SAND REMOVAL AND RESULTING EFFECTS ON GROUND-WATER FLOW IN THE VICINITY OF THE CAMUY MANGROVE FOREST, PUERTO RICO

By Allen Zack, USGS

REVIEW DRAFT

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 83-

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UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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The following factors may be used to convert the inch-pound units published herein to the International System of Units (SI). This report contains both the inch-pound and SI unit equivalents in the station manuscript descriptions.

Multiply inch-pound units	By	To obtain SI units
	Length	
inches (in)	2.54×10^{1}	millimeters (mm)
feet (ft)	2.54×10^{-2}	meters (m)

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ABSTRACT

The effects of sand extraction on the ground-water system in the Camuy mangrove were investigated in 1982 in cooperation with the Puerto Rico Department of Natural Resources. Hydraulic gradients and salinity distributions throughout the mangrove area were measured from batteries of piezometers ranging in depth from 0.5 to 36 feet.

The water requirements of the Camuy mangrove forest are not dependent upon ground-water movement north of the area, where sand extraction has occurred and where more sand removal is planned. The virility of the mangrove is sustained by freshwater seeps within the forest, cyclical tidal flooding through a tidal channel, and a stable water level in the forest.

Sand extraction may have affected the Camuy Mangrove by lowering the sand dunes and reducing their effectiveness in holding back seawater. More frequent inputs of seawater to the forest would probably result in a redistribution of mangrove species.

Reducing freshwater seepage to the swamp by developing ground-water resources south of the mangrove, or through drainage, would have the most devastating effect on the forest.

INTRODUCTION

Mangrove forests are very productive ecosystems which sustain valuable populations of fish, shell fish, and wildlife by producing large quantities of organic matter. Mangroves are important for recreation and human habitation in that they protect coastlines from storm damage.

The Camuy mangrove forest (fig. 1) is one of the most hydrologically interesting mangrove communities in Puerto Rico. It is characterized by an outstanding degree of development - apparently because of a strong, continuous freshwater input from water-table seepage and a long, disturbance-free period from wind or wave action. The forest has produced large trees in four mangrove species: Rhizopora mangle (red), Avicennia nitida (black), Laguncularia racemosa (white), and Conocarpus erectus (Buttonwood). The mangrove is relatively small in area and is swampy, more open water being evident than dry land. The depth and salinity of water throughout the mangrove contribute to the present vigor of the forest; and the distribution of freshwater determines the distribution of prevailing mangrove species.

PURPOSE OF THE STUDY

Sand dunes and sandy soil of high commercial value occur between the mangrove and the Atlantic Ocean. The Puerto Rico Department of Natural Resources (DNR) is concerned that sand extraction by persons owning the land might harm the mangrove by altering ground-water flow between the ocean and the forest. DNR approached the U.S. Geological Survey in summer 1981 to lead an investigation into the present, shallow ground-water flow conditions in the bordering sand deposits. The objective was to determine if water inputs and outputs of the mangrove depended on ground-water flow north of the forest, where sand has been removed and where further sand extraction is planned. If it were determined that the mangrove depended on ground-water flow in the vicinity of the sand-extraction site, sand removal would have to be stopped, or a material would have to be backfilled having the same hydraulic properties as the sand.

WATER REQUIREMENTS OF MANGROVES

The vigor of a mangrove community and the relative abundance of each tree species depend on the amount of freshwater occupying the forest, the cycle of salinity inputs, and the elevation variation of the water surface. Mangroves are facultative halophytes: they withstand highly saline conditions, but are capable of growing in freshwater (Ariel Lugo, personal commun., Feb. 2, 1983). Freshwater, by itself, is capable of supporting a vigorous mangrove forest were it not for the more vigorous competing plants which tend to choke out the less-tenacious mangroves. The unusual tolerance of mangroves for water having high salinity permits them to flourish where periodic inundations of highly saline water occur. Any freshwater plants trying to become established in the mangrove forest would necessarily be severely weakened or destroyed by the saline water. Trees tend to become larger where the periodic inundations are regular but develop best where there are freshwater surpluses and low energy environments (Cintrón and Schaeffer-Novelli, 1982, p.3).

Mangroves can tolerate water having 90% salinity (139,000 umhos/cm at 27.5°C) (Ariel Lugo, personnel commun., Feb. 2, 1983); but in Puerto Rico, mangrove forests generally contain water under 70% salinity (108,000 umhos/cm at 27.5°C) (Martínez and others, 1979, p. 110-128). As soil salinity increases above that of seawater (35% salinity or 54,000 umhos/cm at 27.5°C) respiration increases and net productivity decreases causing a decrease in the ability of trees to concentrate nutrients in photosynthesizing leaves (Lugo and Snedaker in Cintron and others, 1978, p. 118). In these hypersaline conditions mangroves grow slowly, remain stunted in their growth, and are sparse.

