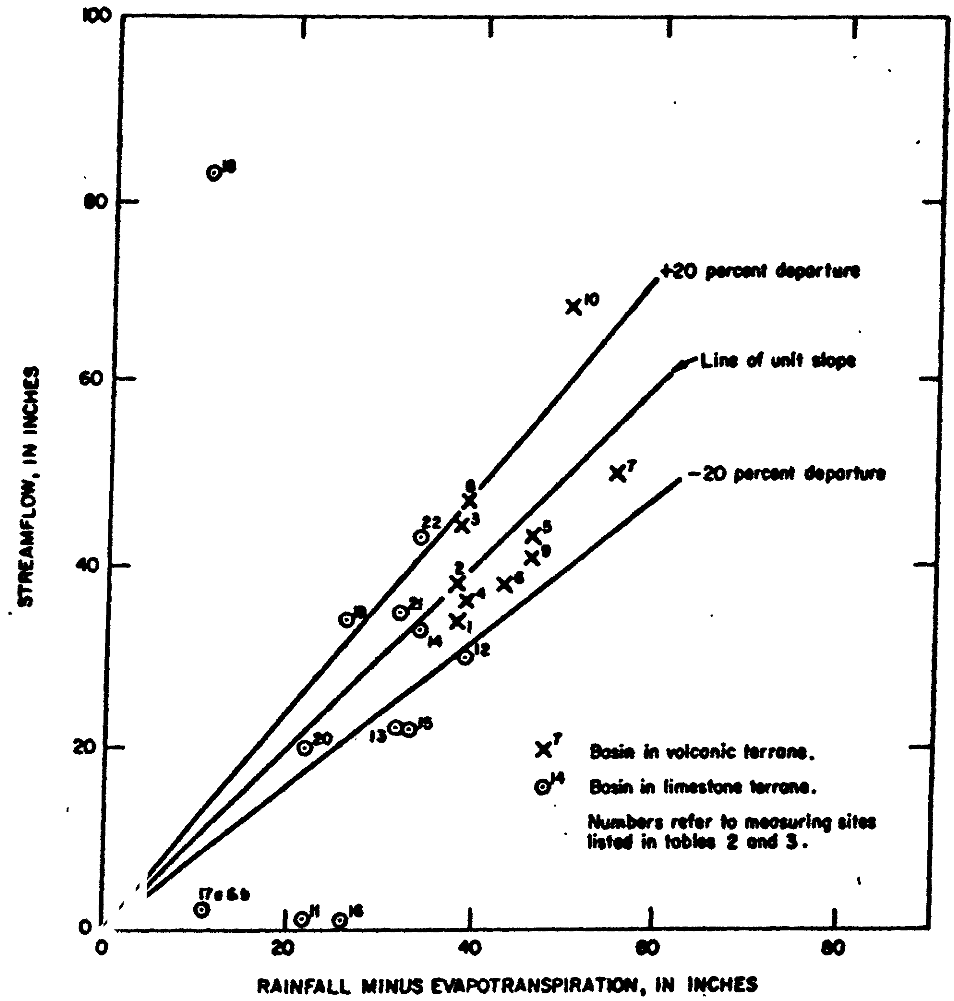


Figure 21.--Streamflow against rainfall minus evapotranspiration for basins in volcanic and limestone terranes. (See table 2, data for November 1969–October 1970.)

Site 18 is for the Caño Tiburones area where local land-drainage and reclamation operations have lowered the water table below sea level, causing infiltration of sea water. The outflow is, thus, a mixture of fresh and sea water. The discharge of 83 inches shown in table 2 is only the fresh-water part; this was estimated from a chemical-quality rating table based on analyses of samples of the outflow collected at various rates of flow. By comparison with other basins in the limestone area, it seems clear that the basin contributing flow to the Caño Tiburones area must be considerably larger than the 17.9 square miles as indicated by topographic maps. The effective drainage basin of the Caño Tiburones area probably includes at least the area to the south (fig. 12) that has no apparent outlet to sea. The additional flow is probably almost all ground water contributed by the Aymamón and Aguada Limestones, and possibly some small leakage from the artisian zones of the Cibao Formation and the Lares Limestone.

Site 16 is for the basin of the lower Río Grande de Arecibo, mainly the valley plain from Lago Dos Bocas to sea. If the flow at the downstream gage is subtracted from that entering at the upstream gage, a loss of streamflow in the limestone terrane is indicated. The small positive flow at site 16 (table 2) is due to the discharge of a spring that formerly discharged into the lower Río Grande de Arecibo but is now diverted from public supply. The valley of the Río Grande de Arecibo seems to act like a sponge, absorbing water during the wet season and releasing it to the stream channel during the dry season, with a net yearly contribution to streamflow near zero. Figure 21 indicates that the lower Río Grande de Arecibo should yield a streamflow of about 20 inches per year. As this flow does not appear in the river, it may in part flow into the Caño Tiburones area through the highly permeable upper Aymamón Limestone, particularly during floods. The cluster of springs in the southwestern Caño Tiburones area may be an indication of this interbasin flow.

Sites 11 and 17a and b in figure 21 represent, respectively, the area drained by Quebrada de los Cedros and that drained by the canal system south of the Caño Tiburones area. Quebrada de los Cedros is usually dry, as its bed lies above the water table; it flows only after prolonged rainfall. Its actual drainage area is, therefore, probably only that part of the basin that has direct communication with the main channel--a small part of the 14.6 square miles assigned to it on the basis of sinkhole alinement. In addition, during floods this stream loses water through its bed all along its course. The canal system south of the Caño Tiburones area seems to flow only in response to rainfall directly on canal surface area. Most of the rainfall on the rest of the drainage area seems to enter the ground-water system and emerge as springflow in the Caño Tiburones area.

In figure 22, the difference between selected daily mean streamflows at the downstream and upstream stations on Río Tanamá is plotted against concurrent daily mean streamflow at the upstream station. The upstream value represents flow from volcanic terrane, whereas the difference between downstream and upstream readings is the contribution to Río Tanamá from the limestone terrane. The scatter of the data suggests that the traditional methods of interstation correlation used in hydrology may not be applicable to estimating daily flows from the limestone areas.

