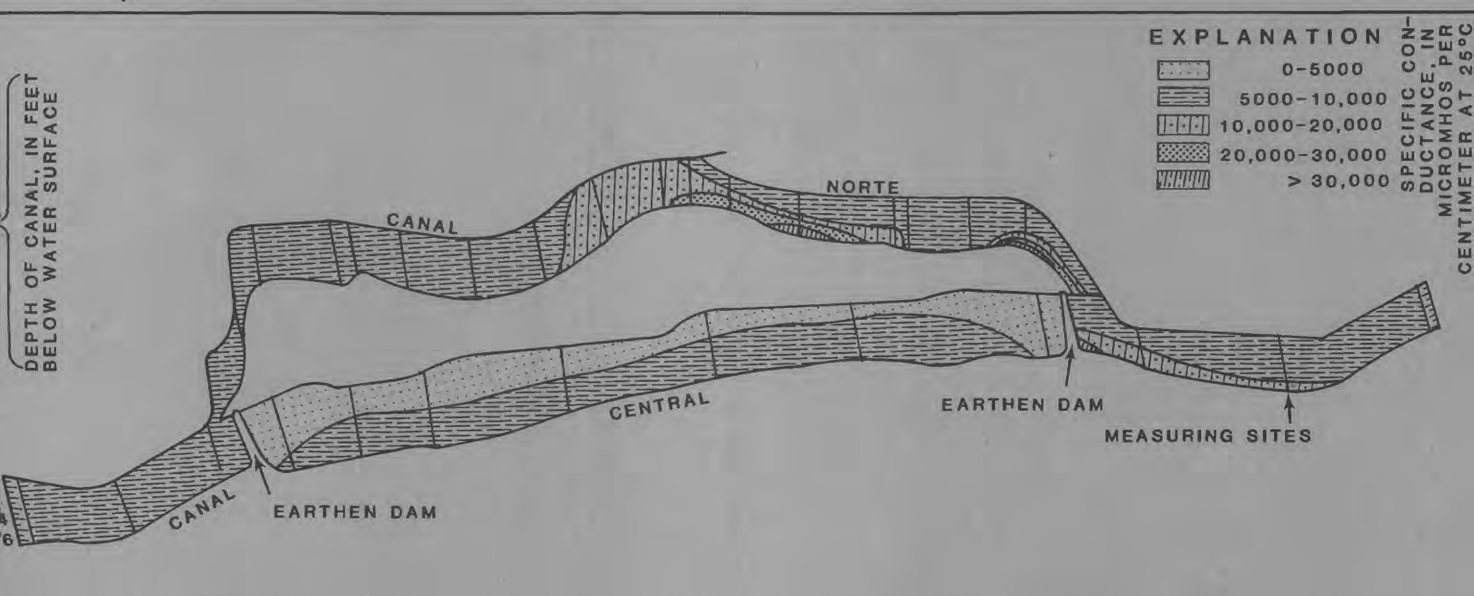
RESTORATION OF FRESHWATER IN THE CAÑO TIBURONES AREA, PUERTO RICO

.S. GEOLOGICAL SURVEY

ATER-RESOURCES INVESTIGATIONS REPORT 83-4071



repared in cooperation with the

UERTO RICO DEPARTMENT OF AGRICULTURE

RESTORATION OF FRESHWATER IN THE CANO TIBURONES AREA, PUERTO RICO

By Allen L. Zack and Angel Class-Cacho

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Prepared in cooperation with the
Puerto Rico Department of Agriculture

San Juan, Puerto Rico
1984

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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CONVERSION TABLE

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)
	2.54×10^{-2}	meters (m)
feet (ft)	3.048×10^{-1}	meters (m)
miles (mi)	1.609×10^{0}	kilometers (km)
	Area	
acres	4.047×10^{3}	square meters (m^2)
	4.047×10^{-1}	square hectometers (hm^2)
	4.047×10^{-3}	square kilometers (km^2)
square miles (mi^2)	2.590×10^{0}	square kilometers (km^2)
	Flow	
cubic feet per second (ft^3/s)	2.832×10^{1}	liters per second (L/s)
	2.832×10^{1}	cubic decimeters per second (dm^3/s)
	2.832×10^{-2}	cubic meters per second (m^3/s)
gallons per minute (gal/min)	6.309×10^{-2}	liters per second (L/s)
	6.309×10^{-2}	cubic decimeters per second (dm^3/s)
	6.309×10^{-5}	cubic meters per second (m^3/s)
million gallons per day (Mgal/d)	4.381×10^{1}	cubic decimeters per second (dm^3/s)
	4.38×10^{-2}	cubic meters per second (m^3/s)
	Specific Conductance	
micromhos per centimeter (umho/cm)	1.000*	microsiemens per centimeter (uS/cm)

* Exact.

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ABSTRACT

Caño Tiburones on the north coast of Puerto Rico originally was a shallow, coastal lagoon, 9 square miles in area. It accumulated freshwater from adjacent rivers and springs and drained to the ocean through unobserved subterranean conduits. Forced drainage by pumping of Caño Tiburones for agriculture was begun in 1949, and resulted in lowering the water level to below sea level. The reversed hydraulic gradient permitted seawater to enter the Caño through the conduits forming seawater "springs". Seawater flooding caused widespread sodium chloride contamination in the canals and laterals and in the soils. Agricultural expectations of the area were not realized.

The present investigation into the freshening potential of Caño Tiburones (1979-1982) determined that ground-water discharge does not contribute to salty conditions.

On-site experiments were performed to segregate freshwater from seawater using differences in hydraulic head. Dams were constructed on canals and laterals, forcing accumulated saltwater to the ocean. Ring levees were placed around the discharging seawater conduits until sea level was reached and flow to the system stopped.

These efforts have succeeded in reducing the amount of seawater in Caño Tiburones to one-third of its original concentration. Most of the water presently in Caño Tiburones is suitable for irrigation.

INTRODUCTION

The Caño Tiburones is a swampy depression on the north coast of Puerto Rico, extending between Río Grande de Arecibo and Río Grande de Manatí (fig. 1). The area contains approximately 6,000 acres (9 square miles) and is the site of a partially successful land-reclamation project. Drainage of the land began in 1907 by the Puerto Rico Department of Agriculture. The hydraulic gradient between the water table in the Caño area and the ocean was reversed as a result of the drainage, and seawater began to inundate the Caño. The accumulations of sodium chloride in the canals and laterals of Caño Tiburones, as well as in the soil, rendered the area virtually unusable for agriculture.

The Caño Tiburones is owned by the Commonwealth of Puerto Rico and administered by the Land Authority within the Department of Agriculture. The Land Authority leases tracts of land to local farmers principally for pastures. The high population density of Puerto Rico and limited quantities of flat agricultural land prompted the investigation of alternatives to recover the valuable Caño area.

The U.S. Geological Survey in cooperation with the Department of Agriculture, began a project in 1979 designed to study the water resources of the Caño Tiburones area and to answer the following questions:

1) Can the Caño Tiburones be made fresh?

2) How long will the freshening process take?

3) Can the water in the area be maintained fresh?

The approach used to answer these questions was as follows:

1) Determine the source and route of saltwater into the Caño flow system.

2) Determine, through experimentation, the best methods of utilizing freshwater to purge accumulated saltwater while at the same time prevent seawater from further contaminating the water and soil in the Caño.

3) Monitor water quality in the system to assess the effects of the experiments.