Mangroves contain structures for ventilation of the root system where stagnant water exists. Chimney-like organs (pneumatophores) arise from the roots of black and white mangroves and allow for gas exchange - oxygen diffuses down to the roots and carbon dioxide is vented out (Cintrõn and Schaeffer-Novelli, 1982, p.6). Red mangroves contain lenticels directly on the stilt roots which perform a similar function. In that pneumatophores and lenticels extend just above the water surface, the water-surface elevation in the forest must not rise above the gas exchange structure for a prolonged time period. Therefore, immediate drainage of accumulated water is essential to maintaining the health of the mangrove forest.

The Camuy mangrove forest is sustained by several freshwater springs or seeps having a specific conductance of 6,000 micromhos per centimeter or less (fig. 1). The freshwater inputs represent the key factor controlling productivity, structure, and species composition in the mangrove forest (Lugo and Cintrõn, 1975 p.840). The springflow maintains an average water-level elevation throughout the forest higher than mean sea level, but lower than mean high tide. During high tides, seawater enters the area through a tidal channel on the western edge of the mangrove (fig. 1). The seawater becomes more dilute as it progresses eastward through the forest, mixing with the spring water. As the tide retreats, the flow direction throughout the forest reverses and some of the accumulated seawater-springwater mix flows out of the forest through the tidal channel, which provides the only drainage from the basin. Backwater conditions in the forest (stagnant water due to higher water elevation in the canal outlet) permit residual saltwater to remain, but it is the areal distribution of fresh springwater which determines the relative abundance of the four prevailing mangrove species.

Red mangroves are most common at the western fringe of the Camuy mangrove where soil salinities are lowest. In this area, seawater enters, freshwater exits and, over the long term, water salinities are the most stable

In the center of the forest soil salinities are higher than toward the periphery because water circulation is less and salts have concentrated through evapotransporation. Here, the more salt-tolerant black mangroves are the most prevalent species. Toward the eastern end of the forest, more freshwater is available from springflow and there is less open water. Here, seawater reaches the area only once or twice a year when tides are very high. White mangroves and are most common and attain great size, reaching as much as 40-50 feet in height. Other freshwater plants prevail but appear to be limited both in extent and in size by the infrequent but sufficiently severe inundations of seawater.

GROUND-WATER FLOW AND QUALITY

Batteries of piezometers were drilled in the bordering sand deposits of the Camuy mangrove to measure the hydraulic gradients areally and with depth, and to determine the distribution of salinity (fig. 2). A typical set of values including water level measurements and specific conductance of water in the piezometers for a particular day is presented in table 1. Twenty one data sets are available representing ground-water responses to various hydrologic events, throughout the study length including high and low tidal height, heavy rainfall, and wave swash.

The piezometers were installed in augered boreholes ranging in depth from 6 inches to 30 feet. Screens - 1½ feet in length - were isolated by rubber packers placed above the screen so that heads and salinities at the depth drilled were representative of the aquifer at that depth. The axes of the beach, sand dunes, sand-extraction area, and mangrove forest are west to east. It was assumed that a north-south profile through the area represents ground-water conditions at any location; so the piezometer batteries were placed in a north-south section extending from the dune line to an area directly south of the mangrove (fig. 1).

Piezometers were installed using no drilling fluids, and water levels were allowed to equilibrate. Periodic measurements of water levels in the piezometers indicate that rainfall exerts the greatest control on vertical and horizontal potentiometric gradients in the shallow ground-water regime. Water that drains to the mangrove from heavy rainfall causes a temporary head increase in the forest. Water levels soon return to normal as the tidal channel drains the accumulated water. The potentiometric surface of the adjacent water table is affected minimally by the temporary flooded conditions. However, rainfall on the sand dunes percolates downward causing a long-lasting freshwater mound which provides a water-table gradient toward the mangrove and in which heads decrease with depth: water flows southward and downward.

When tides are relatively high, seawater flows into the mangrove via the tidal channel and temporarily raises the water-surface elevation in the forest. But again, the effects are temporary as low tide permit the drainage of accumulated seawater out of the forest.

Hydraulic gradients between piezometers therefore are subject to change depending upon relative heads in the mangrove and the water table in the vicinity of the sand dunes. The resulting gradients are practically flat and, whatever slight hydraulic gradient exists, only a small quantity of water actually is in transit.

Piezometers drilled south of the forest indicate that freshwater inputs to the forest, traditionally considered springs, are actually seeps which represent the intersection of the water table with the land surface. The head in these piezometers is approximately two feet higher than that in the batteries of piezometers north of the forest.

