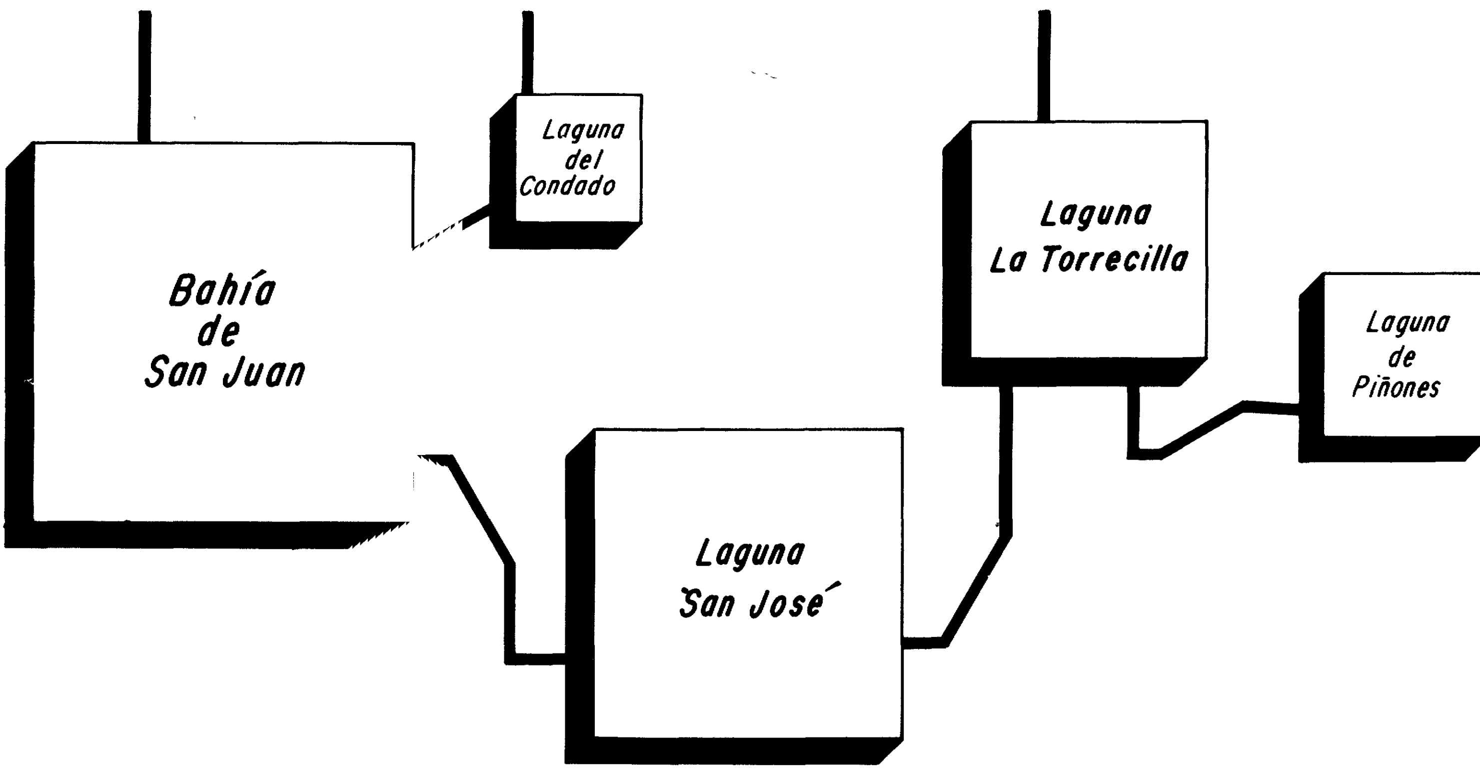
HYDROLOGIC CHARACTERISTICS OF LAGOONS AT SAN JUAN, PUERTO RICO, DURING A JANUARY 1974 TIDAL CYCLE

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 38-75



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The lagoons in the San Juan area, Puerto Rico, consist of Lagunas La Torrecilla, de Piñones, San José, and del Condado. They are interconnected by canals, except for Laguna del Condado, which is connected to the other lagoons via Bahía de San Juan. The lagoons contain saline to brackish water, raw and partly treated sewage, urban runoff, and industrial works. Determining the flows of water and selected chemicals to the ocean and between lagoons, allows water managers and planners to assess the effects of change in one lagoon to the other lagoons. Flows were measured and water-quality was sampled hourly for a tidal cycle (25 hours) in January 1974 at each connecting canal and outlet to the ocean. Interlagoon and ocean-lagoon flows, total organic carbon, total phosphorus, total orthophosphate, and suspended-sediment loads were calculated for a tidal cycle. Combined outflows of the Río Puerto Nuevo and Caño de Martín Peña were calculated for the Caño de Martín Peña at Constitution Bridge site.

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ABSTRACT

The lagoons in the San Juan area, Puerto Rico consist of Laguna La Torrecilla, Laguna de Piñones, Laguna San José, and Laguna del Condado. They are interconnected by canals, except for Laguna del Condado, which is connected to the other lagoons by way of Bahía de San Juan. The lagoons contain saline to brackish water, raw and partly treated sewage, urban runoff, and industrial effluents.

Flows were measured and water-quality was sampled hourly for a tidal cycle (25 hours) in January 1974 at each connecting canal and outlet to the ocean. Interlagoon and ocean-lagoon flows, total organic carbon, total phosphorus, total orthophosphate, and suspended-sediment loads were calculated for a tidal cycle. Combined outflows of the Río Puerto Nuevo and Caño de Martín Peña were calculated for the Caño de Martín Peña at the Constitution Bridge site.

For the tidal cycle, Laguna La Torrecilla had a net outflow of 230,000 cubic metres of water to the ocean and 11,000 cubic metres to Laguna de Piñones. Laguna La Torrecilla had a net inflow of 60,000 cubic metres from Laguna San José and 30,000 cubic metres from Canal Blasina. Laguna San José had a net outflow of 31,000 cubic metres to Bahía de San Juan through Caño de Martín Peña,

and 94,000 cubic metres to Laguna La Torrecilla by way of Canal Suárez. Laguna del Condado had a net inflow of 2,150,000 cubic metres through the Avenida Ashford Bridge and a net outflow of 2,030,000 cubic metres through Dos Hermanos Bridge. Caño de Martín Peña at Constitution Bridge had a net outflow of 500,000 cubic metres for the tidal cycle.

Laguna La Torrecilla had a net outflow of total organic carbon of 8.93 tonnes; total orthophosphate of 0.24 tonne; and total phosphorus of 0.54 tonne to the Oceano Atlantico by way of Boca de Cangrejos. The lagoon had a net inflow of 18.6 tonnes of suspended sediment. Laguna de Piñones had net outflows of 0.71 tonne of total organic carbon, 1.33 tonnes of suspended sediment, and 1.32 tonnes of dissolved oxygen. The lagoon had a net inflow of 0.03 tonne of total phosphorus and 0.03 tonne of total orthophosphate. Laguna San José had net outflows of 4.49 tonnes of total organic carbon, 0.12 tonne of total orthophosphate, and 0.12 tonne of total phosphorus.

Laguna del Condado's inflow probably was balanced by the outflow, within the error of measurements.

Caño de Martín Peña at Constitution Bridge was monitored at different times for each chemical constituent; total organic carbon, from 2000 January 23 to 1800 January 24, had an outflow to Bahía de San Juan of about 16 tonnes; total orthophosphate and total phosphorus, from 0700 January 23 to 1800 January 24, had a net outflow of about 0.4 tonne and 2 tonnes, respectively; and suspended sediment, from 0700 January 23 to 1100 January 24, had a net outflow of about 47 tonnes.

INTRODUCTION

The lagoons in the San Juan, Puerto Rico, area include Laguna La Torrecilla, Laguna de Piñones, Laguna San José, and Laguna del Condado. The population of the metropolitan area surrounding the lagoons is more than 1 million. Many demands and stresses are placed on the lagoons, such as: discharge of sewage and urban runoff; new land (fill) for housing, highways, and other uses; as a source of sand and fill; and recreation. Previous studies have included various parts of the lagoons and canals, but no study has included all parts of the interrelated unit. In July 1973, an investigation of the hydraulic, chemical, and biological conditions of the lagoons was begun by the U.S. Geological Survey in cooperation with the Puerto Rico Environmental Quality Board and the Puerto Rico Department of Natural Resources.

The San Juan lagoons are in the Northern Coastal Lowland physiographic region (Picó, 1950) of Puerto Rico, which is a gently sloping plain covered by deposits of sand, silt, clay, and muck (Anderson, in preparation). The lagoons are either directly interconnected by canals or, as with Laguna del Condado, connected to the other lagoons by way of Bahía de San Juan. Circulation of water in and out of the lagoons is sluggish because the three outlets to the sea--Boca de Cangrejos, Bahía de San Juan by way of Caño de Martín Peña, and Avenida Ashford Bridge channel--have small flow capacity compared to the total volume of the lagoons and the maximum tidal range is less than 1 m. The map in figure 1 shows the lagoons, connecting canals, measuring sites, stage gages, and local features.

Planning and developing the most desirable and efficient use of these shallow salt-water bodies require the understanding of the interrelationship of the lagoons. Because they are interconnected, a change in one lagoon may, with time, affect the others. This report presents observed data on the interlagoon and ocean exchange of the flows of water, sediment, and selected chemicals for a tidal cycle in January 1974.

For use of those readers who prefer to use English units rather than metric units, the conversion factors for the terms used in this report are listed below:

Multiply metric unit	by	to obtain English unit
cubic metres (m^3)	35.31	cubic feet (ft^3)
cubic metres per second (m^3/s)	35.31	cubic feet per second (ft^3/s)
grams per cubic metre (g/m^3)	6.243×10^{-5}	pounds per cubic foot (lb/ft^3)
grams per second (g/s)	2.205×10^{-3}	pounds per second (lb/s)
hectares (ha)	2.471	acres
kilometres (km)	6.215×10^{-1}	miles (mi)
metres (m)	3.281	feet (ft)
millimetres (mm)	3.937×10^{-2}	inches (in)
tonnes (t)	1.102	tons (short)

METHODS AND TECHNIQUES

From January 22 to 25, 1974, the flows of the canals and outlets at seven sites were measured hourly for 25 hours each during the 72-hour period. In addition, hourly water samples were collected for the determination of TOC (total organic carbon), $TOPO_4$ (total

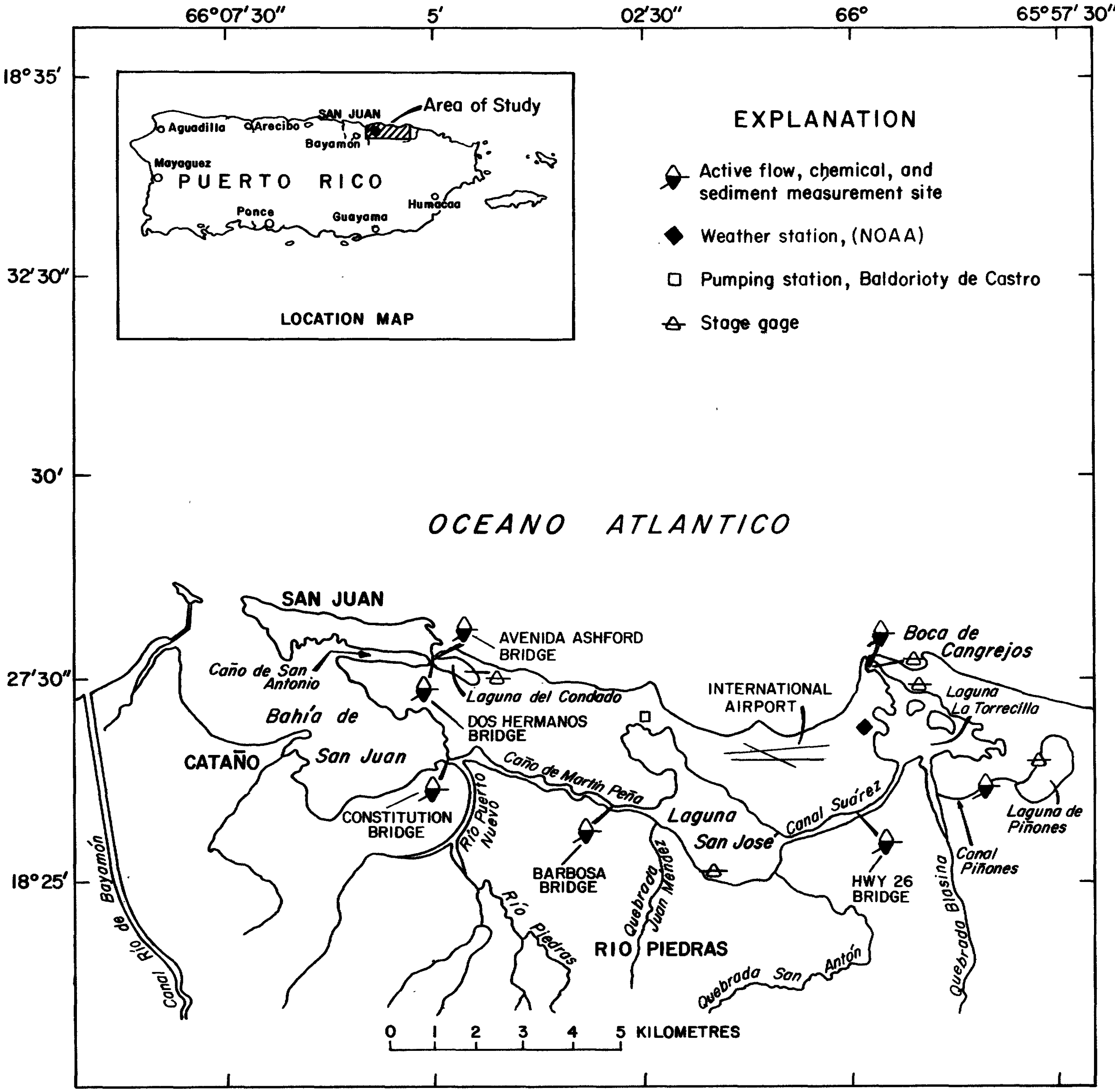


Figure 1.--San Juan lagoon-project area showing stage gages, monitoring sites, weather station, and general features.

orthophosphate), TP (total phosphorus), and suspended sediment. Laguna de Piñones was also monitored for DO (dissolved oxygen).

The flows through the canals and outlets to the sea were determined by a series of current-meter measurements. These were made following standard procedures, as outlined by Buchanan and Somers (1969). All sites were measured approximately at hour intervals. Complete cross-section measurements, at most sites, were made within 30 to 45 minutes except at Canal Suárez. At this site, complete cross-section measurements were made within 15 minutes. Velocities were measured at 0.2 and 0.8 of the depth at each observation point. The calculated volumes for each partial section were maintained within 10 percent of the total volume measured.

The flow measurements were converted to the metric equivalent (m^3/s) and plotted against time. A hand smoothed curve was drawn through the points. The integrated volume contained within the zero flow line and the curve was kept within 5 percent of the volume calculated with the field data without the aid of graphical paper. The difference between the volume of water moving on the flood and ebb directions was the net flow for the complete tidal cycle.

Some of the net flows represent a small percentage of the total flow in any direction. Therefore, the net volumes shown at various sites could very well be in error by several hundred percent, or even be in the opposite direction. Since their magnitudes are small in comparison to the total volume in either direction, this fact demonstrates a near balance between opposite flows. To establish a percentage of error for the volumes measured, a reference base is needed. Since no base of reference is available from which to measure a given deviation of the results obtained, one can only speculate on the percentage of error. Thus, it may be assumed that an equal degree of error exists in measuring the flows in either direction and these cancel out.

To understand the interrelationship of the lagoons, the concentrations of selected constituents were monitored and analyzed in the following way. The difference between the inflow and outflow of a selected water-quality constituent is called the net load. A lagoon with a negative net load exports a selected constituent and a lagoon with a positive net load imports selected constituents. Net loads of carbon, phosphorus, and suspended sediment were obtained at all measuring sites.

TOC was selected because it is a good indicator of the amount of organic matter in water. Although other methods exist for measuring organic matter, the TOC method is the simplest, requires the least time, and is reproducible. Emery and others (1971), and Ford and others (1971) have tried to correlate TOC with chemical oxygen demand and biochemical oxygen demand, but with varying degrees of success. In this study, TOC was used only as an indicator of organic matter. Phosphorus, in the form of $TOPO_4$ and TP, was selected because of its importance as a nutrient in primary production. Riley and Chester (1971) state that in an enclosed lagoon, which receives discharges from sewage treatment plants, phosphorus may be the limiting factor in primary production. They base this statement on the ability of certain nitrogen-fixing algae to flourish even if no combined inorganic nitrogen exists. A nitrogen-fixing alga, Anabaena spiroides, has been observed in Laguna La

Torrecilla, Laguna de Piñones, and Laguna San José. Phosphorus may not be the limiting factor of primary production in this lagoon system. $TOPO_4$ is reported in milligrams per litre (mg/l) of phosphorus. These values of P may be converted to mg/l of $TOPO_4$ by multiplying by a factor of 3.067.

To calculate the amounts of each constituent flowing through the monitoring sites, the following procedure was used. The water generally was sampled on the half hour. The results obtained are in mg/l, which is equivalent to g/m^3. The unit of water flow is m^3/s. The TOC data were multiplied by flow rate and the results, in g/s, were plotted against time as shown in figure 2. Curves were then drawn to give the best possible fit through the points. Values that fell greatly out of line, relative to the other values, were disregarded for smoothing purposes. The smoothed values, in g/s, were extracted from the curves and these values were multiplied by the number of seconds of flow to get the total grams per unit of time. The unit of time was usually one hour, except during reversal of flow. These values were summed for each tidal flow direction to obtain the total inflow and outflow. As a check, the unsmoothed values were multiplied by the time in seconds, and a value (in grams was obtained per unit of time. These values were summed for inflow and outflow and compared with the smoothed values. If the value was not within 5 percent, the smoothed value was redetermined. In most cases the values were within 2 percent.

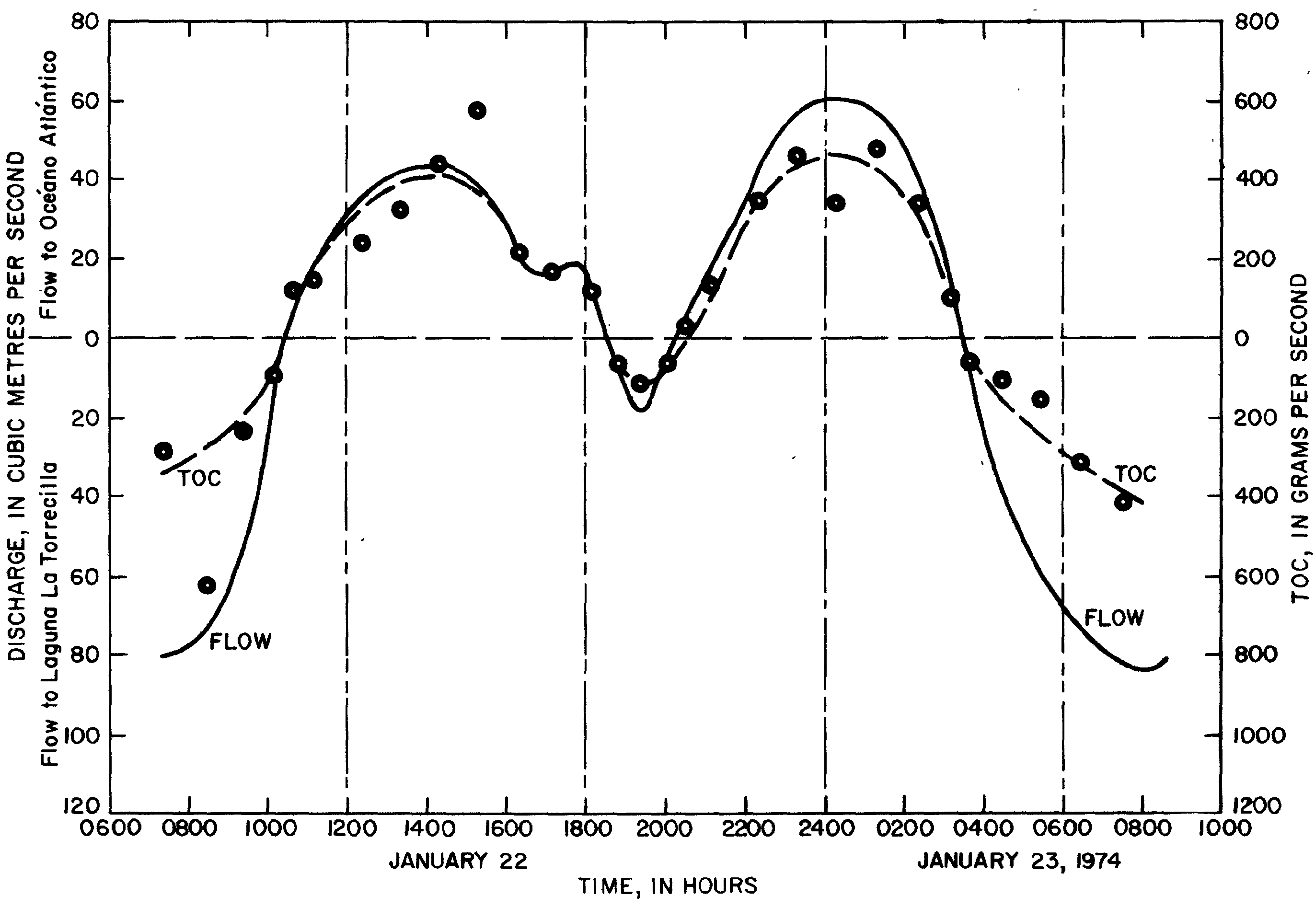


Figure 2.--Smoothing techniques used to establish flow of TOC.