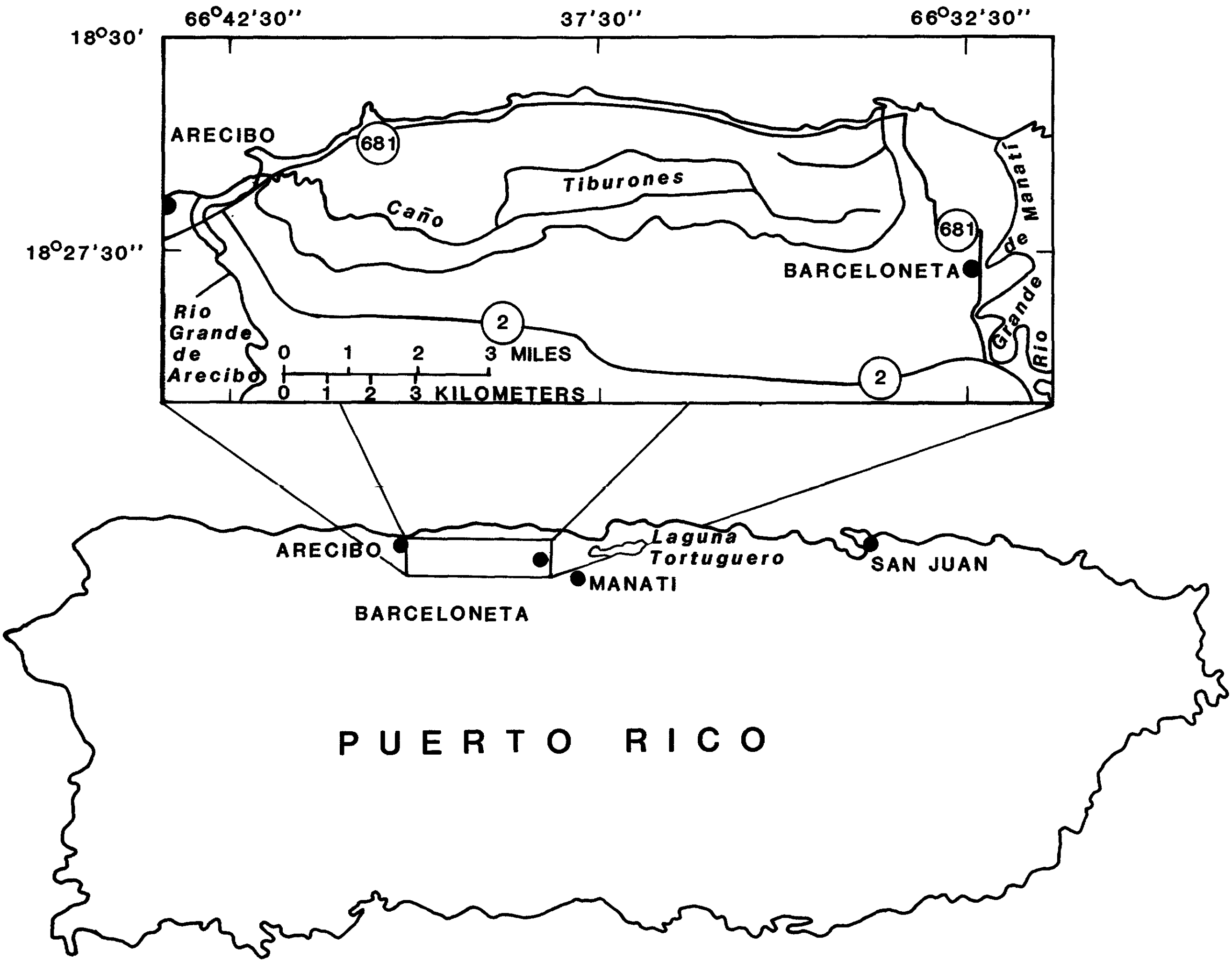

Figure 1.--Caño Tiburones and vicinity.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the many individuals who provided assistance and cooperation throughout the project. Foremost support was provided by F.A. Johnson, hydrologist with the U.S. Geological Survey in Columbia, S.C. Throughout the data-collection phase of the investigation he worked tirelessly and offered many valuable suggestions. Without his help and encouragement, this report would have been impossible.

G. W. Leve and Kenneth Stevens, U.S. Geological Survey hydrologists in Jacksonville, Florida, and Albuquerque, New Mexico, respectively, drilled piezometers and wells and made initial interpretation of the hydrologic data obtained.

The authors are indebted to personnel with the Commonwealth of Puerto Rico Land Authority and Rice Program who generously assisted the project in the earth-moving and extensive rerouting and damming program. Special mention must be made of Agustín Cayere, Luis Picó, Marcos Mercado, and Eliseo Sánchez and his staff.

DESCRIPTION OF THE AREA

The climate of the Caño Tiburones is warm, tropical-marine, with very small fluctuations in temperature. Annual rainfall averages about 55 inches (at Arecibo), but is not evenly distributed throughout the year. Two recording rain gages placed within the Caño (fig. 2--in pocket) have shown that rainfall is at least 10 percent less than that at Arecibo, owing to a strong orographic effect. The rainiest month is May; second rainiest are

October and November. A relatively dry season extends from January through April. Even with these variations in rainfall, the climate of the area is ideal for agricultural activity throughout the year.

Río Grande de Arecibo bounds the Caño Tiburones on the west and has great potential as a source of irrigation water for the area. The average discharge of the Río Grande de Arecibo at Central Cambalache (11 years of record, 1970-1980) is 496 ft^3/s (USGS, 1982, p. 49). During this period flows have ranged from 50 ft^3/s to 23,700 ft^3/s. Flow at Arecibo is regulated by hydroelectric power production at Dos Bocas reservoir, 12 miles upstream of the Cambalache gage.

Río Grande de Manatí, on the eastern border, has less potential as a source of irrigation water for the Caño area. Although its average discharge (10 years of record, 1971-1980, USGS, 1982, p. 70) is 368 ft^3/s, seawater is known to intrude upstream in Río Grande de Manatí as far south as the town of Barceloneta. Seawater intrusion into Río Grande de Arecibo never extends past its mouth.

Studies of the soils in the Caño Tiburones have shown that the area is suitable for a wide variety of agricultural uses, including the growing of rice (Bonnet and Roberts, 1967, pp. 29-67). First, however, the accumulated salts - composed principally of sodium chloride - must be flushed from the soils and freshwater established in the canal and lateral system.

HISTORY OF THE CAÑO TIBURONES

Caño Tiburones was originally a brackish, shallow, coastal lagoon (Meyerhoff, 1933, p.87) similar to what Laguna Tortuguero (fig. 1) is today. According to tradition, local fishermen adopted the name Caño Tiburones as an attempt to dissuade outsiders from fishing the exceptionally rich but "shark infested" waters.

Before reclamation, water in the Caño was composed of freshwater and saltwater components: freshwater from rainfall, overbank flow of the adjoining Río Grande de Arecibo and Río Grande de Manatí during floods, overland runoff from the southern uplands, and springflow; saltwater entered the area from high tides and from migrations up river channels during periods of low flow. Freshwater predominated when tides were low and rainy conditions existed; saltwater was evident during droughts, when tides were high. The area drained seaward through the river basins on either side and through large subterranean conduits, unknown at the time, which connected the area directly with the ocean.

The scarcity of land resources in Puerto Rico for agriculture prompted engineers in 1907 to drain the Caño Tiburones by gravity, using closely-spaced herringbone laterals. Overland floodwater vents to the ocean were constructed at El Vigía and at Palmas Altas (fig. 2--in pocket).

Drainage was accompanied by a gradual dewatering of the soils, resulting in soil shrinkage and land subsidence. Linear desication cracks, often extending below the water table and locally known as "cancoras," developed from shrinkage of the highly organic soils.

Land subsidence continued as water was drained until the elevation of the water table eventually approached sea level. Further gravity drainage of the soil zone became impossible, and in 1949, four low-lift turbine pumps, each rated at 80,000 gal/min were installed at El Vigía. An improved tidal gate was constructed at Palmas Altas [1/] and a more efficient arrangement of laterals and canals was provided for draining accumulated water (fig. 2--in pocket).