It is somewhat paradoxical that piezometers nearest the ocean contain water having lower salinity than in those near the mangrove (figure 2 and table 1). Sandy areas north of the mangrove act as collectors and reservoirs of rainfall and hold the adjacent seawater in check hydraulically. Piezometers near the mangrove contain water with salinities indicative of the tidal seawater that progresses through the swamp via the tidal channel and percolates downward into the shallow sediments. The frequent changes in gradient and accompanying reversals of flow direction tend to mix and dilute the rainfall inputs at the sand dunes and the seawater inputs from the swamp.

The water requirements of the forest, in terms of quantity, quality, and water-surface elevation, are not dependent upon the movement of water through sandy areas between the mangrove and the ocean. The rapid transfer of seawater in and out of the mangrove via the tidal channel provides the forest with the essential quantity and quality of water for sustained, healthy growth. Accordingly, it appears that sand removal between the sand dunes and the swamp would not affect the present well- being of the Camuy mangrove forest insofar as ground-water flow is concerned.

Lowering of the water-table south of the mangrove, however, would most certainly have a devastating effect on the forest. Freshwater seepage to the area would become less if the water-table elevation were lowered by any means, including ground-water development or drainage for purposes of sand extraction. The effects would be immediate insofar as a redistribution of species is concerned. Salinites would quickly reach levels intolerant to white mangroves and buttonwoods. The changes would be irreversible as the forest approached hypersaline conditions. The importance of maintaining the present ground-water conditions south of the Camuy mangrove cannot be overstated.

EFFECTS OF SAND EXTRACTION ON THE SAND DUNES

Sand extraction from the Camuy mangrove area has indirectly affected the natural protection that the forest has had from seawater advancement by lowering the dune height. Larger quantities of seawater are now permitted easier and more frequent access to the forest.

Removal of sand between the dunes and the forest appears to have affected the sand dunes in two ways. First, the natural, leeward angle of repose of the dunes could no longer be maintained due to the lowering of the land surface. Accordingly, the sand dunes collapsed, advancing southward until a new angle of repose was established. Second, the extraction of sand altered the overland drainage to the forest and exposed the water table which subsequently was made to drain laterally to areas of lower elevation so that sand extraction could proceed under dry conditions. In response to the lowered water-table elevation in the sand-extraction area, the water table beneath the dunes also was lowered. With more extraction and drainage, the water table in the dune became lower and lower in elevation. Subsequently, the vegetation on top of the dune (seagrapes, coco palms, etc.), which provided stabilization in times of high winds or beach erosion, began to die apparently because the available freshwater in the dune was lowered below the root zone of the plants.

The collapse of the dunes has occurred from below; that is, the top of the dunes containing myriad roots of plants has settled downward, riding on top of the collapsing base of the dunes. The tops of the dunes are estimated to be as much as 10 feet lower in elevation than in 1979 (Martínez and others, 1979, p. 68) and possibly 30 or 40 feet lower than in 1972 (fig. 3); the sand has advanced southward, almost burying the northernmost battery of piezometers. Aerial photographs of the Camuy mangrove from 1936 to 1980 and a topographic map of 1972 shows much higher and extensive sand dunes than occur today (figure 3).

Hydraulic equilibrium of the Camuy mangrove was interrupted in October 13-15, 1982 by extraordinarily high tides (wave swash) caused by strong winds from a low-pressure system in the Atlantic Ocean. The inundation of seawater was more widespread and long-lasting because the natural barricade to seawater flooding - the sand dunes - was lower in elevation and much less effective in holding back the seawater. Seawater spilled over the dunes and filled the entire mangrove forest with seawater.

The effects on the ground-water environment north of the mangrove were severe (fig. 4). The inordinately high tide and wave action, when advancing over the sand dunes, replaced accumulated rainfall with seawater and increased the elevation of the water table. The lowered land-surface elevation south of the dunes resulting from sand removal tended to collect and pond the spilled seawater. Lack of maintenance of the overland drainage ditches heretofore used to drain the water table, effectively raised the water table to what may have been previous elevations.

Significant as it may seem to the geohydrology of the area, the effects were short-lived and the flow system within the mangrove soon returned to previous conditions. When ocean elevations returned to normal, the forest drained through its traditional tidal channel. Drainage lasted approximately two weeks as the inordinate quantities of salty backwater eventually retreated. It appears that although residual salinities are somewhat higher in the mangrove, freshwater from springflow has replaced most of the seawater, and the surface-water elevation has returned to its previous level.

It is important to recognize the importance of maintaining the tidal channel as the only route for seawater entry to the forest, and the only exit for accumulated water in the swamp. Had the mouth of the channel been blocked by the wave swash, the water-surface elevation throughout the mangrove would have risen above the pneumatophores. Many white and black mangroves would not have been able to perform their essential gas-exchange function and would have certainly died.