Monthly flows correlate somewhat better as shown in figure 23, where the total monthly discharges at the downstream station on Río Tanamá are plotted against the total monthly discharges at the upstream station. In this method, the total flow at the downstream site is used rather than the difference in flows between the two stations and a biased correlation is obtained, because the downstream flows include the upstream flows as a component. The results, however, indicate that interstation correlation on a monthly basis may be meaningful.

Base Flow

The separation of streamflow into components of flood flow and base flow involves definitions that are somewhat arbitrary. As used in this report, the term "flood flow" refers to that part of streamflow that produces discrete and clearly defined peaks on the hydrograph, as in figure 24. The remainder of the streamflow is considered base flow. It should be noted that these definitions are based upon the appearance of the surface-water hydrograph, rather than upon the origin of the water making up the various flow components.

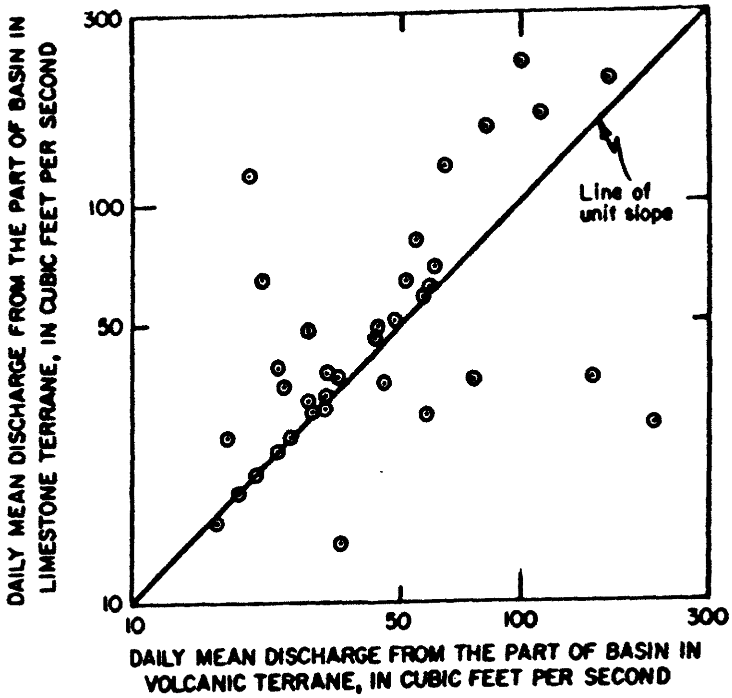


Figure 22.--Selected daily mean discharges from the part of the Río Tanamá basin in limestone terrane against those from the part in volcanic terrane.

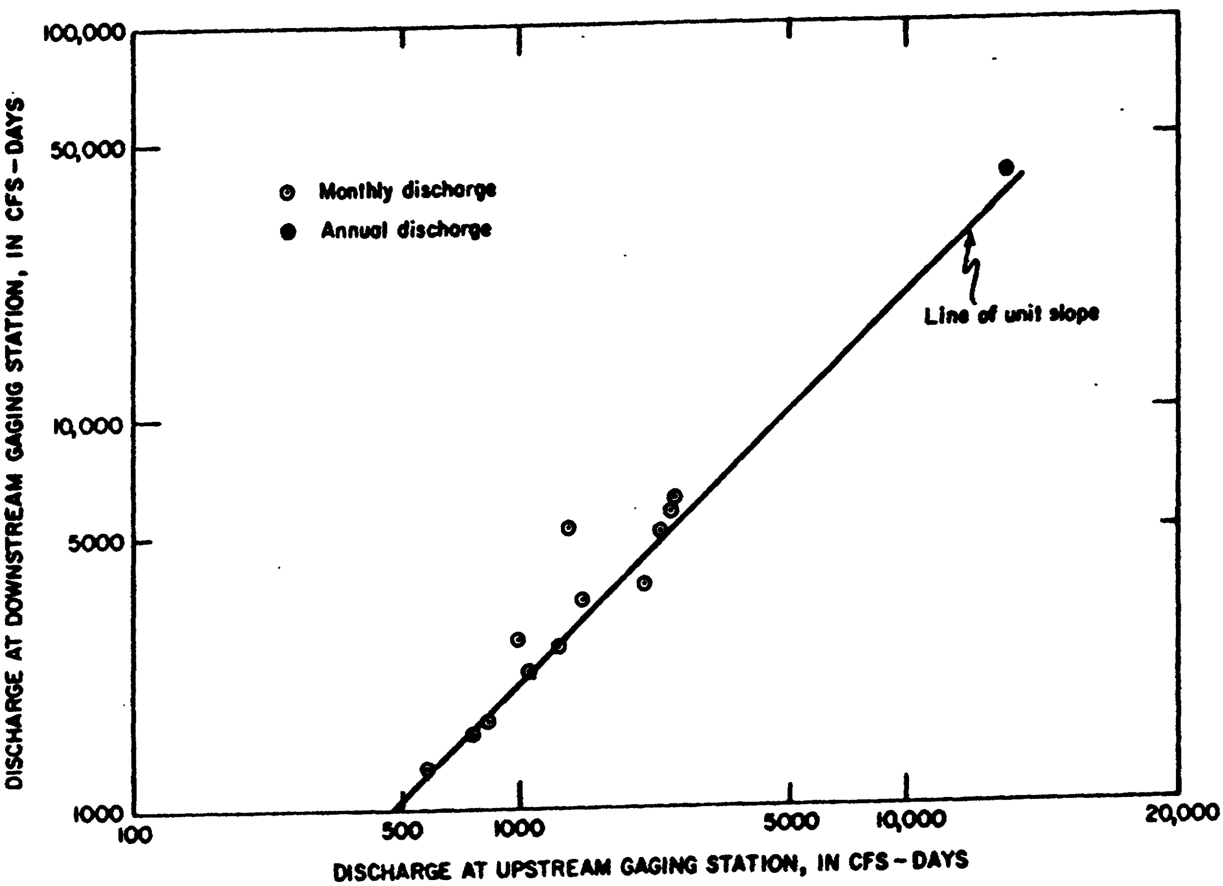


Figure 23.--Monthly and annual discharges of Río Tanamá, downstream gaging station against the upstream gaging station.