Continuous removal of water from Caño Tiburones by the pumping station at El Vigía further depressed the water table until it was lowered below sea level, thereby reversing the hydraulic gradient with the ocean. The heretofore unobserved conduits which originally vented accumulated water now permitted seawater to enter the Caño area. With additional subsidence of the land surface, more pumping was required to lower the water table which increased the hydraulic gradient from the ocean to the Caño. Subsequently, more seawater entered the area requiring additional pumping to maintain static levels throughout Caño Tiburones. Normal, dry conditions required approximately 37 pump-hours per day to maintain equilibrium water-levels and salinity throughout Caño Tiburones.

The continuous presence of saltwater in many parts of the Caño has, through the years, permitted the accumulation of sodium chloride in the soil. Saltwater infiltrated the soil zone from the canals and laterals by percolation and capillary action. The water was then removed

[1/] Original plans called for the construction of another pumping plant at Palmas Altas, but funds were exhausted after the plant at El Vigía was completed (oral commun., Salvador García, May 1979).

HISTORY OF THE CAÑO TIBURONES (Continued)

by evapotranspiration, and residual salts, mainly sodium chloride were left behind in the soil. The organic soils which occur throughout the Caño, once drained and dry, resist rewetting and are almost impermeable. Therefore, rainfall has been ineffective in flushing away the accumulated sodium chloride in the soil. Occasional flooding from pump shutdowns has contributed to widespread sodium-chloride contamination. The most recent pump shutdown at El Vigía occurred in July 1977 and lasted 20 days during which time Caño Tiburones became flooded with seawater. Water from the ocean entered the area through the subterreanean conduits and reached an elevation of mean sea level within two days. When pumping began and water levels declined, residual sodium chloride from evaporation of the ponded saltwater remained over a wide area in the upper few inches of the organic soil.

SURFACE HYDROLOGY OF CAÑO TIBURONES BEFORE WATER MANAGEMENT

The present investigation into the freshening potential of the Caño Tiburones began in Spring 1979. At that time there was no pattern or consistency of flow within the system. Water in laterals was permitted to flow either north or south and canals, east or west. In addition there was no pattern to the distribution of saltwater in the canals and laterals (fig. 3--in pocket).

Generally, Canal Norte collected the saltiest water from nearby subterranean conduits or "springs" which discharged to adjoining canals and laterals, all below sea level. The conduits discharged crystal-clear water and contained myriad seawater fishes and molluscs. Some conduits formed discharging pools, hundreds of feet in diameter, and over 50 feet deep at the spring orifice. Figure 4 shows the complexity of one of the smaller "spring pools." Some conduits flowed as much as 20 ft^3/s; others were only seeps. All, however, flowed continuously and would have a head of approximately sea level if flow was blocked. It was not known if the conduits were the only source of salinity in the Caño; nor was it known if each conduit was hydraulically independent of the others.

Freshwater springs and seeps also were found to contribute water to the Caño flow system (fig. 2--in pocket). These were concentrated generally in the area of Canal Central, although some were observed to occur nearer to the coast and within 10 feet of seawater conduits. The largest of the freshwater springs were located in the southwest part of the Caño and flowed as much as 20 ft^3/s, but in most areas the freshwater inputs were seeps. Hydraulic head tended to decrease toward the coast but always was lower than sea level. The specific conductance of freshwater springs ranged from 1,100 to 1,300 micromhos per centimeter (umhos/cm).

The percentage of freshwater observed in the canals and laterals increased dramatically with heavy rainfalls. Runoff immediately entered adjoining laterals and canals. Some floodwater vented to the ocean through tidal gates at Palmas Altas and through siphons; the remainder was discharged to the ocean through the pumping station at El Vigía. Heavy rainfalls required that all four pumps [2/] be in operation. Pumping of the excess water would usually return water levels in the canals to prerainfall levels within 24 hours.

[2/] At the beginning of the study, it was determined that the pumps had lost some efficiency; their individual estimated capacities ranged from 50,000 to 56,000 gal/min.

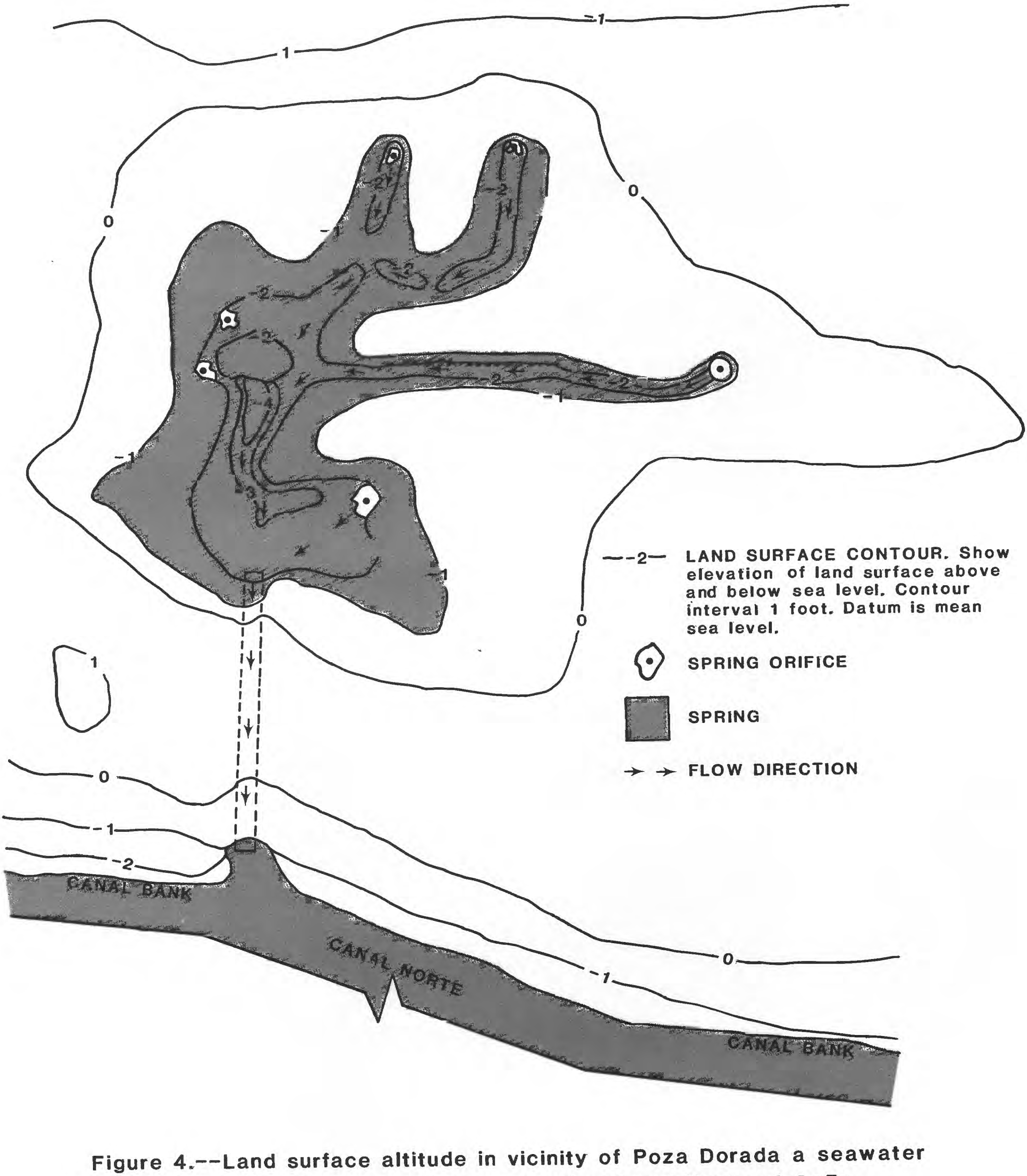

Figure 4.--Land surface altitude in vicinity of Poza Dorada a seawater spring, or seep, draining to the Canal Norte of Caño Tiburones.

