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HYDROLOGIC CHARACTERISTICS OF LAGOONS AT SAN JUAN, PUERTO RICO, DURING AN OCTOBER 1974 TIDAL CYCLE

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS
OPEN-FILE REPORT 82-349

Prepared in cooperation with:
PUERTO RICO ENVIRONMENTAL QUALITY BOARD AND
PUERTO RICO DEPARTMENT OF NATURAL RESOURCES

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1983

UNITED STATES DEPARTMENT OF THE INTERIOR

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

The metric System of measurements (SI or International System) is used in this report. The following factors may be applied for conversion of metric values to inch-pound units:

Multiply SI units	By	To obtain inch-pound units
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.621	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.386	square mile (mi^2)
hectare (ha)	2.47	acre
	Volume	
cubic centimeter (cm^3)	0.061	cubic inch (in^3)
liter (L)	1.06	quart (qt)
cubic meter (m^3)	35.32	cubic foot (ft^3)
cubic hectometer (hm^3)	810.7	acre foot (acre-ft)
	Weight	
gram (g)	0.035	ounce, ovoirdupois (oz avdp)
kilogram (kg)	2.203	pound, avoirdupois (la avdp)
	Temperature	
degree Celsius (°C)	((1.8x°C)+32)	degree Fahrenheit (°F)
	Specific Combinations	
cubic meter per second (m^3/s)	35.3	cubic foot per second (ft^3/s)

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ABSTRACT

Flow and water-quality changes were studied during a period of intense rainfall in the San Juan Lagoon system. The study covered a 25-hour period beginning 0900 hours 22 October, 1974. Precipitation during the study period averaged 70 millimeters. Sampling stations were located at Boca de Cangrejos, the main ocean outlet; Canal Piñones between Laguna de Piñones and Laguna La Torrecilla; Canal Suárez between Laguna San José connects to Laguna La Torrecilla; and Caño de Martín Peña between Laguna San José and Bahía de San Juan. In addition water-elevation recording gages were installed at each lagoon.

Water samples from the canal stations were analyzed for organic carbon, nitrogen and phosphorus species, and suspended sediment. Specific-conductance measurements were used with the chemical data to estimate the runoff contributions of nutrients.

Runoff into the lagoons system during the study period was about 2.8 million cubic meters, or about 70 percent of the average precipitation. The runoff contributed chemical loadings to the lagoons of 95,000 kilograms total-organic carbon; 2,700 kilograms of total phosphorus; and 10,000 kilograms of total Khjeldhal nitrogen. A comparison with a prior study during which there was no significant rain, show that dry-period loadings are less than 10 percent of the wet-period loadings. At the end of the study period the system had not reached equilibrium, and the lagoons retained 80 percent of the water inflows from 50 to 90 percent of the chemical loads. Nearly 95 percent of the water outflows occurred at the Boca de Cangrejos sea outlet. The three lagoons and interconnecting canals form a very complex hydraulic system that is difficult to study using traditional techniques. A model of the system will facilitate management to improve the quality of water in the lagoons.

INTRODUCTION

The San Juan, Puerto Rico, metropolitan area includes several lagoons and interconnecting canals. The Laguna San José, Laguna La Torrecilla, and Laguna de Piñones (fig. 1) constitute an important natural resource and an integral element to the largest mangrove forest on the Island. The lagoons and tidal canals have been altered significantly within the last 25 years by extensive dredging, filling, and discharging of domestic and industrial effluents. The potential development of the lagoons for recreation has been hindered by the poor quality of the waters, obnoxious odors, and frequent fish kills.

The U.S. Geological Survey, Water Resources Division, began an investigation in July 1973 to define the hydraulic, chemical, biological and bacteriological characteristics of the lagoon system. The study was conducted in cooperation with the Puerto Rico Environmental Quality Board and the Puerto Rico Department of Natural Resources.

Results of the investigation describing the hydrologic and hydraulic characteristics of the lagoons have been published previously (Ellis, 1976; Ellis and Gómez-Gómez, 1976). The report by Ellis and Gómez-Gómez describes the hydrologic response of the lagoons to a tidal cycle in January, when rainfall was minimal.

This report summarizes the lagoon's response to an intense storm in October 1974. Changes in water flows, chemical constituents, and suspended-sediment were documented during the event. This information, as well as the previously published reports, provides valuable data to assist in the development of alternatives for improving the quality of the water in the lagoons.

Purpose and Scope

The principal objectives of the October 1974 study were:

1. To define the flow characteristics at tidal canal outlets to the lagoon complex during an intense storm.

2. To determine the amount and effects of excessive storm runoff on the water-quality characteristics at Boca de Cangrejos, Canal Piñones, Canal Suárez, and Caño de Martín Peña, principal outlets to the lagoons.

3. To estimate the contribution of nitrogen, phosphorous and carbon from storm runoff to the lagoons.

The data were collected from sampling stations established at each of the tidal canals (fig. 1). Flow and stage were measured, and samples collected hourly at each site during a 25-hour period (one tidal cycle) beginning at 1000 hours October 22, 1974, through 1100 hours, October 23, 1974.

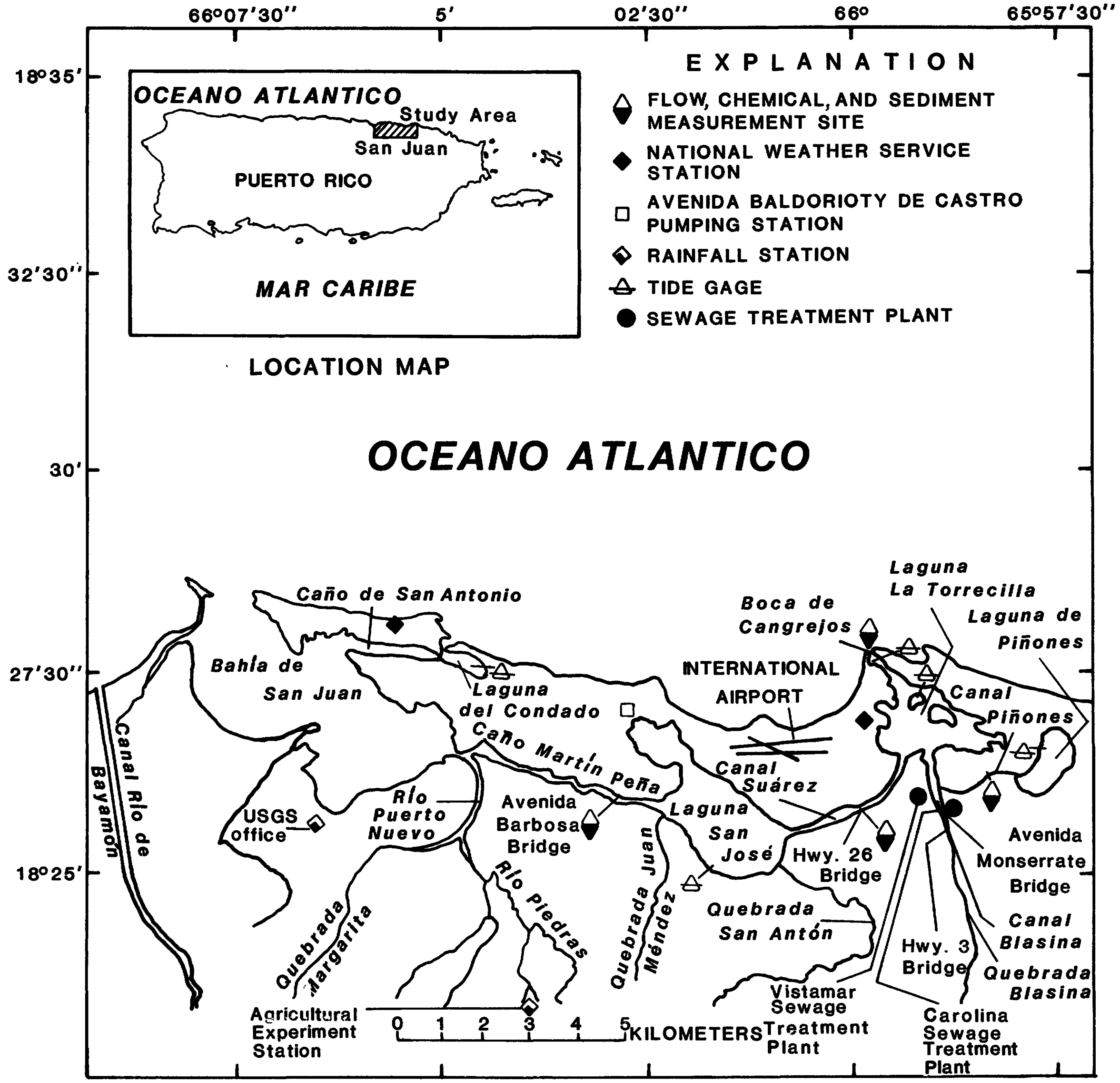


Figure 1.--General features of San Juan Lagoons project area.

Flow measurements were made at each site hourly during the tidal cycle. Procedures described by Buchanan and Sommers (1969) were used. Stages were recorded from staff gages installed at each site and referenced to local datums.

Water samples for chemical and suspended-sediment analyses were collected with point samplers in accordance with procedures described by Brown and others (1970) and Guy (1969). Samples were integrated vertically and horizontally.

Analyses of the water samples included field determinations of specific conductance and temperature. Laboratory analyses were performed at the U.S. Geological Survey Central Laboratory in Doraville, Georgia, and included determinations of total and dissolved species of phosphorus, nitrogen, and organic carbon. Suspended-sediment samples were collected only at Boca de Cangrejos, Canal Piñones, and Canal Suárez, and analyzed at the U.S. Geological Survey field laboratory in Puerto Rico.

The storm-runoff contributions to each lagoon were computed from changes in water-surface elevations and the flow measurements at each canal or outlet. Loads of total organic carbon, total phosphorus, and total Kjeldahl nitrogen (nitrogen available in organic matter and as ammonia) were computed similarly.

Precipitation data were obtained from a network of stations operated by the National Weather Service and supplemented by data from the U.S. Geological Survey. Runoff and direct contribution of rainfall to the lagoons were computed from average precipitation loads and surface areas of the lagoons or drainage basins.

The techniques used to compute the flow of water at the outlet sites and to compute the chemical loads are described by Ellis and Gómez-Gómez (1976). The data collected during this study are published in "Water Quality and Hydraulic Data San Juan Lagoons System, Puerto Rico, by S.R. Ellis and Fernando Gómez-Gómez, 1975".

PHYSICAL CHARACTERISTICS OF THE SAN JUAN LAGOONS SYSTEM

The San Juan Lagoons System

The San Juan Lagoons system includes Laguna San José, Laguna La Torrecilla, and Laguna de Piñones (fig. 1). The lagoons are hydraulically connected by a system of natural and man-made canals. Laguna San José, the largest of the three, is connected to Bahía de San Juan by way of Caño de Martín Peña. Two main creeks (Quebrada Juan Méndez and Quebrada San Antón) flow directly into Laguna San José. Canal Suárez connects Laguna San José to Laguna la Torrecilla which is located east of the Isla Verde International Airport. Laguna la Torrecilla is perhaps the most complex of the three lagoons, since it is also connected to the Océano Atlántico at the Boca de Cangrejos outlet and to Laguna de Piñones through Canal Piñones. It also receives the flow of Quebrada Blasina, a creek flowing from the southeast end of the study area. The creek has been dredged and becomes Canal Blasina north of Highway 3. Canal Blasina provides the actual connection of Laguna de Piñones with Laguna la Torrecilla by way of Canal Piñones. Laguna de Piñones, the smallest of the three, is surrounded by Bosque Estatal de Piñones, the largest mangrove forest in Puerto Rico. Canal Piñones is the lagoon's only outlet.

The tidal and hydraulic characteristics of the San Juan lagoons have been described by Ellis and Gómez-Gómez (1976). Tide records during periods unaffected by runoff were as follows: at Laguna San José a maximum daily amplitude of 0.15 meter (m); at

Laguna La Torrecilla, much closer to the system's principal ocean outlet, Boca de Cangrejos, maximum daily tidal amplitude of 0.6 m; at Laguna de Piñones a maximum daily amplitude of 0.26 m. Approximate boundaries of the basins draining into the San Juan Lagoons are shown in figure 2.

Laguna San José

Laguna San José, the largest lagoon, has a surface area of 547 ha (fig. 3). It has an average volume of 13.2 hm^3 and an average depth of 2.4 m. About 90 percent of the watershed area of the lagoon is urbanized. Mangrove stands border the north and east perimeters.

Laguna San José has been dredged locally to depths ranging from 5 to 11 m. About 17 percent of the entire lagoon area has been dredged below the natural maximum depth of 2.5 m (Ellis, 1976).

Most of the freshwater that flows into Laguna San José is urban runoff. Quebrada San Antón and Quebrada Juan Méndez (fig. 3) with a combined drainage area of 22 km^2, provide most of the runoff to the lagoon. Additional runoff from an area of about 2 km^2 flows into the lagoon from a combined sewage-storm-drain system at the Baldorioty de Castro Avenue pump station. Several unnammed tributaries and culverts add about 15 km^2 to the drainage area. The limestone aquifer which underlies the San Juan area may be discharging up to 18,000 m^3 per linear kilometer per day along a fresh- salt-water zone (Anderson, 1975). This source may contribute as much as 50,000 m^3/d of freshwater to the lagoon.