Table 3.--Streamflow data of the North Coast Limestone area, November 1969–October 1970 (See fig. 12 for location of sites.)

	Site number	Stream basin	Drainage area	Lowest daily flow recorded		Average daily flow				Ratio of base flow to total flow
						Base flow		Total flow		
			sq mi	cfs	cfs/sq mi	cfs	cfs/sq mi	cfs	cfs/sq mi	
Basins in volcanic terrane	1	Upper Río Guajataca	3.2	0.3	0.10	3.4	1.1	7.8	2.4	0.44
	2	Upper Río Camuy	7.6	3.5	.46	11.1	1.5	21.1	2.8	.53
	3	Río Criminales	4.5	2.2	.49	8.7	1.9	15.3	3.4	.57
	4	Upper Río Tanamá	18.4	9	.49	31.9	1.7	49	2.7	.65
	5	Río Grande de Arecibo below Lago Dos Bocas	169	--	--	--	--	535	3.2	--
	6	Río Cialitos	17.0	2.5	.15	18.6	1.1	48	2.8	.39
	7	Upper Río Grande de Manatí	128	30	.23	122	.95	470	3.7	.26
	8	Río Unibón	5.3	--	--	8.1	1.5	18.5	3.5	.44
	9	Upper Río Cibuco	15.1	--	--	17.0	1.1	46	3.0	.37
	10	Río Mavilla	9.5	--	--	19.7	2.1	47.4	5.0	.42
Basins in limestone terrane 1/	11	Quebrada de los Cedros	14.6	0	--	0	--	1.0	.07	0
	12	Río Guajataca to Lago Guajataca	30.4	--	--	--	--	67	2.2	--
	13	Río Guajataca to mouth	29.5	10	.34	17.6	0.60	48	1.6	.37
	14	Lower Río Camuy	65.6	19.3	.30	45.8	.71	162	2.5	.28
	15	Lower Río Tanamá	39.2	9.5	.24	37.6	.96	65	1.7	.58
	16	Lower Río Grande de Arecibo	29.4	--	--	--	--	2.2	.07	--
	17 a&b	South Canal (two sites)	20.6	0	--	.07	.003	3.4	.16	.03
	18	Caño Tiburones Outlet	17.9	75	4.2	86.7	4.7	109	6.1	.80
	19	Lower Río Grande de Manatí	67.0	27.5	.41	71.0	1.0	166	2.5	.43
	20	Laguna Tortuguero Outlet	16.8	10*	.6	19.5	1.5	26	1.6	.75
	21	Lower Río Cibuco	65.7	10*	.15	33.4	.51	156	2.4	.21
	22	Río Lajas	8.4	.8	.10	6.3	.75	26.5	3.2	.24
		Total limestone belt		162		318		832		

1/ For streams that rise in volcanic terrane, discharge is downstream flow minus upstream flow. Drainage area refers to that part of the basin that lies in limestone terrane.

* Estimated.

A computer program to separate base flow from the total streamflow was prepared for the purposes of this study by T. D. Steele of the U.S. Geological Survey. This program is based on the recognition of points of minima in the hydrograph of daily flows; an empirical function allows for the separate computation of base flow and direct runoff, with the sum of the two being the total discharge. An example of this base-flow separation is shown in figure 24. In general, the program served its purpose well except for a few sites where the base-flow component was somewhat underestimated. The results are shown in table 3.

There are significant differences in the base flow of streams in the limestone terrane and the volcanic terrane. Most base flow in the limestone terrane ranges from about 0.5 to 1.0 cfs per sq mi, whereas base flow in volcanic terrane ranges from about 1 to 2 cfs per sq mi. In figure 25, the ratios of base flow to total flow are plotted against total annual flow per unit area for selected basins in limestone and volcanic terranes. The figure shows that, in general, the ratio of base flow to total flow is larger in the volcanic terrane than in the limestone terrane.

Exceptions to this are Laguna Tortuguero Outlet and Caño Tiburones Outlet, which are coastal discharge features rather than typical stream basins. Therefore, they receive ground-water drainage from areas of considerably greater extent than indicated by topographic divides, as discussed previously.

Flood Flow

As defined in this report, flood flow is the difference between total flow and base flow. As noted previously, the flood flow contributed from limestone terrane is proportionally greater than that contributed from volcanic terrane, owing chiefly to contributions from shallow ground-water circulation that appear in the streams during the period of the hydrograph peak.

Figure 26 is a plot of combined monthly flood flow from the limestone and volcanic terranes against monthly flood flow from volcanic terrane for each of the major streams in the area. A line of equal values has been drawn on the graph. Points that plot above this line indicate a higher monthly flood flow at the downstream stations than at the upstream stations and, thus, a gain in flood flow as the stream crosses the limestone. Points that plot below the line indicate lower flood flow downstream than upstream and, thus, show a loss of flood flow as the stream crosses the limestone.

Figure 26 shows that only in the Río Grande de Arecibo basin is there a consistent loss from flood flow. This probably reflects in part seepage from the lower reaches of the river into the alluvium and the Aymamón Limestone, and subsequent ground-water discharge to springs and the Caño Tiburones area, as described previously. In the Río Grande de Manatí and Río Cibuco basins there is loss when flood flow is small, but gain when flood flow is large. These losses probably reflect water held by flood plain and bank storage during small hydrograph peaks and later released as base flow. All the rivers showing losses--Ríos Grande de Arecibo, Grande de Manatí, and Cibuco--have well-developed flood plains. The rivers showing consistent gains--Ríos Guajataca, Camuy, and Tanamá--have no extensive alluvial plains. Thus, the loss of flow from the rivers during floods may owe primarily to seepage into the alluvium.

Patterns of Flow

Figure 27 shows schematic diagrams of estimated annual hydrologic conditions and theoretical flow patterns in the limestone and volcanic terranes using averaged data from tables 2 and 3. Infiltration refers to water that infiltrates the soil cover and is not consumed by ET. Direct runoff refers to water that moves over the land surface toward a stream or rivulet during or after a storm, thus contributing to flood flow.

Figure 27-A shows hydrologic conditions in the volcanic terrane where deep circulation of ground water into regional flow patterns is generally precluded by the slight permeability of the rocks at depth. In general, water that infiltrates the soil cover moves in a pattern of shallow ground-water circulation toward the nearest stream valley.