SURFACE HYDROLOGY OF CAÑO TIBURONES BEFORE WATER MANAGEMENT (Continued)

The salinity of the water in the canals and laterals returned to equilibrium levels in a matter of days because of immediate seawater replacement of freshwater and zero bank storage of rainfall.

Since 1970, the saltwater situation in the Caño Tiburones has been exacerbated by seawater leakages through the tidal gates at Palmas Altas. Local fishermen forced tires and other objects into the tidal flaps to allow seawater into the Caño to improve crabbing and fishing. The siphons discharging to the Río Grande de Manatí had been altered for no apparent reason, allowing water to move either way through them, and had on occasion leaked seawater to the Caño. As a result, high tides at the mouth of Río Grande de Manatí and sewage discharges containing saline water from a sewage-treatment plant at Barceloneta also contributed large quantities of salty water into the area through the siphons.

GEOHYDROLOGY

The Caño Tiburones consists of swamp deposits and limey blanket sands as much as 100 feet thick (Díaz, 1973, plate 2) of Holocene and Pleistocene age. The swamp deposits were probably deposited when cross flows existed between Río Grande de Manatí and Río Grande de Arecibo. Rich, organic soils containing large quantities of plant remains are evidence of past, rich, floral assemblages. The blanket sands are partly derived from dissolved limestone residues (Briggs, 1966, p. 60). The swamp deposits and blanket sands are bounded by alluvial deposits of sand and gravel deposited by Río Grande de Arecibo and Río Grande de Manatí. Underlying the entire area is the Aymamón Limestone, of early Miocene age. Giusti and Bennett (1976, p.33) showed that Río Grande de Arecibo loses flood flow to underlying alluvium and the Aymamón Limestone. They concluded that some of this water subsequently discharges to the Caño Tiburones as freshwater springflow described earlier, presumably through the Aymamón Formation.

The Caño is separated from the ocean by calcite-cemented sand dunes (eolionite), beach sand, and remnants of the Camuy Formation, also a limestone of Miocene age, but younger than the Aymamón. The subterranean conduits described earlier apparently developed by dissolving limey parts of the Camuy Formation and the eolionite when the water-table elevation in the Caño was greater than sea level.

Limestone hills (mogotes) composed of the Aymamón Formation bound the area on the south. These mogotes are residual limestone hills formed by solution of limestone beneath the blanket sands (Monroe, 1976, p. 46).

An in-depth discussion of ground-water flow is beyond the scope of this investigation because ground water is neither the source nor the cause of salinity in the Caño flow system and in the soil. However, because fresh springflow constitutes the principal source of water to Caño Tiburones, its relation to artesian pressures in the Aymamón Limestone will be discussed briefly.

Where deep fissures or highly permeable zones occurred in the blanket sands and swamp deposits and penetrated to or were in contact with the Aymamón Limestone, water was freely transmitted upward to be discharged as freshwater springs. However, where tight, virtually impermeable soil occurred above the Aymamón, ground water under artesian pressure in the Aymamón migrated upward through the sediments progressively losing hydraulic head to be discharged at the surface as seeps.

The constant removal of water from the Caño by pumping and the long-term maintenance of the same water-level elevation throughout the area had, up until 1970 or so, established equilibrium heads in the Aymamón. Since that time, however, artesian pressures have declined in the Aymamón Limestone, probably attributable to ground-water withdrawals south of the area along Highway 2. The effect that artesian pressure decline has had on the amount of freshwater that ultimately enters the flow system of Caño Tiburones has not been clearly defined.

It would appear that the percentage of freshwater in the brackish mixture discharged at El Vigía during dry (equilibrium) conditions would decrease in accordance with artesian-pressure decline in the Aymamón. This has not been the case. The percentage of freshwater in the brackish mixture measured during dry conditions by various investigators over the past 20 years has remained the same: 66 percent or approximately 78 Mgal/d. This phenomenon is probably attributable to the importance of the Río Grande de Arecibo in recharging nearby parts of the Aymamón Limestone. The water discharges from the Aymamón as springflow and seepage and would not be measurably affected by a decline in artesian pressure from ground-water withdrawals away from the area along Highway 2. It is possible that freshwater seepage has kept relatively constant in spite of ground-water level declines in the eastern Caño area because of accompanying land subsidence. The effective ground-water gradient has remained the same.

It is also possible that the decline in artesian pressure in the Caño area has not been great enough to significantly affect the flow of the springs. Three wells drilled into the upper part of the Aymamón Limestone in 1981 indicated that heads were above the land surface in the Caño, but were approximately two feet below mean sea level (table 1). It is assumed that this elevation represents the freshwater spring head in Caño Tiburones.

Table 1.--Representative values of specific conductance and water levels at various depths in wells plus specific conductance in adjacent canal in the Caño Tiburones area.

WELL NUMBER	DATE	DEPTH BELOW LAND SURFACE, FEET		SPECIFIC CONDUCTANCE MICROMHOS/ CENTIMETER
Central Canal	1-15-80	---		13,000
1	Do.	40	Blanket sands	1,500
	do	48	Camuy Formation	1,950
	do	58	Camuy Formation	2,000
	do	68	Aymamón Limestone	1,800
	do	98	Aymamón Limestone	2,200
	do	108	Aymamón Limestone	2,200
	do	128	Aymamón Limestone	2,500
	do	148	Aymamón Limestone	4,800
Lateral	1-12-80			4,500
2	do	58	Camuy Formation	1,100
	do	60	Camuy Formation	1,400
	do	78	Camuy Formation	1,400
	do	88	Aymamón Limestone	1,750
	do	108	Aymamón Limestone	2,600
North Canal	1-10-80			32,000
3	do	31	Blanket sands	2,500
	do	53	Camuy Formation	3,400
	do	60	Camuy Formation	3,500
	do	80	Aymamón Limestone	2,850
	do	84	Aymamón Limestone	2,850
	do	99	Aymamón Limestone	4,600
	Do.	140	Aymamón Limestone	6,000

The decline in artesian pressure has affected the upward migration of water through the blanket sands and swamp deposits. The near-surface vertical hydraulic gradient apparently has changed during the past 10 to 15 years since the advent of large ground-water withdrawals south of the area. Studies of the near-surface hydrology between October 1966 and April 1968 indicated that widespread upward seepage occurred through the upper 28 feet of sediment (Quiñones and Others, 1970, p. 21). At the time, Quiñones reported that most of the piezometers finished at a depth of 28 feet produced flowing wells.

Thirty shallow piezometers ranging in depth from six inches to 33 ft and drilled in 1980 indicated that the hydraulic gradient in the near-surface saturated sediments has reversed (table 2). Apparently, the loss of pressure in the Aymamón has reduced the height to which water can be pushed in the tight, impermeable soil above the Aymamón. Accordingly, soils are now draining in response to the pressure decline in the Aymamón. The extremely low percolation rate prevents the saturated sediment from draining very quickly in response to the loss of pressure. Further reductions of pressure in the Aymamón Limestone will probably be accompanied by a further lowering of the water table (soil drainage) throughout Caño Tiburones, but will probably not measurably affect freshwater springflow in the southwestern part of the Caño because much of it probably originates as seepage loss from Río Grande de Arecibo.

During the present investigation, chloride-ion measurements in the piezometers and wells indicated that salinity decreased with depth generally being the least in the upper part of the Aymamón (tables 1 and 2). This is further evidence that much of the Caño Tiburones is presently draining. Had the area been discharging ground water upward through the sediments, the water quality would probably have been the same as that in the underlying Aymamón Limestone. Higher than water-table heads in canals and laterals containing seawater allow slow downward and lateral percolation of surface water, with subsequent mixing through diffusion and dispersion; hence salinity decreases with depth. The distribution of saltwater in the soils and the surficial material in the Caño complements the distribution of salty water in the canals (table 2), (fig. 3--in pocket). The conductivity profiles in canals approximate those of the soil regime adjacent to the canal.