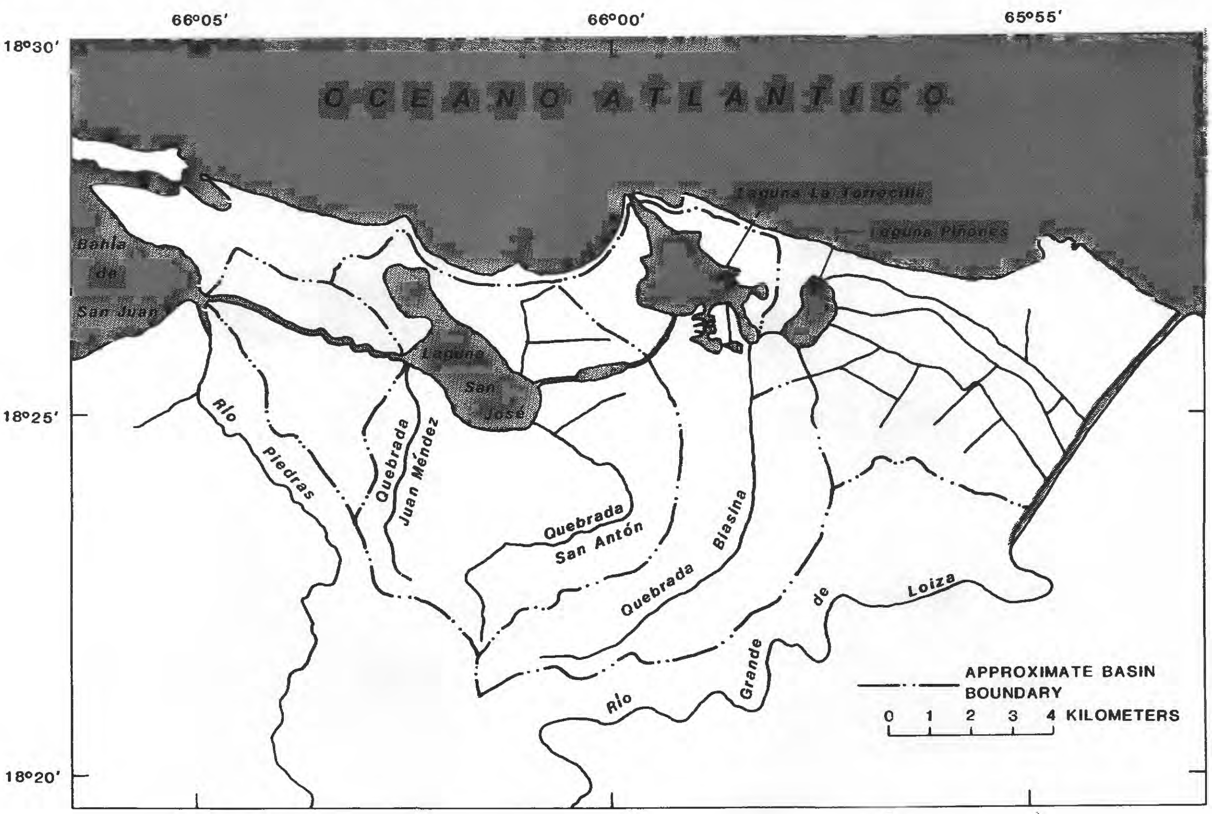


Figure 2.--Drainage basins of San Juan Lagoons.

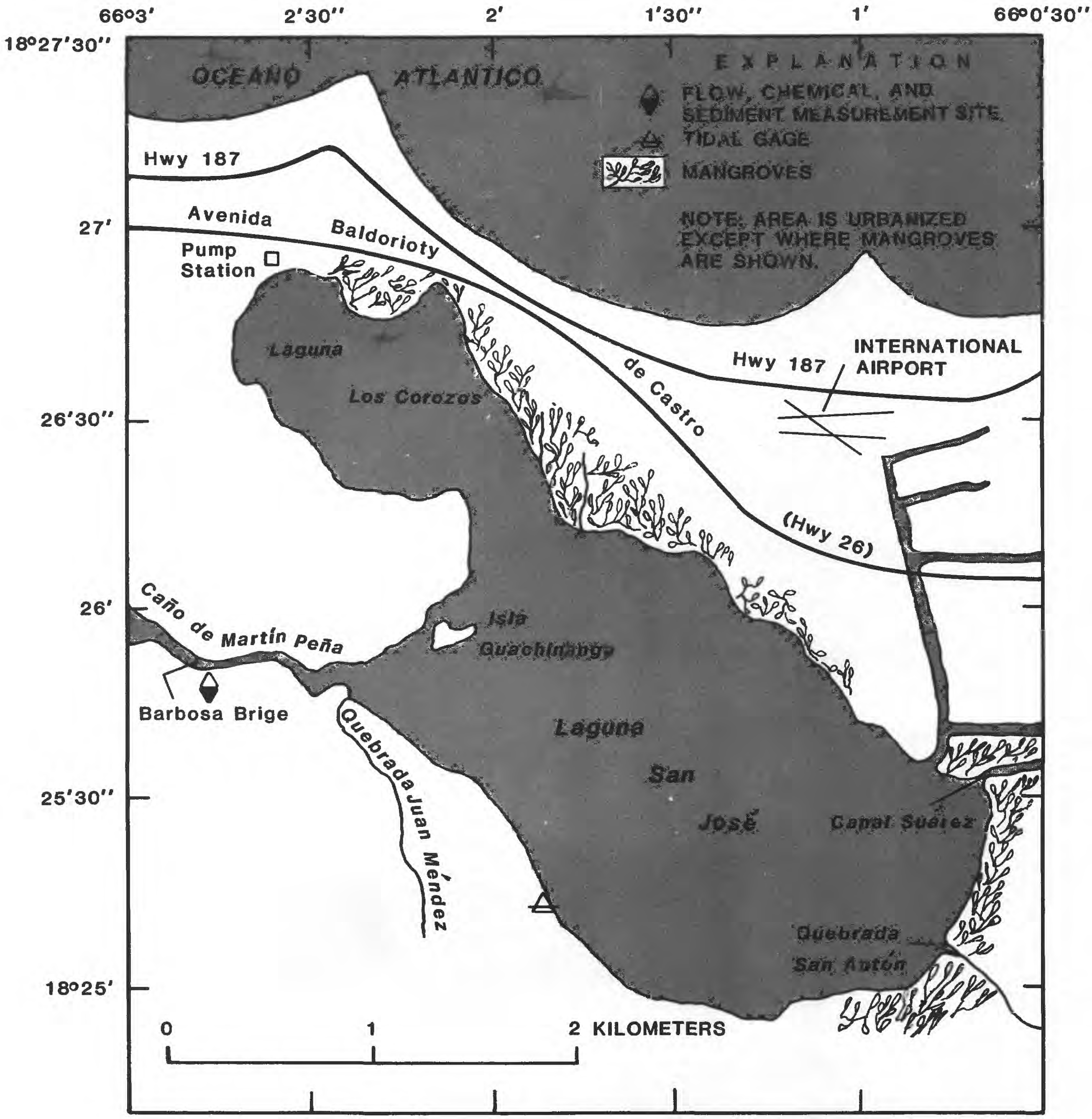


Figure 3.--General features of Laguna San José.

Brackish water flows into Laguna San José through Canal Suárez and Caño de Martín Peña. Canal Suárez connects Laguna San José to Laguna La Torrecilla, where brackish water results from the inflow of sea water at the Boca de Cangrejos outlet. The canal, about 3.3 km long, 2 to 7 m deep, and 5 to 50 m wide, is an unimproved man-made channel bordered by mangroves. Caño de Martín Peña, which connects Laguna San José to Bahía de San Juan, meanders through several densely populated areas, receiving significant amounts of domestic-waste discharges and urban runoff. The Caño has an average depth of 1 m, is 10 to 30 m in width, and is 5.1 km in length. At many places it is clogged with debris.

Ellis and Gómez-Gómez (1975) report that the annual average specific conductance at Laguna San José is about 20,000 micromhos per centimeter (umhos/cm) in areas less than 2.5 m deep. In areas dredged below 2.5 m depth, the specific conductance averages 40,000 umhos/cm.

Laguna La Torrecilla

Laguna La Torrecilla has a surface area of about 246 ha and an average depth of about 2.4 m. The lagoon is connected on the north to the ocean by way of Boca de Cangrejos, a natural opening to the sea (fig. 4).

The lagoon's principal freshwater source is Canal Blasina (Quebrada Blasina). The canal, which drains a mostly urban area of about 22 km^2, is affected by tides as far inland as Avenida Monserrate Bridge (fig. 1). Canal Blasina is heavily polluted with sewage discharges from the Carolina and Vistamar sewage-treatment plants.

The combined discharges from these plants into the canal average about 10,000 m^3/d. Additional sewage flows are discharged into the headwaters of the stream upstream from the study area. Flow from the headwaters, during low flow conditions, is about 10,000 m^3/d thus average discharge to the lagoon is about 20,000 m^3/d. Ground-water flow into the lagoon is negligible since the lagoon is seaward of the underlying aquifer's fresh-salt water interface.

Dredging in Laguna La Torrecilla has been more extensive than at any of the other two lagoons. Ellis (1976) estimated that the volume of the lagoon has been increased about 2.8 times by dredging. Seawater flowing through Boca de Cangrejos accumulates in the dredged areas. The salinity of the water in Laguna La Torrecilla can be as much as 90 percent that of seawater, with extreme variations in the water column and with time. The annual average specific conductance for depths less than 1 m is about 45,000 umhos/cm. At depths greater than 3 m the specific conductance is equal to that of sea water--50,000 umhos/cm.

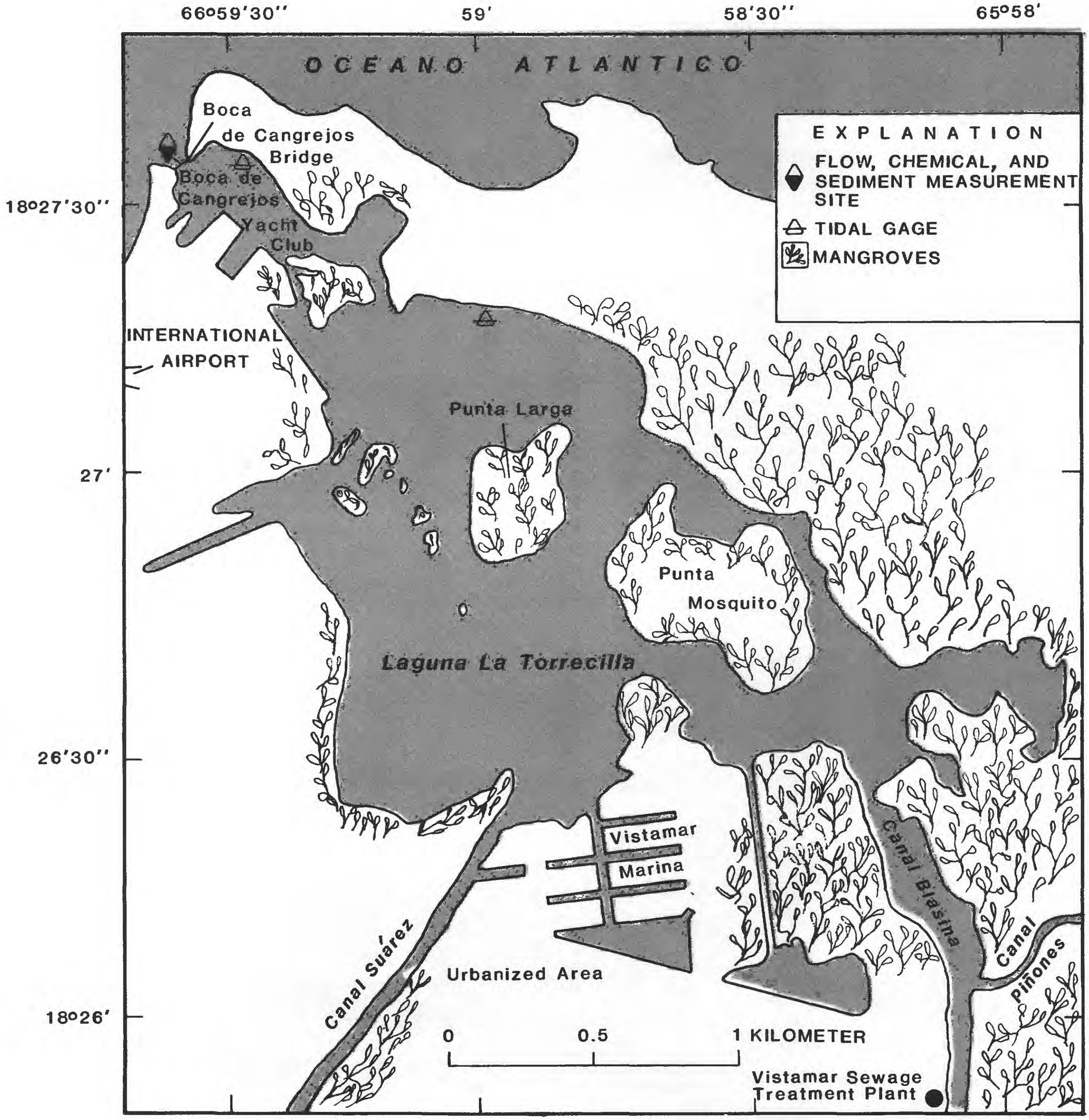


Figure 4.--General features of Laguna La Torrecilla.

Laguna de Piñones

Laguna de Piñones, the smallest of the lagoons, has a surface area of 105 ha, an average volume of 0.87 hm^3, and an average depth of 0.8 m (fig. 5). The lagoon is surrounded by the Bosque Estatal de Piñones, a mangrove forest. The forest is bisected by a network of man-made drainage canals (fig. 2). The lagoon is connected to Canal Blasina and Laguna La Torrecilla by Canal Piñones. During extreme floods the lagoon, mangrove swamp and canal receive flow from the Río Grande de Loíza (Haire, 1975). The total area draining to the lagoon is indeterminate as a result of the complex canal system in the mangrove forest.