GENERAL CHARACTERISTICS

Laguna La Torrecilla

Laguna La Torrecilla (fig. 3) has a water-surface area of about 246 ha and is the second largest of the lagoons. Dredging and other activities of man have significantly altered the shoreline, bottom, and immediate area. Areas of the mangrove forest that once surrounded the lagoon have been cleared on the western and southern shore; the shoreline has been altered by dredging and fill; and the apparently once shallow lagoon (estimated maximum depth of about 1 m) has been deepened locally by dredging for sand to a depth as great as 18 m.

The maximum tidal range is about 0.6 m. The average specific conductance for depths shallower than 1 m is about 45,000 micromhos. The specific conductance for depths greater than 3 m is about 50,000 micromhos.

Seawater enters and leaves the lagoon by way of Boca de Cangrejos. Brackish water from Laguna San José and Laguna de Piñones enters and leaves the lagoon by way of Canal Suárez and Canal Piñones, respectively. Fresh water enters the lagoon from Canal Blasina (the dredged lower reach of Quebrada Blasina) but at times more than half the flow (0.3 m^3/s) is effluent from two sewage treatment plants. In addition to the outflow at these plants, some raw sewage is discharged into Quebrada Blasina (Environmental Protection Agency, written commun., 1974).

Some general characteristics of the lagoon are given in table 1 (below):

Table 1.--General characteristics of the lagoons

Lagoon	Area[1/] ha	Average volume $m^3 \times 10^6$	Depth Max m	Depth Average m	Max length km	Width[2/] km	Shoreline[3/] Total km	Shoreline[3/] Mangrove km
Laguna La Torrecilla	246	5.91	18	2.4	2.50	1.65	19.1	14.8
Laguna de Piñones	105	.87	1.3	.8	1.58	.82	4.91	4.66
Laguna San José	547	13.2	11	2.4	4.52	2.20	13.5	6.35
Laguna del Condado	31	1.42	11	4.5	1.20	.31	2.70	0

[1/] Area of water surface only, not including islands.

[2/] Open water width at approximately right angle to the maximum length.

[3/] Including island shorelines.

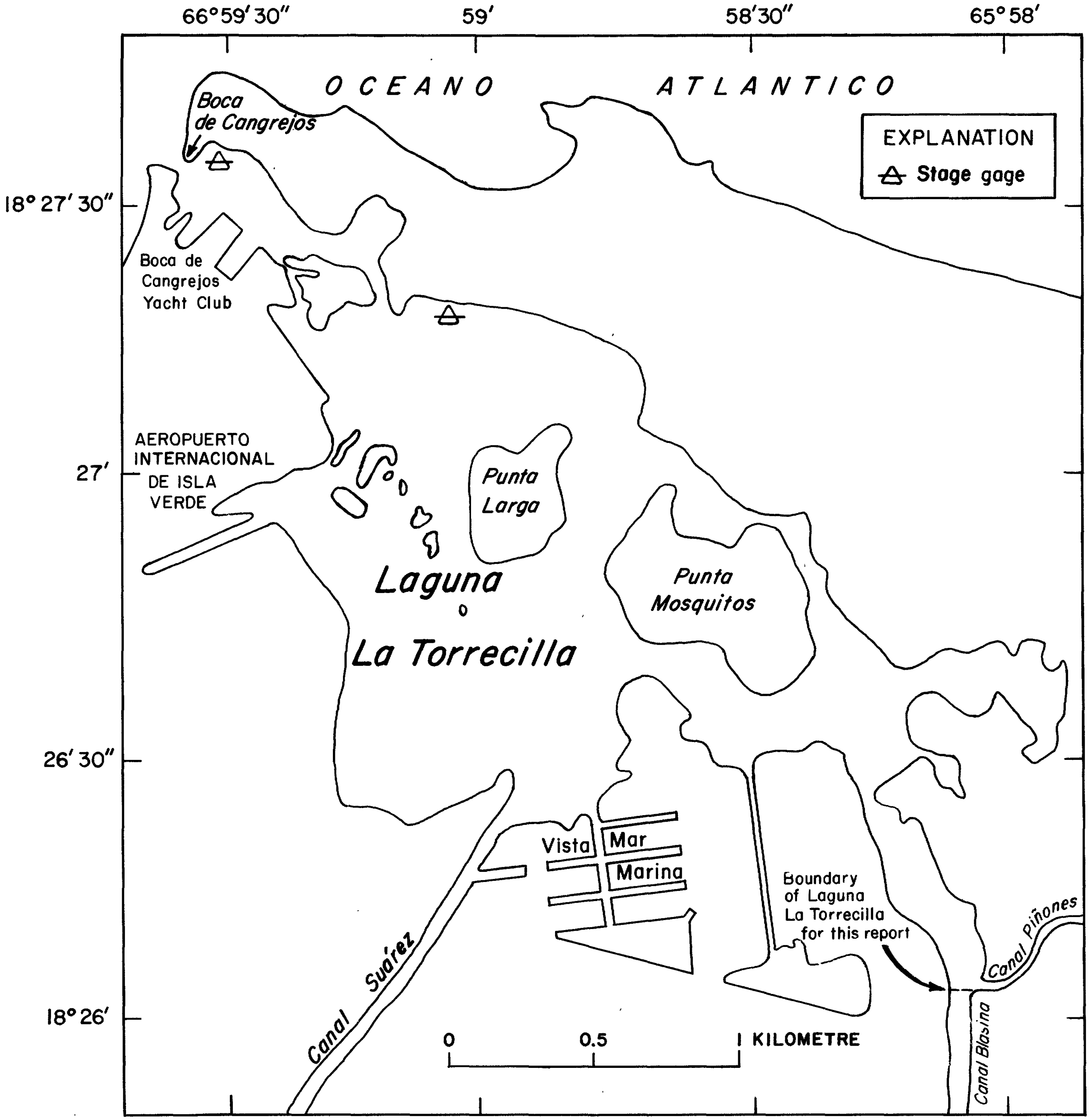


Figure 3.--General features of Laguna La Torrecilla.

Laguna de Piñones

Laguna de Piñones with a surface area of 105 ha, located east of Laguna La Torrecilla, is the only lagoon in the area in a nearly natural state (fig. 4). Dredging and filling has not occurred in the lagoon and only about 5 percent of the shoreline has been cleared of mangrove. The cleared area, on the northeast shore, is occupied by a forestry station and two or three homes. The maximum tidal range is about 0.3 m. The average specific conductance is about 43,000 micromhos.

Laguna de Piñones likely would contain fresh or slightly brackish water were it not for the connection with Laguna La Torrecilla by way of Canal Piñones. Brackish water from Laguna La Torrecilla and nutrients from Canal Blasina enter Laguna de Piñones through the canal.

Some general characteristics of Laguna de Piñones are given in table 1.

Laguna San José

Laguna San José (fig. 5), located west of Laguna La Torrecilla, is the largest lagoon, with a surface area of about 547 ha. U.S. Geological Survey topographic maps show the lagoon as two lagoons, Laguna Los Corozos in the northern part and Laguna San José in the southern part. For the purpose of this study, the entire body of water is referred to as Laguna San José.

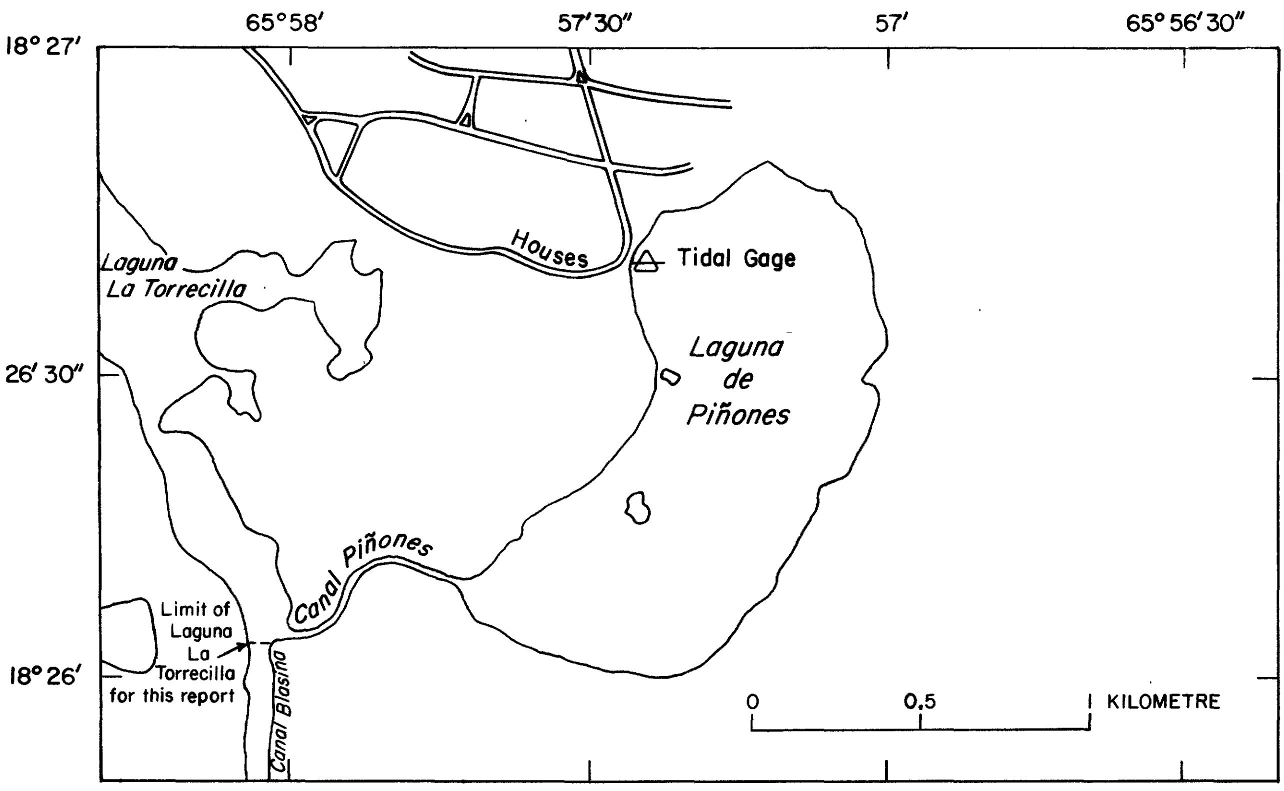


Figure 4.--General features of Laguna de Piñones.

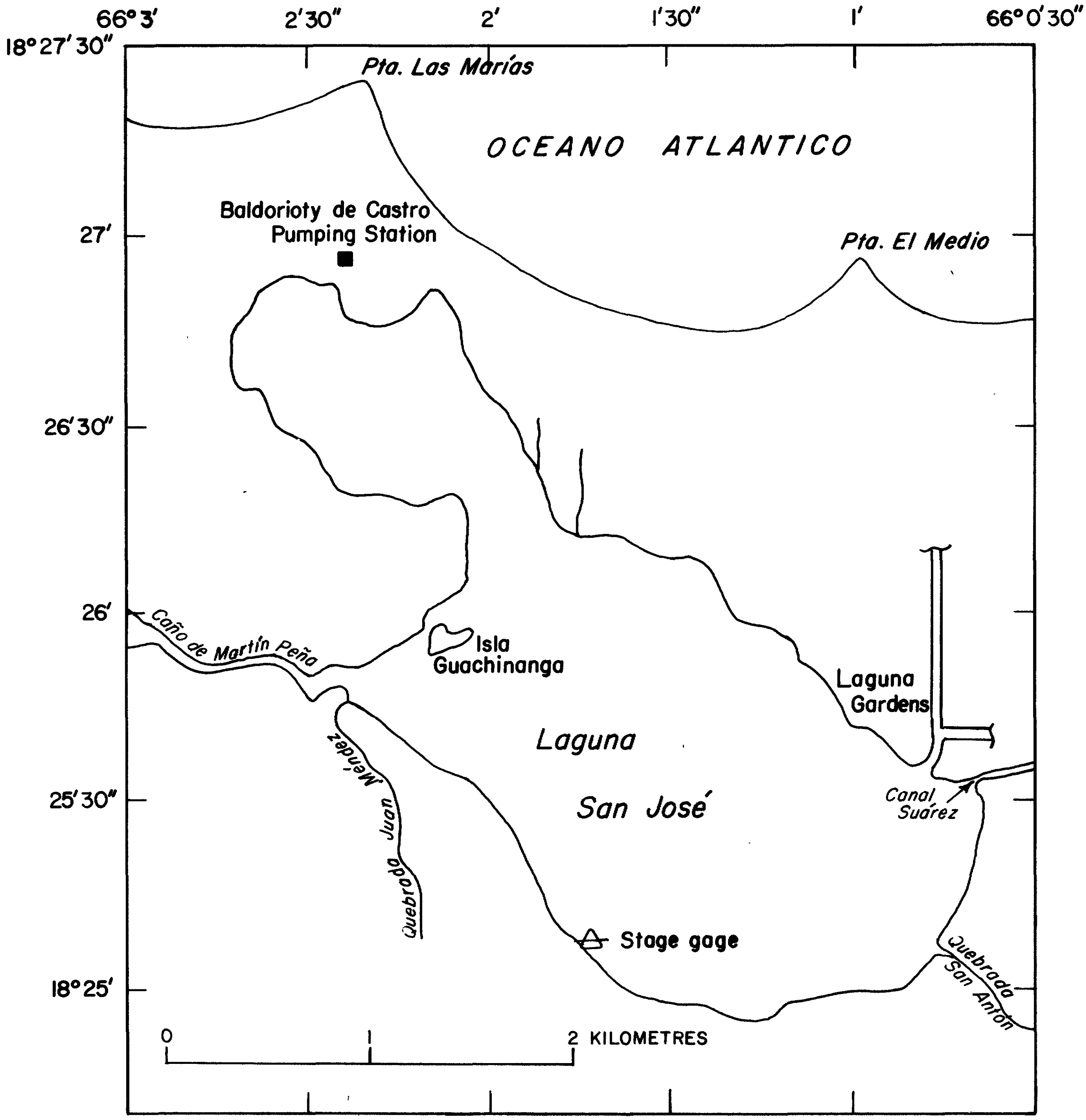


Figure 5.--General features of Laguna San José.

Dredging and activities by man have altered the bottom and immediate area. The apparently once uniform bottom of the lagoon (estimated predredged maximum depth of about 3 m) has been deepened locally to about 11 m; and the mangrove forest that once surrounded the lagoon has been cleared, except on the southern and eastern shores.

Laguna San José has the smallest tidal range of the lagoons, about 0.15 m maximum. This is probably caused by the long, narrow connecting canals. Canal Suárez, which connects Laguna San José to Laguna La Torrecilla, is about 3.3 km long and Caño de Martín Peña, which connects Laguna San José to Bahía de San Juan is about 5.1 km long.

The average specific conductance of Laguna San José, the lowest of the lagoons, is about 20,000 micromhos in shallow areas and to a depth of about 1 m in dredged areas and about 40,000 micromhos below 1 m. The low specific conductance is due to the large amount of freshwater inflow from the Baldorioty de Castro pumping station (about 16,000 m^3 per day), ground water (as much as 10,000 m^3 per day; Anderson, in preparation), storm drains, and streams. The two streams, Quebrada San Antón and Juan Méndez, contribute little water except during storm-runoff periods.

The largest volume of brackish water entering Laguna San José is through Canal Suárez. Data collected in August 1973 indicate that about 70 percent of all the brackish water entering and leaving Laguna San José flows through Canal Suárez. The canal receives wastes from at least two drainage canals. Wastes in the drainage canals have foul odors and their colors range from bright red to black. The discharge is usually small, less than 0.03 m^3/s; however, it degrades the quality of the incoming water from Laguna La Torrecilla.

Caño de Martín Peña is the secondary source of brackish water for Laguna San José, about 30 percent of the total volume (Environmental Protection Agency, 1971). Newspaper articles and visual inspection show that the canal is a carrier of many forms of pollution--oil, grease, sewage, and industrial wastes.

Some general characteristics of the lagoon are given in table 1.

Laguna del Condado

Laguna del Condado (fig. 6), the smallest lagoon, has a surface area of about 31 ha and has the highest average specific conductance; about 50,000 micromhos. The lagoon has no connecting canals to the other lagoons. It is directly connected to the Oceano Atlantico, by way of the channel under Avenida Ashford Bridge and to Bahía de San Juan by way of Caño de San Antonio; however, the outlet to the ocean is partly blocked by Avenida Ashford Bridge. The lagoon receives freshwater from storm drains.

The maximum tidal range observed is about 0.6 m. The tidal oscillations are similar in magnitude and shape to those observed at Boca de Cangrejos, but without the interferences of momentum, due to storage in connecting water bodies and the effect of inflow.

Some general characteristics of the Laguna del Condado are given in table 1.

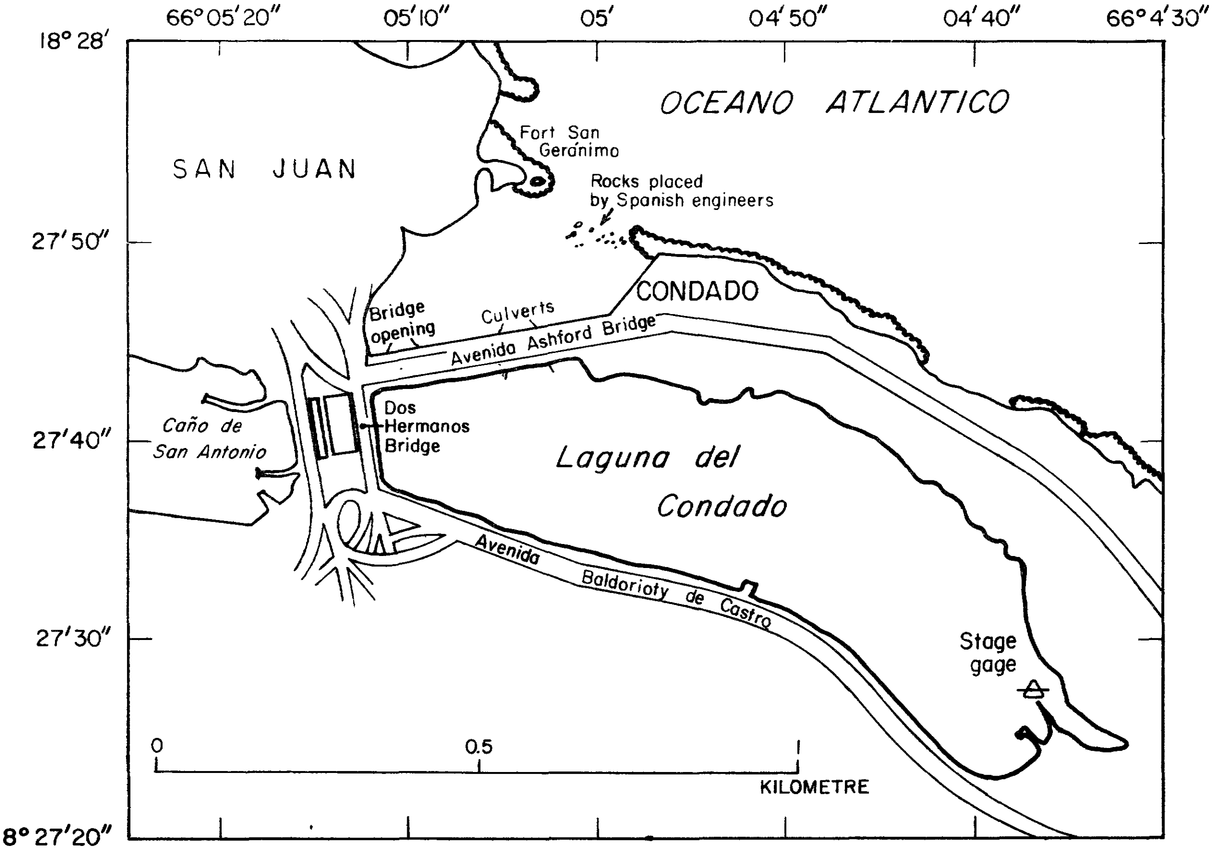


Figure 6.--General features of Laguna del Condado.