The long-term effects of this inundation - as well as future saltwater floods - on the Camuy mangrove is not known. It is possible that over many years of more severe seawater inundation now permitted by the lowered sand dunes and a somewhat higher-energy environment, the delicate balance of mangrove species in specific areas of the forest might be disrupted. What zonation of species that has evolved over centuries of relatively constant input cycles of freshwater and seawater might change in response to longer and heavier charges of seawater. Many investigators have demonstrated that there are increases in respiration and decreases in net productivity with increases in soil salinity.

As interstitial salinities increase, the canopy height decreases (Cintrón et al in Cintrón and Schaeffer-Novelli, 1982, 24 p.) as well as the size of individual trees.

The Camuy mangrove is not representative of most mangrove systems in Puerto Rico. It is much smaller, very healthy, is fed by ground-water seepage and has a well-defined drainage canal connected to the ocean. The canal replenishes the mangrove with seawater and relieves accumulated springwater by the action of the tides. In that the Camuy mangrove is small, the regularity of the tides can replenish and drain it in a very short time. A more typical mangrove community usually receives contributions of freshwater from rivers and from slow percolation of rainfall through shallow sediments. In such a system, there may be no surface drainage and accumulated, hypersaline water in the center of the swamp infiltrates downward, also through the shallow sediments. Therefore, in the case of more typical mangrove forests, the effect of sand extraction on the ground-water system would be more significant. Individual studies would have to be made at each mangrove site to determine the significance of ground water depletion from sand extraction or well-field development.

SUMMARY

The removal of sand between the dunes and the Camuy mangrove probably affects the mangrove community only insofar as it has contributed to sand dune degradation. The effect that extraction has had on ground-water flow is minimal, and in itself, would not have been cause for concern with respect to maintenance of the mangrove community. The relative population of the four mangrove species and the vigor of the forest are related to stable water levels in the swamp and to the cyclical nature of tidal flooding and gradual replacement by freshwater springflow as established over centuries of consistency. The rainfall accumulations in the sand dunes and the relation between head and water quality areally and with depth are significant hydrologically, but play a minor role in supporting the Camuy mangrove.

Reducing fresh springflow to the swamp by developing ground-water resources south of the mangrove or through drainage would have the most devastating effect on the forest.

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TABLE 1.--Water level elevations and values of specific conductance in piezometers, December 8, 1982, Camuy Mangrove Area.

	Piezometer identification number	Depth of piezometer in feet	Water-level depth above mean sea level, in feet	Specific Conductance in micromhos per centimeter	Remarks
Sand dune piezometer battery	10	1/2	no water	no water	Water percolating downward
	9	2	4.00	20,000	
	8	4	3.97	14,500	
	7	6	3.83	19,000	
	6	10	3.33	15,000	
	D	20	3.28	7,000	
	C	30	3.20	13,000	
	C1	36	3.23	7,000	
North mangrove piezometer battery	5	1/2	4.36	49,000	Water percolating downward and to the north
	4	2	4.28	39,000	
	3	4	4.27	37,000	
	2	6	3.89	35,000	
	1	10	4.11	26,500	
	B	20	3.63	15,000	
	A	30	3.47	6,500	
	A1	36	3.47	6,500	
South mangrove piezometer battery	S1	2	5.40	1,500	
	S2	4	5.30	2,000	
	S3	8	5.13	1,500	