Brackish-water flows into Laguna de Piñones from the eastern end of Laguna La Torrecilla through Canal Piñones. Ellis (1976), documented the density, tidal, and canal configuration features that induce the flow of brackish water into the lagoon. Prior to the start of the present study, Laguna de Piñones had a stable specific conductance of about 43,000 umhos/cm.

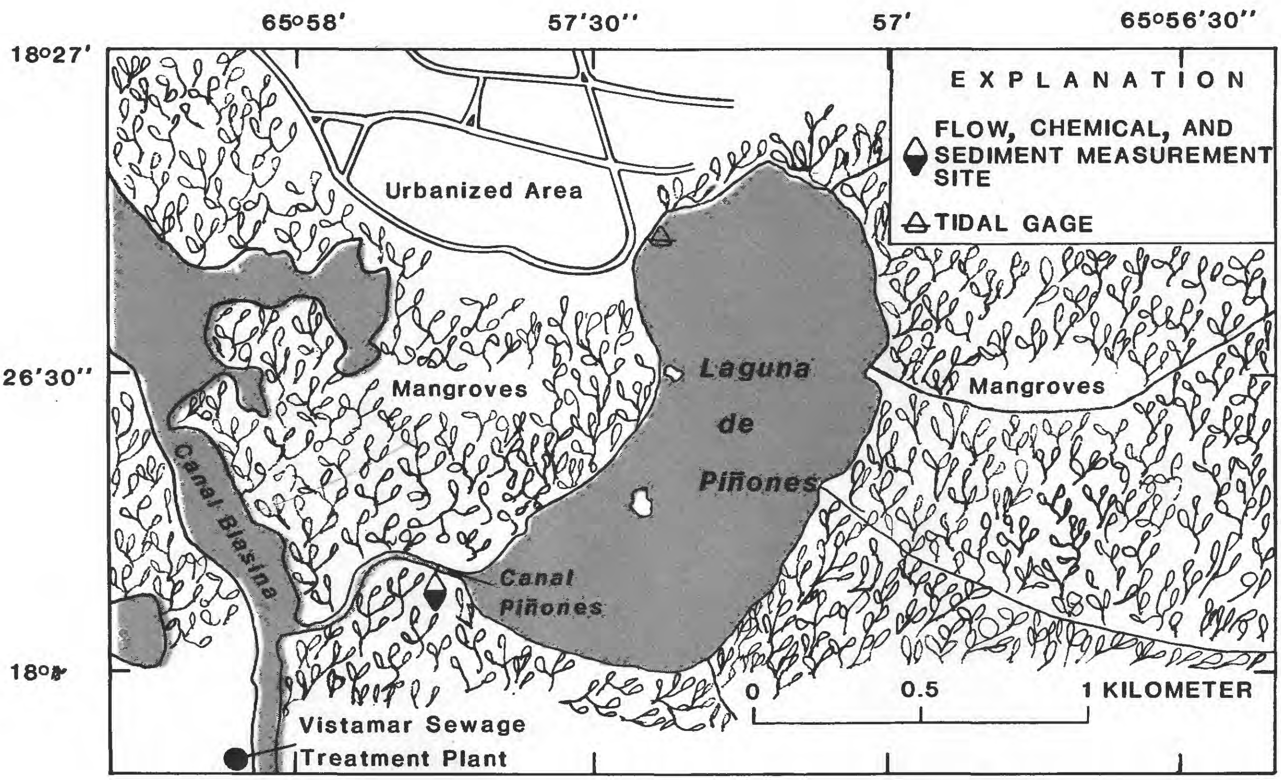


Figure 5.--General features of Laguna de Piñones.

STORM CHARACTERISTICS

Precipitation

Precipitation from the storm of October 22 to 23, 1974 in the San Juan metropolitan area ranged from about 60 millimeters (mm) at the National Weather Service (NWS) station at the International Airport, to 120 mm at the U.S. Geological Survey office near Cataño. About 60 percent of the precipitation was recorded between 0100 and 0800 hours October 23, 1974, near the end of the study period. For the most intense 12-hour period of the storm, the recurrence interval was 1.0 year (U.S. Department of Commerce, 1961).

The total amount of precipitation recorded at the Isla Verde International Airport station during the tidal cycle (1000 October 22 to 1100 October 23) was assumed to be representative of the rainfall directly over the lagoons. This was 39 mm as indicated by the NWS records.

The precipitations over other areas in the basin was computed from the data obtained at the other stations. An average of 70 mm of rain was estimated to have fallen throughout the basin south of the lagoons.

Stage Changes

The inflows to the lagoons of storm runoff resulted in higher water-surface elevations at the end of the tidal cycle. Water-surface fluctuations during the tidal cycle at each lagoon and at the inland side of the Boca de Cangrejos bridge (sea outlet of Laguna La Torrecilla) are shown in figure 6. The fluctuations are referenced to an arbitrary datum to provide net changes in stage. The moment (s) of zero flow at tidal canals, previous to runoff effects, was used in establishing the datum. The tidal cycle at Laguna del Condado (fig. 1) was assumed to be representative of the conditions at the coast.

Laguna La Torrecilla had a maximum stage amplitude of 0.25 m, equal to the amplitude observed at the Boca de Cangrejos outlet. A net gain of 0.127 m was recorded in the stage at Laguna La Torrecilla during the study period.

Laguna de Piñones showed an overall gain in stage of 0.153 m, most of which occurred during the early hours of October 23. The dampening effects of Canal Piñones in the amplitude of the tide fluctuation, as well as the time lag (2 hours) with the tide at Laguna La Torrecilla, are evident.

The most significant change in stage in the lagoons was recorded at Laguna San José, with a net change of about 0.312 m during the tidal cycle. The size of the lagoon, with its larger contributing drainage area, and constricted outlets contributed to the significant increase in stage.

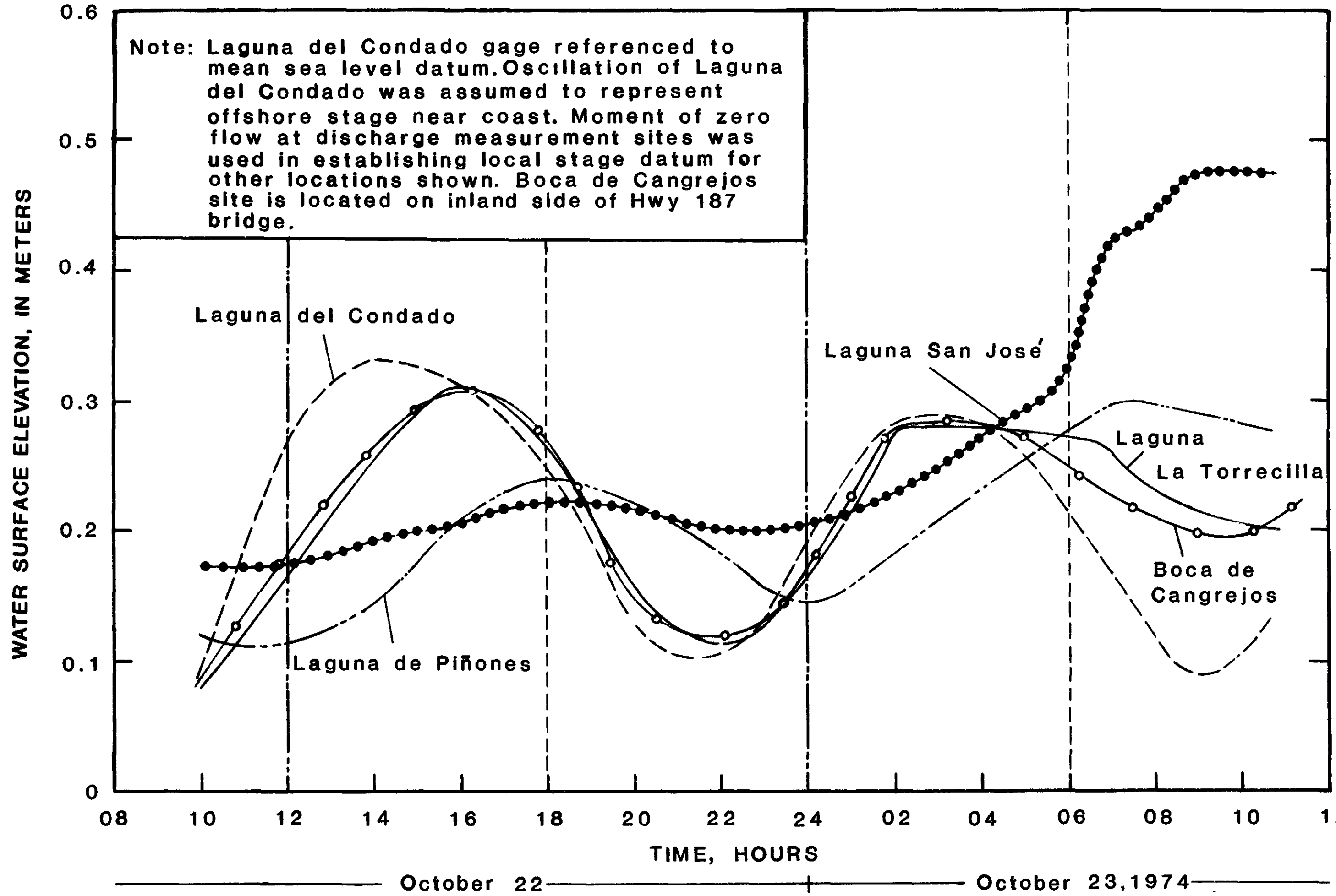


Figure 6.--Water-surface fluctuations at Laguna del Condado, Boca de Cangrejos, Laguna San José, Laguna La Torrecilla, and Laguna de Piñones.

FLOW CHARACTERISTICS AND MAGNITUDE

The effects of storm runoff on the lagoon system during periods of either normal or intense precipitation can be determined only by simultaneous flow and stage measurements at the inlets and outlets that feed or drain the lagoons. Flow and stage determinations at the selected stations (fig. 1), are complicated by changes in direction of flow with changes in tide or outflow from a particular lagoon.

The termination of the study at the end of the tidal cycle prevented an assessment of the overall effects of the storm in the flow characteristics at the measured sites. At the end of the study, stages and flows were still actively changing, and most of the accumulated runoff was still stored in the lagoons. However, the data collected can be used to estimate or model the hydrologic behavior of the lagoon system over the entire storm-response cycle.

Boca de Cangrejos Outlet

The flow direction at Boca de Cangrejos outlet followed the tidal fluctuations (fig. 7). The proximity of the ocean was reflected in the domination of flow direction by the tide. A significant increase in the flow toward the ocean occurred during the second ebbtide. Integration of the hourly measurements indicate that 1.5 hm^3 entered Laguna La Torrecilla from the floodtides and 2.9 hm^3 left the lagoon by way of Boca de Cangrejos from the combined effects of the ebbtide and storm runoff.

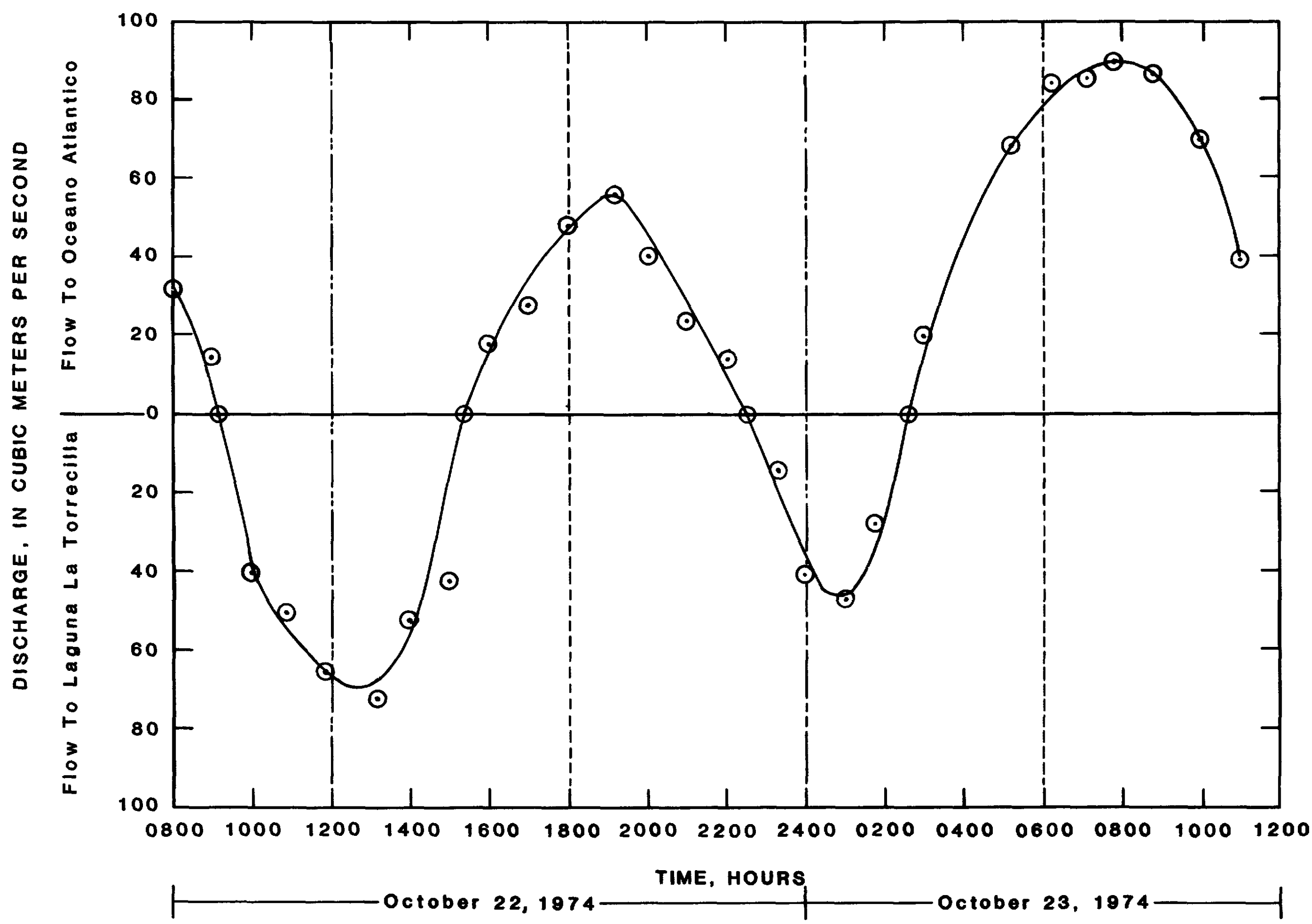


Figure 7.--Flow pattern at Boca de Cangrejos.