Laguna del Condado has been studied on several occasions. The Environmental Protection Agency (1971) and the University of Puerto Rico, School of Medicine (1968) found the lagoon to be contaminated with raw or partly treated sewage. Several sources of pollution have been eliminated from the lagoon since the Environmental Protection Agency study of January 1971. At present, this lagoon probably has the best water quality of any of the lagoons.

The School of Medicine study (University of Puerto Rico, 1968) reported that flow through Laguna del Condado was short circuited between the Ashford and Dos Hermanos Bridge openings. A tidal cycle study in August 1973 by the U.S. Geological Survey, during which current meter measurements were made at hourly intervals, indicated no reversal of flow. Several visual observations of flow direction, using a weighted line with streamers attached, verify the work of the School of Medicine and previous findings of the Geological Survey, except for two occasions.

The one-directional flow probably is caused by a series of shallow reefs that form an arc from the water's edge west of the mouth of Laguna del Condado to a point about 0.5 km offshore and about 2 km east of the mouth. The prevailing winds, ocean currents, and wave action combine to produce a westerly flow in this area. The shallow reefs block the flow and water tends to build up inside the reef area, near the mouth of Laguna del Condado. The mouth offers an escape route and the flow moves from the high build-up area into the lagoon through the Avenida Ashford Bridge.

The placement of the bridge opening in Avenida Ashford, at the west end of the lagoon (see fig. 6), diverts the flow toward nearby Dos Hermanos Bridge opening and into Bahía de San Juan through the Caño de San Antonio. The ocean, Bahía de San Juan, and Laguna del Condado probably have about the same tidal fluctuations; thus, the tidal fluctuations do not interrupt the flow gradient, and the flow is usually inward at Avenida Ashford Bridge and outward at Dos Hermanos Bridge.

On the few occasions when flow has been observed outward through Avenida Ashford Bridge, a south or southeasterly wind has been recorded by the weather station at Isla Verde International Airport. The ocean was observed to be calm, with little or no wave action. The south or southeasterly wind had apparently broken down the prevailing wave and current movement, thus reducing the buildup in the reef area. Flow then could move outward through Ashford Avenue Bridge during an ebb tide.

RESULTS OF THE TIDAL-CYCLE STUDY

Monitoring Sites

Seven sites were selected to measure the water that flows in and out of each lagoon (see fig. 1). The sites selected were assumed to be representative of the flow between connecting lagoons or the ocean. The name of the site and identification number are given in table 2. Figure 1 also shows the locations of the 5 stage gages in Laguna La Torrecilla, Laguna de Piñones, Laguna San José, and Laguna del Condado.

Flow Data

The tidal fluctuation during the study period at Boca de Cangrejos, Laguna La Torrecilla, Laguna de Piñones, Laguna San José, and Laguna del Condado recording stage gages are shown in figures 7 through 11. Due to unreliable bench marks located in the eastern part of the study area, the stage gages, with the exception of Laguna del Condado, were not tied to mean sea level.

Hourly readings were taken at a staff gage on Canal Suárez at Highway 26 Bridge.

The period before the January 22–25, 1974, study was relatively dry, with less than 5 mm of precipitation in each of the two preceding days. The initial freshwater inflow was probably near base-flow conditions. About 20 mm of rain fell in the western part of the study area, while only about 3 mm was recorded at the Isla Verde International Airport station during the night of January 23-24. These rains produced high flow in the canals from heavy overland runoff in the western part. See table 3 for climatological data.

Table 2.--Listing of numbers, names, latitudes and longitudes of stage gages, and monitoring sites

U.S.G.S. index number	Name	Latitude	Longitude	Type of site
50 0503 30	Laguna de Piñones near Carolina --------	18°26'39"	65°27'26"	Stage gage
50 0503 60	Laguna La Torrecilla near Carolina -------	18°27'18"	65°59'02"	Stage gage
50 0503 80	Boca de Cangrejos near Carolina --------	18°27'27"	65°59'30"	Stage gage
50 0500 20	Laguna del Condado at Santurce---------	18°27'26"	66°04'34"	Stage gage
50 0498 00	Laguna San José at San Juan -----------	18°25'06"	66°01'44"	Stage gage
50 0498 40	Caño de Martín Peña at Barbosa Bridge at San Juan------------	18°25'52"	66°02'51"	Monitoring
50 0499 00	Caño de Martín Peña at Constitution Bridge at San Juan------------	18°26'28"	66°04'58"	Monitoring
50 0500 45	Laguna del Condado at Avenida Ashford Bridge at Santurce------------	18°27'44"	66°05'10"	Monitoring
50 0555 50	Laguna del Condado at Dos Hermanos Bridge at Santurce------------	18°27'41"	66°05'13"	Monitoring
50 0503 46	Canal Piñones near Carolina-----------	18°26'10"	65°57'46"	Monitoring
50 0503 53	Canal Suárez at Highway 26 Bridge near Carolina---------------	18°25'47"	65°59'26"	Monitoring
50 0503 75	Boca de Cangrejos Bridge near Carolina----	18°27'36"	65°59'34"	Monitoring

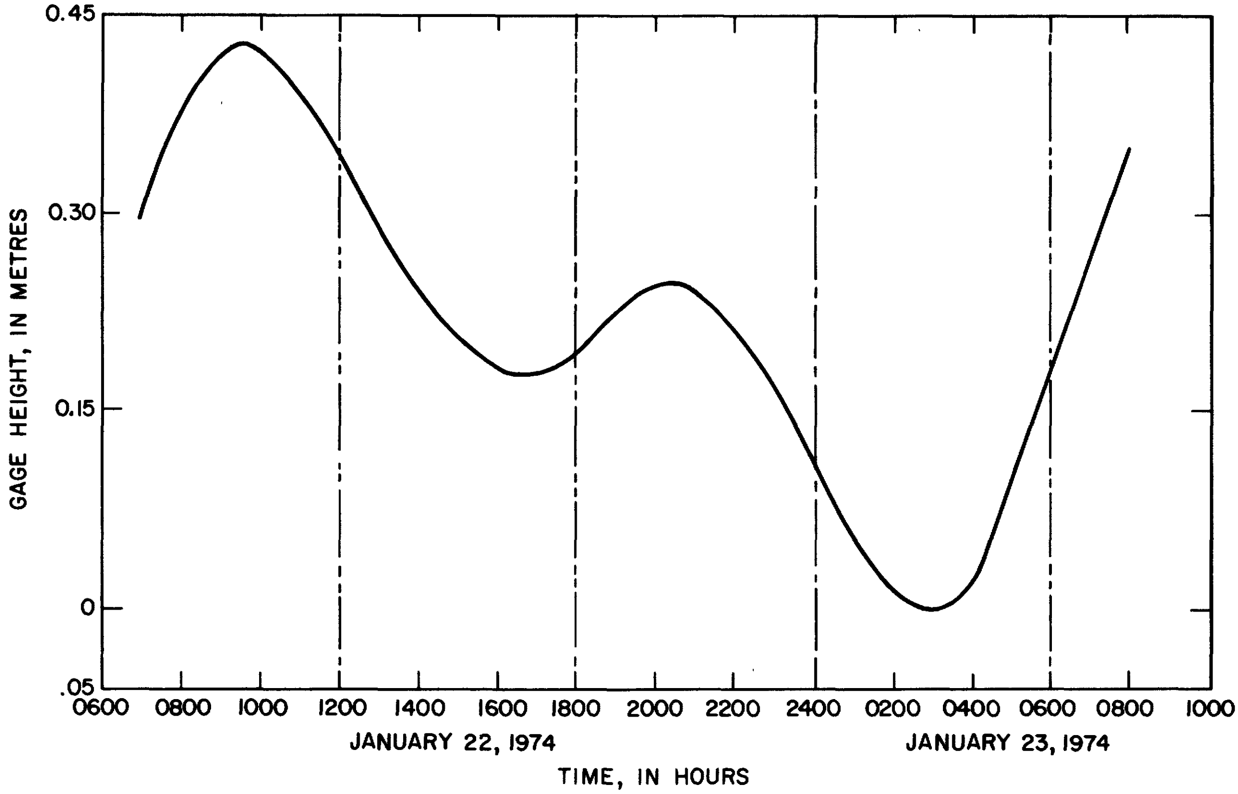
Table 3.--Climatological data for January 20-25, 1974

Hour	Wind[1/] Direction	Wind[1/] Speed	Precipitation[2/] 3-hour total	Hour	Wind[1/] Direction	Wind[1/] Speed	Precipitation[2/] 3-hour total
			January 20, 1974				
0300	17	06	0	1500	08	28	0
0600	12	09	0	1800	09	28	0
0900	11	19	1.0	2100	11	17	0
1200	09	32	2.5	2400	16	09	0
			January 21, 1974				
0300	14	09	0	1500	10	28	0
0600	12	11	T	1800	16	24	T
0900	10	09	2.3	2100	10	22	1.8
1200	09	22	.5	2400	13	11	0
			January 22, 1974				
0300	14	11	T	1500	08	26	0
0600	16	09	1.0	1800	09	20	0
0900	10	13	0	2100	10	22	0
1200	07	19	1.5	2400	17	09	3.6
			January 23, 1974				
0300	18	09	1.5	1500	09	32	T
0600	15	09	00	1800	09	26	T
0900	10	22	0	2100	09	28	0
1200	12	30	0	2400	09	32	0
			January 24, 1974				
0300	10	30	.2	1500	08	33	0
0600	10	30	2.3	1800	10	26	.8
0900	09	26	.5	2100	09	26	0
1200	08	30	T	2400	11	22	0
			January 25, 1974				
0300	10	22	0	1500	08	32	0
0600	10	19	T	1800	09	13	1.5
0900	11	26	.2	2100	14	09	T
1200	09	26	0	2400	09	28	.2

[1/] Direction is that from which the wind blows, indicated in tens of degrees from true North: i.e., 09 for East, 18 for South, 27 for West, and 36 for North. Speed in kilometres per hour.

[2/] Values in millimetres. T = trace and indicates precipitation in an amount too small to measure.

[Data from National Oceanic and Atmospheric Administration Weather Station, Isla Verde International Airport, Puerto Rico.]



Fiqure 7.--Tidal fluctuations of Laguna La Torrecilla at Boca de Cangrejos.

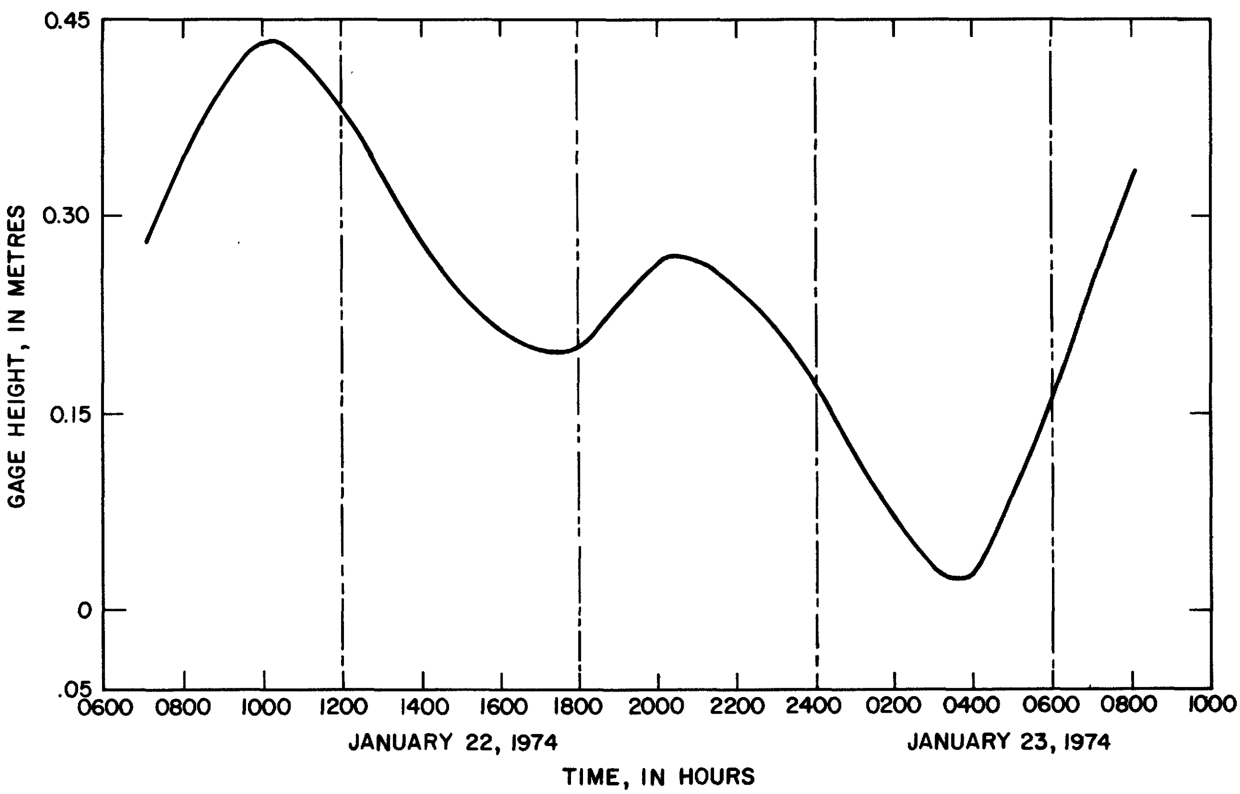


Figure 8.--Tidal fluctuations of Laguna La Torrecilla.

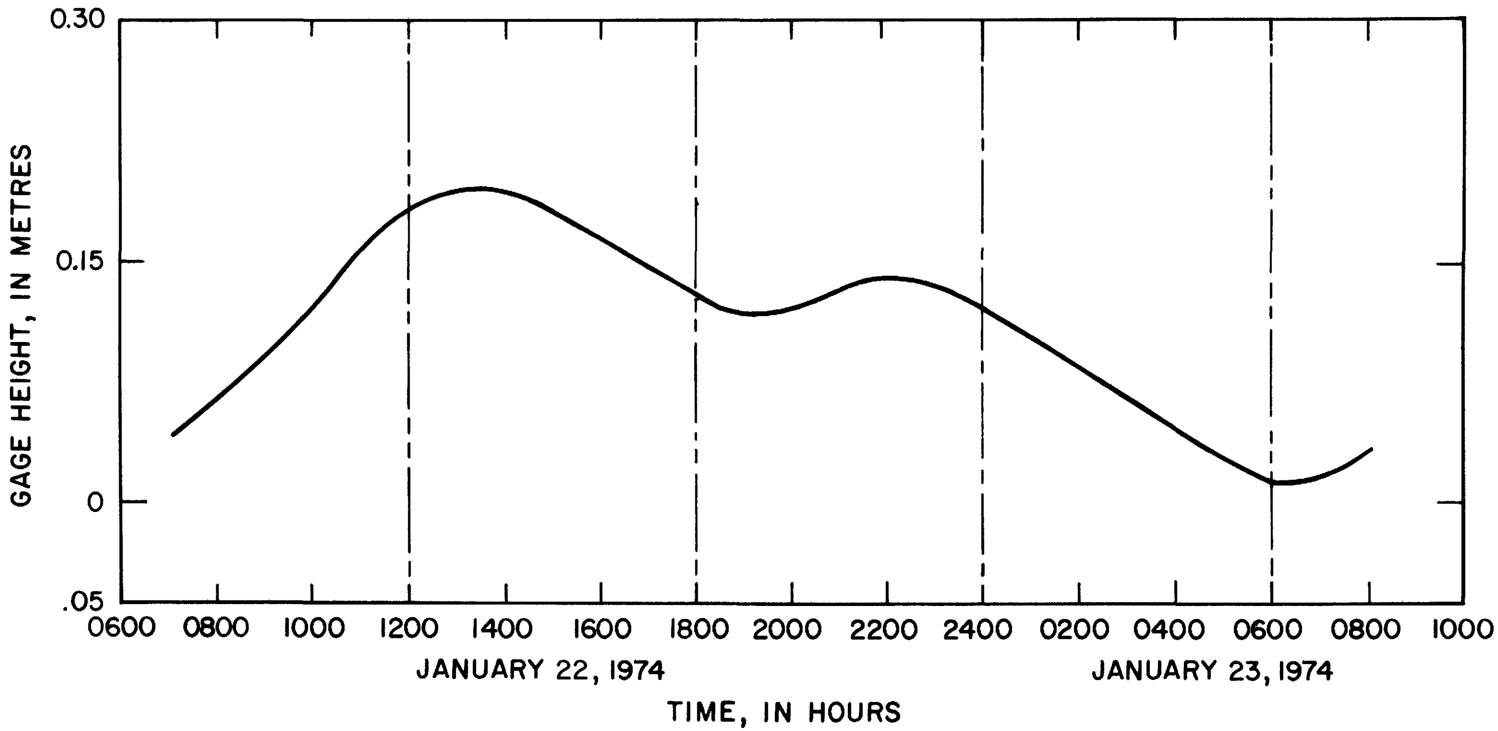


Figure 9.--Tidal fluctuations of Laguna de Piñones.

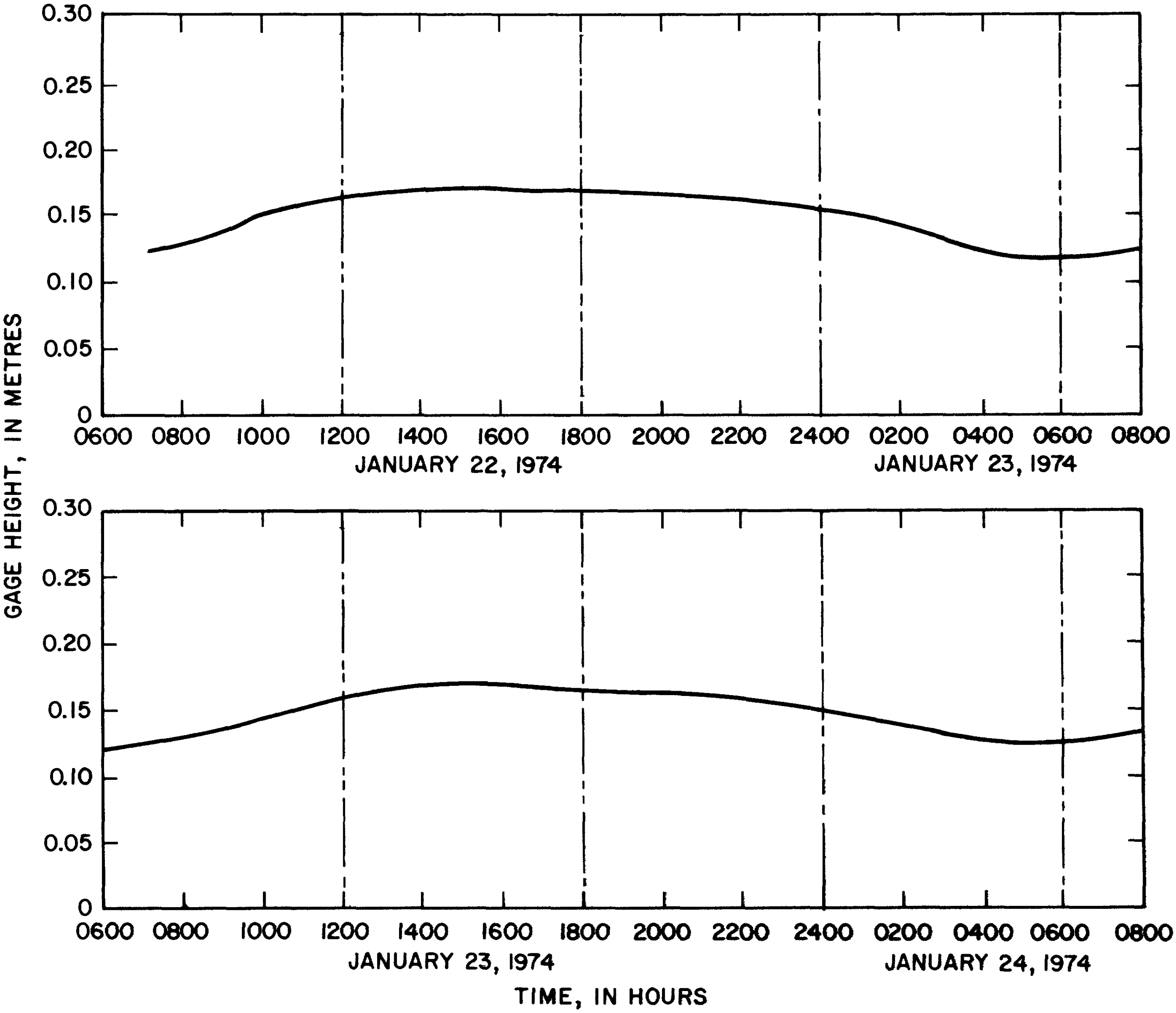


Figure 10.--Tidal fluctuations of Laguna San José.