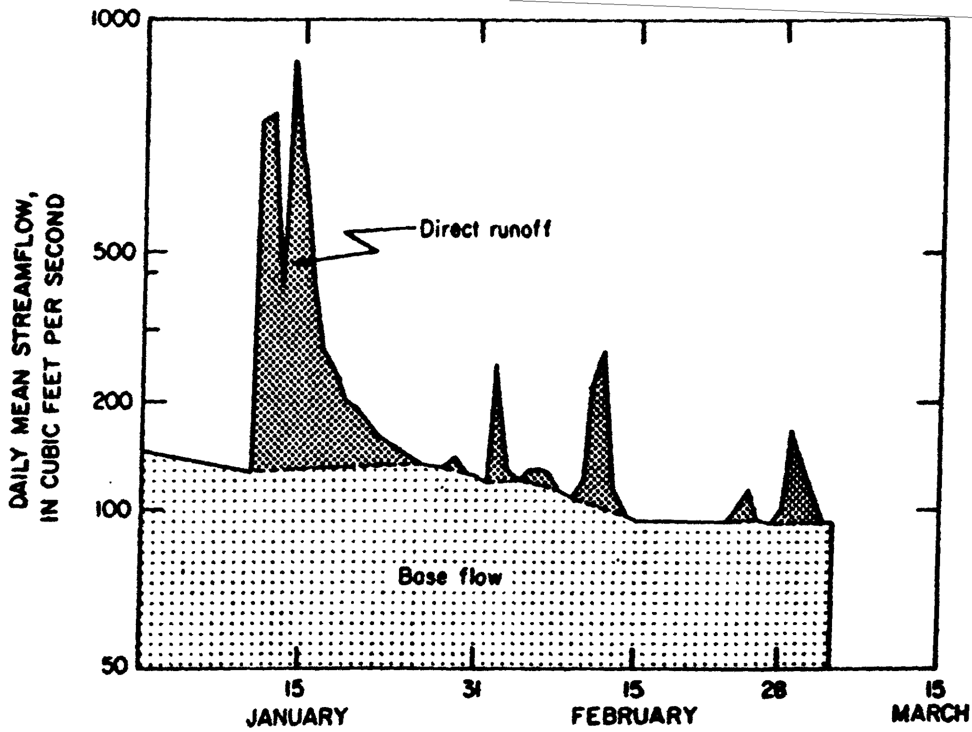


Figure 24.--An example of hydrograph separation by computer.

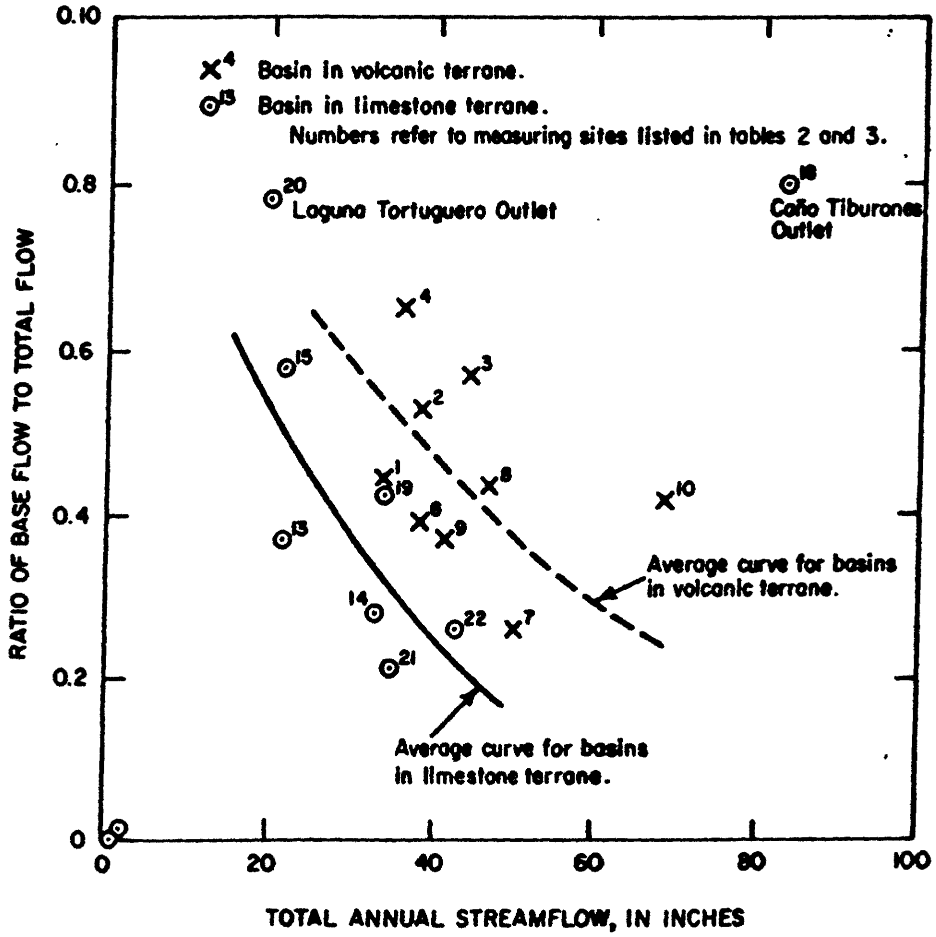


Figure 25.--Ratios of base flow to total flow against total annual streamflow for basins in volcanic and limestone terranes. (Selected data from tables 2 and 3, data for November 1969–October 1970.)