Canal Piñones

The flow measurements at Canal Piñones showed that the water movement also followed the tide patterns (fig. 8). During the tidal cycle, about 0.21 hm^3 of water flowed into Laguna de Piñones, while 0.15 hm^3 discharged through Canal Piñones. The water flowing into Laguna de Piñones in addition to rainfall runoff, may have been from either Canal Blasina or Laguna La Torrecilla. The combination of the amount of runoff in Canal Blasina, and the head of water in Laguna La Torrecilla, determines the source of the inflows to Laguna de Piñones. Differences in the chemical characteristics in the waters from the two sources may be used to determine which was the main flow contributor to Laguna de Piñones. This is explained in the section on water-quality characteristics.

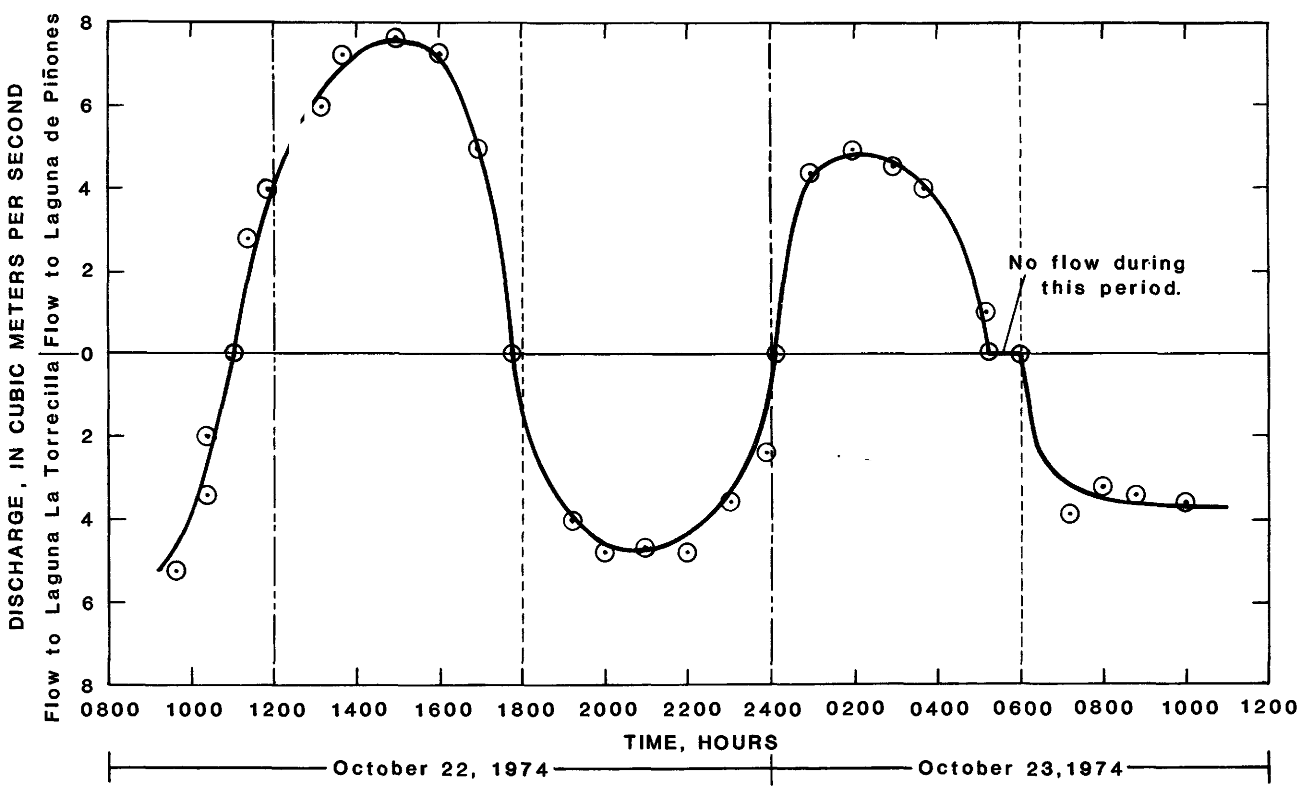


Figure 8.--Flow pattern at Canal Piñones.

Canal Suárez at Highway 26 Bridge

The measuring site at Canal Suárez was located at the Highway 26 (old) bridge. Staff gages were placed on both abutments of the bridge and stage readings were made concurrent with each flow measurement as the flow at the site is constricted by the bridge. This is evident from water-surface elevations that drop in the direction of the flow (fig. 9). The site is tidal affected with fluctuations during dry weather conditions from about 0.05 m on the Laguna San José side to 0.16 m on the Laguna La Torrecilla side.

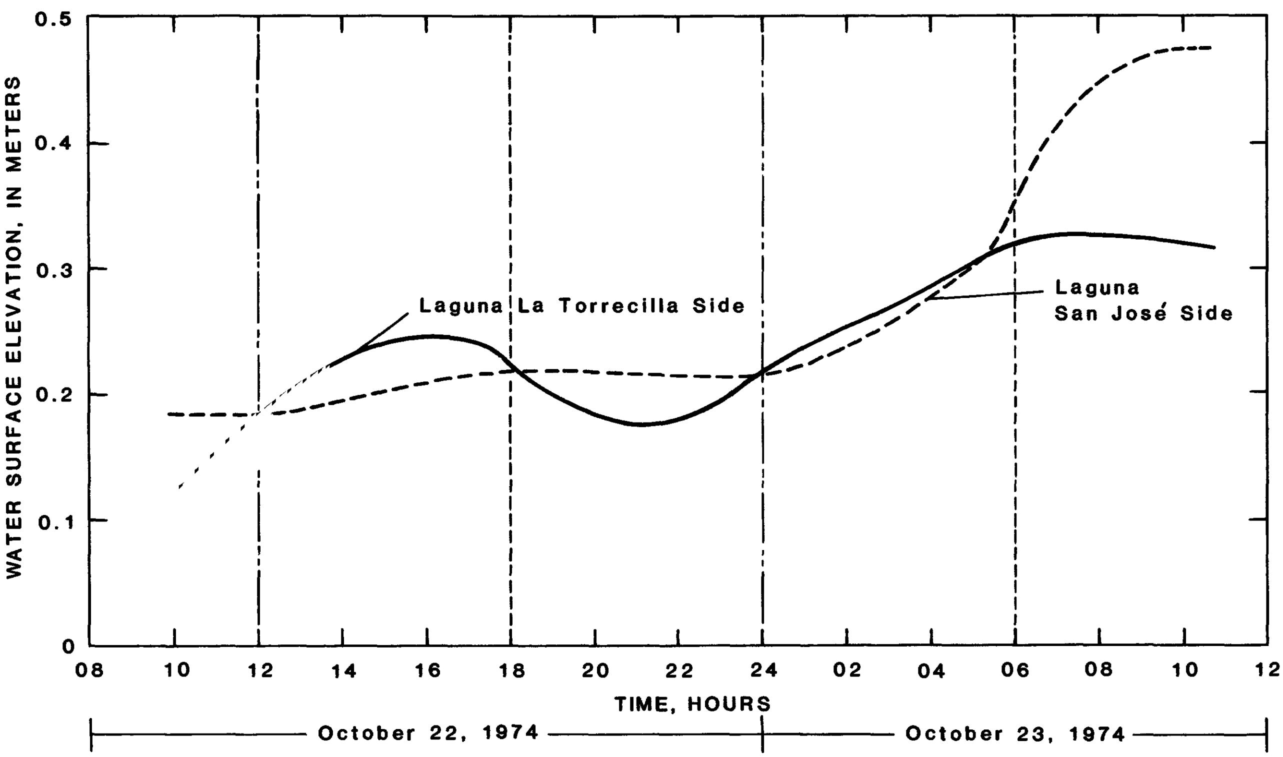


Figure 9.--Water-surface fluctuations at upstream and downstream sides of Hwy. 26 bridge at Canal Suárez. (Arbitrary datum, same as that of figure 6.)

Integration of the flow-rate curve at the Canal Suárez site (fig. 10) showed that 0.27 hm^3 entered Laguna San José from Canal Suárez during the floodtides, while 0.43 hm^3 were discharged from the combined ebbtide and storm runoff effects.

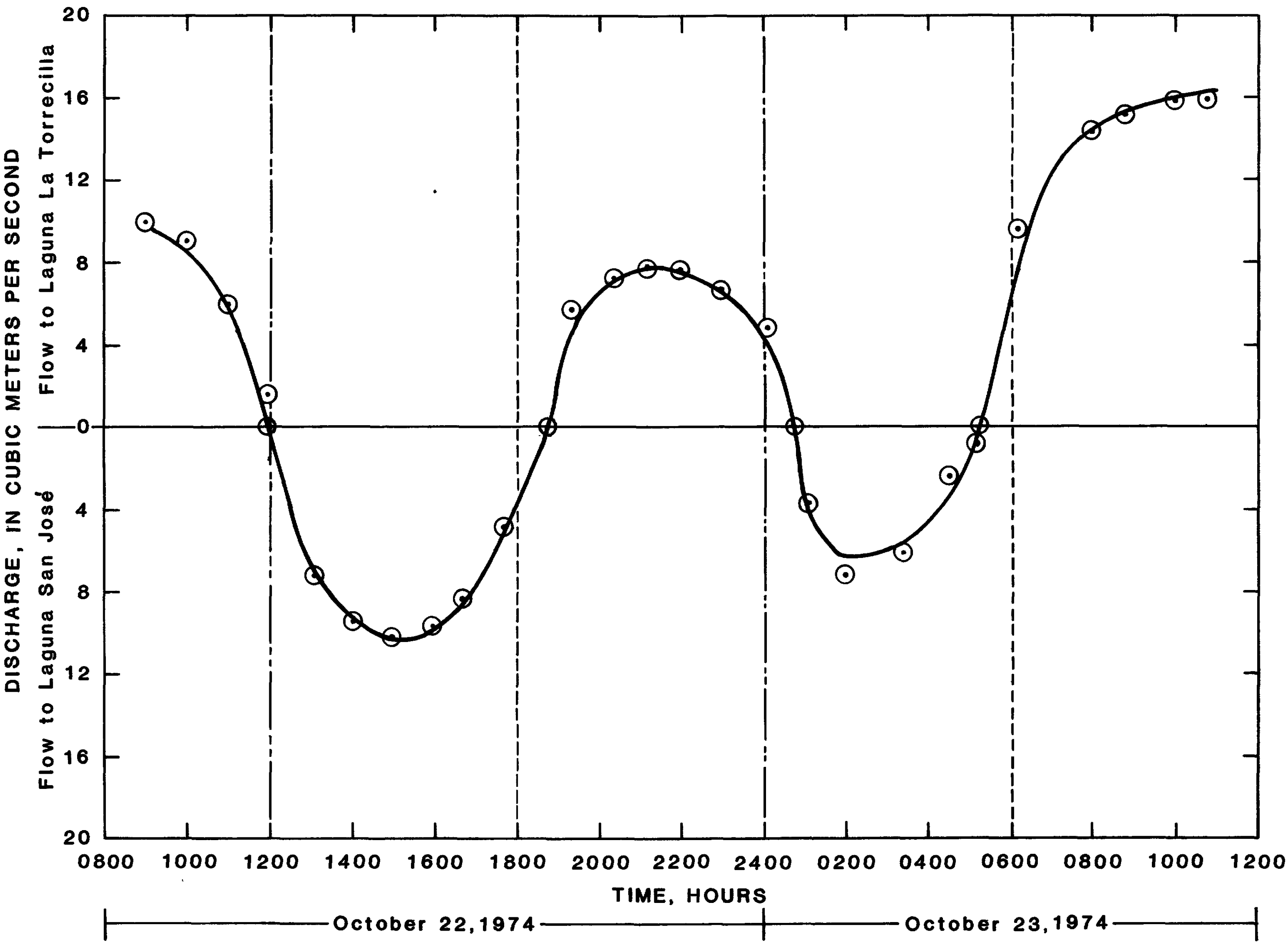


Figure 10.--Flow pattern thru Canal Suárez at Hwy. 26 bridge.

Caño de Martín Peña at Avenida Barbosa

The Caño de Martín Peña site was located at the Avenida Barbosa bridge (fig. 1). The flows in the Caño, which connects Laguna San José to Bahía de San Juan followed the predicted tidal pattern until about 2200 hours on October 22, (fig. 11). At that time the ebbtide was interrupted and the flow reversed toward Laguna San José. The flow direction in Caño de Martín Peña was in phase with the flow at Canal Suárez until storm runoff reached the canals. This canal is unique in that it is the only one which receives directly a significant amount of the total basin runoff (fig. 2). The areas in the Hato Rey and Santurce districts (fig. 1), which drain about 9.5 km^2 of urban developments, drain directly into Caño de Martín Peña. The relatively small surface area of Caño de Martín Peña in comparison to its immediate drainage basin and the limited conveyance of the canal are responsible for rapid rises of its water surface during intensive rainstorms. Flow into Laguna San José from Caño Martín Peña lasted about one hour longer than that from Canal Suárez.