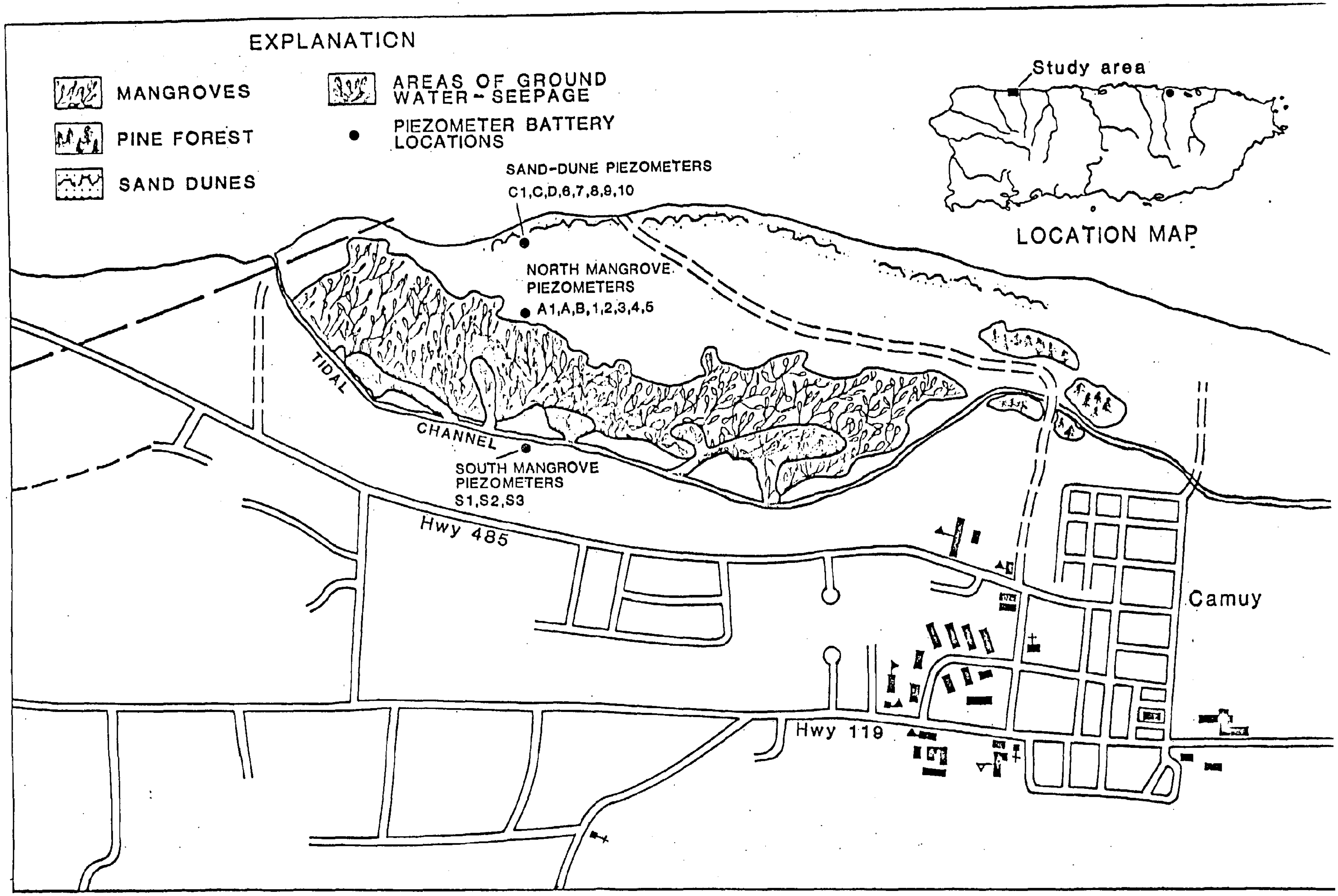


Figure 1.— Camuy mangrove area, Puerto Rico and vicinity showing principal geographic features and piezometers locations.