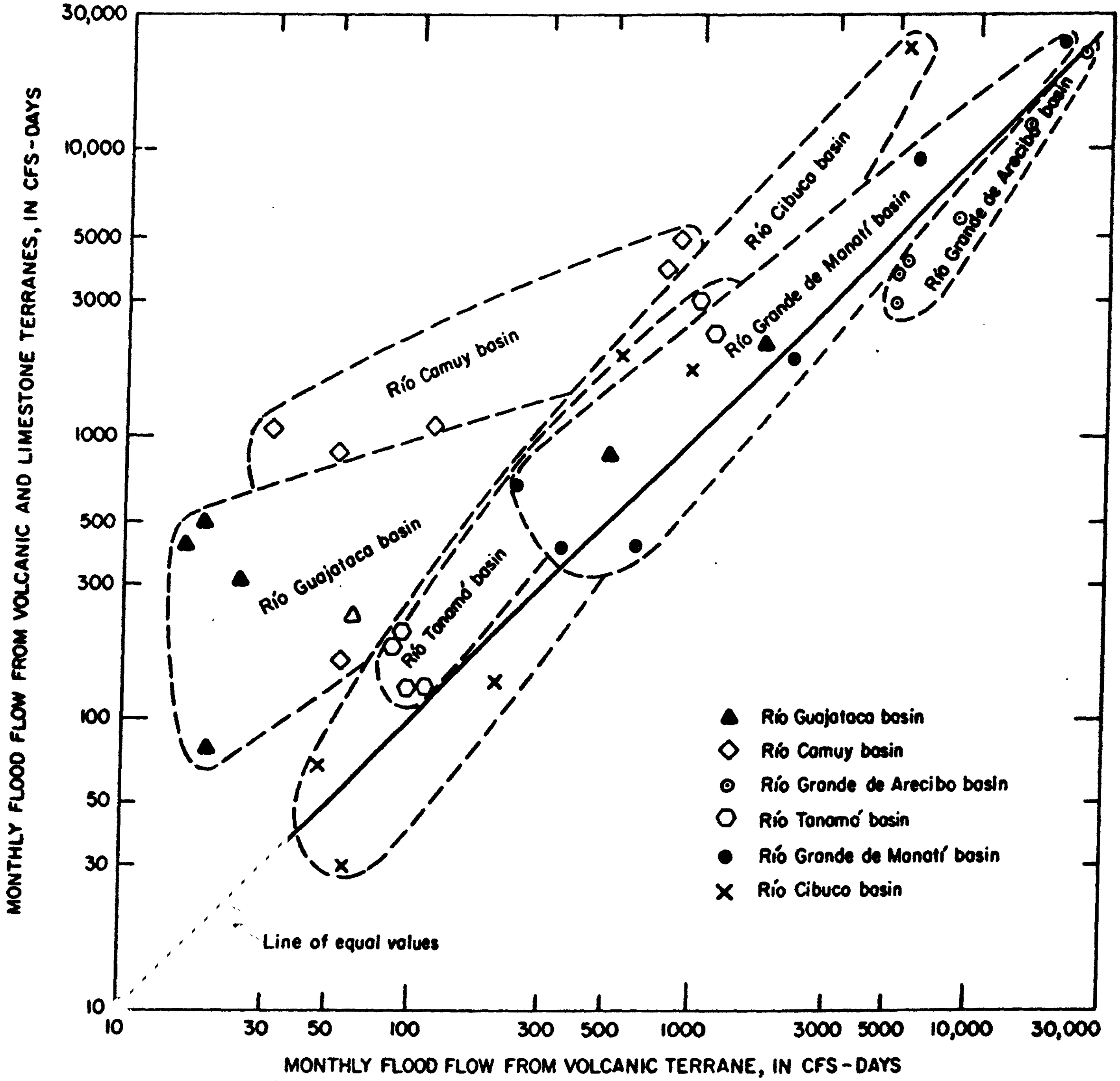


Figure 26.--Selected monthly flood flows at downstream measuring sites (combined flow from volcanic and limestone terranes) against concurrent monthly flood flows at upstream measuring sites (flow from volcanic terrane) for the major streams in the area.