Water inflow to Laguna San José through Caño de Martín Peña during the tidal cycle was 0.17 hm^3. Discharges from the lagoon to Bahía de San Juan totalled 0.15 hm^3 during the same period.

Storm Runoff Contributions to the Lagoons

One of the main objectives of the study was to determine the storm runoff contributions to the San Juan Lagoons system. This was achieved by flow measurements at the principal outlets and inlets to the three lagoons and by a water balance of all the other inflow-outflows.

The water balance at each lagoon may be represented by the equation:

$$IS = SR + DR + TC + BF$$

where IS = increase in storage;
SR = storm runoff contribution;
DR = direct rainfall;
TC = net flow measured at the tidal canals; and
BF = base-streamflow contributions from 1000 hrs to 2400 hrs, Oct. 22.

The increase in storage at each lagoon was computed from changes in water levels during the study period. The net water-level changes were obtained from the recording gages at each lagoon. The net change in water level was multiplied by the surface area of the lagoon to compute the change in volume. The general assumption was made that the surface area of the lagoons did not increase significantly due to the increase in volume because the banks of the lagoons are nearly vertical. These computations showed an increase in storage of 1.7 hm^3 for Laguna San José, 0.30 hm^3 for Laguna La Torrecilla, and 0.16 hm^3 for Laguna de Piñones.

The contributions from rainfall were computed by multiplying the surface area of each lagoon by the amount of precipitation. As previously indicated, an average of 39 mm of rainfall was assumed to represent the direct rainfall over the lagoons. The precipitation contribution to laguna San José was 0.21 hm^3, with 0.10 hm^3 computed for Laguna La Torrecilla, and 0.04 hm^3 for Laguna de Piñones.

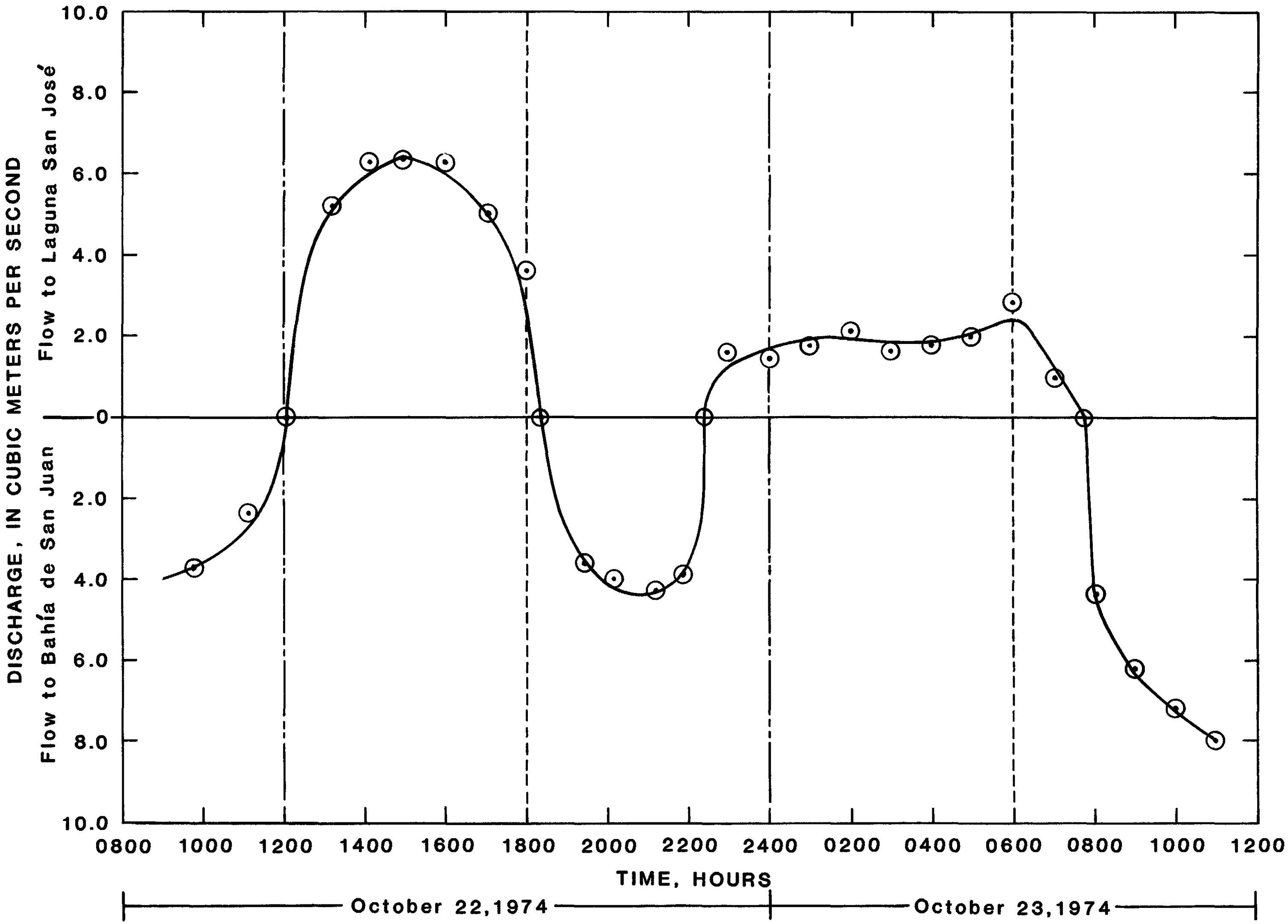


Figure 11.--Flow pattern thru Caño de Martin Peña at Avenida Barbosa bridge.

Base-flow contributions are summarized as follows:

a) Quebrada San Antón and Quebrada Juan Méndez = 0.02 hm^3

b) Quebrada Blasina, Carolina and Vistamar STP's = 0.01 hm^3

c) Avenida Baldorioty de Castro pump station = 0.01 hm^3

The contribution from the pump station to Laguna San José was obtained from daily pumpage records. A total of 0.05 hm^3 was pumped during the storm period.

The computations and water balances for each lagoon are summarized in figure 12. The direction of the arrows indicate the direction of flow. There were no adjustments for evapotranspiration losses, which probably were negligible during the study period.

The data in figure 12 show that the storm runoff during the period of study received by the lagoons totalled about 3.2 hm^3, of which about 50 percent flowed into Laguna San José, 48 percent into Laguna La Torrecilla and 2 percent into Laguna De Piñones. At the end of the study period, Laguna San José retained in storage about 75 percent of the total water input. In comparison, Laguna La Torrecilla had discharged through the Boca de Cangrejos outlet nearly 85 percent of the inflows it received. Flows out of Laguna San José were restricted at Caño de Martín Peña by the increase in head in this canal from direct storm runoff flowing into it. The discharges from Laguna San José are also restricted by the limited conveyance in Canal Suárez.

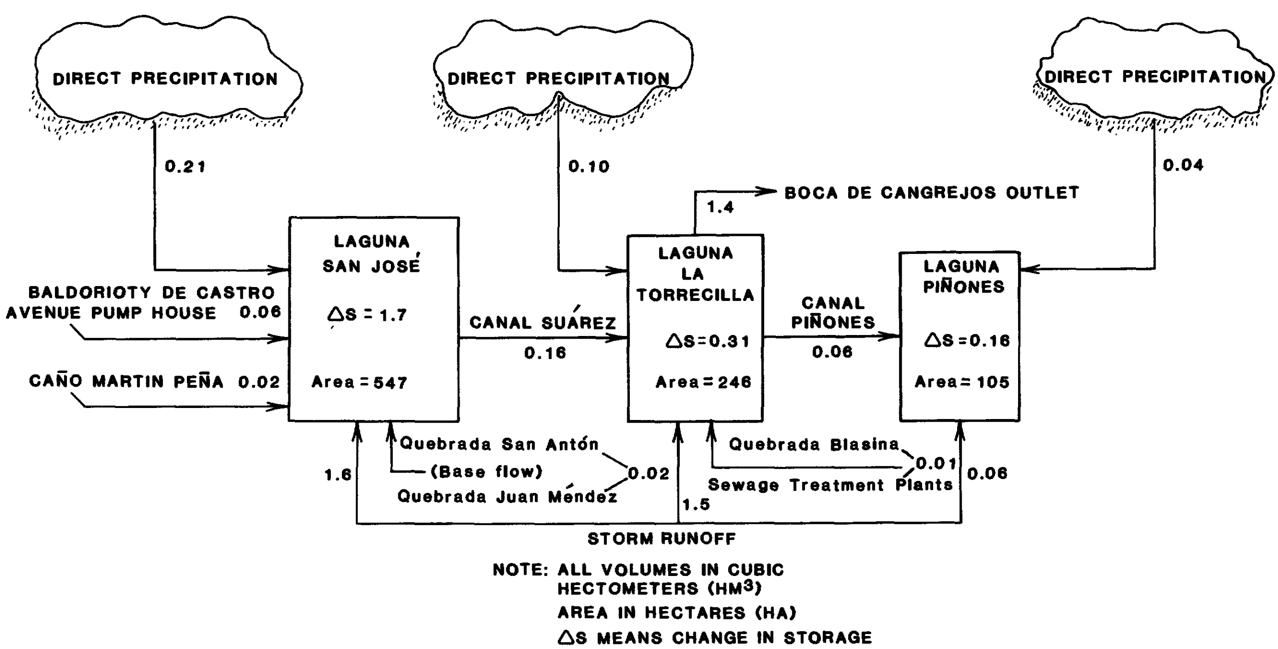


Figure 12.--Net water flows and gain in storage at Laguna San José, Laguna La Torrecilla, and Laguna de Piñones, during the 22-23 October, 1974 storm.

Water from Canal Blasina flows with a minimum of resistance into Laguna La Torrecilla, water in the Lagoon also flows toward the ocean at the open outlet of Boca de Cangrejos; only extreme floodtides may create enough backwater to limit the flows. Laguna de Piñones, in the meantime, did not undergo any net outflow, but increased its storage until backwater from Laguna La Torrecilla was no longer effective.

WATER QUALITY CHARACTERISTICS

Water Quality in the San Juan Lagoons

Ellis and Gómez (1975) described the general water-quality characteristics of Laguna San José, Laguna La Torrecilla and Laguna de Piñones lagoons. Their findings indicate that very poor water-quality conditions prevail in the lagoons system. The key water-quality indicators are representative of heavily polluted systems. Dissolved-oxygen concentrations range from supersaturation caused by massive algal blooms to anaerobic conditions that result in widespread fish kills. Nitrogen and phosphorus concentrations are characteristic of hypereutrophic systems, and organic carbon-concentrations reflect the organic loads discharged into the lagoons from domestic sewage. The extensive dredging in Laguna La Torrecilla and Laguna San José, which has created deep pockets of stagnant saline water devoid of oxygen, compounds the problem (Ellis, 1976). Overall, Laguna San José is the most heavily polluted of the three lagoons.

During periods of low flows the principal tributaries to the lagoons contribute relatively large concentrations of organic matter and nutrients. Chemical analyses of samples collected at the principal surface-water inflows to the lagoons during low flows are summarized in table 1. All the samples except the one at the Baldorioty Avenue Pump Station, were collected on October 22, 1974, prior to the storm. The sample from the Pump Station was collected in February 1975. The results of the Pump Station sample are considered valid, since there had been no significant changes in the area drained by the Pump Station.

The data in table 1 show that the quality of the water in the tributaries varies considerably during any day. Daily fluctuations in the quality of the effluent from sewage treatment plants have been documented by Metcalf and Eddy (1972). Regardless of the daily variations, the analyses show that these sources contribute significant loads of carbon and nutrients to the lagoons. The low-flow effects of these loads are described by Ellis and Gómez (1976); however, as shown in the following section, the low-flow contributions to the lagoon system are relatively minor when compared to those of storm runoff.

The study objective to determine the contribution from storm runoff to the water-quality conditions in the lagoons directed the nature and scope of the sampling during the October 22 to 23 storm. The parameters sampled are associated with the most critical problems in the lagoons. Organic carbon provides a measure of domestic loads and biological activity.

The dissolved and suspended species of nitrogen and phosphorus, and their different oxidation states (that is organic, ammonia, nitrite, and nitrate-nitrogen), provides evidence of degree of eutrophication, and biological activity. Specific conductance determinations were used to estimate brackish water contributions and extent.

TABLE 1.--Water quality of surface-water flows into lagoons during low-flow conditions, October 22, 1974 (all values are in milligrams per liter, except SC which is in micromhos per centimeter at 25°C)

Site	Time	SC	TOC	TP	$ToPO_4$-P	TKN	TON	TNH_4-N	$NO_{2,3}$-N
1	0925	492	10	1.7	1.5	6.0	1.1	4.9	0.06
1	1640	519	23	2.6	1.8	.26	.26	.00	.01
2	0850	376	8.0	.84	.79	2.6	.50	2.1	.24
2	1625	309	12	.60	.48	2.1	.70	1.4	.34
3	0730	517	14	1.1	.92	4.1	1.1	3.0	.27
3	1600	328	20	.76	.63	1.4	1.0	.38	.60
4	1040	678	29	7.6	6.5	22	.00	22	.01
5	0900*	19,000	15	1.3	.98	5.4	1.3	4.1	.03

Site number	Source
1	Quebrada Blasina at Highway 3
2	Quebrada San Antõn at Avenida Campo Rico
3	Quebrada Juan Méndez at Calle Belmonte
4	Carolina Sewage Treatment Plant Outfall
5	Avenida Baldorioty de Castro Pump Station at sump

*Sample taken on February 25, 1975, when low-flow conditions prevailed at at this site similar to flow rate prior to the lagoon study.