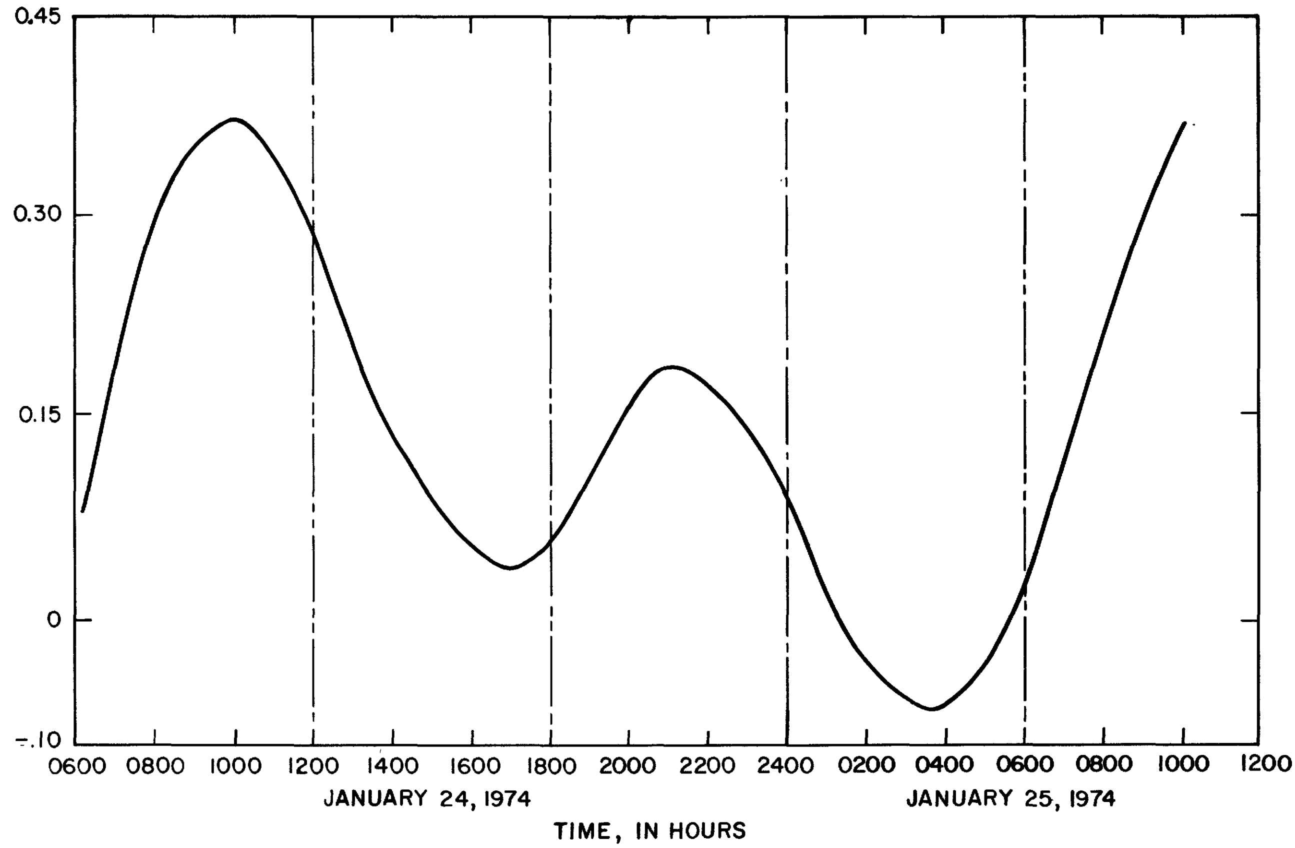


Figure 11.--Tidal fluctuations of Laguna del Condado.

Boca de Cangrejos

A net outward flow of water through Boca de Cangrejos of 230,000 m^3 was measured during the study; although, the Boca de Cangrejos and Laguna La Torrecilla tidal gages registered a higher water elevation at the end of the study than at the beginning. Figure 12 is a graphic illustration of the flow through Boca de Cangrejos. A summary of the flow data is given in table 4.

Laguna La Torrecilla is a complex hydraulic system. It receives and discharges water through three channels: Boca de Cangrejos (to and from the Oceano Atlantico), Canal Piñones (to and from Laguna de Piñones), Canal Suárez (to and from Laguna San José), and receives water from Canal Blasina (Quebrada Blasina). At a given time, Torrecilla can be receiving water from all channels, discharging to all channels, or a combination of both. During the 25-hour study, water was flowing out of Laguna La Torrecilla through all exits from 1030 to 1320 January 22 and was flowing in through all channels from 0340 until 0540 on January 23.

Canal Piñones

A net flow of water into Laguna de Piñones, 11,000 m^3, was measured even though the tidal gage registered identical stages at the start and finish of the study. The difference (less than 3 percent) is a small part of the total flow and is within the error of flow measurements. Figure 13 shows the flow through Canal Piñones. A summary of the flows is included in table 4.

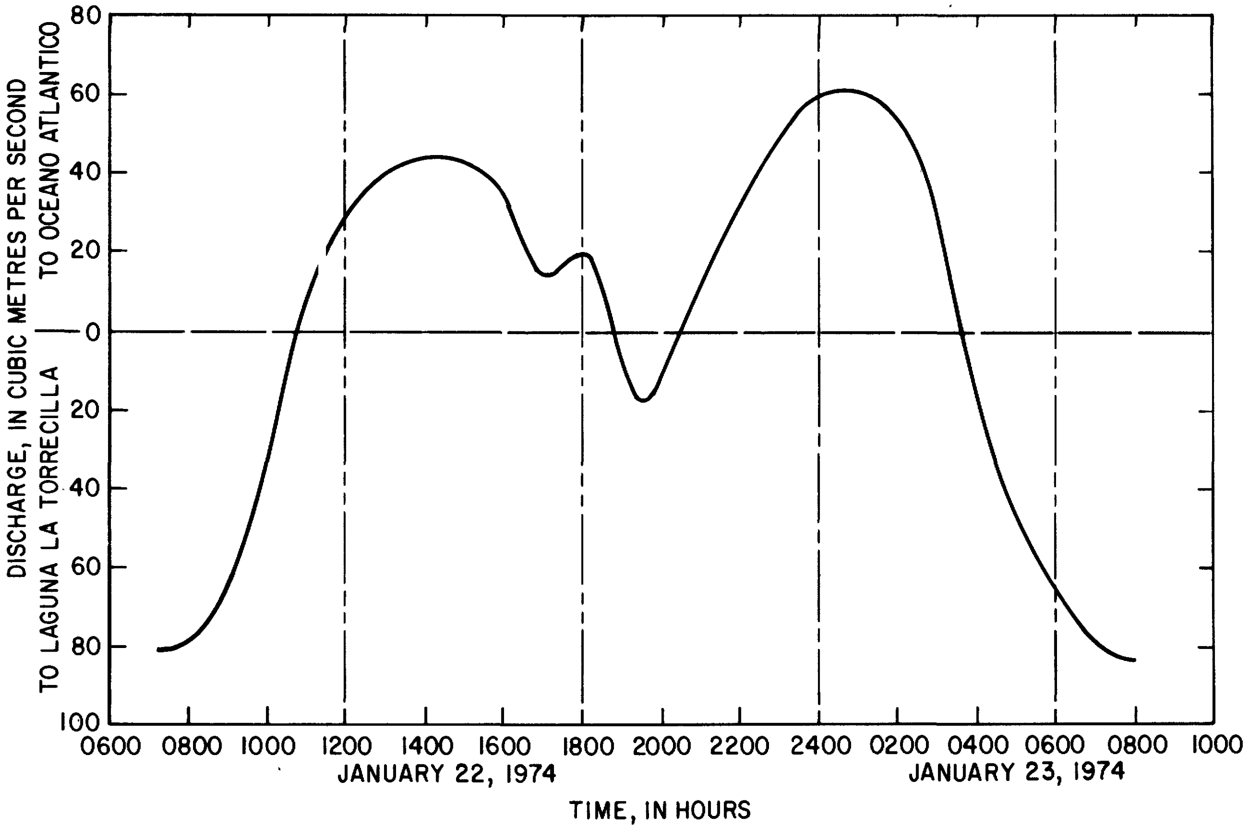


Figure 12.--Flow through Boca de Cangrejos.

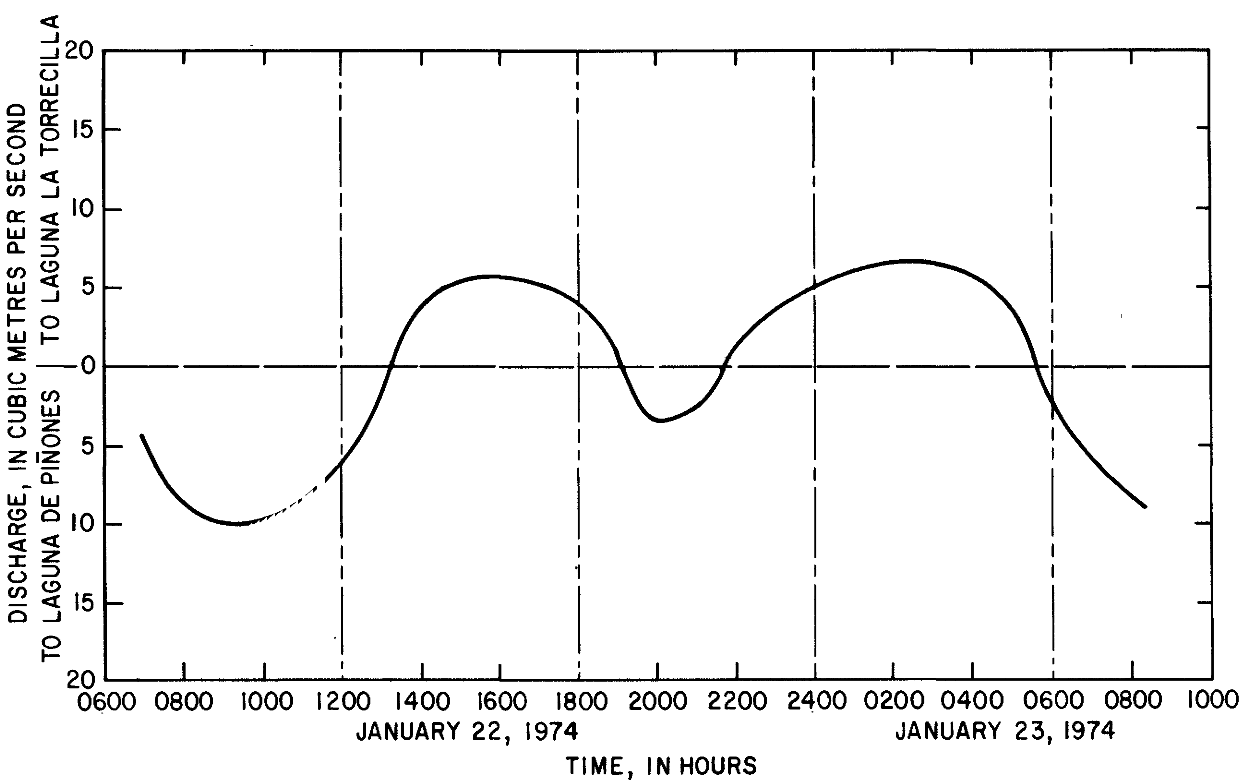


Figure 13.--Flow through Canal Piñones.

Table 4.--Flow data for the tidal-cycle study sites

Site	Date (January 1974)	Direction	Volume $m^3 \times 10^3$	Direction	Volume $m^3 \times 10^3$	Net flow	
						Direction	Volume $m^3 \times 10^3$
Boca de Cangrejos. .	22-23	Ocean	1,920	Torrecilla	1,690	Ocean	230
Canal Piñones	22-23	Torrecilla	225	Piñones	236	Piñones	11
Canal Suárez	22-23	Torrecilla	350	San José	290	Torrecilla	60
Canal Suárez	23-24	Torrecilla	370	San José	276	Torrecilla	94
Caño de Martín Peña at Barbosa Bridge	23-24	Bahía de San Juan	153	San José	122	Bahía de San Juan	31
Caño de Martín Peña at Constitution Bridge	23-24	Bahía de San Juan	637	San José	137	Bahía de San Juan	500
Laguna del Condado at Avenida Ashford Bridge .	24-25	Ocean	0	Condado	2,150	Condado	2,150
Laguna del Condado at Dos Hermanos Bridge	24-25	Bahía de San Juan	2,030	Condado	0	Bahía de San Juan	2,030

The effects of rainfall runoff on the flow patterns of Laguna de Piñones is shown by comparison of the January 22-23, 1974, study with a similar study November 13-14, 1973. Precipitation preceded the November 1973 study (see fig. 14 for hourly precipitation and Laguna de Piñones tidal fluctuations) causing an increase in the elevation of Laguna de Piñones. The net flow was 81,000 m^3 outward from Laguna de Piñones (fig. 15); whereas, the stage increased 0.006 m from the start to the finish of the study.

Canal Suárez at Highway 26 Bridge

At this site, measurements of flow were made from 0700 January 22 to 0800 January 24, 1974. The first 25 hours were used for the flow data of Laguna La Torrecilla and the second 25 hours for the flow data of Laguna San José. Figure 16 shows the flows for the two collection periods. The data are summarized in table 4.

Two staff gages were set to the same datum on opposite sides of the old Highway 26 bridge, which is about 10 m west of the present bridge. The distance between staff gages is about 30 m. The water elevations were recorded before and after each hourly measurement. These data were analyzed to determine the effect of the bridge on the flow conditions of Canal Suárez. Results of the readings recorded during the study show that the Laguna San José side of the bridge had a tidal fluctuation of 0.06 m; whereas, the Laguna La Torrecilla side had a tidal fluctuation of 0.21 m. The maximum flow velocities were about 1.0 m/s. These data indicate that the bridge acts as a hydraulic constriction.

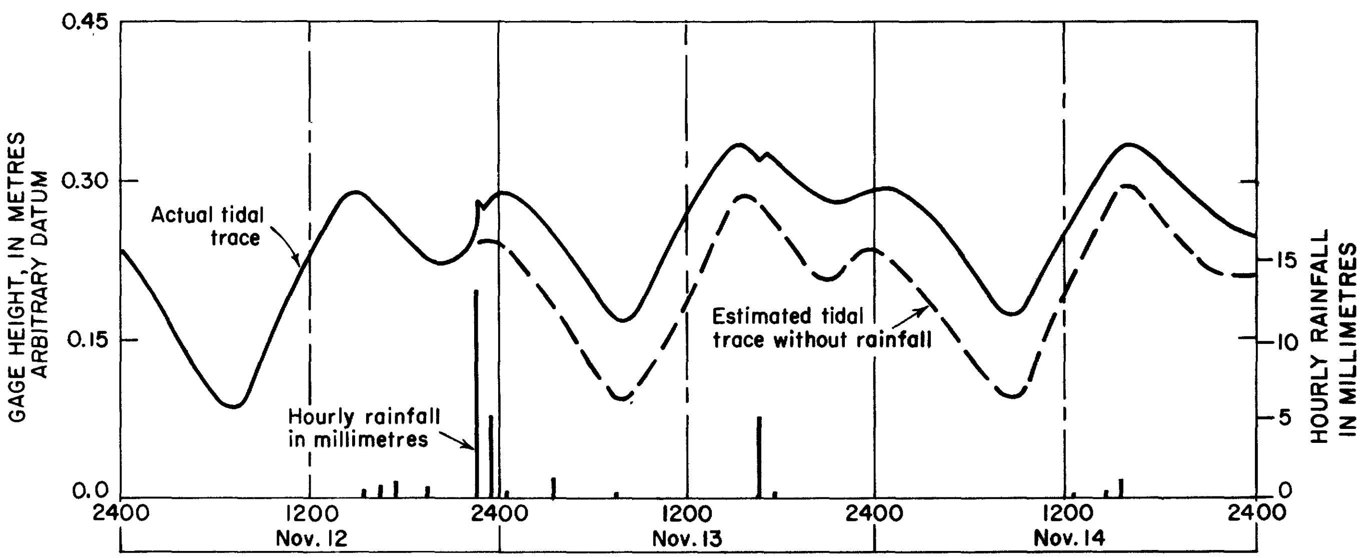


Figure 14.--Differences between actual tidal trace and estimated tidal trace without rainfall at Laguna de Piñones, November 1973.

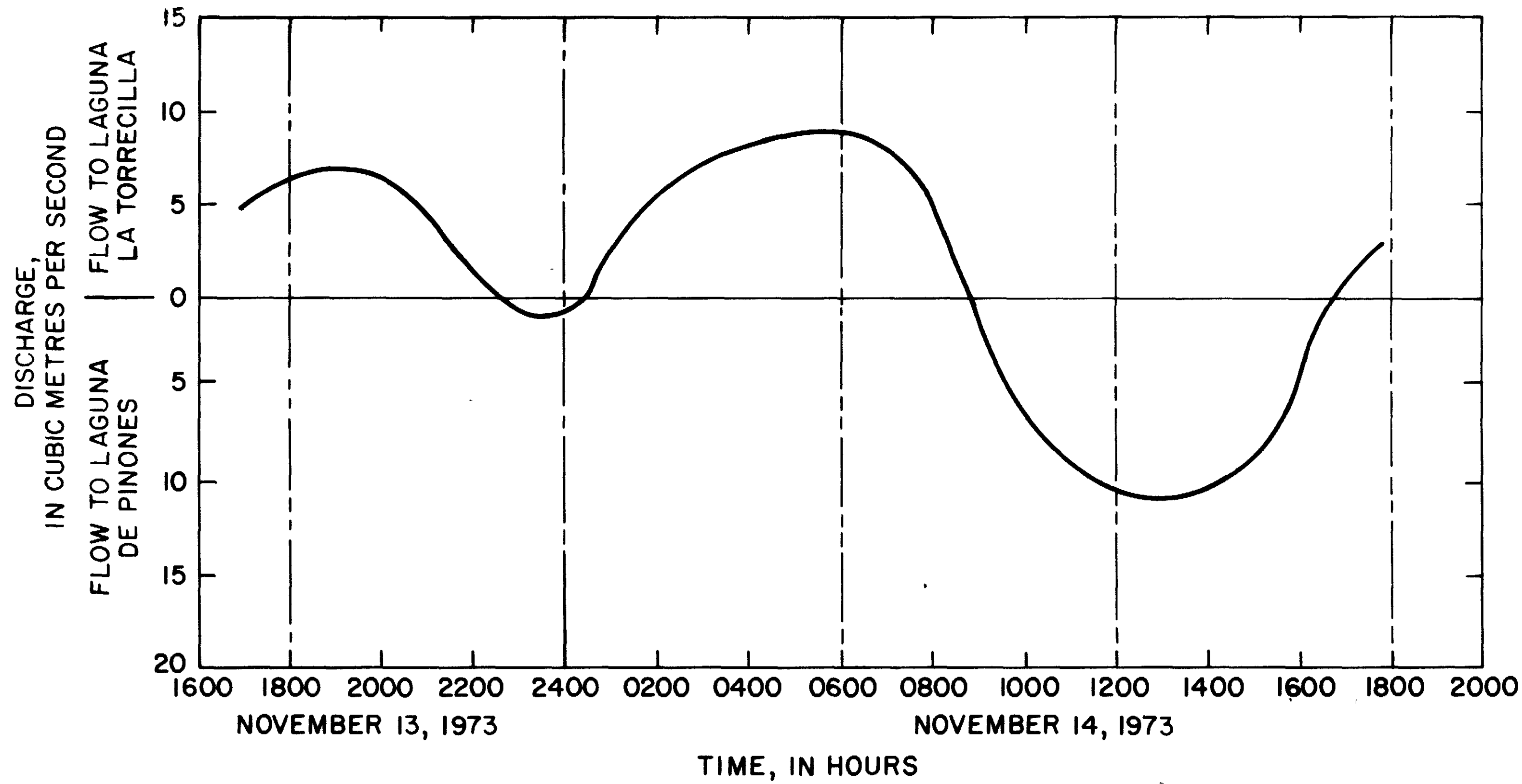


Figure 15.--Flow through Canal Piñones, November 1973.