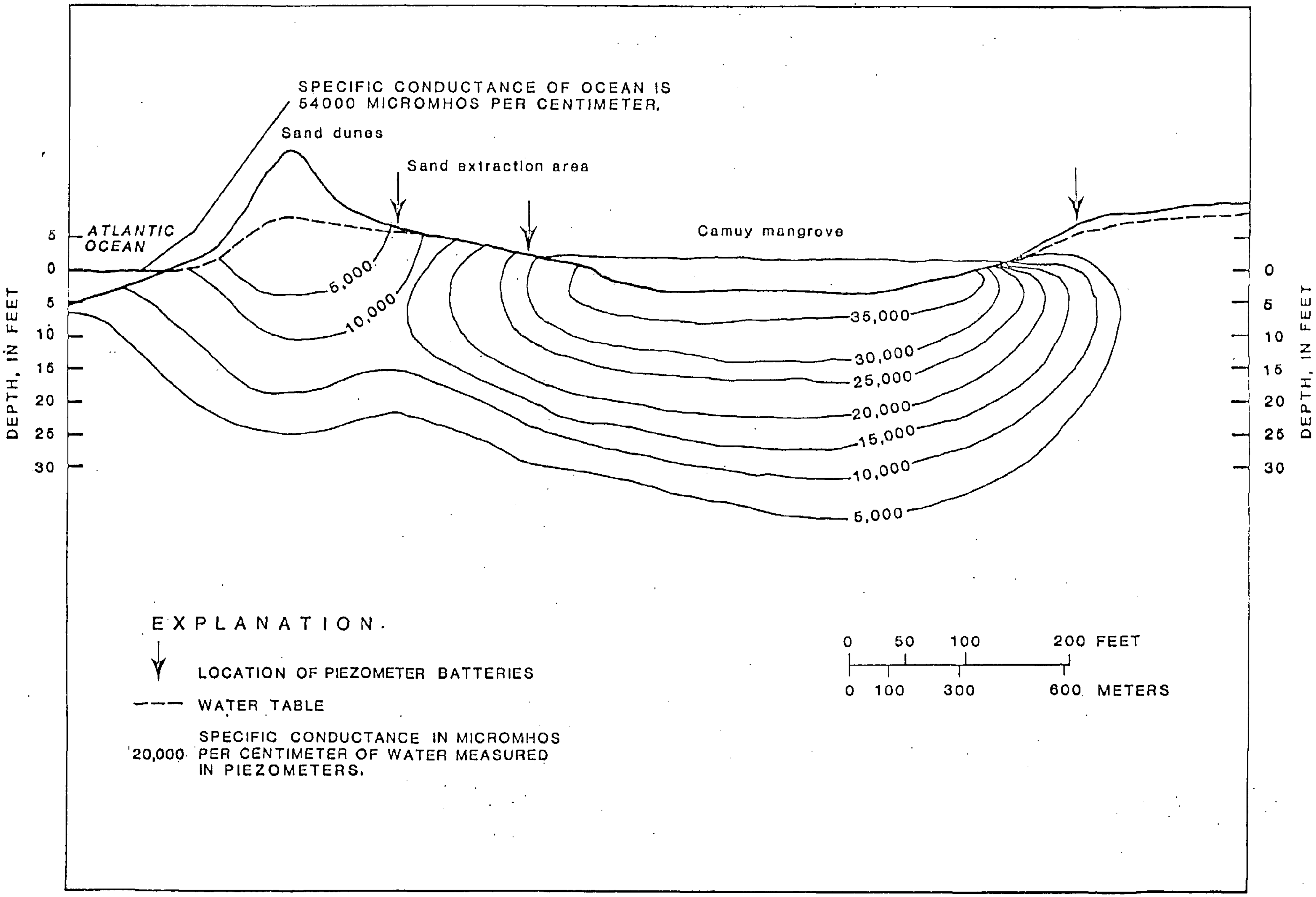
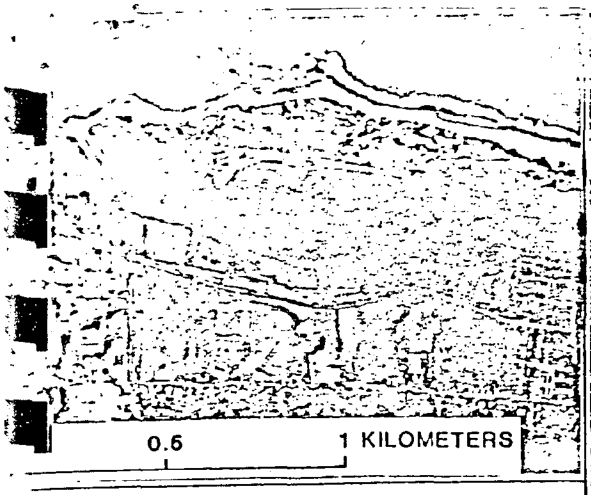
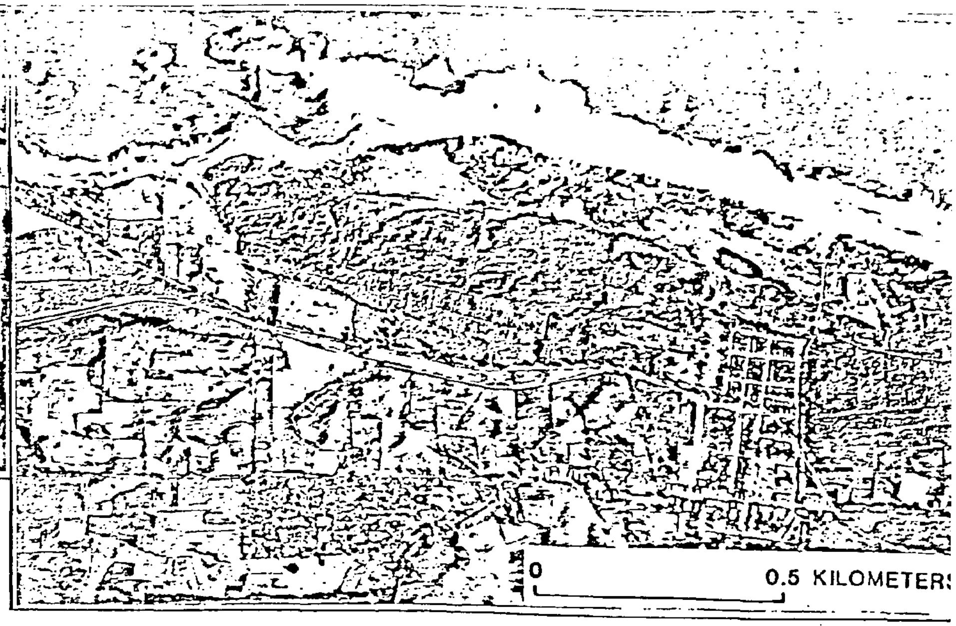