Chemical Loads During the October 22-23, 1974 Storm

The loads of selected components through each of the principal inlets-outlets of the lagoon system were computed on the basis of the instantaneous samples and flow determinations at each site. The computations include loads of total organic carbon (TOC), total phosphorus (TP), total orthophosphate (TPO_4-P), total organic nitrogen (TON), total ammonia nitrogen (TNH_4-N), nitrate (NO_3-N), nitrite (NO_2-N), and suspended sediment (SED).

Boca de Cangrejos

Load data for the Boca de Cangrejos outlet show that all of the components measured followed the prevailing tidal pattern (fig. 13). Discharges to the ocean increased with the ebbtide, receding for several hours during the early hours of October 23, and increasing again toward the ocean as the storm runoff reached Laguna La Torrecilla. From 80 to 100 percent of the individual components were in solution. Most of the phosphorus was in the more soluble orthophosphate state, readily accessible for assimilation by algae.

The suspended-sediment curve in figure 13 shows almost a balance between the inflows and outflows. Strong winds and wave actions during the floodtide may have caused the suspension and inflow into Laguna La Torrecilla of sand particles. On the first floodtide (before storm effects) mean velocities into the lagoon at the outlet were as high as 0.69 meter per second (m/s), with maximum suspended-sediment concentrations of 25 milligrams per liter (mg/L). On the second floodtide, (during the storm) the mean velocity into the lagoon peaked at 0.41 m/s while the suspended-sediment concentration was about 35 mg/L, reflecting the increased sediment load in the coastal water (fig. 14).

Canal Piñones

The load and flow-rate curves at the Canal Piñones station followed the prevailing tidal cycle (fig. 15). Between 0520 and 0600 hours, October 23, flow at the canal was stagnant, probably due to storm runoff into Canal Blasina over-coming the flood tide in its early stage.

Overall, the integration of the transport curves show that the net inflow to Laguna De Piñones of each of the measured components exceeded the outflow. This could indicate that Laguna de Piñones is a sink in the lagoon system for organic carbon, nitrogen, and phosphorus. However, since the system had not reached equilibrium from the storm effects at the time the study was terminated, additional exports probably occurred during the next ebbtide.

Chemical analyses of filtered samples show that a significant part of the carbon, phosphorus and nitrogen flowing through Canal Piñones was in solution. Soluble phosphorus varied from 45 to 90 percent, with the higher percentages occurring during the period of heavy runoff (early hours October 23). Ammonia nitrogen followed a trend similar to phosphorus with the soluble fraction varying from 35 to 90 percent of the total. An average of 30 percent of the organic nitrogen was in solution throughout most of the period.

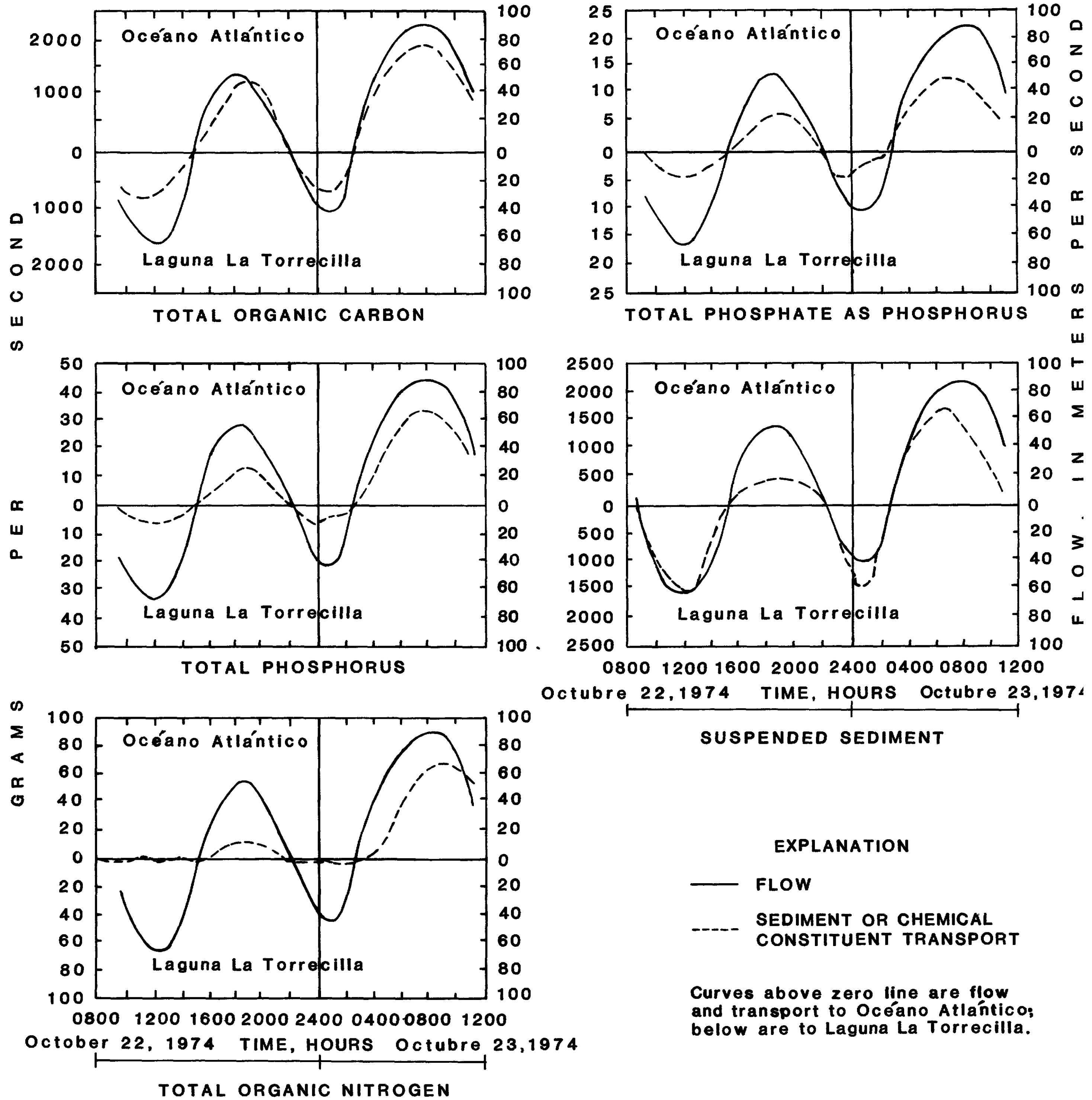


Figure 13.--Flow pattern of chemical constituents and suspended sediments thru Boca de Cangrejos.

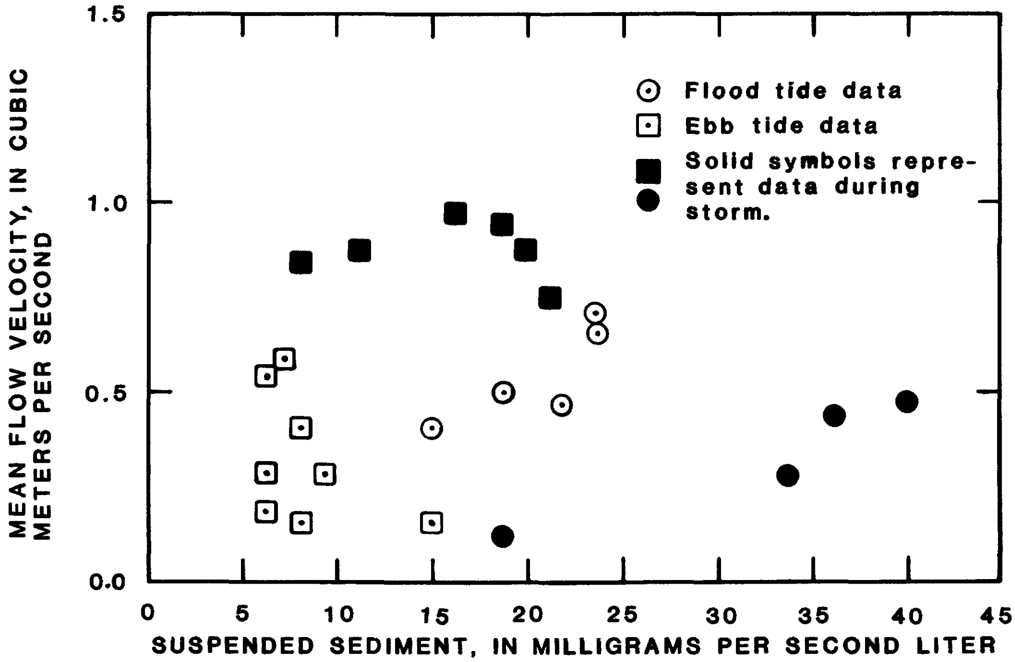


Figure 14: Suspended sediment concentration as related to mean flow velocity at Boca de Cangrejos during October 22-23,1974 study.

Figure 14.--Suspended sediment concentration as related to mean flow velocity at Boca de Cangrejos during the 22-23 October, 1974 study.

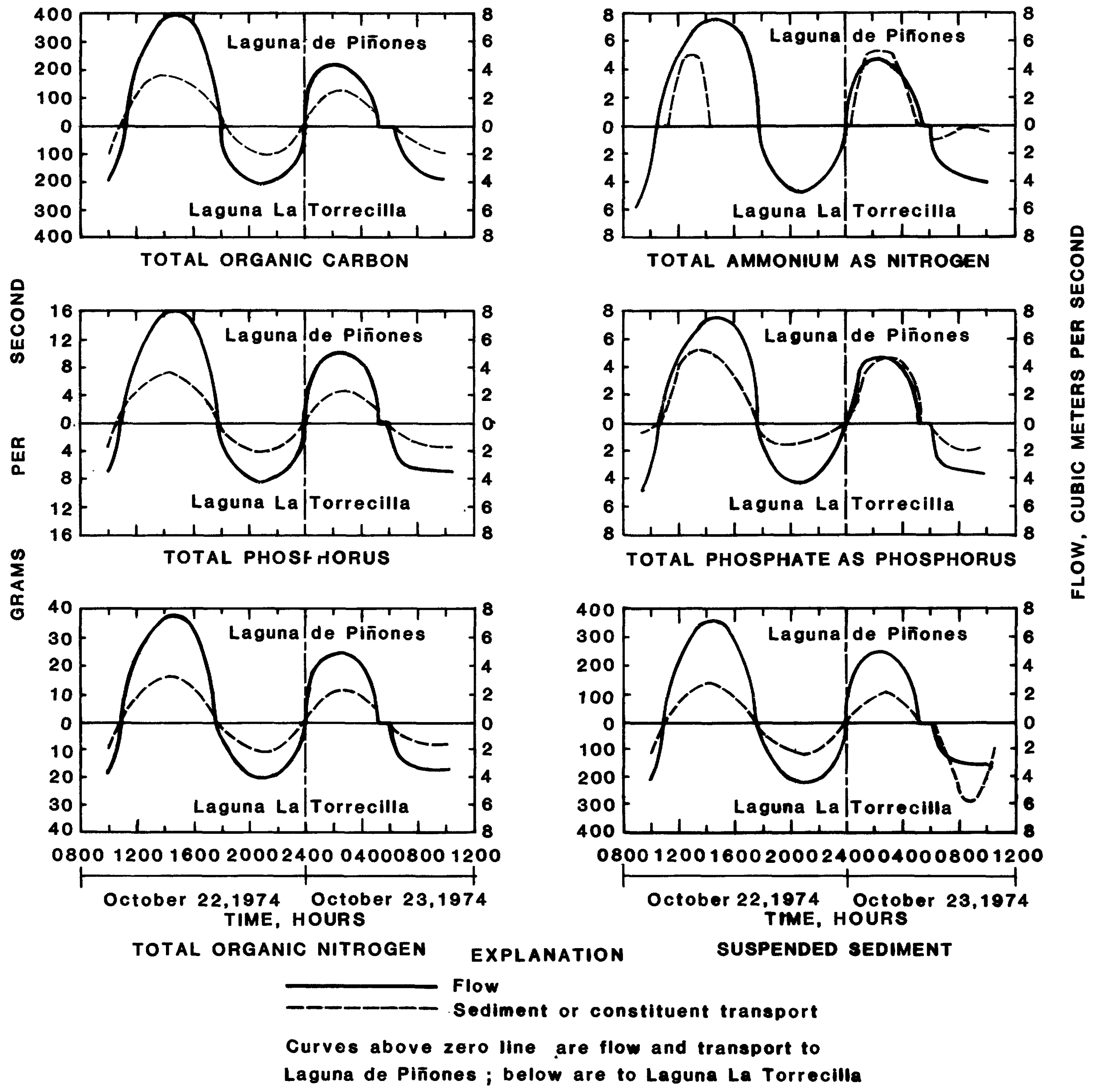


Figure 15.--Flow pattern of chemical constituents and suspended sediment thru Canal Piñones.

The average ratio of TPO_4-P to TP at Canal Piñones was 0.18 during the ebbtides and 0.42 during the floodtides. Sewage inputs into Canal Blasina, rich in inorganic orthophosphates, contribute to increase the flow of TPO_4-P into Laguna de Piñones. A sample collected at the Carolina sewage treatment plant discharge into Canal Blasina showed that about 85 percent of the phosphorus was in the orthophosphate form. Similarly, there was essentially no ammonia nitrogen flowing out of Laguna de Piñones during the ebbtide, while about 30 percent of the total nitrogen during the floodtides was in the form of ammonia. In the sewage treatment plant effluent, all of the available nitrogen was ammonia nitrogen.