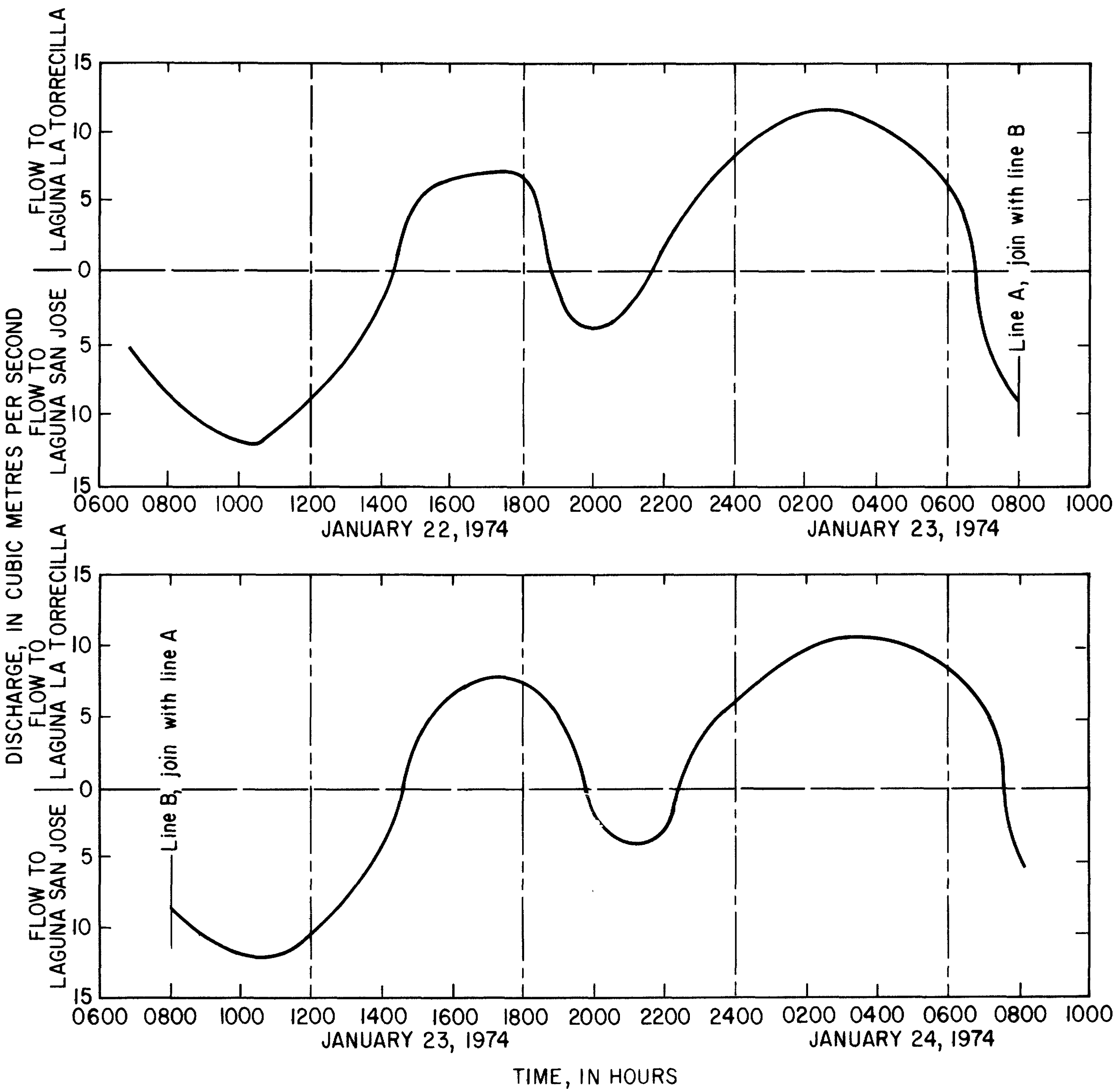


Figure 16.--Flow through Canal Suárez at Highway 26 Bridge.

Caño de Martín Peña at Barbosa Bridge

This site was monitored from 0700 January 23 to 0800 January 24, 1974. The flow data are shown in figure 17 and a summary is presented in table 4. Slow velocities and the very soft bottom made flow measurements difficult.

A similar type of study in August 1973 showed Caño de Martín Peña and Canal Suárez to be in phase as to the flow in and out of Laguna San José. The time of reversals of flow in both canals was within 1 hour of each other. During the time from about 1930 to 2230 January 23 a reversal of flow, resulting in flow out of Laguna San José, was expected at the Caño de Martín Peña at the Barbosa Bridge site. This reversal of flow did not occur; instead, a slight flow of water, about 1 m^3/s, continued into Laguna San José. During this period, a reversal of flow occurred at the Canal Suárez site, with water flowing out of Laguna San José. Apparently, localized showers centered west of the airport caused higher flow in the lower Río Puerto Nuevo basin and heavy pumping of storm-drain runoff into Caño de Martín Peña. The combination was sufficient to override the tidal reversal in Caño de Martín Peña, resulting in continuing flow into Laguna San José.

Caño de Martín Peña at Constitution Bridge

Heavy localized showers occurred during the night of January 23-24, causing higher-than-normal flows for the lower Río Puerto Nuevo. These higher flows and resultant pumping into Caño de Martín Peña from a stormdrain pumping station resulted in no reversal of flow from 0920 January 23 to 1800 January 24 when the study was terminated.

The total volume of outflow into Bahía de San Juan was 1.2×10^6 m^3 for the period 0920 January 23 to 1800 January 24, 1974. The flow data suggest a reversal of flow would have occurred in the absence of local runoff at about 1800 January 23 and 0300 January 24. These conditions may often occur because local runoff of this type is common. The overall shape of the flow curve is probably similar to a flow curve that would have resulted without the heavy rainfall. Figure 18 shows the flow curve. The data for the 25-hour study (0700 January 23 to 0800 January 24) are summarized in table 4.

Laguna del Condado at Avenida Ashford and Dos Hermanos Bridges

The flow curves (shown in figs. 19 and 20) from the two monitoring sites, Avenida Ashford and Dos Hermanos Bridges, show that flow direction of the tidal currents never reversed. At both sites, flows were consistantly between 18 and 32 m^3/s. Although no tidal reversals occurred at the sites, the effect on tidal action on the flow at each site can be seen when the flow curves and the tidal-fluctuation graph are combined (fig. 21). The net difference between the flow of the two sites at a given time is about equal to the calculated volume needed to maintain the rate of fluctuation of the lagoon.

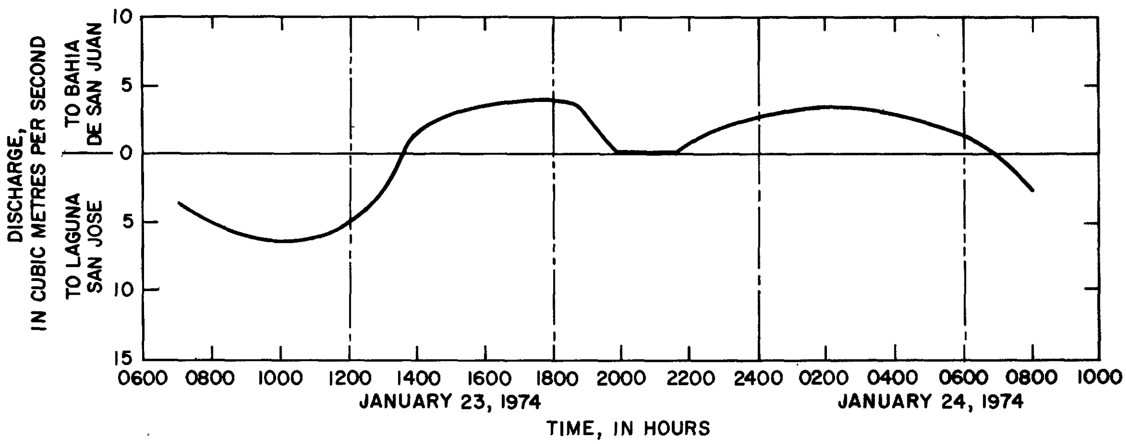


Figure 17.--Flow through Caño de Martín Peña at Barbosa Bridge.

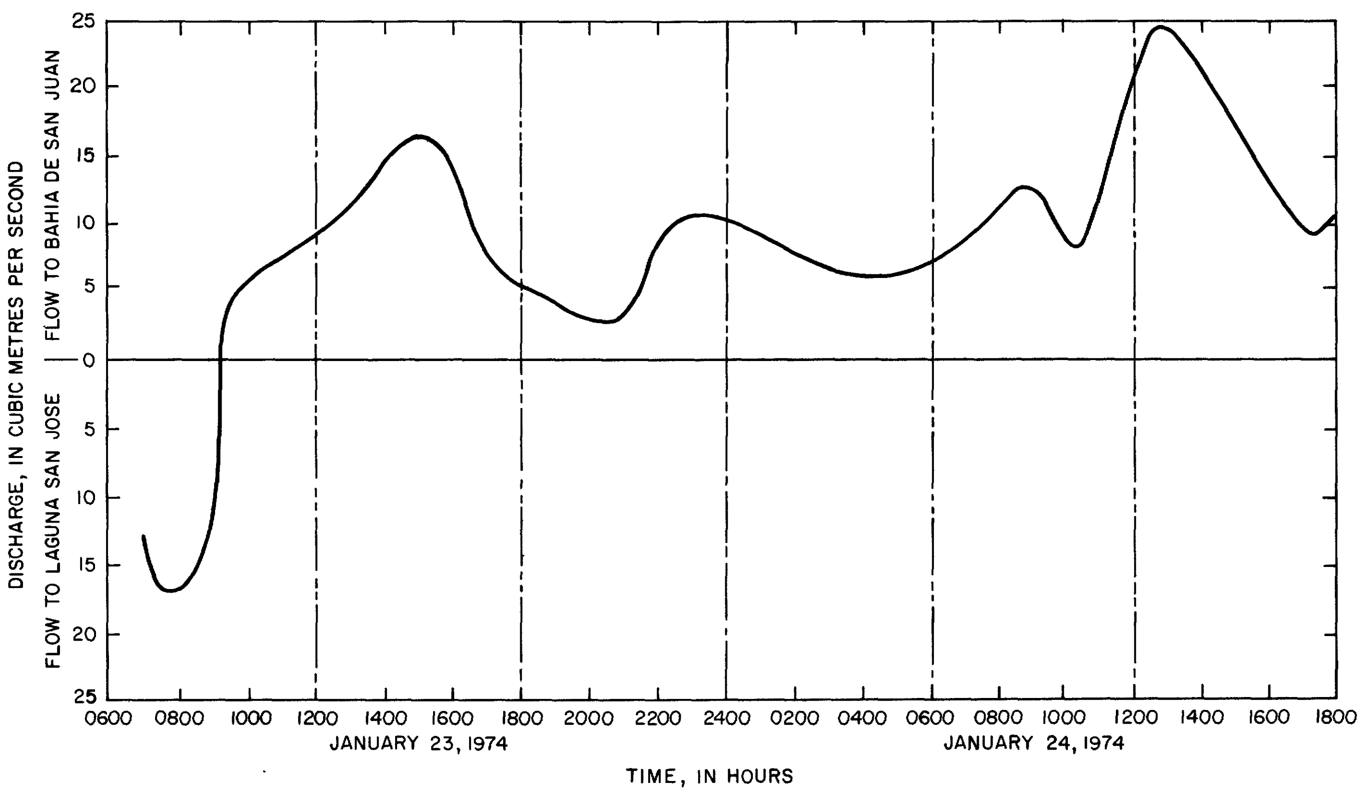


Figure 18.--Flow through Caño de Martín Peña at Constitution Bridge.

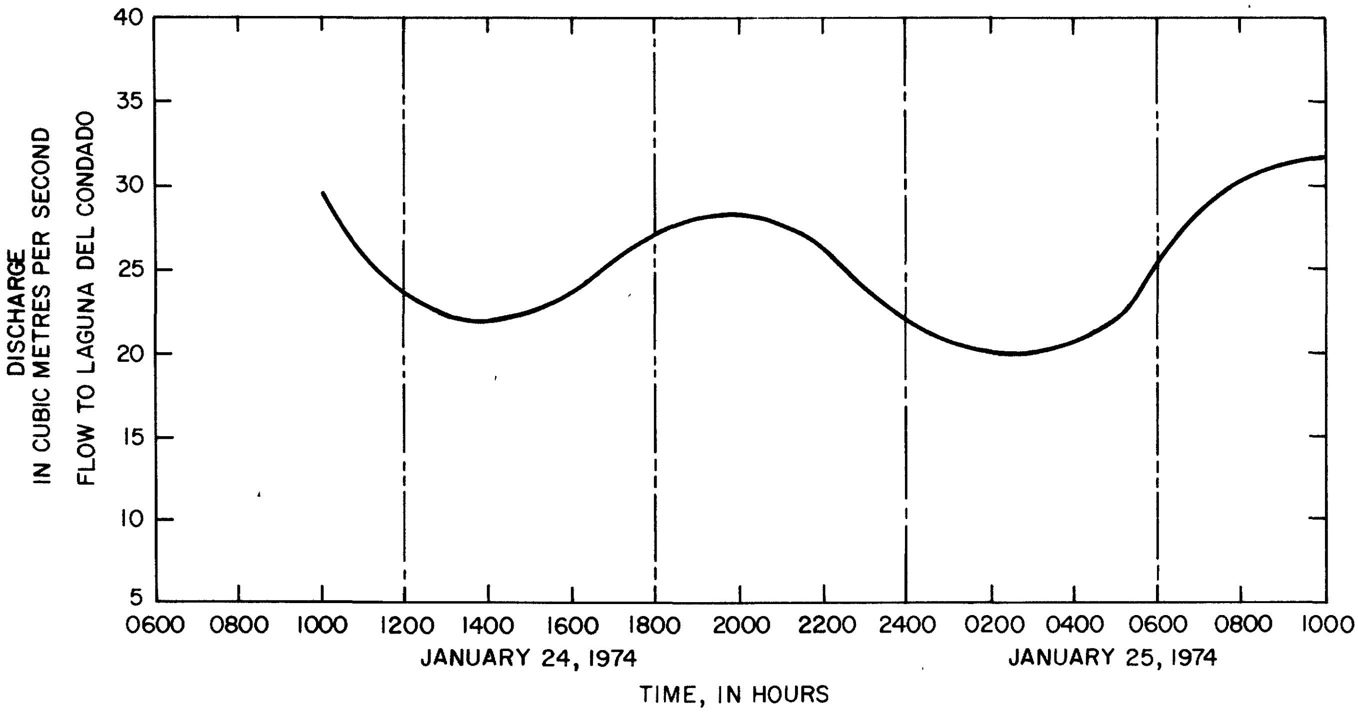


Figure 19.--Flow through Avenida Ashford Bridge.

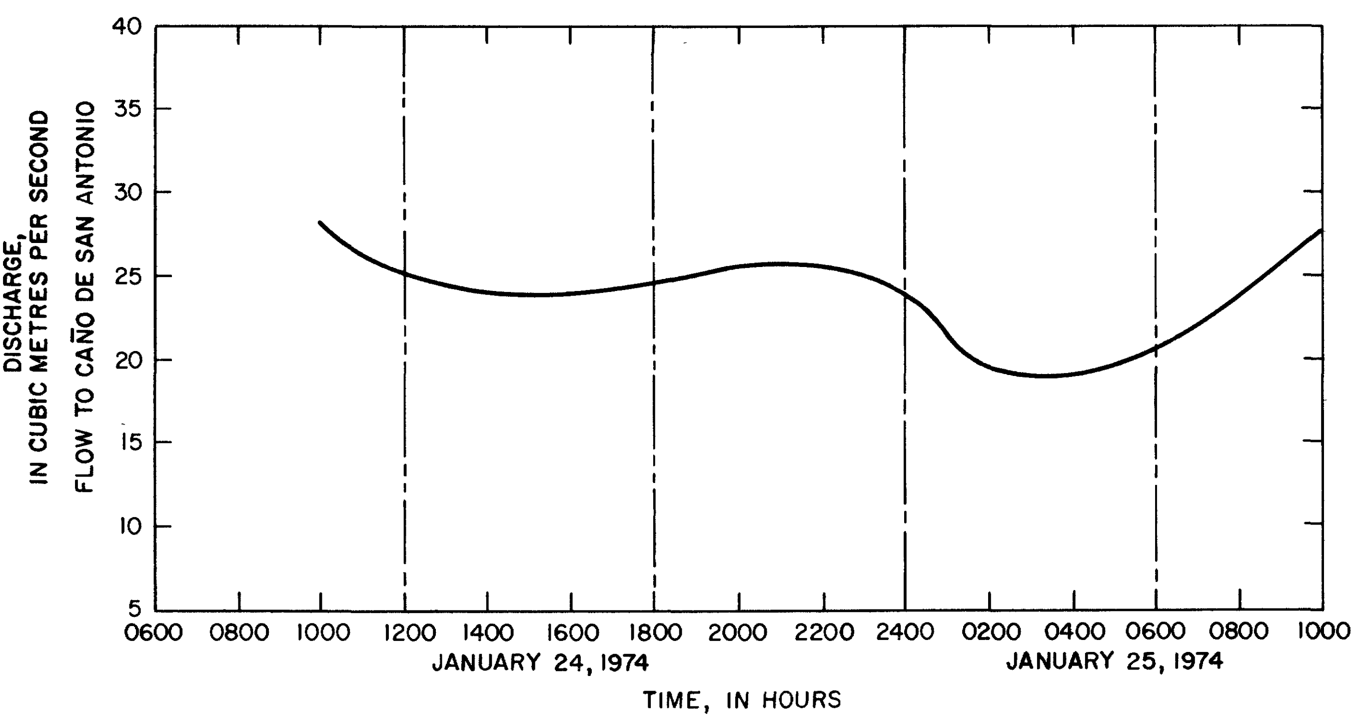


Figure 20.--Flow through Dos Hermanos Bridge.

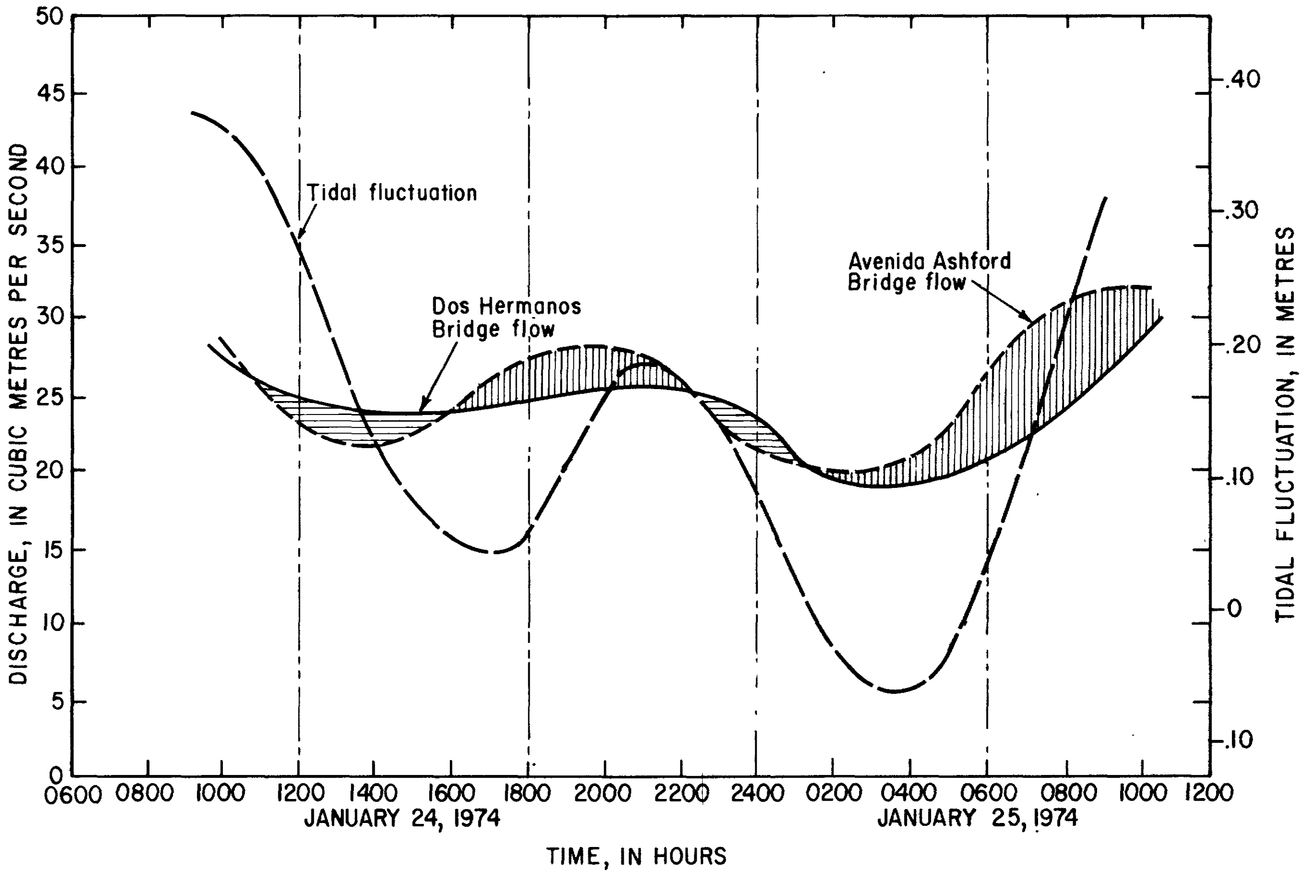


Figure 21.--Relation of flows through Avenida Ashford and Dos Hermanos Bridges and the tidal fluctuation of Laguna del Condado.