The water throughout the Caño represents a mixture of freshwater and seawater. The ratio of sodium to chloride in water from the Caño is the same as the sodium to chloride ratio of seawater (fig. 5). The relation between chloride and the ratio of calcium to magnesium shows nonconservative mixing between seawater and calcium carbonate ground water (fig. 6). Seawater necessarily has a low calcium to magnesium ratio because sea animals selectively remove calcium ions from seawater and form calcium carbonate for shells (molluscs) and skeletal structure (corals). What remains is seawater with a Ca/Mg ratio (in mg/L) of about 0.3. Terrestrial waters, regardless of their sodium and chloride concentrations, will usually have a much higher ratio because of the greater proportion of calcium to magnesium in the rocks of the earth. In addition,

Table 2.--Representative values of specific conductance, chloride, and water levels at various depths within the blanket sands, and specific conductance in adjacent canal, Caño Tiburones.

PIEZOMETER NO.	DATE	DEPTH BELOW LAND SURFACE, IN FEET	SPECIFIC CONDUCTANCE, IN MICROMHOS PER CENTIMETER	CHLORIDE, IN MILLIGRAMS PER LITER	WATER LEVEL BELOW LAND SURFACE, IN FEET	DISTANCE FROM NEAREST CANAL OR LATERAL, IN FEET
North Canal	8-2-79		47,000			
1A	Do.	10.3	8,900	2,800	5.38	10
1B	do	9.7	2,550	680	3.37	50
1C	do	8.1	6,500	1,900	1.14	110
1D	do	9.4	7,300	3,100	6.34	10
1E	do	14.0	9,500	3,700	6.34	10
1F	do	8.8	7,200	2,600	3.24	50
1G	do	32.8	4,900		20.65	10
Central Canal	do		17,000			
2A	do	8.3	2,420	690	3.12	10
2B	do	14.8	1,100	400	12.76	10
Lateral	do		10,000			
3A	do	4.1	8,000	3,000	0.07	10
3B	do	4.1	10,000	3,700	0.21	2
3C	do	4.1	3,750	2,150	4.33	50
North Canal	8-2-79		35,000			
4A	do	7.0	11,000	4,300	3.22	10
4B	do	6.7	6,500	2,550	0.52	50
4C	do	7.0	8,200	3,150	0.0	110
4E	do	10.1	9,000	3,400	3.06	10
4F	do	7.2	9,200	3,100	2.80	50
4G	Do.	24.1	4,000	1,140	5.40	10

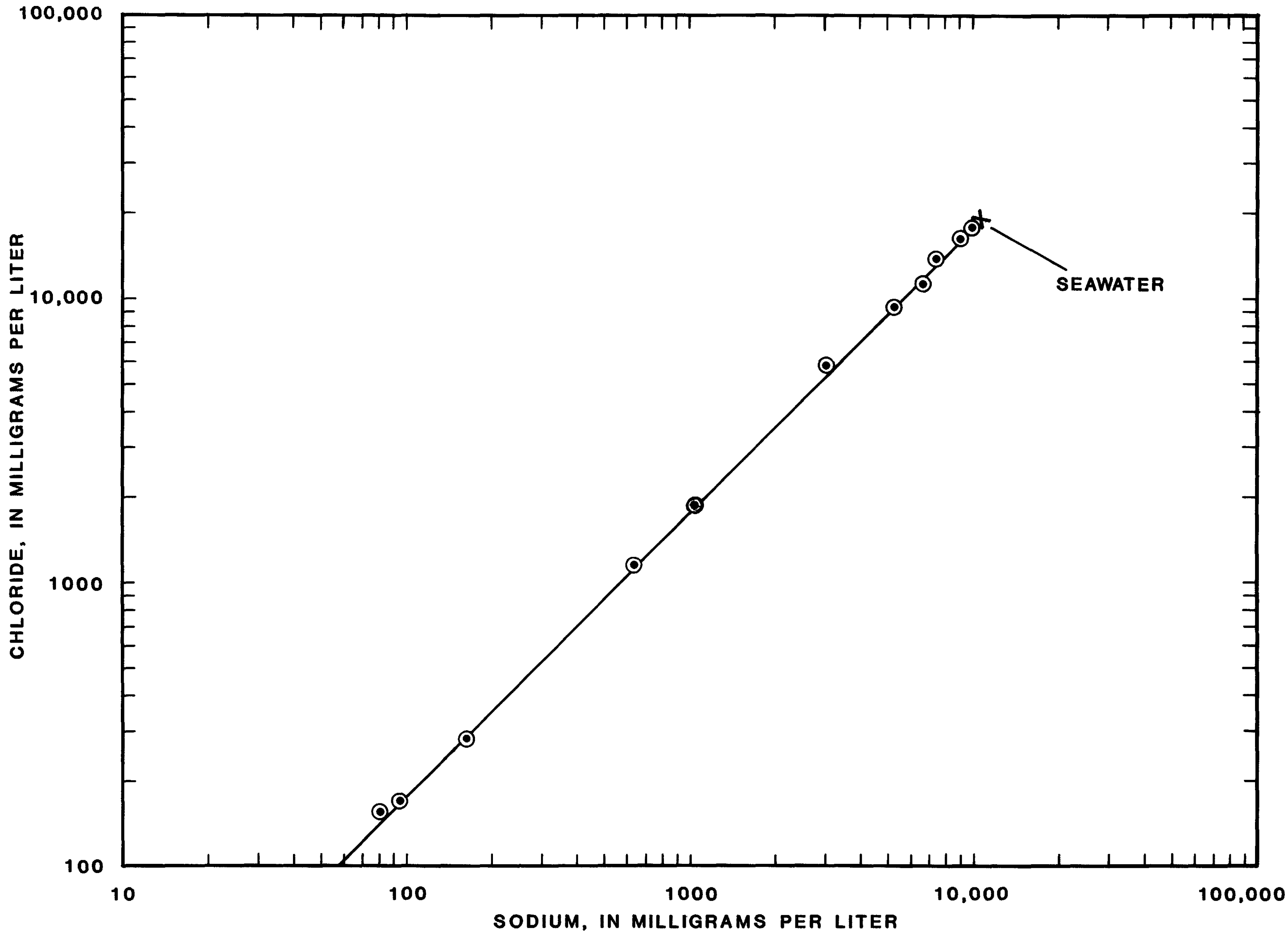

Figure 5.--Relation of sodium to chloride in water from canals and springs in Caño Tiburones.