The suspended-sediment concentration at Canal Piñones was about 21 mg/L during both the ebb and flood-tides prior to the storm. At the peak of the storm-runoff, the suspended-sediment concentration flowing out of Laguna de Piñones was about 83 mg/L. Runoff from the mangrove forest contributed to the increased sediment concentration.

Canal Suárez at Highway 26 Bridge

The transport and flow curves at the Canal Suárez station indicate a net outflow from Laguna San José to Laguna La Torrecilla of each of the chemical constitutents determined (fig. 16). The flushing of Laguna San José into Laguna La Torrecilla during periods of high storm runoff is evident.

Similar to the other tidal stations in the lagoon system, most of the organic carbon, nitrogen, and phosphorus were in solution. About 95 percent of the organic carbon was in soluble form, while soluble phosphorus varied from 75 to 90 percent of the total. The available nitrogen, 96 percent of which was organic, included about 85 percent in solution.

The suspended-sediment concentration at Canal Suárez varied from 20 to 43 mg/L. The maximum occurred during the floodtide prior to the storm. High-suspended sediment in the discharge from culverts near the station may have influenced the maximum measured concentration.

Perhaps the most significant feature of the transport curves in figure 16 is the magnitude of the increase in the concentration of the chemical constituents with the increase in flow. In an unsteady system, one would expect that after the initial slug of water with high chemical concentrations, additional slugs would tend to have lower concentrations. However, except for ammonia and suspended sediment, which peaked around 0900 hours on October 23, all of the components followed the rise in flow until the termination of the study. Normally, a limited amount of carbon and nutrients is available in the basin to be flushed by storm runoff. It is possible that this point was not reached in the study, and the basin was still yielding large loads of carbon and nutrients. A second possibility is that lagoons, in particular Laguna San José, act as temporary sinks of chemicals. These are removed and transported during storms. Continuation of the study could have yielded additional data to answer these questions.

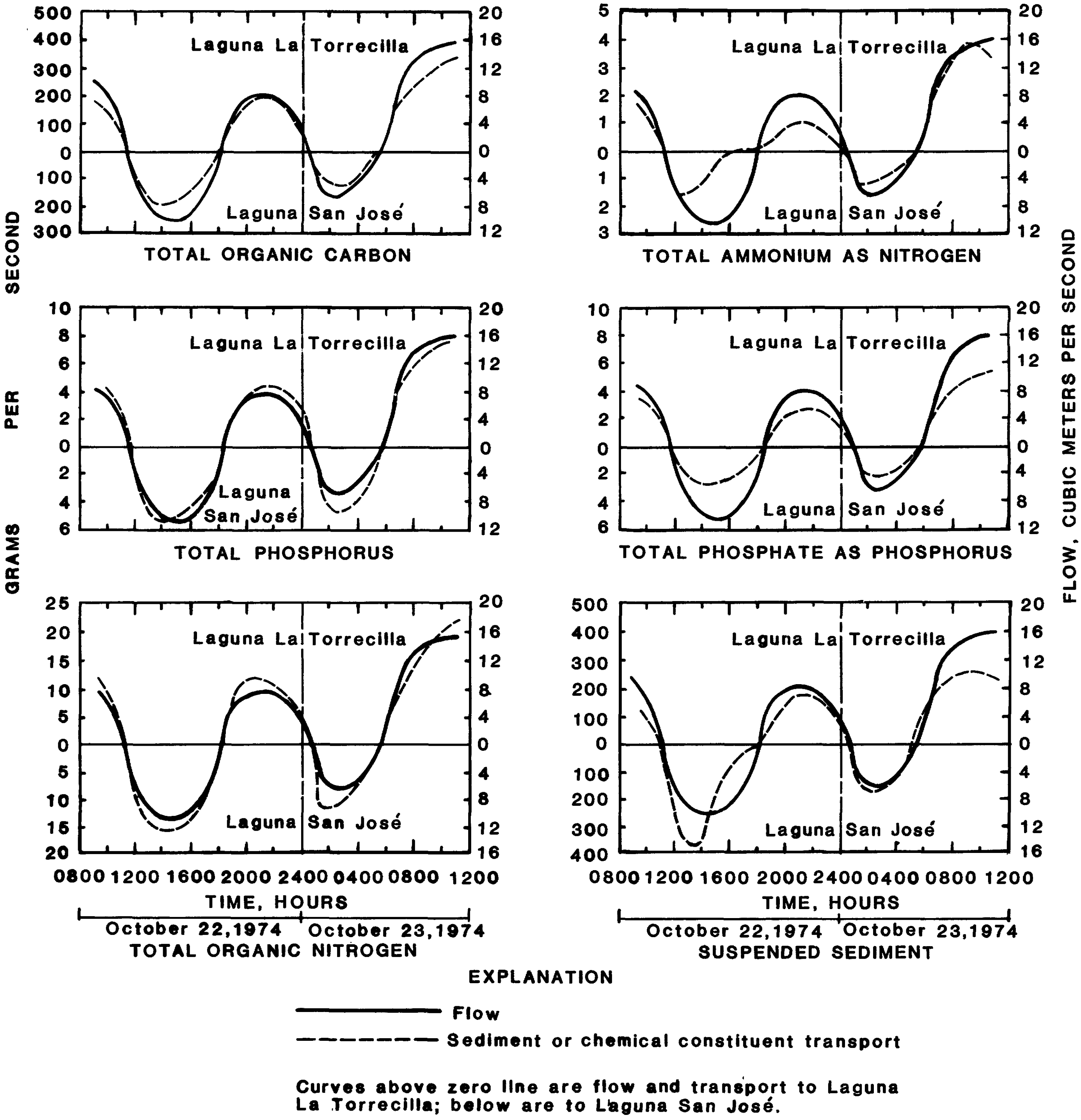


Figure 16.--Flow pattern of chemical constituents thru Canal Suárez at Hwy. 26 bridge.

Caño de Martín Peña at Avenida Barbosa

The net contributions of organic carbon and nutrients from Caño de Martín Peña to the lagoons system was minimal during the storm period. The transport and flow curves at the Avenida Barbosa Station show that after the ebbtide of October 22 a near flat response occurred in the flow and transport of each chemical component (fig. 17). As previously stated, storm runoff into Caño de Martín Peña may cause rapid surges in the canal. However, the increases in head at Laguna San José reversed the flow in the Caño toward Bahía de San Juan ahead of the ebbtide.

The percentages of organic carbon and nutrients in solution at Caño de Martín Peña changed after the effects of the storm reached the sampling station. Dissolved organic carbon decreased from 70 to 50 percent of the total, while phosphorus remained nearly unchanged at 70 percent in solution. However, the percentages of organic nitrogen in solution increased from 28 to 46 percent, while dissolved ammonia also increased from 41 to 80 percent, of the total. These changes indicate that organic carbon in particulate form, and nitrogen species with a low oxidation state (typical of sewage) were washed into the canal from the urban areas of Hato Rey and Santurce.

A comparison between the transport curves at Canal Suárez (fig. 16) and Caño de Martín Peña (fig. 17) shows a significant difference in the quality of the water between the two sites. Laguna San José is the dominating feature in the lagoons' hydraulic system. Once a near steady-stage equilibrium is reached in the system during a storm, water flows from Laguna San José at both Canal Suárez and Caño de Martín Peña. If the quality of the water in Laguna San José were homogeneous, once equilibrium was reached, the quality of the water at the other two tidal sites should have been similar. The differences in the quality of the water between the two sites show that either Laguna San José did not reach a homogenous state, or other contributions to Caño Martín Peña are more significant than the flow from Laguna San José.

Net Loads in the Lagoon System

Net flows (loads) of organic carbon, nutrients, and suspended sediment at the tidal canals and the Boca de Cangrejos outlet to the ocean are summarized in figure 18. Storm runoff contributions of some of the parameters also are shown. The contributions of storm runoff were estimated from a mass balance analysis. Estimates were made only for TOC, TP, and total Kjeldahl nitrogen (TKN-equivalent to the sum of TON and TNH_4-N). The computations of the loads in storm runoff appear reasonable on the basis of comparisons with measured loads at the tidal canals. The most significant departures between measured loads budget for the tidal cycle, the contributions in and out of Laguna de Piñones are minimal. An error in the flows in and out of Laguna de Piñones is not as significant as for the other two lagoons.

Estimates of the nitrogen in rainfall are based on studies by Reid (1961). Similar data were obtained by Jordan and Fisher (1977) in a study of chemical quality of rainfall in St. Thomas, U.S. Virgin Islands.

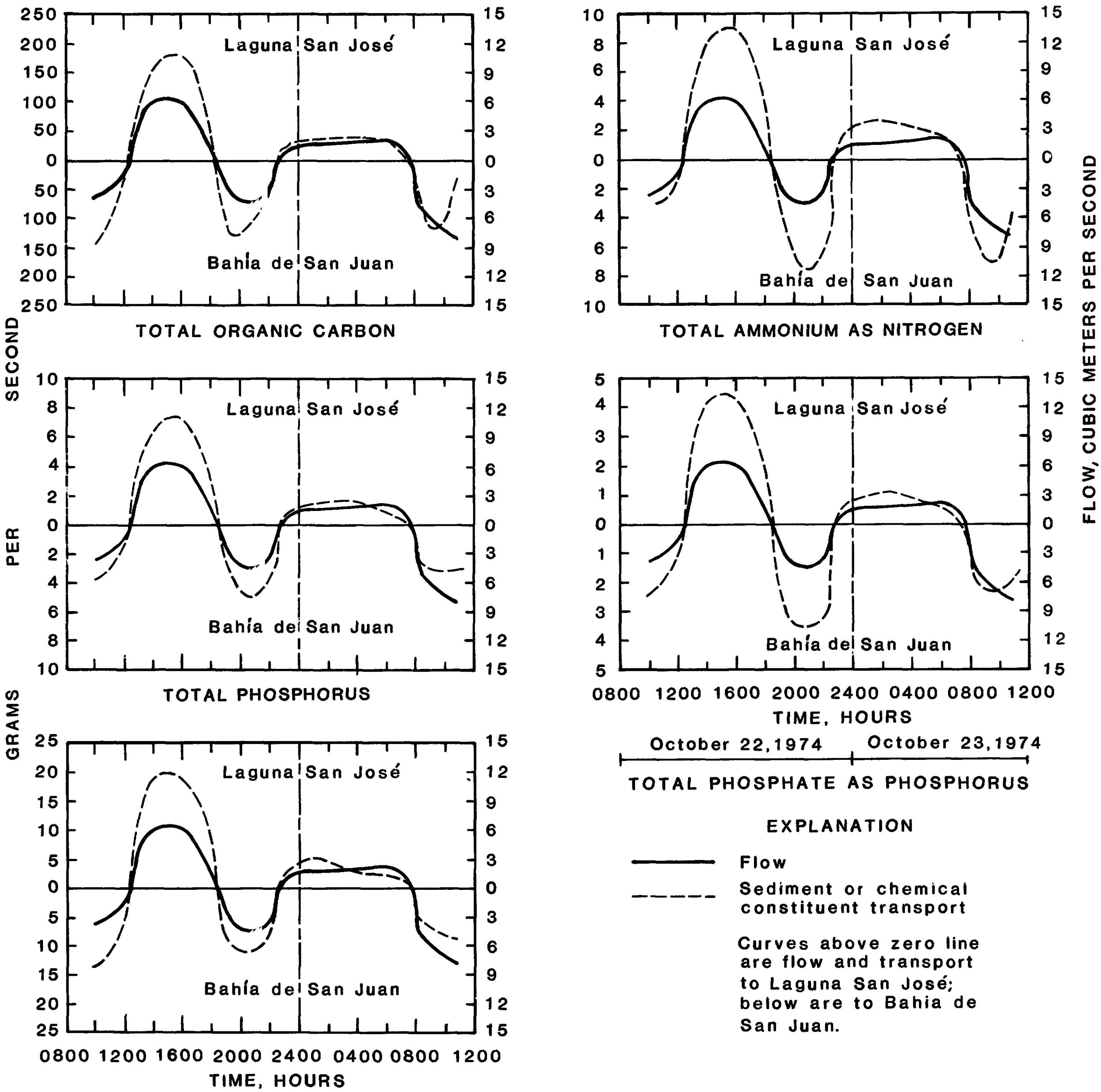
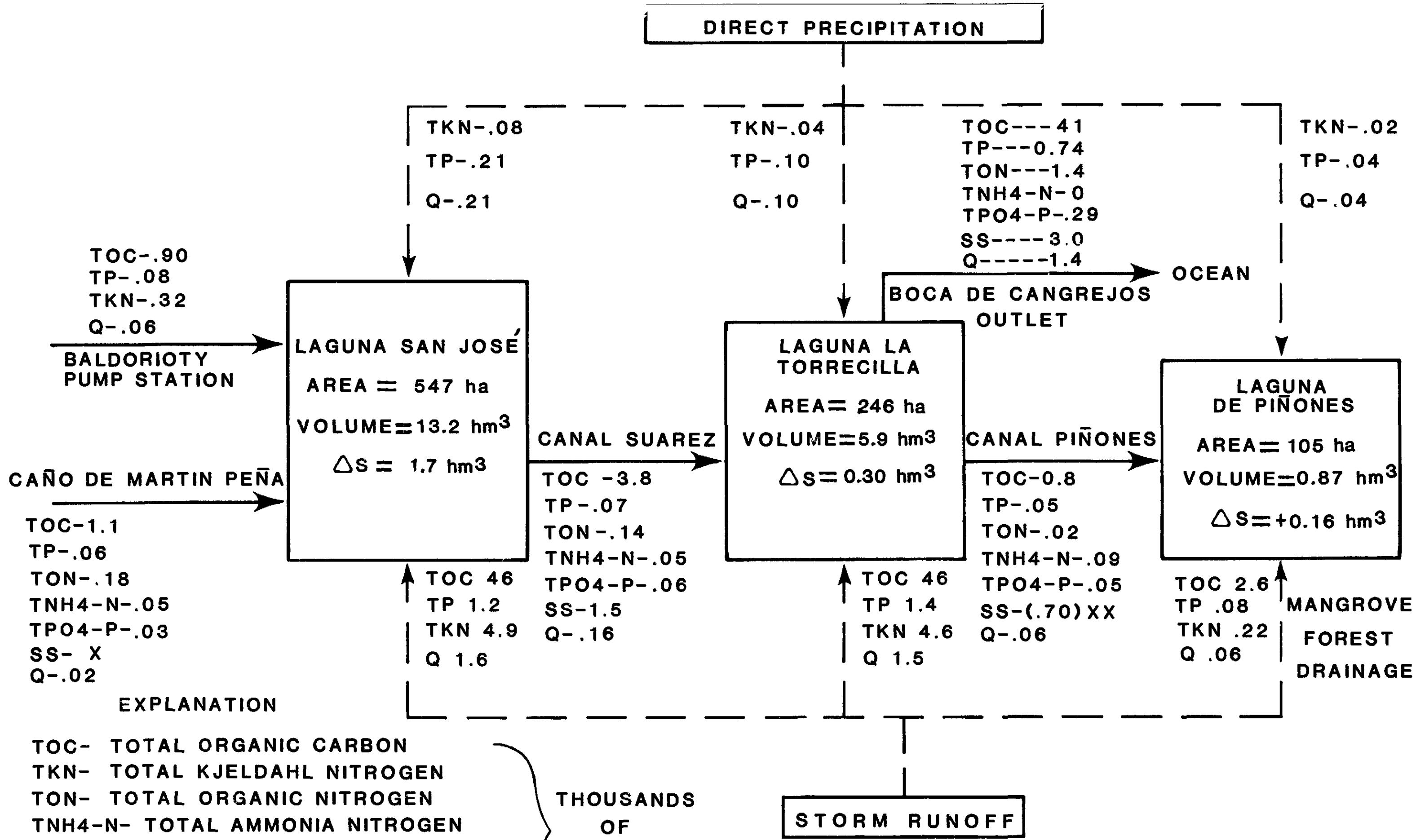