Water Quality

From January 22 to 25, 1974, water samples from the canals and outlets were collected hourly during the 25-hour measurement cycle at the seven sites. These samples were analyzed for TOC, $TOPO_4$, TP, and suspended sediment. Laguna de Piñones was also monitored for dissolved oxygen (DO).

Net loads, the difference between inflow and outflow of water quality constituents in g/s, were computed for carbon, phosphorus, and suspended sediment. A negative net load means a selected constituent is exported, and a positive net load means that a selected constituent is imported.

Boca de Cangrejos

TOC, $TOPO_4$, and TP are negative net loads at Boca de Cangrejos, with respect to Laguna La Torrecilla (fig. 22 and table 5). The only positive net load is suspended sediment. A possible explanation is that the wave action of the ocean maintains sand particles in suspension and during flood tide, sand particles are swept into the lagoon. Bottom samples taken from a large shallow area, east of Boca de Cangrejos and just inside the lagoon, show that the area is covered mainly by sand particles. The area was reported to have been dredged to about 3 m but is now less than 1 m.

Table 5.--Summation of inflow, outflow and loading of TOC, $TOPO_4$, TP, and suspended sediment of Laguna La Torrecilla through Boca de Cangrejos

Parameter	Inflow (tonnes)	Outflow (tonnes)	Net load (tonnes)
TOC..........	7.14	16.07	-8.93
$TOPO_4$, as P	.15	.39	- .24
TP, as P.......	.18	.72	- .54
Suspended sediment....	59.5	40.9	+18.6

Canal Piñones

TOC, DO, and suspended sediment are negative-net loads (fig. 23 and table 6) while TP and $TOPO_4$ are positive net loads with respect to Laguna de Piñones. The TP and $TOPO_4$ loads are balanced, probably, within the accuracy of the method. A lagoon that has balanced loads for one or more parameters is in equilibrium, in respect to these parameters, with the body of water to which it is connected for the given time period.

Of special interest to the ecology of Laguna de Piñones is the load of DO. Before this study, it was questioned whether the lagoon had the ability to produce DO necessary for aquatic life. The DO was believed to have been imported into the lagoon through Canal Piñones. The data from this present study, as well as data from a previous 24-hour primary productivity study, show that the lagoon is highly productive in terms of oxygen evolution and is an exporter of DO.

Table 6.--Summation of inflow, outflow and loading of TOC, $TOPO_4$, TP, suspended sediment, and dissolved oxygen of Laguna de Piñones through Canal Piñones

Parameter	Inflow (tonnes)	Outflow (tonnes)	Net load (tonnes)
TOC..........	2.42	3.13	-0.71
$TOPO_4$, as P	.14	.11	+.03
TP, as P.......	.20	.17	+.03
Suspended sediment....	1.92	3.25	-1.33
Dissolved oxygen.....	.51	1.83	-1.32

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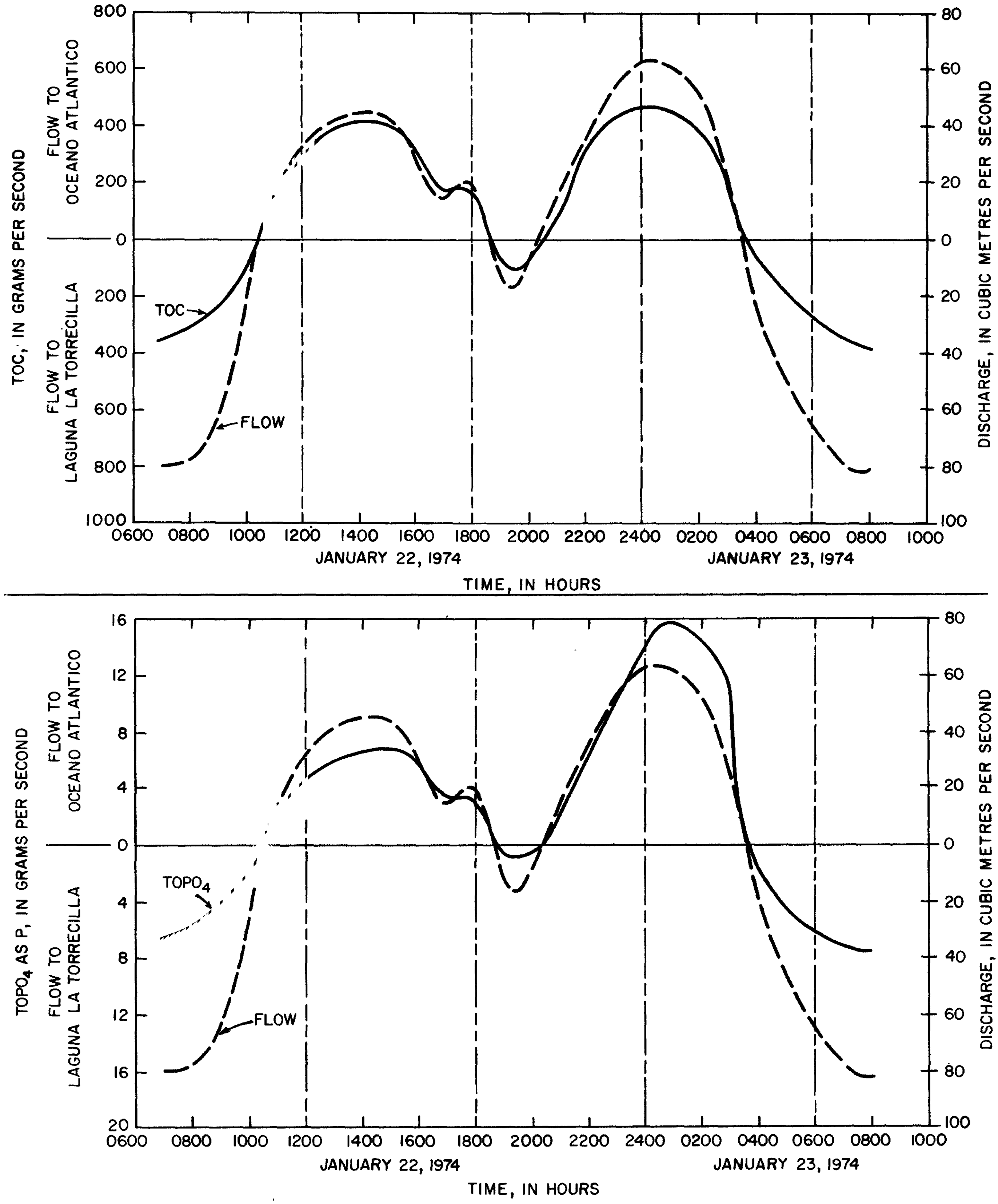
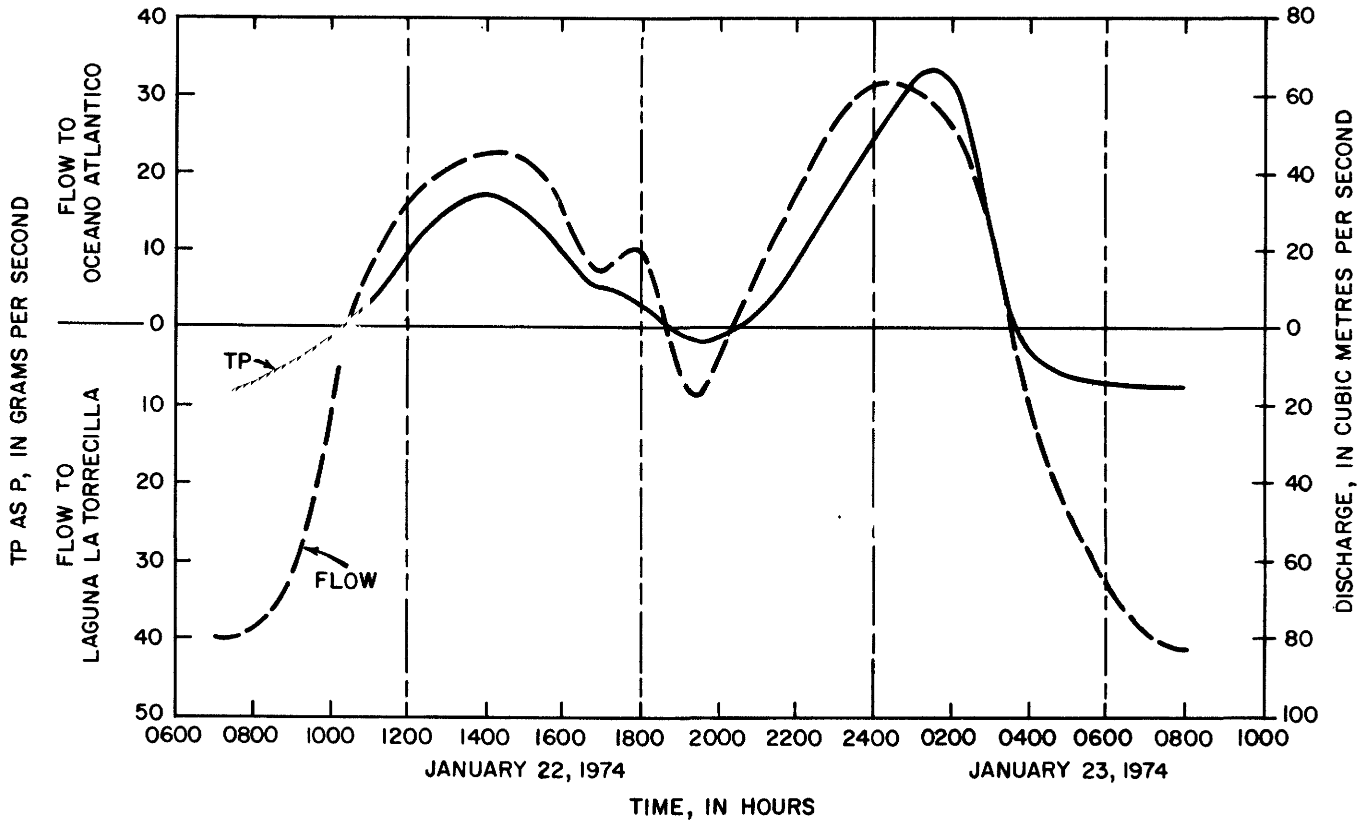


Figure 22.--Flow of selected water-quality parameters through Boca de Cangrejos [TOC (above) and $TOPO_4$ (below)].



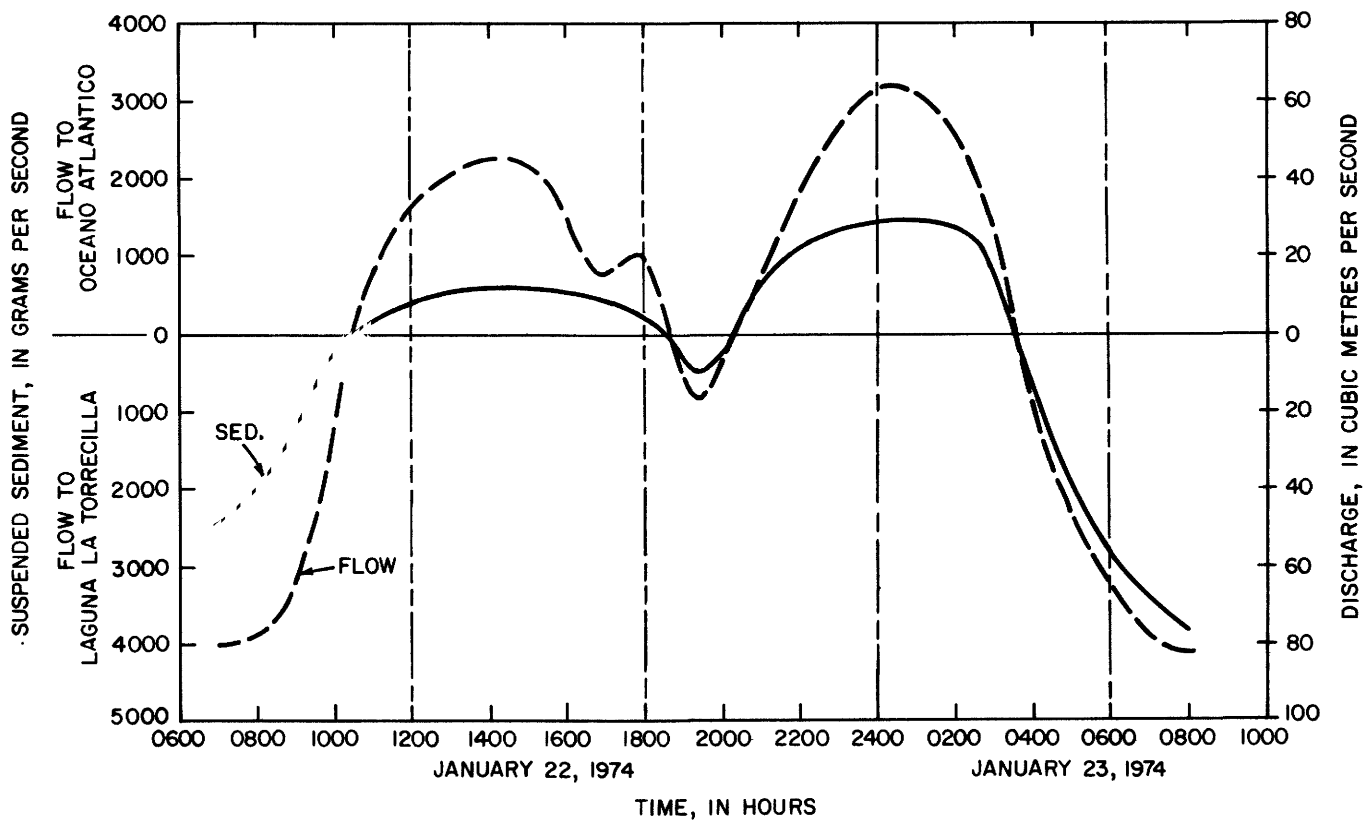
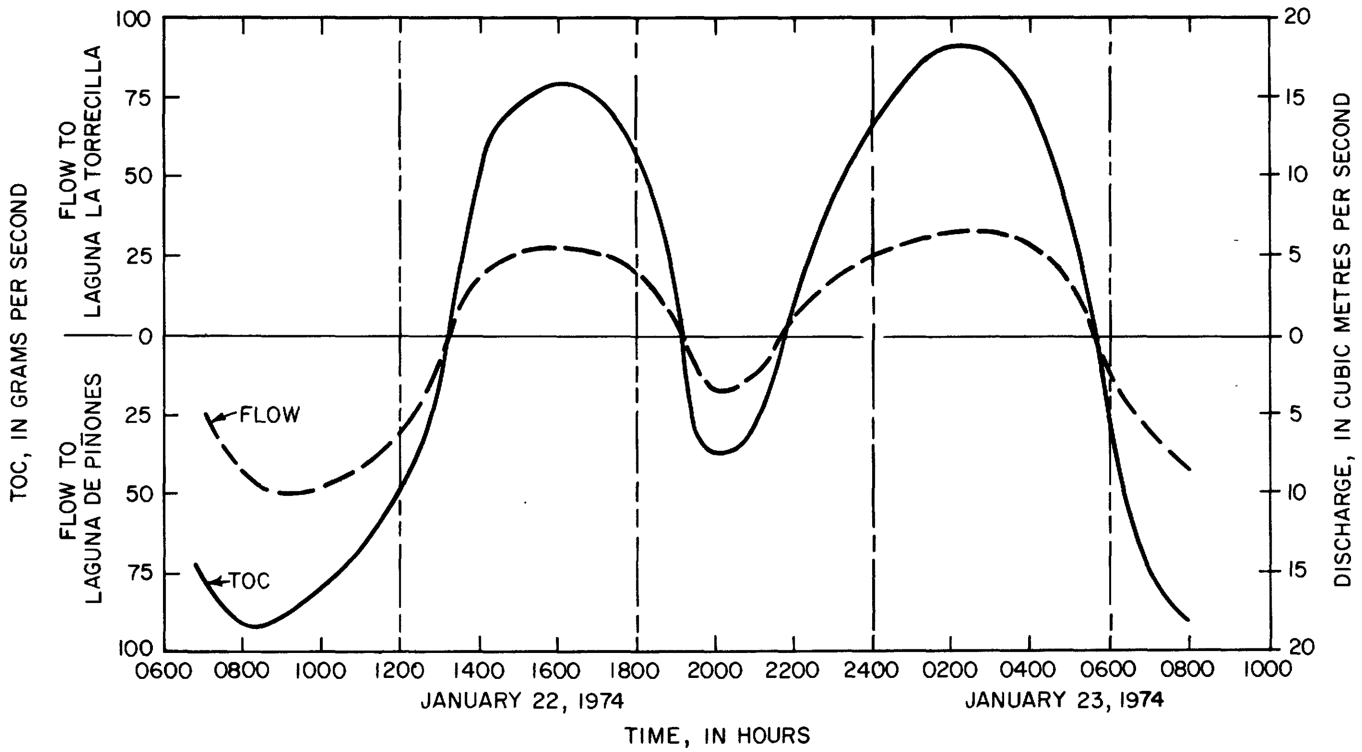


Figure 22.--Continued [TP (above) and suspended sediment (below)].



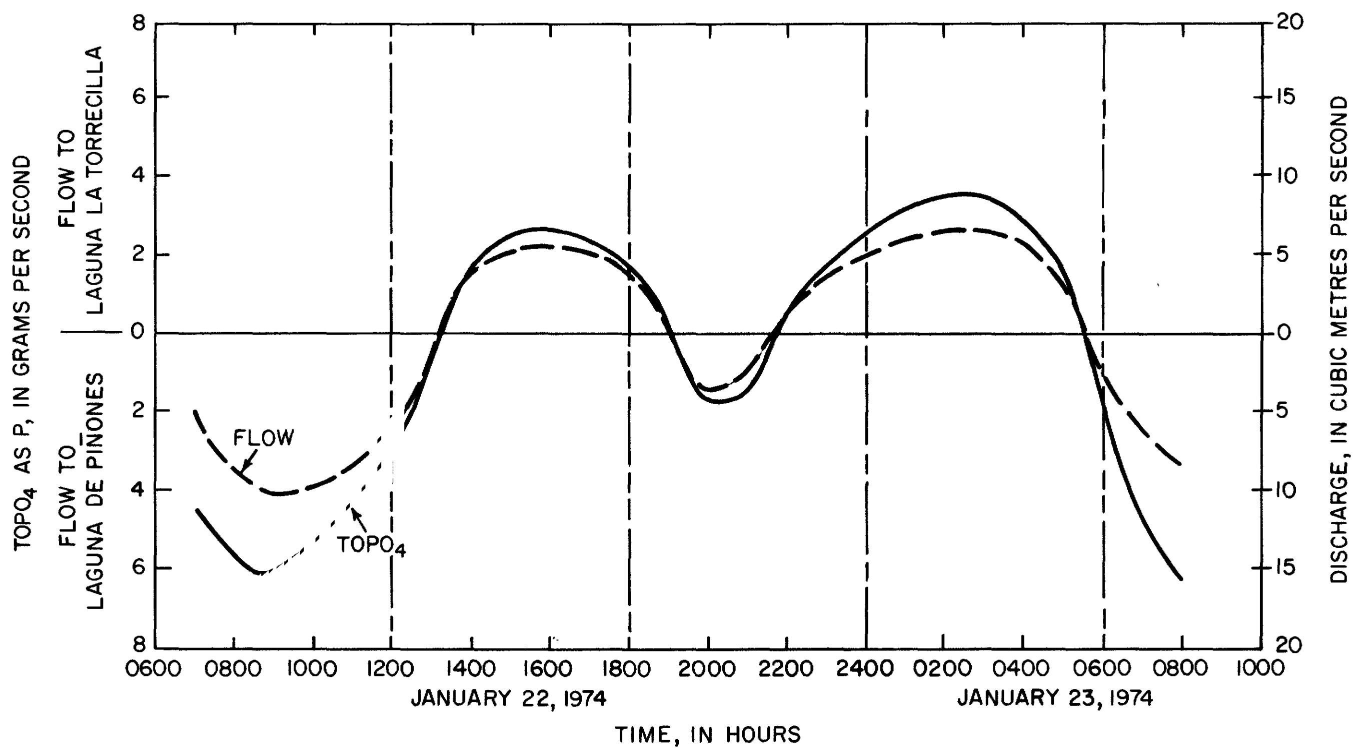


Figure 23.--Flow of selected water-quality parameters through Canal Piñones [TOC (above) and $TOPO_4$ (below)].