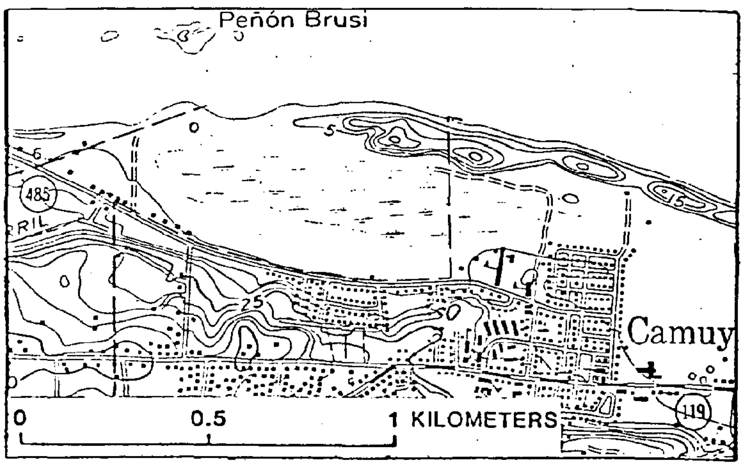
Figure 2.-- Profile of Camuy mangrove area in June 18 1982 during equilibrium conditions.



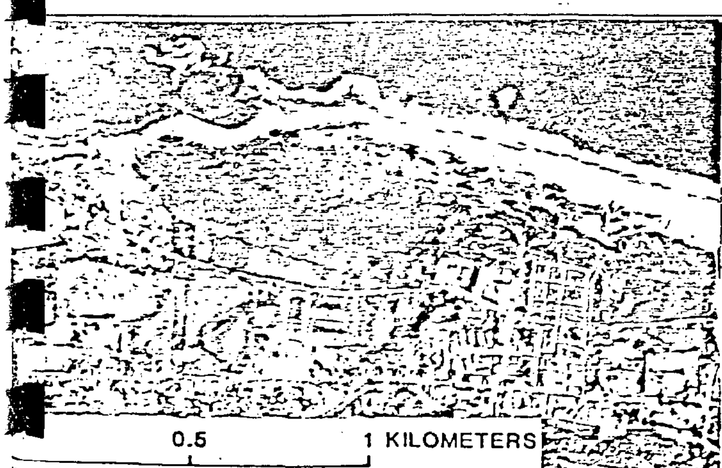
TREES IN MANGROVE APPEAR TO BE
E. MORE OPEN WATER IS EVIDENT, POS-
ϡLY DUE TO VERY DESTRUCTIVE HUR-
CANES WHICH OCCURRED IN 1928 AND



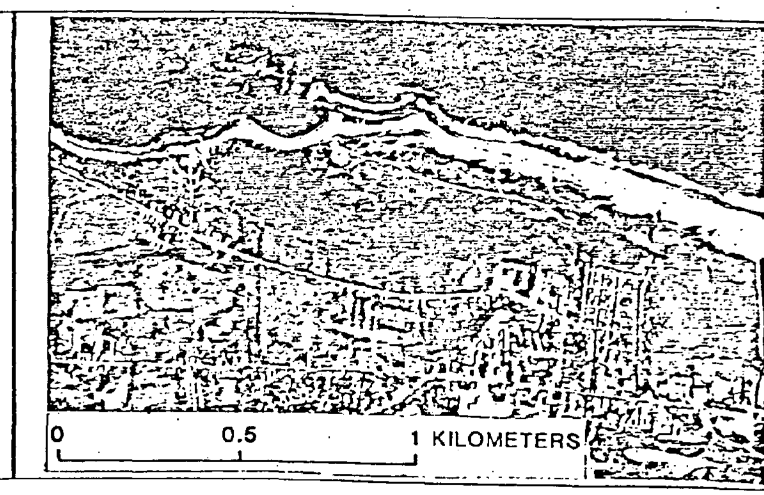
1950– LINEATIONS IN MANGROVE RELATED TO HARVESTING OF TREES FOR CHARCOAL.



1972– NOTE HEIGHT OF SAND DUNES IN METERS .