Figure 17.--Flow pattern of chemical constituents thru Caño de Martin Peña at Avenida Barbosa bridge.



EXPLANATION

TOC- TOTAL ORGANIC CARBON
TKN- TOTAL KJELDAHL NITROGEN
TON- TOTAL ORGANIC NITROGEN
TNH4-N- TOTAL AMMONIA NITROGEN
TP- TOTAL PHOSPHORUS
TPO4-P- TOTAL ORTHOPHOSPHATE AS PHOSPHORUS
SS- SUSPENDED SEDIMENT

(TOC- through SS-: THOUSANDS OF KILOGRAMS)

Q- FLOW IN CUBIC HECTOMETERS
ΔS- CHANGE IN STORAGE IN CUBIC HECTOMETERS
P- PRECIPITATION IN CUBIC HECTOMETERS
X- LOAD NOT DETERMINED DUE TO SCATER OF DATA POINTS
XX- NET FLOW FROM LAGUNA DE PIÑONES TO LAGUNA LA TORRECILLA

VOLUME OF LAGOONS ARE AT MEAN SEA LEVEL (ELLIS,1976)

Figure 18.--Net water flows, nutrients, and suspended-sediment loads, in the San Juan Lagoons during the storm-affected tidal cycle of 22-23 October, 1974.

The data in figure 18 show that during the study period, both Laguna San José and Laguna La Torrecilla received more organic carbon, nitrogen and phosphorus than was exported. A mass balance on Laguna San José shows that of about 45.4 x 10^3 kilograms (kg) of organic carbon, only about 8 percent was exported. Nitrogen and phosphorus show similar trends. In Laguna La Torrecilla, of a total organic carbon loading of about 51.8 x 10^3 kg, almost 84 percent was exported to the ocean and Laguna de Piñones.

The retention of organic matter and nutrients by both Laguna San José and Laguna La Torrecilla is a key factor in the water-quality conditions in the lagoon system. The organic loading exerts inordinate biochemical oxidation demands on the lagoons, particularly in Laguna San José. The nutrients that accumulate, either in solution or in bottom deposits, enhance high biological activity which creates extremes in oxygen levels. Dissolved-oxygen concentrations may be driven to zero or near zero values as a result of the organic loading, or to supersaturation levels due to biological activity. Both extremes (0-9.7 mg/L at 1 m, Ellis and Gómez-Gómez, 1975) probably are the main reasons for the frequent fish kills in the lagoons.

A summary of the flow and chemical loads in the lagoon system during a normal tidal cycle (dry weather conditions) is shown in figure 19. The data are presented to provide a comparison of flows and chemical loadings between the normal tidal cycle, without intense precipitation, and those of the

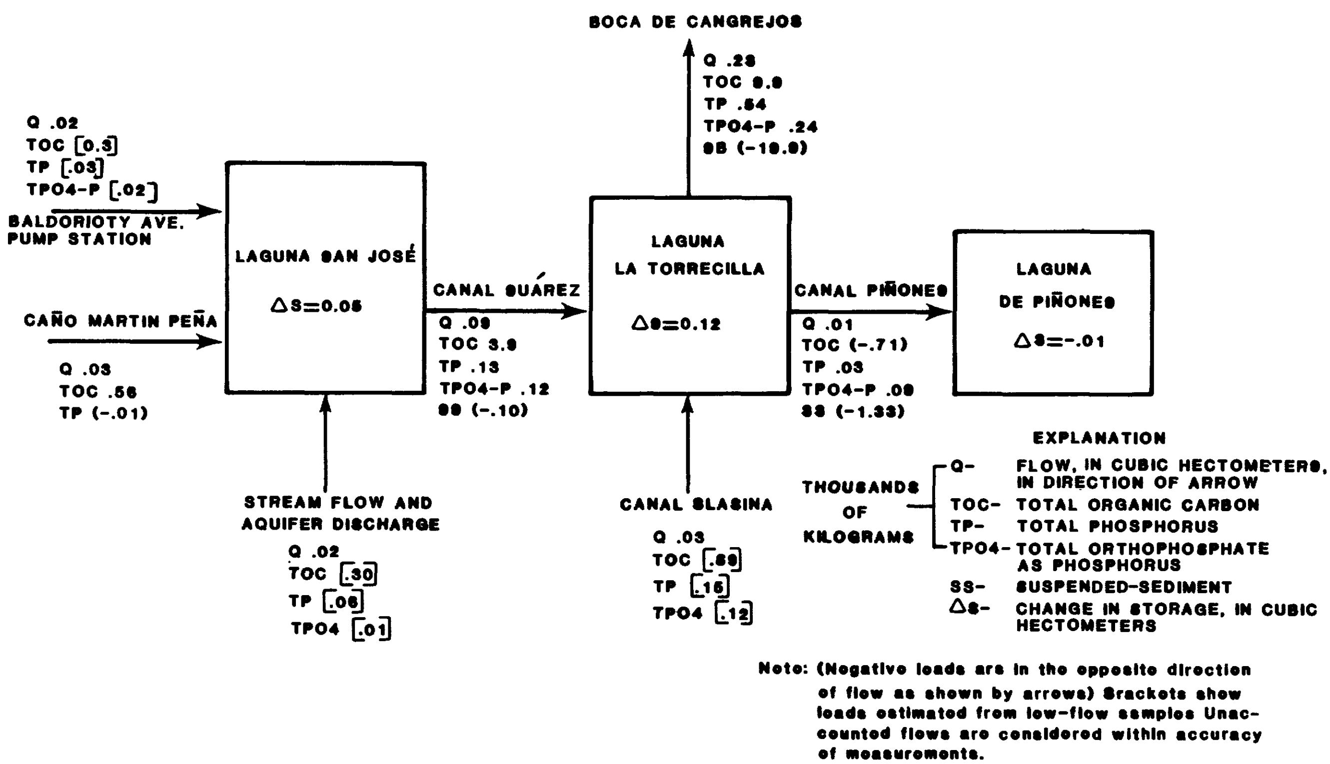


Figure 19.--Net water flows, nutrients, and suspended-sediment loads at the San Juan Lagoons system during a 22-23 January, 1974 tidal cycle. (Modified from Ellis and Gómez-Gómez, 1976.)

present study. Since the study by Ellis and Gómez-Gómez (1976) did not include determinations of the chemical loads at the Avenida Baldorioty de Castro pump house, streamflow into Laguna San José, and Canal Blasina discharges to Laguna La Torrecilla, these were estimated. The estimates were based on samples collected during low flows representative of the low-flow tidal cycle.

A further analysis of the data in figures 18 and 19 provides additional evidence that during storm events a significant amount of nutrients is stored in the lagoons. During dry conditions the lagoons export these to the ocean. The difference during both studies can be seen in table 2.

Table 2.--Net loads of major nutrients and total-organic carbon during wet and dry periods at Laguna San José and Laguna La Torrecilla (values in 1000 kilograms).

COM-	WET PERIOD			DRY PERIOD		
PONENTS	IN	OUT	RETAINED	IN	OUT	RETAINED
			Laguna San José			
TOC	47	44	3	0.6	7.1	-6.5
TP	1.6	0.8	0.8	0.1	.2	-0.1
TKN	5.5	2.2	3.3		NO DATA	
			Laguna La Torrecilla			
TOC	86	104	-18	7.9	15.5	-7.6
TP	2.2	1.9	0.3	0.4	1.0	-0.6
TKN	6.8	3.6	3.2		NO DATA	

Note: Negative sign indicates no retention. Amount indicated leached from bottom sediments, contributed by detritus or autotrophic production.

These loads were computed by adjusting values to zero storage change. Canal Suárez, which conveys in excess of 80 percent of the water out of Laguna San José was assumed to carry its entire flow. The ratio of nutrient load (TOC, TP or TKN) to flow (Q) from figures 18 and 19 was assumed to remain equal until the excess water volume in the lagoon was flushed. The same was assumed at Laguna La Torrecilla for Boca de Cangrejos outlet, but the net outflow from Laguna San José to Laguna La Torrecilla was included in the latter's inflow loads.

Comparisons between this study and that conducted during dry weather conditions show that low-flow contributions of TOC and nutrients to the lagoons are small when compared to inputs during a significant storm. The frequency of such storms in the metropolitan San Juan area clearly indicates the importance of storm runoff in the lagoons system.

The termination of the study after 25 hours of measuring and sampling was premature. The data in figure 18 shows that the lagoon system had not achieved equilibrium in terms of water flows and transport of chemical loads. It is probable that the export of TOC and nutrients from Laguna San José to Laguna La Torrecilla, and thereafter to the ocean outlet, would have continued above base levels. Many questions relative to the balance in the system remain unanswered. What is the sediment load (particularly the sand fraction) of the major streams? What would have been the Canal Suárez flow and chemical transport characteristics as storm runoff receded? Would Laguna San José begin to export TOC and nutrients by way of Caño de Martín Peña on the next receding ebbtide in the absence of runoff from the urban areas?

These and many other questions that relate to the hydraulic and chemical characteristics of the San Juan Lagoon system cannot be answered within the scope of this study. The system is too complex, with too many interactions involving tides, volumes, flow constraints in the canals, fresh-salt water mixing, ground-water inputs, and so forth. A solution to systems as complex as the San Juan Lagoons usually involves development and calibration of a mathematical model. Such models are available and the data collected during the investigations in the San Juan Lagoons can be used to calibrate a model.

CONCLUSIONS

Storm runoff to the San Juan lagoon system on 22 to 23 October, 1974 was about 70 percent of the storm precipitation in the basin. The mostly urbanized area probably prevents infiltration and reduces the travel time of the storm runoff into the lagoons. The hydraulic system of the lagoons, which normally follows the prevailing tides, is significantly effected by storm runoff. As storm runoff accumulates in Laguna San José, the increasing head reverses tidal flows in Canal Suárez and Caño de Martín Peña. The combination of flows from Laguna San José and Canal Blasina forces Laguna La Torrecilla to discharge to the ocean as much as 95 percent of the total inflows to the lagoons.

The transport of carbon, nutrients, and suspended-sediment in the lagoon system appears to be affected principally by inputs from storm runoff. Low-flow contributions, in terms of loads, are a fraction of those during intense storms. Although several point sources along Canal Blasina contribute significant organic and nutrient loads, a storm as intense as the one during the study contributes many times those loads. This indicates that the water-quality problems in the lagoon system cannot be solved by eliminating only the point sources. The control of non-point sources in the urbanized basin is essential.

Nutrients and organic matter are released from the lagoons during dry-weather conditions at a rate greater than what can be accounted for from inputs. This is more evident in Laguna San José and Laguna La Torrecilla. In the dredged areas of both lagoons, anaerobic conditions prevail most of the time. This suggests that the dredged areas may be an important storage pool of the organic matter and nutrients discharged to the lagoons. These storage areas will continue to yield nutrients and organic matter to the lagoons even after point and non-point sources of these components are controlled. This will prevent a quick improvement of the water-quality conditions in both lagoons.

The San Juan Lagoons constitute a very complex system that cannot be properly defined by conventional techniques. The data from this and other studies can be used to model the response of the lagoons to variable hydraulic and chemical-load conditions. Models are available and could be calibrated to provide management with alternatives to study and improve the quality of the water in the San Juan Lagoons system.

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