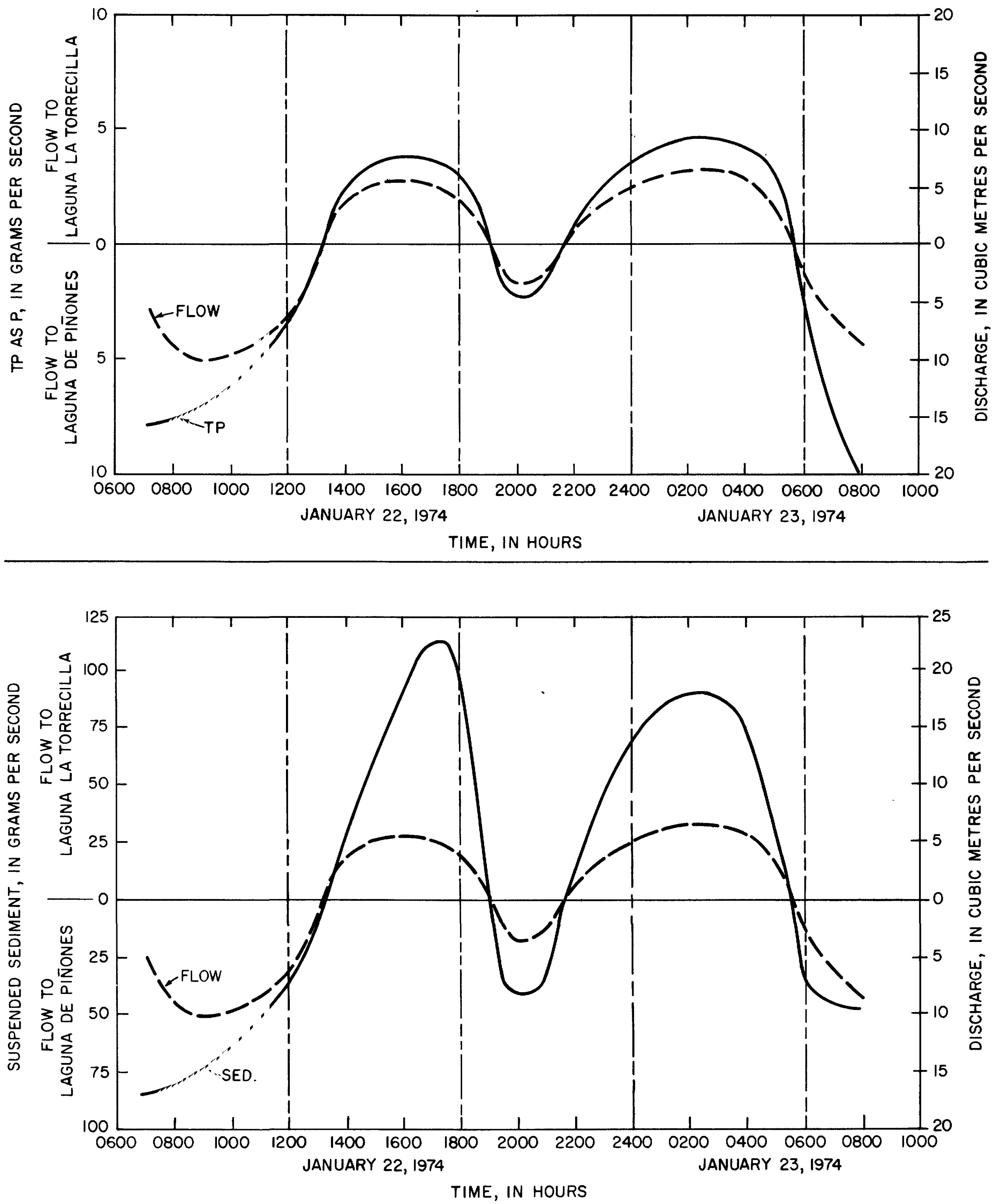


Figure 23.--Continued [TP (above) and suspended sediment (below)].

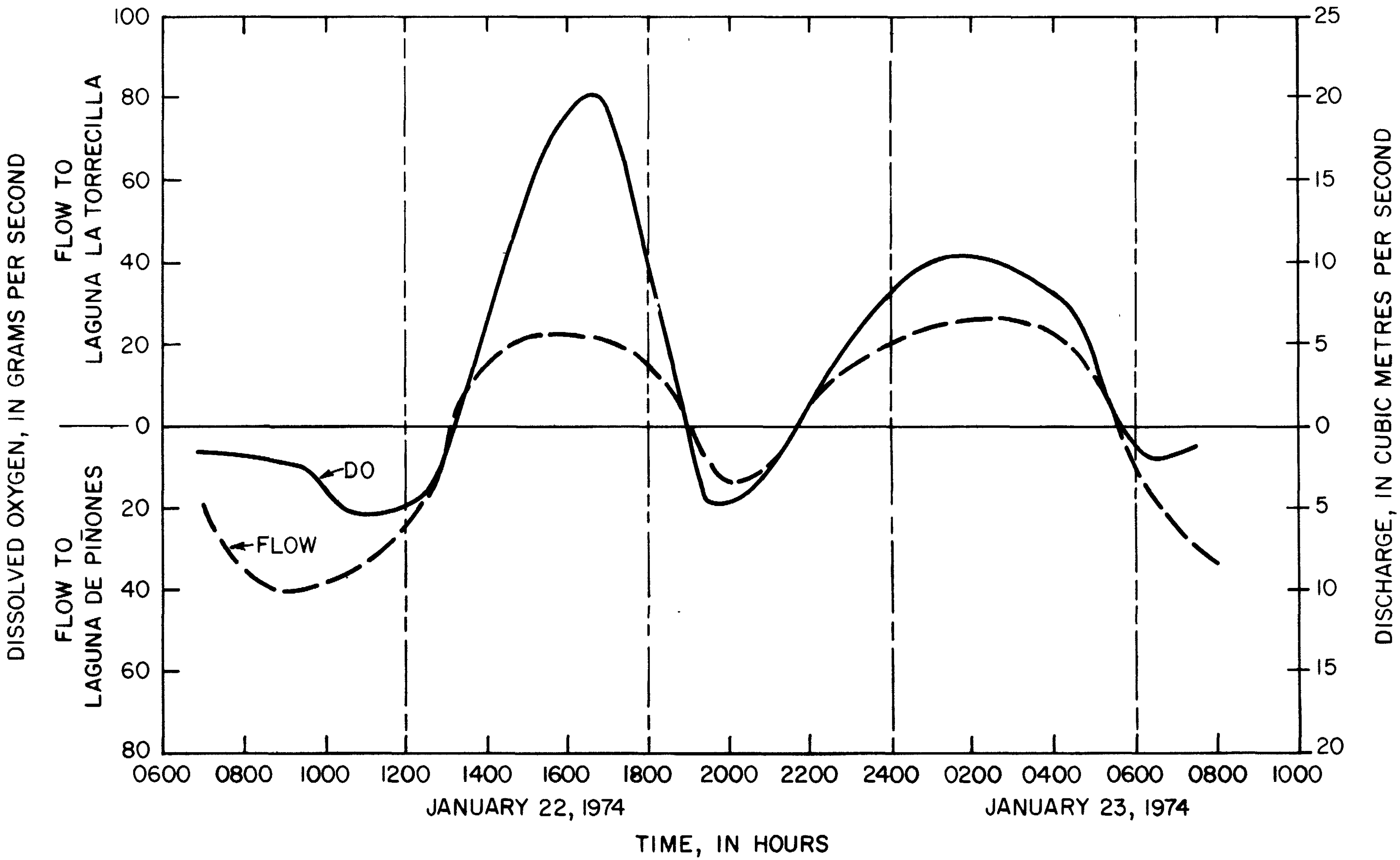


Figure 23.--Continued [DO].

Canal Suárez at Highway 26 Bridge

Canal Suárez connecting Laguna La Torrecilla with Laguna San José has negative loads of TOC, $TOPO_4$, and TP (fig. 24 and table 7) with respect to Laguna San José. Suspended sediment is a positive load, and this slight difference, about 5 percent, is probably within the accuracy of the measurements.

Table 7.--Summation of inflow, outflow and loading of TOC, $TOPO_4$, TP, and suspended sediment of Laguna San José through Canal Suárez at Highway 26 Bridge

Parameter	Inflow, (tonnes)	Outflow, (tonnes)	Net load, (tonnes)
TOC.........	4.77	8.70	-3.93
$TOPO_4$, as P ...	.19	.31	-.12
TP, as P......	.26	.39	-.13
Suspended sediment....	4.32	4.22	+0.10

Caño de Martín Peña at Barbosa Bridge

Suspended-sediment data from this site were not analyzed because of inconsistency and widely scattered results. This was probably due to the slow velocities in the canal and to the inability of the collector to distinguish the edge of the soft bottom in the canal. Some samples were contaminated with bottom material.

Results of the other parameters were consistent and are shown in figure 25 and summarized in table 8. The only parameter that showed net loading was TOC, which was negative with respect to Laguna San José. The other parameters are balanced or within the error of the method of measurement.

Table 8.--Summation of inflow, outflow, and loading of TOC, $TOPO_4$, and TP of Laguna San José through Caño de Martín Peña at Barbosa Bridge

Parameters	Inflow (tonnes)	Outflow (tonnes)	Net load (tonnes)
TOC	2.52	3.08	-0.56
$TOPO_4$, as P....	.13	.13	--
TP, as P	.21	.20	+0.01

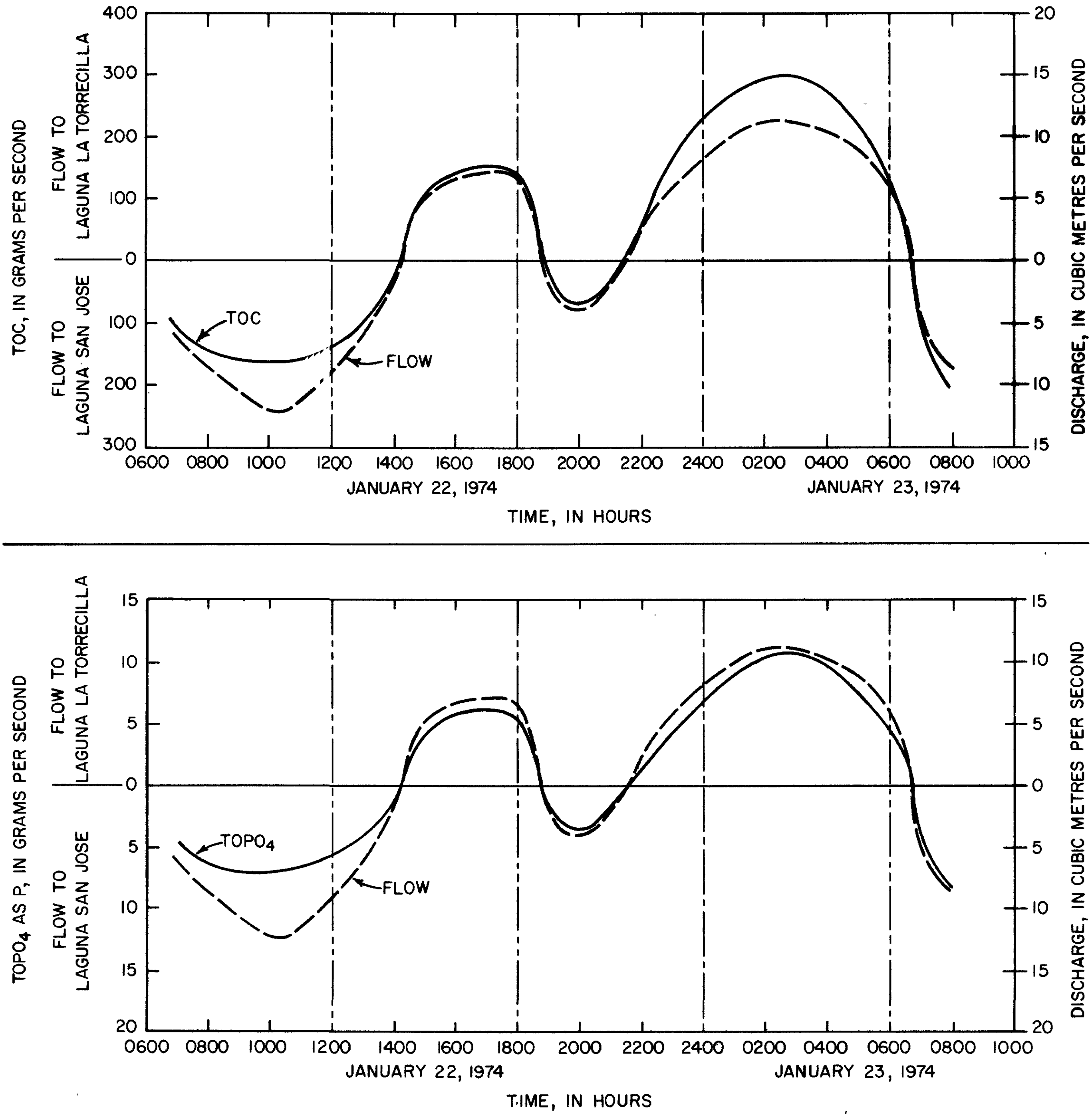


Figure 24.--Flow of selected water-quality parameters through Canal Suárez at Highway 26 Bridge [TOC (above) and $TOPO_4$ (below)].

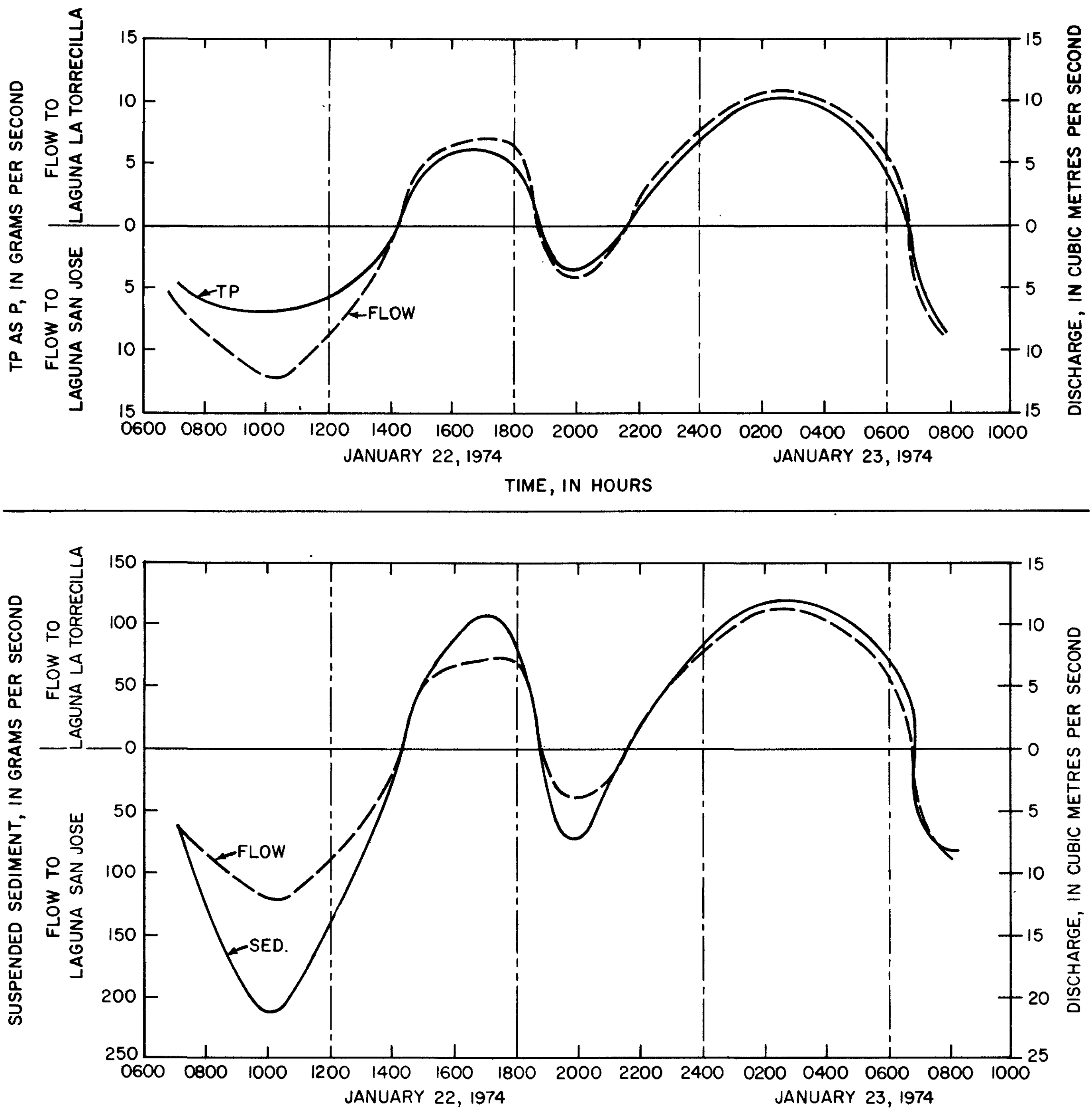


Figure 24.--Continued [TP (above) and suspended sediment (below)].

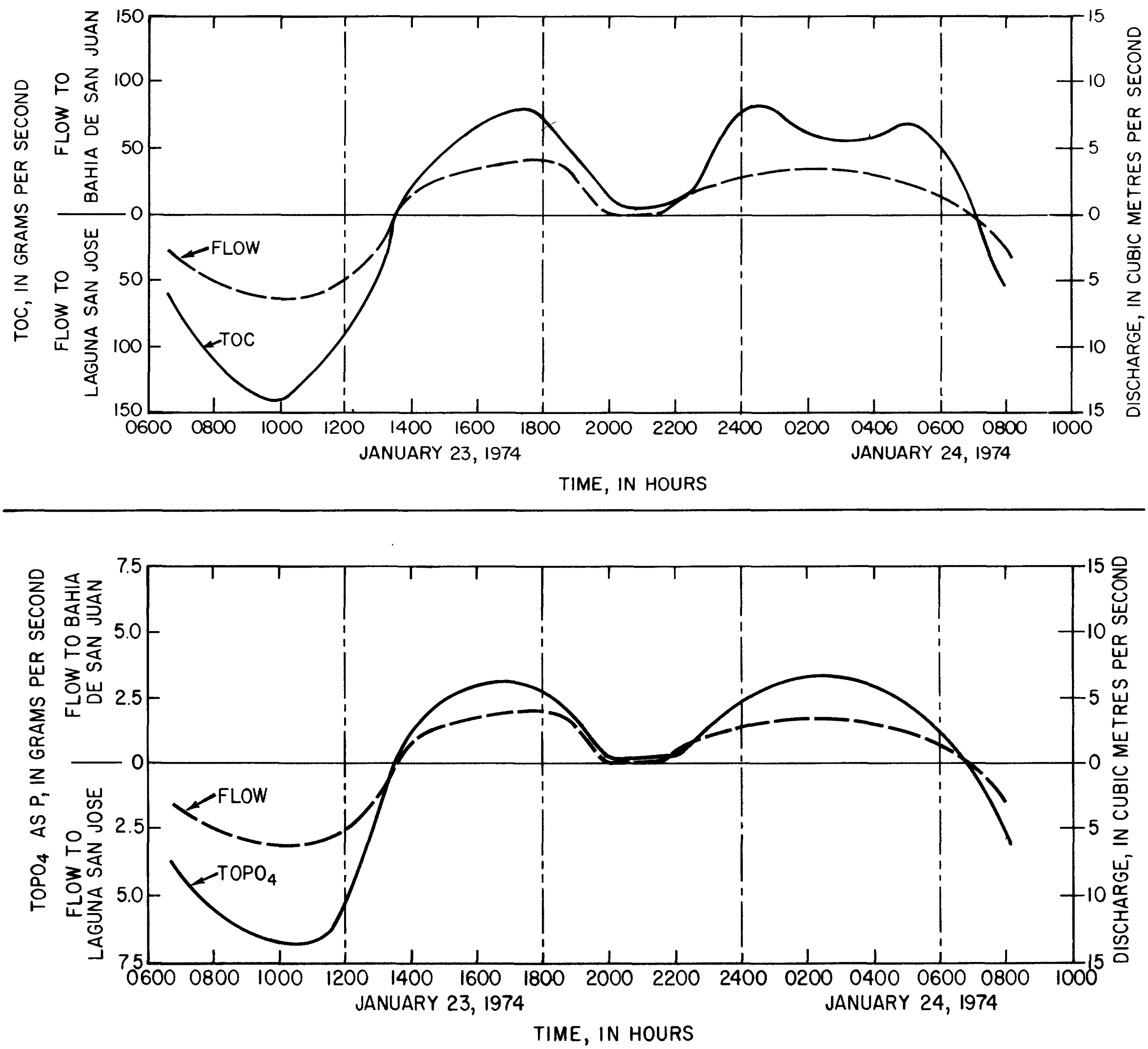


Figure 25.--Flow of selected water-quality parameters through Caño de Martín Peña at Barbosa Bridge [TOC (above) and $TOPO_4$ (below)].