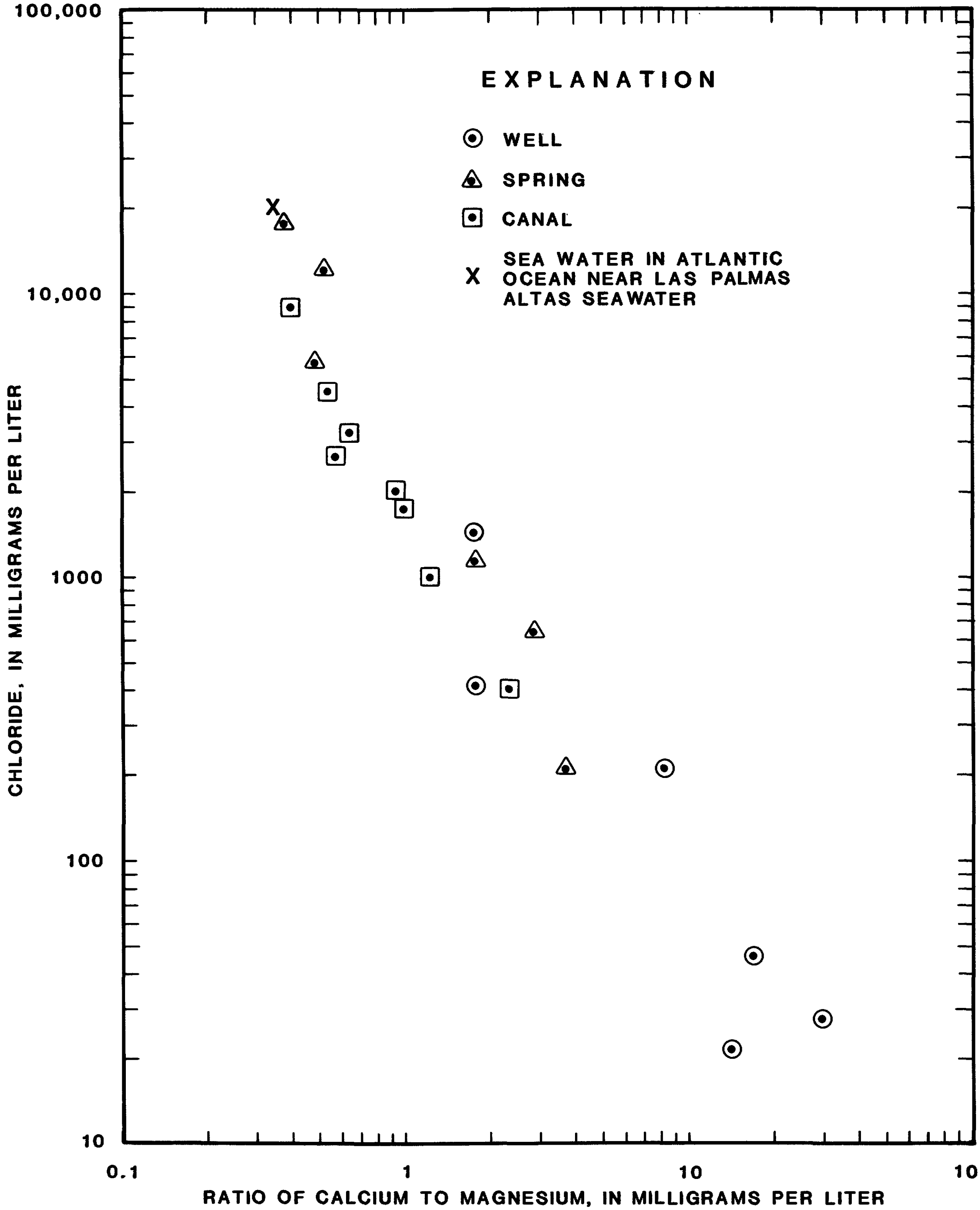

Figure 6.--Relation of chloride and the ratio of calcium to magnesium in water samples from wells, springs, canals, and the ocean, Caño Tiburones area.

seawater slowly percolating through the calcium-rich limestone in the vicinity of Caño Tiburones would, over a very long period of time, reach a solubility-product equilibrium which permits a greater concentration of calcium (and lesser concentration of magnesium) in accordance with the law of mass action and the relative quantities of calcium and magnesium in the limestone.

Accordingly, the geologic and geochemical evidence of the seawater derivation of sodium chloride in the Caño Tiburones precludes the hypothesis that salinity is derived from underlying calcareous rocks. The evidence sustains the theory that all sodium chloride encountered in the Caño is derived from direct hydraulic connection with the ocean for if it were not, the water in the Caño would have a greater concentration of calcium to magnesium and a ratio of sodium to chloride greater than that of seawater.

SEGREGATION OF SALTWATER AND FRESHWATER

Flow measurements and conductivity profiles originally made in the canals and laterals of Caño Tiburones indicated that the concentration of saltwater in the system was related to its nearness to saltwater conduits. However, owing to the flat hydraulic gradient throughout the Caño, flow could proceed in any direction depending only on minute differences in head between points within the canal and lateral system. The general movement of water in the canals was east to west, toward the pumping station at El Vigía. However, on occasions, water was observed to move toward the east in the eastern part of the Canal Central.

The absence of a pattern or consistency of flow permitted free mixing of saltwater and freshwater throughout the Caño (fig. 3--in pocket). In order to force the system to flow in one direction only and at the same time segregate freshwater from saltwater, a program was initiated by the Puerto Rico Department of Agriculture in February 1980 to rehabilitate many of the flow structures in the Caño Tiburones and construct dams at appropriate locations in the canals and laterals.

Two large earthen dams were built across canals: one in Canal Central, just before its western union with the Canal Norte; and one in the Canal Norte at its eastern extent (fig. 7--in pocket). The dams established a new hydraulic gradient from south to north across the canals and laterals. Freshwater from springflow accumulated in Canal Central at the same time water levels in Canal Norte were depressed by pumping at El Vigía.

Dams were also built across laterals to direct the drainage from seawater conduits and springs. Laterals draining seawater conduits were forced to drain northward to Canal Norte by dams which isolated them from Canal Central. In laterals draining freshwater springs, dams were placed at their northern extent to isolate them from Canal Norte. Concurrently, important laterals were cleaned and dredged by dragline, and appropriate culverts were repaired or replaced so a south-to-north or a north-to-south drainage could proceed. The flow system was engineered to distribute fresh springflow to each north-flowing lateral, so that all parts of the Caño flow system would be equally flushed of accumulated salts.

SEGREGATION OF SALTWATER AND FRESHWATER (Continued)

The importance of maintaining an effective hydraulic gradient from south to north and the position of freshwater and seawater inputs to the system required considerable restriction of flow in the western laterals (by constriction) and unimpeded flow of eastern laterals.

After a week or so, equilibrium conditions prevailed in the Caño under the new flow regime (fig. 7--in pocket). Canal Central and laterals draining freshwater springs accumulated and distributed freshwater to laterals hydraulically connected to Canal Norte. Laterals which did not drain springs, were permitted to flow south-to-north, unimpeded by dams. Laterals draining seawater conduits, prevented from flowing south, drained to Canal Norte. Canal Norte served as a sacrificial canal for collected seawater and for drainage from Canal Central.

CONTAINMENT OF SEAWATER ENTERING CAÑO TIBURONES

The principal source of seawater to Caño Tiburones since reversal of the hydraulic gradient has been the constantly flowing seawater conduits, directly connected to the ocean. Until the conduits were plugged, sealed, or otherwise checked, the Caño Tiburones was unable to become any fresher than that obtainable by the dam emplacements alone (fig. 7--in pocket).

Plugging or sealing of the hundreds of seawater conduits was virtually impossible. Assuming that an effective seal could be determined and injected or installed in each conduit, maintenance difficulties would be a recurring problem. In addition, it was not known with certainty if: (1) the hydraulic head in every seawater conduit would approach sea level if it were prevented from flowing and, (2) each conduit was hydraulically independent of the others. Clearly, the plugging of a major seawater conduit would necessarily increase flows in nearby conduits if they were hydraulically connected, particularly if heads were much higher than anticipated.

Several sites were selected to examine the head and hydraulic independence of the conduits. At each site the head and flow of all nearby seawater conduits were measured. A large, centrally located conduit was selected and a dike or ring levee was placed around the conduit and increased in height until the conduit stopped flowing. The new equilibrium water level of the diked conduit increased approximately 2-1/2 feet, or about the elevation of sea level. After equilibrium conditions returned to the flow system, heads and flows of the adjacent conduits were measured again. There was no increase of head or flow observed in the adjacent seawater conduits. Had there been hydraulic connection between conduits, the system would have readjusted its subterranean routing of flow. Hydraulic head of the diked conduit would have been somewhat less than sea level and the head and flow of the nearby conduits would have increased. The hydraulic independence of conduits was observed at all locations tested.