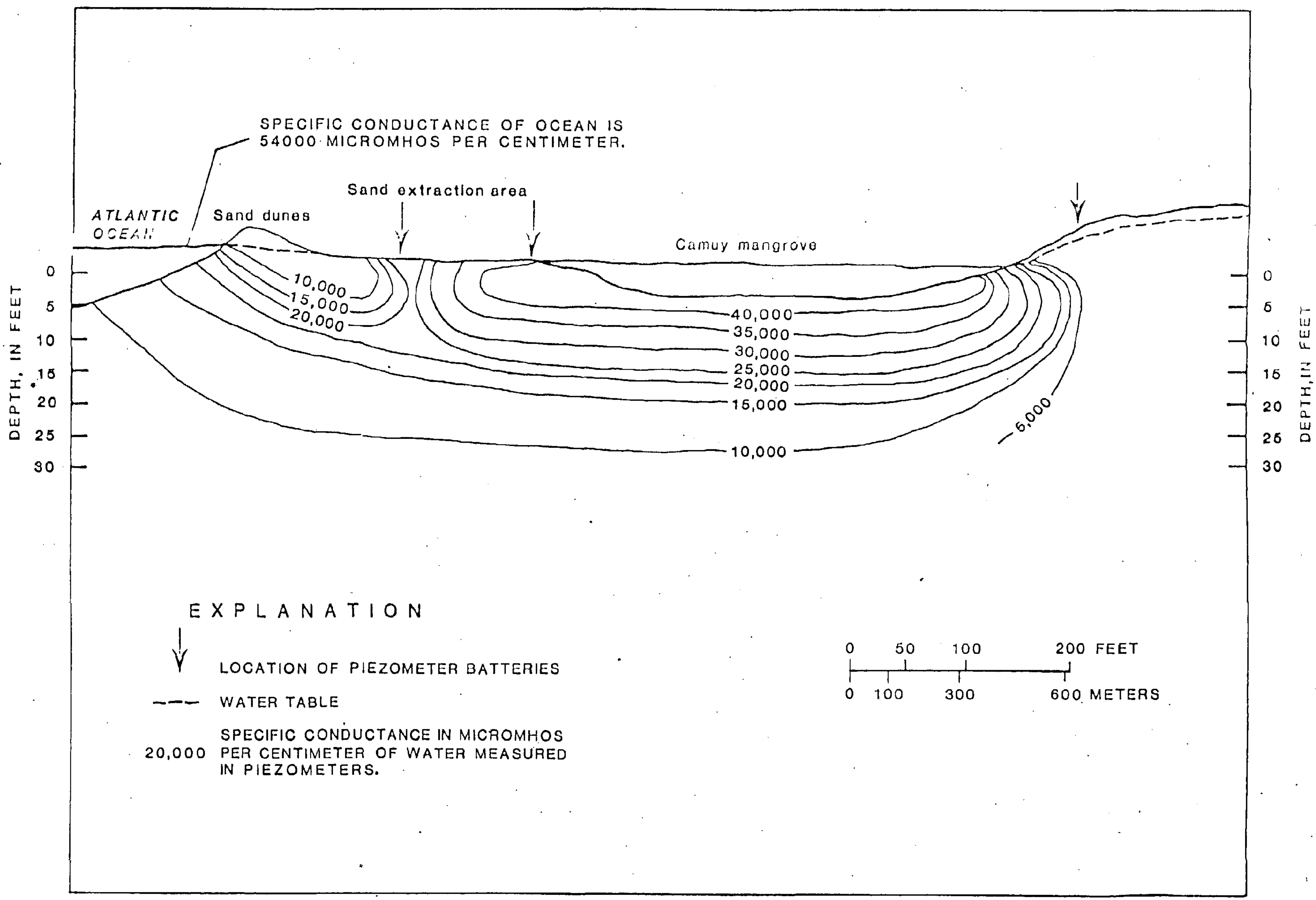


– MANGROVE APPEARS HEALTHY AND EXTENDS
HE DUNES. CHARCOAL WAS NO LONGER USED
THE PRIMARY FUEL IN PUERTO RICO AND THE
AND HAD BEEN FREE OF DESTRUCTIVE HURRI-
ES SINCE 1932.



1980– PRE-SAND EXTRACTION.

igure 3.-- Photographic and topographic record of the Camuy mangrove area since 1936.


SPECIFIC CONDUCTANCE OF OCEAN IS 54000 MICROMHOS PER CENTIMETER.
ATLANTIC OCEAN
Sand dunes
Sand extraction area
Camuy mangrove
10,000
15,000
20,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
6,000
DEPTH, IN FEET
0
5
10
15
20
25
30
DEPTH, IN FEET
EXPLANATION
LOCATION OF PIEZOMETER BATTERIES
WATER TABLE
20,000 SPECIFIC CONDUCTANCE IN MICROMHOS PER CENTIMETER OF WATER MEASURED IN PIEZOMETERS.
0 50 100 200 FEET
0 100 300 600 METERS