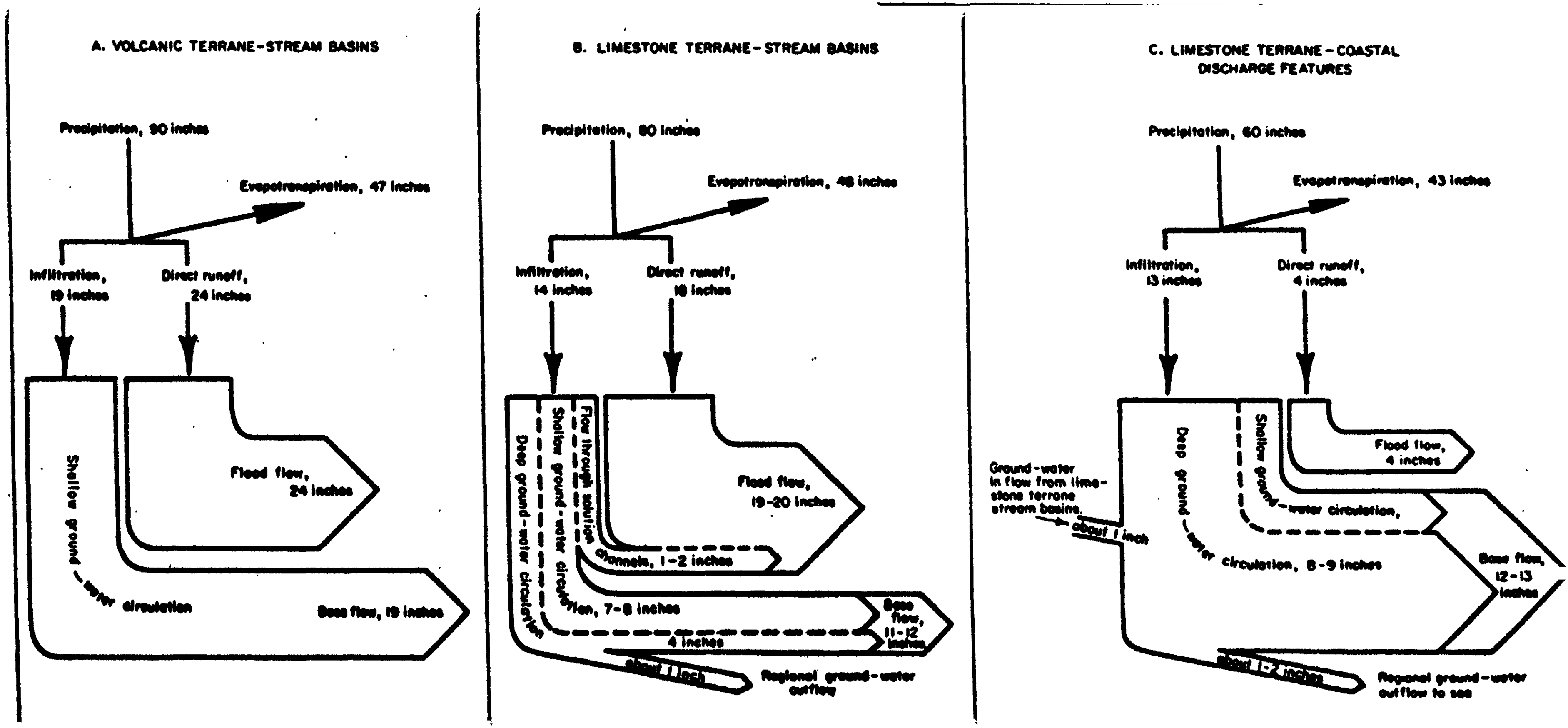


Figure 27.--Estimated average annual hydrologic conditions and theoretical flow patterns for stream basins in volcanic and limestone terranes. (See tables 2 and 3.)

Normally, this movement occurs in a shallow-weathered zone roughly paralleling the land surface, in which permeability is moderate. The infiltrating water moves slowly through this zone, providing a sustained release to the streams over fairly long periods between storms. This slow, steady release appears on the stream hydrograph as base flow. Water also moves through fractures in the surface of the underlying volcanic rock but more slowly and in less quantity. There is no appreciable subsurface ground-water outflow from the basin, and no appreciable contribution to flood flow from water that has infiltrated the soil cover. The streamflow generated by these processes includes a high proportion of base flow, as suggested by figure 27-A. These results are in keeping with the findings of Olmsted and Hely (1962), who found a high ratio of base flow to total flow in an igneous rock environment.

Hydrologic conditions in stream basins in the limestone terrane are shown in figure 27-B. The infiltration in these basins is separated into three components: deep ground-water circulation that may enter the streams as base flow or may leave the basin as ground-water outflow; shallow circulation that may enter the streams slowly as base flow; and shallow circulation that may reach the streams rapidly and become part of the flood flow. The last component is found wherever a shallow network of solution channels or "pipes" provides a high-permeability path to streams. A sizable part of the infiltrating water is then able to reach the streams in hours, rather than days or weeks, and so contributes to flow during the hydrograph peak--that is during the period of direct runoff and flood flow. Some evidence of the rapidity with which shallow ground water may move in the limestone is provided by a dye study made in the Río Tanamá basin in 1966 (R.B. Anders, written comm., 1971) where a rate of travel of 2.6 feet per minute was computed.

The net result of these limestone drainage processes is an increase in flood flow and a decrease in base flow, as compared to a volcanic basin. Comparison of figures 27-A and 27-B indicates that for equal infiltration of the soil cover, and using the definitions of base flow and flood flow given previously, a limestone basin should have larger flood flow and lower base flow than an equivalent volcanic basin. The rapid reappearance of some of the infiltrating water as flood flow is probably a more significant factor than the diversion of some of the deep ground-water circulation to regional ground-water outflow, although both act to decrease base flow.

Figure 27-C shows hydrologic conditions in the coastal discharge features--that is, Laguna Tortuguero and the Caño Tiburones areas, which differ fundamentally from stream basins in that they are swampy areas parallel to the coast and have small areas of direct surface runoff. The discharges from these features to sea are largely derived from deep ground-water circulation. For the Caño Tiburones area, infiltration takes place over an area extending to the south, possibly to the outcrop of the Cibao Formation. Some direct outflow of ground water to sea may take place beneath each feature, and in the Laguna Tortuguero area this discharge may be as much as 25 percent of the coastward ground-water flow. Inflow of ground water from adjacent stream basins is difficult to estimate, but probably constitutes at least a small component of the input to each feature. Because flow from deep ground-water circulation is much less variable than direct runoff, the outflow of these coastal-drainage features is relatively steady and is characterized by a flat hydrograph with few discrete peaks. Base flow is, thus, large relative to flood flow and constitutes a considerable part of the discharge from these features.

The ground-water flows summarized in table 1 represent regional ground-water movement or, in the terminology of figure 27, deep ground-water circulation. The shallow ground-water circulation of figure 27 represents transient, local, and in some places unsaturated flow, which would usually have no long-term influence on the water-level gradients used in the computations of ground-water flow. The total ground-water discharge for the limestone area as shown in table 1 is 194 cfs; the lowest daily flows recorded, as shown in table 3, for the limestone terrane represent deep ground-water circulation and total 162 cfs. It, therefore, seems that regional ground-water flow sustains the minimum base flow of the streams, whereas total base flow, as suggested in figures 27-B and 27-C, includes contributions from other sources. The difference of 32 cfs between the computed ground-water flow and the total of the lowest daily flows may represent ground water discharged directly to sea.

The agreement between base flow and regional ground-water flow, as computed by Darcy's law, is much closer for the Caño Tiburones area and Laguna Tortuguero than for the stream reaches. This adds strength to the theory that the base flows of these features are derived largely from coastward ground-water flow. Further, it seems that storage in the limestone is more effective in sustaining the coastward flow than in sustaining the flow into streams during drought.

Water Quality

A general presentation of the chemical quality of the surface water and ground water is given in table 4. The effect of the limestone solubility is apparent in the concentrations of calcium and bicarbonate. Water from volcanic terrane, such as that from Río Guajataca at Lares before it enters the limestone, shows half the concentration of calcium as after it has traversed the limestone area. The ground-water inflow from the limestone carries a calcium bicarbonate solute, which leads to an increase of these constituents in the river water. The decrease in the concentration of silica and sodium results from an increase in streamflow, which leads to less concentration. In other words, the total quantity of silica and sodium in river water out of the volcanic terrane probably remains the same as the river flows through the limestone area; however, the ground-water inflow from the limestone into the river increases the flow and leads to a dilution of silica and sodium content.

The quality of the ground water, including that from the artesian zones, is not markedly different from that of the rivers, which were sampled during the dry season when the flow is largely derived from ground-water discharge. The quality of the water is good for most purposes and because large supplies can be found readily in the Aymamón Limestone, the area is a desirable place for water development. The great permeability of the limestone leads to the easy retrieval of water through wells, but it also can lead to rapid lateral spreading of any contaminants that might enter the ground-water system. Near the coast, excessive pumpage can locally induce movement of sea water inland.