If all seawater conduits maintained a head consistent with that of mean sea level and were hydraulically independent, they could be stopped from flowing by constructing dikes around their periphery. Beginning in July, 1980 a program was begun by the Department of Agriculture to construct earthern dikes around all seawater conduits to a height of approximately 1-1/2 feet above mean sea level. Where draglines could not be supported by the soils or where myriad conduits occurred in a small area, ring levees were placed around entire fields. Approximately 20 individual dikes were built. The dammed seawater quickly reached mean sea level because it was prevented from draining into adjoining laterals or canals. The vast majority of seawater was stopped from leaking into the flow system.

The result of emplacing ring levees around the seawater conduits can be realized by observing the level of salinity now measured in the canal system (fig. 8--in pocket). With seawater blocked from the system, the entire Caño Tiburones becomes progressively fresher with time. Every rainfall replaces more of the residual saltwater in the system. If the dams are maintained and all seawater entrances checked, even Canal Norte can be used as a source of irrigation water when remaining saltwater in canals, laterals, and soils is eventually flushed from the area.

As discussed earlier, sodium chloride adheres tenaciously to the highly organic, impermeable soil. Rainfall is ineffective in washing away the accumulated salts. However, by damming individual fields and applying freshwater, the fields can be planed and furrowed, thereby rewetting the upper foot or so of soil. Subsequently, the water can be brought into contact with more soil surface and more sodium chloride can be liberated to the water. Upon draining, reapplication of freshwater, and further mixing, soils can be flushed of the sodium chloride. It is estimated that for 75 percent of the fields in the Caño, one flushing of the soil will be

CONTAINMENT OF SEAWATER ENTERING CAÑO TIBURONES (Continued)

required to reduce sodium chloride to levels acceptable for most agricultural purposes, including rice cultivation. At the more salty sites, more than one flushing may be necessary.

TESTING EQUILIBRIUM WATER LEVELS BY STOPPING PUMPING AT EL VIGIA

In the past, the stopping of pumping at El Vigía resulted in widespread saltwater flooding in which the height of water in the Caño Tiburones reached sea level. An experiment was performed on April 5, 1982 to measure water-level responses to a pump stoppage with the seawater conduits (and other seawater entrances) blocked. At 9:00 A.M. on April 5, the pumps were turned off for the first time since July 1977 and water-level response was measured for 4 days (fig. 9).

The time rate-of-change of water level rise in the canal at the El Vigía pumphouse decreased logarithmically and approached the freshwater spring head some two feet below sea level. Although some minimal flooding occurred, the test demonstrated that continuous pumping at El Vigía was no longer required to keep water from flooding throughout the valley now that seawater conduits were secured.

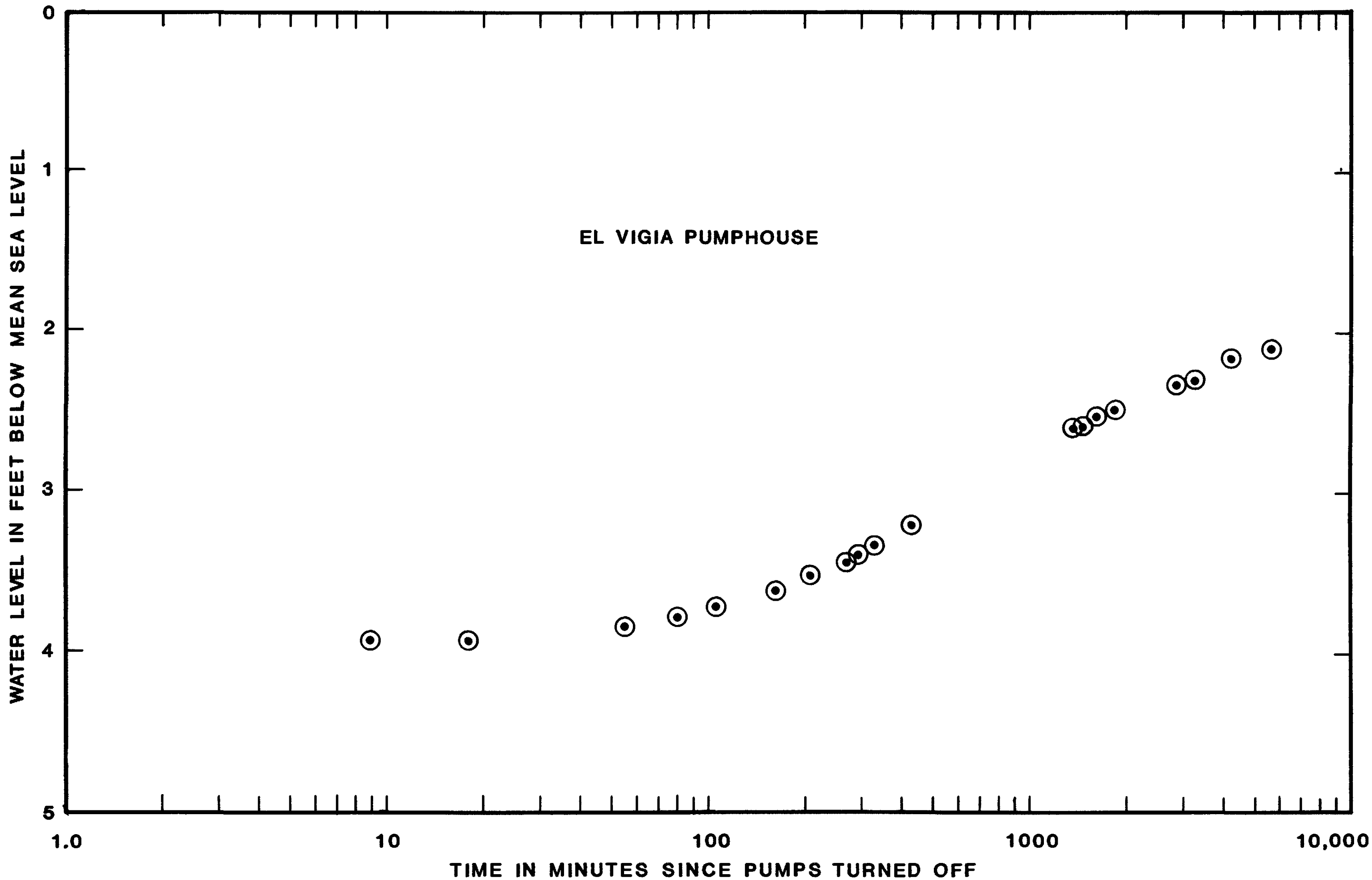

Figure 9.--Water level response to a pump stoppage at El Vigia pumphouse, April 5-9, 1982.

MEASUREMENT OF FRESHENING EFFORTS IN CAÑO TIBURONES

Efforts in improving flow conditions and establishing freshwater within the Caño were continuously monitored by digital, specific-conductance recorders, placed at strategic locations throughout the area (fig. 2--in pocket). The recorders were installed in July 1979 and are still maintained (February 1984). Although there has been some missing record from malfunctions and vandalism, the results are highly informative.

Before rerouting the flow, salinity varied widely throughout the Caño and the amplitude of long-term daily conductivity fluctuations (caused by lower nightime pumping rates) was about 10,000 umhos/cm in Canal Norte. Three stations at sites A, B, and C (fig. 2--in pocket) demonstrate the changes in salinity (fig. 10). Background conductivities at station A, B, and C were 18,000, 44,000, and 17,000 umhos respectively. Rainfall associated with Hurricanes David and Frederick (approximately 10 inches in 7 days) freshened the Caño for several days in early September 1979. After the rain stopped, seawater flow from the conduits replaced the freshwater and the salinity returned to its previous high levels in about 6 days.

Soon after the dams were constructed, the dramatic effects of freshening solely by fresh springflow throughout the Caño were observable (fig. 10). Water consistently moved in one direction; ponding of saltwater in the canals and laterals was avoided and smaller fluctuations of specific conductance recorded. Water from rainfall also lingered in both Canal Central and south-flowing laterals twice as long as before the dams were built, causing the freshening effects of rainfall to last much longer.