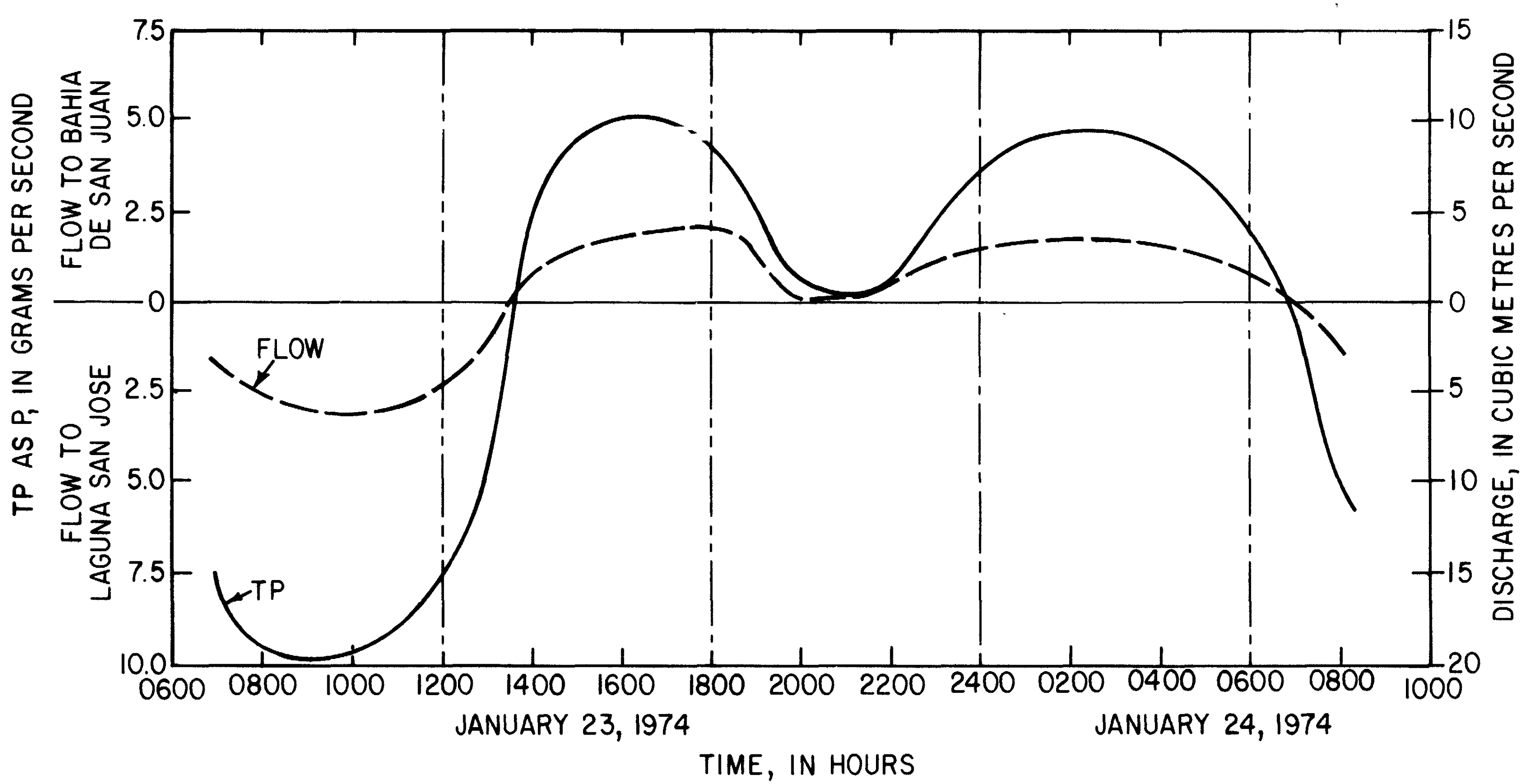


Figure 25.--Continued [TP as P].

Caño de Martín Peña at Constitution Bridge

During the period of measurement at this site, flows higher than normal, due to rainfall runoff, occurred in the Río Puerto Nuevo, which enters the canal just east of the bridge. The overall effect was that the water in the canal tended to override the incoming tide and produced an outward movement of water during the monitoring period, except for the first 2 to 3 hours. The results are therefore not representative of the usual tidal conditions.

TOC was monitored from 2000 January 23 to 1800 January 24, resulting in an outflow of about 16 tonnes in Bahía de San Juan. TP and $TOPO_4$ were monitored from 0700 January 23 to 1800 January 24, resulting in a net outflow of about 2 and 0.4 tonnes, respectively. Suspended sediment was monitored from 0700 January 23 to 1100 January 24, resulting in a net outflow of about 47 tonnes.

Laguna del Condado at Avenida Ashford and Dos Hermanos Bridges

Data from the Avenida Ashford and Dos Hermanos Bridge sites were not analyzed in the same manner as the other sites, due to the one-directional flow and either greatly scattered or non varying water-quality data. The water-quality data were used, with flow, to obtain an approximate load for each site. At Avenida Ashford Bridge about 11 tonnes of TOC, 0.6 tonne of TP, 0.2 tonne of $TOPO_4$, and 41 tonnes of suspended sediment entered Laguna del Condado. At Dos Hermanos Bridge about 8.0 tonnes of TOC, 0.6 tonne of TP, 0.2 tonne of $TOPO_4$, and 36 tonnes of suspended sediment flowed out of Laguna del Condado.

TOC and suspended sediment had apparent positive net loads, in respect to Laguna del Condado. TOC and suspended sediment had widely scattered hourly values; therefore, they may be balanced within the accuracy of the measurements. TP and $TOPO_4$ are balanced, showing no loading with respect to Laguna del Condado.

SUMMARY AND CONCLUSIONS

The San Juan lagoons may be separated into three hydraulic parts: Laguna La Torrecilla and Laguna de Piñones; Laguna San José; and Laguna del Condado. Caño de Martín Peña at Constitution Bridge is treated as a separate unit. The Laguna La Torrecilla system is connected to the ocean by Boca de Cangrejos, and is connected to other lagoons by Canal Piñones and Canal Suárez. Canal Blasina is an important contributor of nutrients and freshwater. The Laguna San José system receives freshwater from the Baldorioty de Castro pumping station, streams and ground water. It is connected by Canal Suárez and Caño de Martín Peña to Laguna La Torrecilla and Bahía de San Juan, respectively. The Laguna del Condado system is connected to the ocean through the Avenida Ashford Bridge and to Bahía de San Juan through the Dos Hermanos Bridge.

The Laguna La Torrecilla system was monitored in the 1974 study from 0700 January 22 to 0800 January 23. The block diagram in figure 26 shows a net inflow from Canal Suárez and

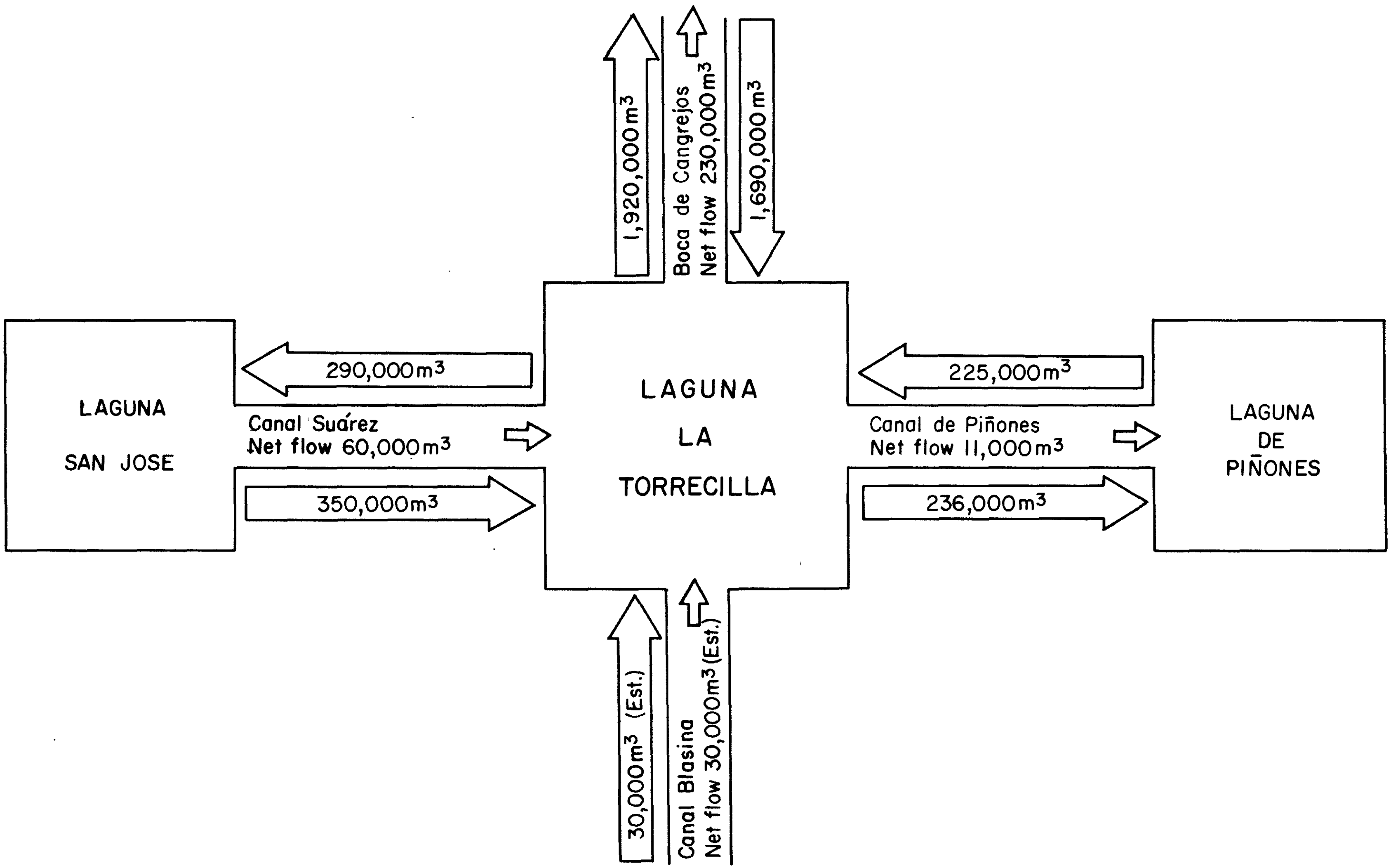


Figure 26.--Water movement through Laguna La Torrecilla system for January 22-23, 1974.

Canal Blasina of 90,000 m^3 and an outflow of 11,000 m^3 to Canal Piñones; thus, 79,000 m^3 is input to the system. The net outflow from the system through Boca de Cangrejos was 230,000 m^3. About 151,000 m^3 of outflow is not accountable by the data, which is about 3 percent of the total flows measured in the Laguna La Torrecilla system. This is probably within the percent of error of the measurements.

The Laguna San José system was monitored from 0700 January 23 to 0800 January 24. The total outflow (fig. 27) from the lagoon is 125,000 m^3. This is about 13 percent of the total measured flow. The methods used to obtain these flows are probably more accurate than 13 percent; thus, there is probably an unmeasured inflow to this system. Possible sources of this unmeasured water are ground-water flow to the lagoon from the underlying aquifer and runoff from storm drains.

The Laguna del Condado system was monitored from 1000 January 24 to 1000 January 25. The lagoon is directly connected to the sea with no storage in intermediate bodies. The net inflow was approximately the same as the net outflow within the accuracy of the measurements. The wind and wave height, in the ocean, may be a prime factor in the flow regime of this lagoon.

Caño de Martín Peña at Constitution Bridge was monitored from 0700 January 23 to 1800 January 24. Higher than normal flow in the Río Puerto Nuevo basin and urban runoff resulted in no reversal of flow from 0920 January 23 to 1800 January 24. A net outflow of 500,000 m^3 occurred during the tidal cycle, 0700 January 23 to 0800 January 24.

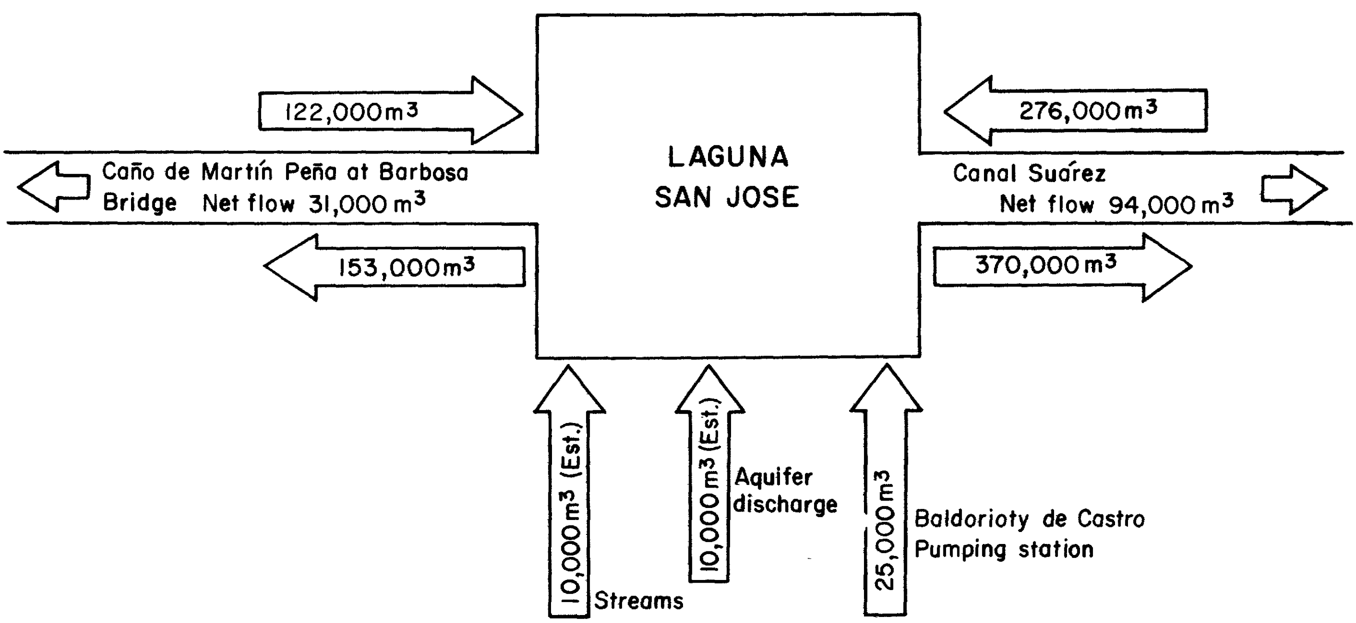


Figure 27.--Water movement through Laguna San José system for January 23-24, 1974.

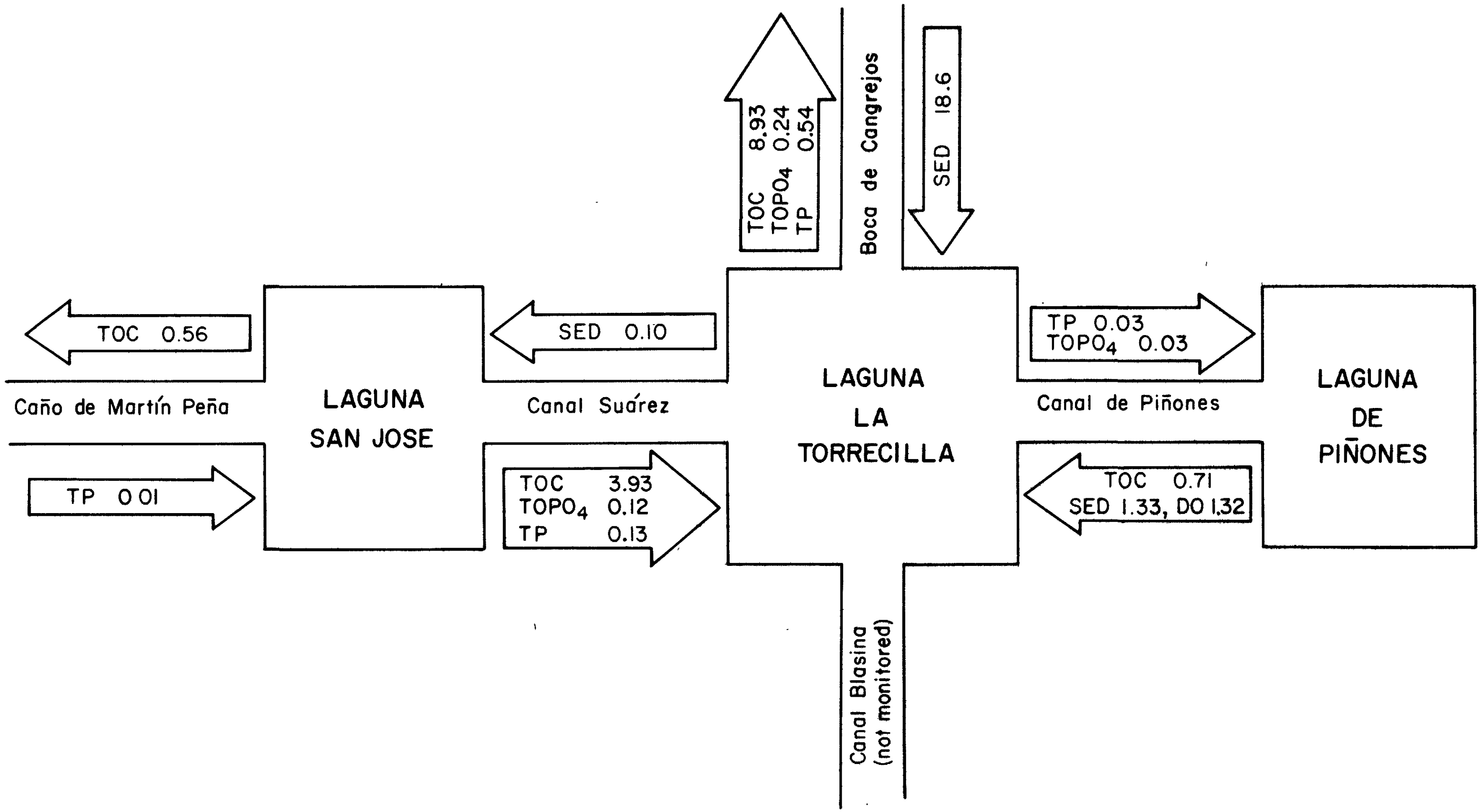


Figure 28.--Loading of selected water-quality parameters of Laguna La Torrecilla, Laguna de Piñones, and Laguna San José (in tonnes).

Laguna La Torrecilla (fig. 28), with respect to the Oceano Atlantico, had a negative net load for TOC, TP, and $TOPO_4$ of 8.93, 0.54, and 0.24 tonnes (respectively) and a positive net load of suspended sediment of 18.6 tonnes. Laguna de Piñones had a negative net load for TOC, suspended sediment, and DO of 0.71, 1.33, and 1.32 tonnes (respectively) and a positive net load of TP and $TOPO_4$ of 0.03 tonne for each. Laguna San José discharge through Canal Suárez had a negative net load for TOC, TP, and $TOPO_4$ of 3.93, 0.13, and 0.12 tonnes (respectively) and a positive net load of 0.10 tonne of suspended sediment. These measurements were made during the period of no storm runoff; therefore, they can be considered representative of base conditions for the given tidal cycle.

Laguna San José through Caño de Martín Peña at Barbosa Bridge had a net negative load of 0.56 tonne TOC, and a positive net load of 0.01 tonne TP. $TOPO_4$ inflows and outflows were balanced, showing no loading. Because localized showers occurred preceding the monitoring periods, these results cannot be assumed to be representative of base-flow conditions. Local showers of this type are a frequent occurrence in the San Juan area; therefore, these results may be representative.

Laguna del Condado probably had no net loading. Because wind and wave height may be a prime factor in the flow regime, they probably also influence the loading of Laguna del Condado. Varying wind and wave conditions could produce different results, when other factors remain constant.

Caño de Martín Peña at Constitution Bridge was monitored during various periods for the outflow of chemical constituents into the Bahía de San Juan. TOC, from 2000 January 23 to 1800 January 24, resulted in an outflow of about 16 tonnes; whereas, TP and $TOPO_4$, from 0700 January 23 to 1800 January 24, resulted in a net outflow of about 2 and 0.4 tonnes (respectively). The net outflow for suspended sediment, from 0700 January 23 to 1100 January 24, was about 47 tonnes.

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