The water of Laguna Tortuguero is almost fresh. Its mineral content, higher than that of river water, reflects the nearness of the lagoon to sea and, possibly, the inflow of springs. In the northern part of the lagoon springs may be fed from a zone of diffusion where the ground water has a mineral concentration between that of sea water and fresh ground water.

The water of the Caño Tiburones area is a mixture of fresh water and sea water, as mentioned previously.

CONCLUSIONS

Hydrology

The hydrology of the North Coast Limestone area differs considerably from that of areas where a fluvial drainage is present and where there are alluvial ground-water provinces. On an annual basis, however, the quantity of rainfall on the limestones can be largely accounted for by ET, streamflow and lagoonal discharge. A small amount of ground water also is discharged directly to sea, possibly more in the western part of the area than elsewhere.

Average rainfall ranges from 60 inches per year in the northwest to 80 inches per year at the higher altitudes and averages about 70 inches for the entire area. Pan evaporation averages about 60 inches per year.

Actual ET averages about 45 inches per year for the area, leaving about 25 inches per year (about 36 percent of the rainfall) to be discharged by surface and subsurface flow. The flow is predominantly through streams on the impure Cibao Formation, with subsequent infiltration in the karst of the Aguada Limestone to seaward. Streams are also developed in the westernmost part of the Lares Limestone outcrop area. Elsewhere, the flow is subsurface, partly as transient flow through a shallow zone during periods of rainfall that contributes to flood flow and partly as regional ground-water flow. Both types of subsurface flow emerge as stream or lagoonal discharge--the shallow circulation as base flow and flood flow, and the deep circulation, or regional ground-water flow, as base

Table 4.--Chemical-analyses data for surface and ground waters of the limestone area

	Name	Rock type	Milligrams per litre of given constituents										Hardness as $CaCO_3$	Specific conductance, micromhos per cm at 25°C	Remarks
			SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	NO_3			
Surface Water	1. Río Guajataca														
	a. At Lares	Volcanic	33	27	6.5	14	2	125	5.0	10	0	3	90	250	Average of 3 samples
	b. Below Lago Guajataca	Volcanic; limestone	8	47	3.7	6	1.1	160	7.8	7.7	0	.6	133	291	1 sample
	c. Near mouth	Volcanic; limestone	10	52	5	8	1.1	175	6	12	.2	2.2	150	330	Average of 2 samples
	2. Río Lajas	Limestone	11	90	7.6	11	2.2	298	12	23	.1	3.2	253	548	1 sample
	3. Laguna Tortuguero	Limestone	4.3	86	48	302	7.5	164	99	550	.1	1.7	415	2,300	Average of 2 samples
	4. Caño Tiburones	Limestone	7.2	280	511	(3,500*)		232	912	6,600	.4	.2	2,610	18,300	1 sample
Wells	1. Water table	Limestone	7.7	74	3.1	11	.6	224	16	14	.3	20	197	431	1 sample
	2. Upper artesian zone	Limestone	3.6	78	10	6.2	.3	272	7.2	10	0	4.5	236	458	1 sample
	3. Lower artesian zone	Limestone	5.8	69	18	7.8	.6	284	10	12	.2	3.2	246	485	1 sample

*Na + K

Note: Analyses of river water are from samples of dry season flow (January—April 1970), hence concentrations are near maximum values. Analyses of well water are more nearly an average as ground water shows little variation in chemical quality with time.

flow. Water is under water-table conditions in the Aguada and Aymamón Limestones. In the Montebello Limestone Member of the Cibao Formation and the Lares Limestone water is under artesian conditions; confinement is provided by slightly permeable layers in the Cibao Formation. Some artesian flow may possibly emerge in the swampy and lagoonal areas near the coast east of Arecibo.

The lateral hydraulic conductivity of water-yielding zones in the limestones may decrease exponentially with stratigraphic depth; the range is from about 2,700 ft/day for the upper Aymamón Limestone to about 0.1 ft/day for the basal Lares Limestone. Regarding vertical hydraulic conductivity, only indirect evidence is available; for example, vertical hydraulic conductivity must be fairly large in the Aymamón Limestone because the water table is at depths of over 200 feet in some places and yet seems to receive recharge rapidly from the surface. On the other hand, vertical hydraulic conductivity would naturally have to be very low for some of the confining layers associated with the artesian zones.

The water table is generally flat through the Aymamón and upper Aguada Limestones, where gradients of 3 to 4 feet per mile are common. Southward, across the outcrop area of the Aguada Limestone, there is an increase in water-table gradient owing to the underlying Cibao Formation of lower permeability, which keeps the water-table slope parallel to the dip of the formation. In the outcrop areas of the Cibao Formation and Lares Limestone, the gradient of the water table is about 15 to 20 feet per mile. This reflects the fact that these are recharge areas where at shallow depths vertical movement into the aquifer is greater than lateral movement. Near the coast in the artesian aquifers the potentiometric head is about 350 feet above sea level.

In general, in the upper Aymamón Limestone the chances are good of drilling wells capable of yielding 1,000 gpm. In the area between Arecibo and Barceloneta along Highway 2, artesian wells drilled through the Montebello Limestone Member of the Cibao Formation would probably yield about 2,000 gpm, whereas tapping the artesian part of the Lares Limestone would yield about 1 gpm per foot of penetration. Artesian conditions outside this area are untested, but because the recharge areas are smaller the long-term yield of wells cannot be as great as between Arecibo and Barceloneta. The yield from wells drilled through the lower Aymamón and the Aguada Limestones can be expected to range from 100 to 800 gpm. The Cibao Formation and the Lares Limestone in general are poor water-table aquifers--yields may range from 100 to 200 gpm.

Because of the high permeability and solution channels in some of the limestones, the aquifers are highly susceptible to contamination. Along the coast, the high permeability of the upper Aymamón Limestone can facilitate rapid sea-water intrusion if well fields are overpumped.