After the seawater springs were contained, the salinity in the canal system improved greatly (fig. 10), and continues to improve with the contribution of freshwater from springs and with the additional emphasis from each rainfall. In May 1982 the eastern dam in Canal Norte was moved to Canal Central because of sewage discharges from a sewage-treatment plant at Barceloneta. This further improved conditions in Canal Central. Amplitudes have been significantly reduced and the freshening effects of rainfall are even more long-lasting.

The fraction of seawater (based on conductivity measurements) in the entire canal and lateral system of Caño Tiburones during periods of dry weather in 1979 was 34 percent. As of August 1982, the amount of seawater has declined to 15 percent and this percentage is now decreasing daily. The Canal Central contains one eighth the seawater it contained in 1979. Today water from Canal Central and north-flowing laterals can be used for irrigation. With time and maintenance of the dams and canals, Canal Norte also will become much fresher. Some water with a higher specific conductance lingers in low, stagnant reaches of the canal system. Laterals which transmit water from south to north are not as deep as the canals; therefore, complete flushing of Canal Central by freshwater springflow and rainwater is impeded.

A small quantity of seawater drains into Canal Central just before El Vigía and is responsible for the elevated levels of specific conductance observable in figure 10 for the pumphouse monitor. It appears to be important only when high water levels are maintained in the Caño.

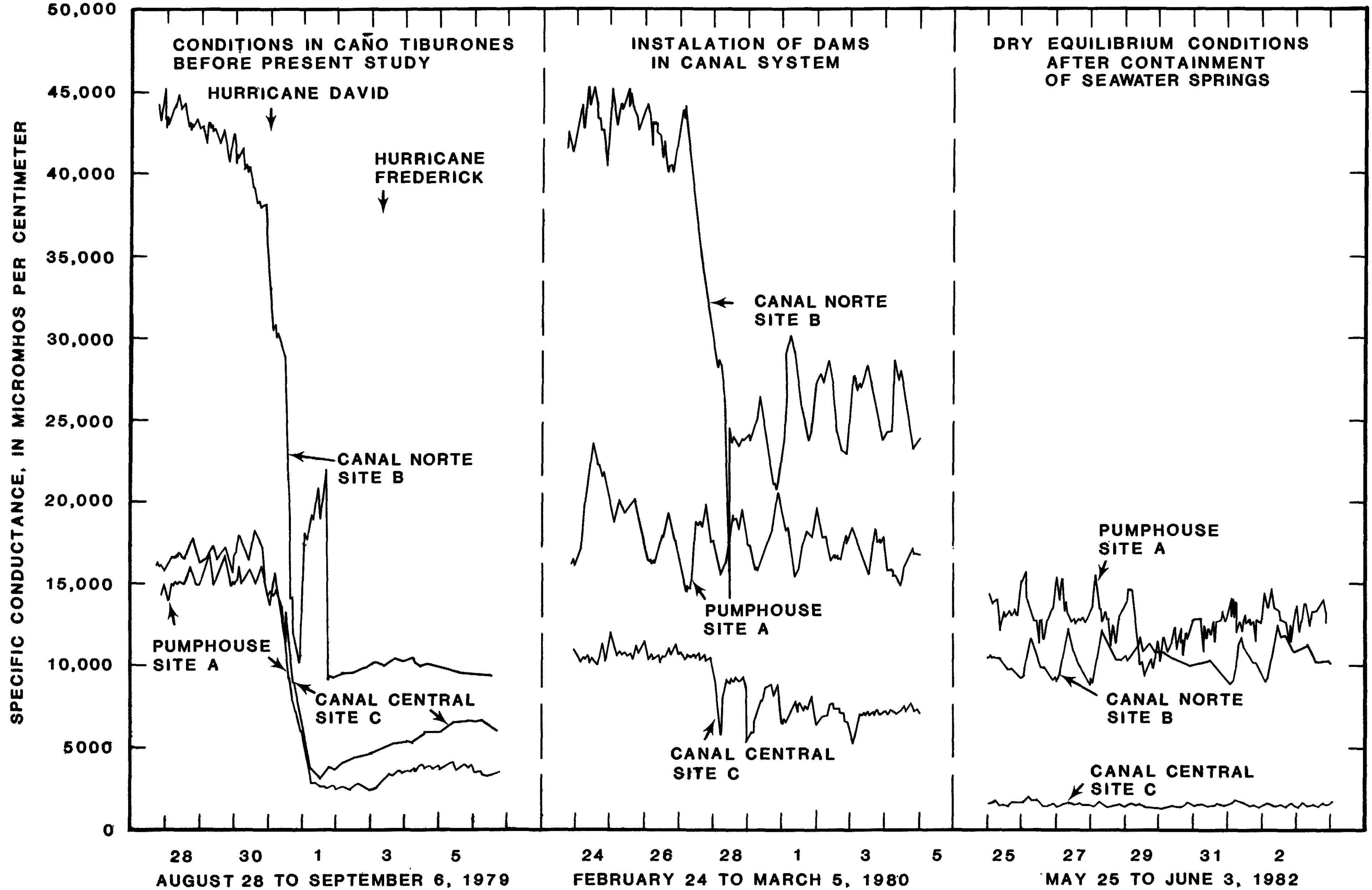

Figure 10.--Specific conductance of water at three sites in Caño Tiburones showing improvement in freshening due to reorganization of flow and containment of seawater springs.

CONCLUSIONS

There are three major findings of the Caño Tiburones freshwater-restoration project:

1) Ground-water discharge is not the cause of salty conditions in Caño Tiburones. A test-drilling program verified that ground water in the vicinity of the Caño was much fresher than surface water. In addition, the low hydraulic conductivity of blanket sands and swamp deposits prevents significant upward or downward percolation.

2) Seawater entering the Caño through subterranean conduits is the source of salinity in the canals and laterals. This was determined by conductivity profiles and by chemical analysis. Relations of sodium to chloride and calcium-magnesium ratios of Caño water verify its derivation from seawater.

3) Salinity of organic soils is attributed to (a) infiltration and capillary action by saltwater from adjacent canals and laterals and, (b) flooding of the land surface by saltwater where pumping at El Vigía was stopped. In each case subsequent evapotranspiration concentrates the salinity.

The soils of Caño Tiburones are no longer accumulating sodium chloride. The surface-water system, now much fresher, aids the flushing of residual salinity in the Caño flow system. Flushing of soil will necessarily proceed slowly and will leach large quantities of sodium chloride to the canal and lateral system for some time. As soils become fresher, the salinity of the water in the Canal Norte will lessen.

Soil flushing and irrigation of the Caño Tiburones can be expedited by using water from other sources such as Río Grande de Arecibo. Canal Sur as well as the Canal Central are ideal reservoirs and distribution system for this water.

Excess irrigation water can be lifted to nearby dammed seawater conduits instead of being discharged to Canal Norte. The conduits, in their ability to maintain a head of mean sea level, can accept relatively large quantities of water ultimately to be discharged to the ocean. This procedure would keep canal discharges low, permitting less pumping at El Vigía. Conceivably, the pumps at El Vigía would only be used to evacuate floodwater from inordinate rainfalls and the periodic excesses of intense rice irrigation.

Dams placed at appropriate locations on canals and laterals have been used to segregate freshwater from seawater in Caño Tiburones by creating differences in hydraulic head. Ring levees prevent seawater from entering the flow system. These efforts have succeeded in reducing seawater in Canal Central and north-flowing laterals to one-eighth of their original concentration or approximately 1,800 micromhos per centimeter. At this level of specific conductance, the water can be used for most agricultural purposes. With proper maintenance of dams and levees, restoration of freshwater can be maintained.

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