Streamflow entering the limestone area from the volcanic terrane to the south is increased by transient shallow subsurface flow in the limestones during rainy periods and by ground-water seepage during drought. The base-flow component of streamflow is less in limestone basins than in volcanic basins. The total annual flow, however, is about the same for either type of terrane. The flood plains of the larger rivers provide a dampening effect to the flood flow by retaining water through bank storage--this water is released later as base flow. Part of the flood flow of Río Grande de Arecibo may emerge as spring flow in the Caño Tiburones area.

The water quality is generally good, even if hard, and the water can be used with varying degrees of treatment for most demands. The potential of the water resources of the area is much greater than present use. Only in the Cruce Dávila area is there a concentration of wells potentially capable of overtaxing the local ground-water resources.

Possibilities for Additional Study

This reconnaissance of the North Coast Limestone area provides preliminary data for the short range day-to-day problem of selecting locations for drilling wells and describes the general magnitude and distribution of streamflow. For a more comprehensive evaluation of water usage and hydrology, a model of the area could be considered as a next step. Much of the data in this report are useful for constructing a model. At the start the hydraulic conductivity, water budget, and some water-level data probably could be used, but more work would have to be done. Contouring of the flat water table in the

Aymamón Limestone would require a topographic survey with an accuracy of ± 0.10 foot. Data on storage coefficients would be needed, although a range from 0.20 to 0.01 might be used at the beginning. Any pumping test that could be made might give information to evaluate hydraulic conductivity and to provide data on storage coefficients. But, more important, at least three wells could be drilled to the top of the San Sebastián Formation to clarify the nature of the artesian aquifers; such drilling would preferably be near the coast in the general area of Isabela, Camuy, and Vega Baja. Commonwealth agencies could consider drilling deeper than necessary in their normal program of developing water supplies, where important information could be obtained at small additional cost. Specifically, any well drilled in the Cibao Formation could be considered for testing the underlying Montebello Limestone Member, and any well drilled in the Montebello Limestone Member could be considered for testing both the artesian Montebello and the underlying Lares Limestones.

The present withdrawal of ground water is small, below the potential. However, a program of collection of pumpage data--always needed and seldom available--could be implemented.

Recording gages could be installed in the few wells that are not being used in the upland karst to assess the fluctuation of the water table, at least through a wet and a dry period. The fresh-water sea-water interface by the coast would need to be defined. And the existence of the proposed fault in the Caño Tiburones area would require verification.

Only the gross aspects of streamflow have been investigated, and no long-term data are available. Acceptable long-term data may be computed from synthetic streamflow generated through rainfall-runoff models, regionalization techniques, or correlation with long-term stations.

What kind of model would be effective? Given the size of the area and the present state of the art, the ground-water characteristics of the North Coast Limestone area perhaps would be best represented by an electric-analog model with one layer simulating the Aymamón and Aguada Limestones, one the Cibao Formation, and one the Lares Limestone. Streamflow modeling computations are routinely carried out on digital computers. The hydrologic models could serve as a source of information for an evaluation of the best use of the water resources.

Alternatives for Management

Most schemes of land development that affect the water resources could be tested and evaluated with hydrologic modeling. This has been done to a limited extent (Bennett, 1972) in a study of the effects on the ground-water system of the proposed construction of a harbor in Tortuguero Lagoon. Similar studies could be carried out for other projects using hydrologic models as mentioned previously in this report.

An important problem concerns the most efficient method to supply water to the burgeoning industry of the north coast belt. The concentration of industry, such as that at Cruce Dávila, may lower the water table in the immediate area and, in time, may lead to decreasing well yields and sea-water encroachment. In terms of optimum ground-water use, withdrawal would be proportionally distributed throughout the belt, but such withdrawal may not be efficient or economical. The converse, spacing withdrawal widely, may also be inefficient and uneconomical.

The alternative of distributing water from reservoirs to points of water demand throughout the year or seasonally, coupled with ground-water withdrawal during the dry season, is another possibility. And, at a larger scale yet, the projected diversions of surface water from the north coast to the south coast would clearly influence the pattern of water-resources usage at either place.

SELECTED REFERENCES

Bennett, G. D., 1972, Ground water in the Tortuguero area, Puerto Rico, as related to proposed harbor construction: P. R. Water Resources Bull. 10, 25 p.

Briggs, R. P., 1961, Geology of Kewanee Interamerican Oil Company test-well number 4CPR, northern Puerto Rico, in Oil and Gas Possibilities of Northern Puerto Rico: P. R. Mining Comm., 23 p.

______ 1965, Geologic map of the Barceloneta quadrangle, Puerto Rico: U. S. Geol. Survey Misc. Geol. Inv. Map I-421.

______ 1966, The blanket sands of northern Puerto Rico: Caribbean Geol. Conf., 3rd, Kingston, Jamaica, 1962, Trans., p. 60-69.

Briggs, R. P., and Akers, J. P., 1965, Hydrologic map of Puerto Rico and adjacent islands: U. S. Geol. Survey Hydrol. Inv. Atlas HA-197.

Kaye, C. A., 1959, Shoreline features and Quaternary shoreline changes, Puerto Rico: U.S. Geol. Survey Prof. Paper 317-B, p. 49-140.

Leopold, L. B., 1969, Quantitative comparison of some esthetic factors among rivers: U. S. Geol. Survey Circ. 620, 16 p.

McHarg, Ian, 1969, Design with nature: Natural History Press.

Meyerhoff, H. A., 1944, Geology of Puerto Rico: Univ. P. R. Mon., ser. B, no. 1, 306 p.

Monroe, W. H., 1968, The karst features of Northern Puerto Rico (abstract): Natl Speleol. Soc. Bull., v. 30, no. 3, p. 75-86; Geol. Soc. America Spec. Paper 101, p. 144.

______ 1969, Geologic map of the Aguadilla quadrangle, Puerto Rico: U. S. Geol. Survey Misc. Geol. Inv. Map I-569.

Nelson, A. E., and Monroe, W. H., 1966, Geology of the Florida quadrangle, Puerto Rico: U. S. Geol. Survey Bull. 1221-C, 22 p.

Olmsted, F. H., and Hely, A. G., 1962, Relation between ground water and surface water in Brandywine Creek basin, Pennsylvania: U. S. Geol. Survey Prof. Paper 417-A.