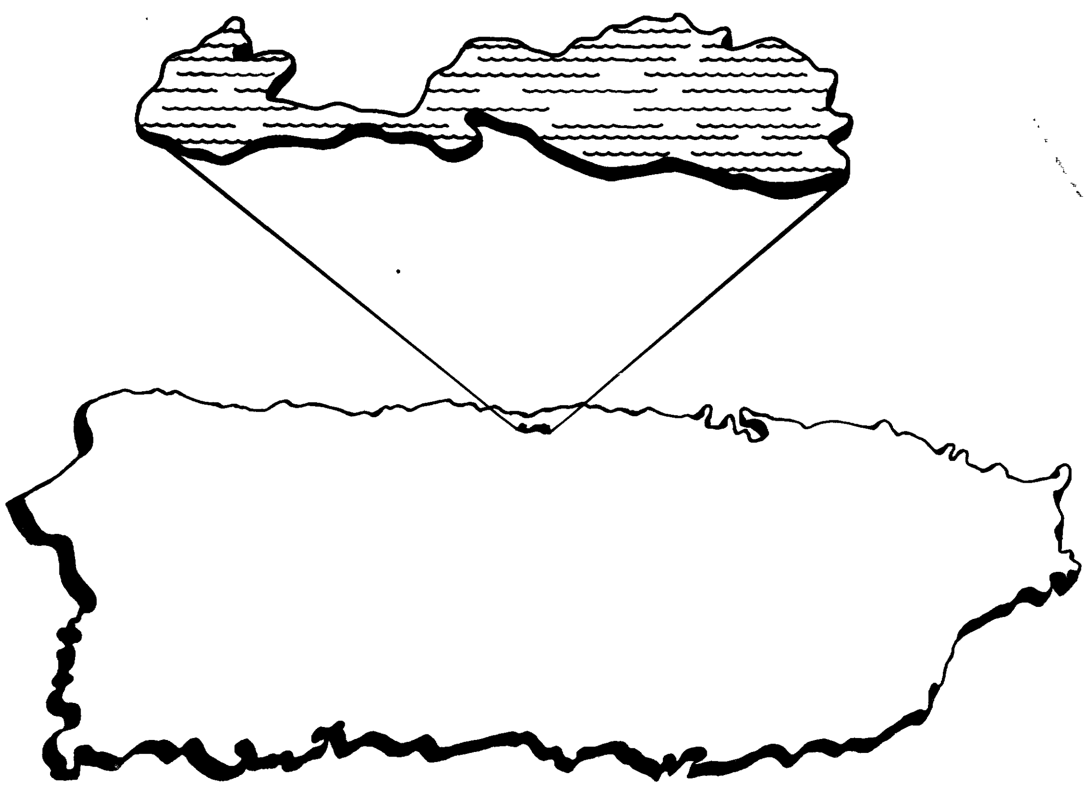
LIMNOLOGY OF LAGUNA TORTUGUERO, PUERTO RICO

U.S. GEOLOGICAL SURVEY
Water Resources Investigation 77-122



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16. Abstracts

The principal chemical, physical and biological characteristics, as well as the hydrology of Laguna Tortuguero, Puerto Rico, were studied from 1974-75. The lagoon, with an area of 2.24 square kilometers and a volume of about 2.68 million cubic meters, contains about 5 percent of seawater. Drainage through a canal on the north side averages 0.64 cubic meters per second per day, flushing the lagoon about 7.5 times per year.

Chloride and sodium are the principal ions in the water, ranging from 300 to 700 mg/L and 150 to 400 mg/L, respectively. Among the nutrients, nitrogen averages about 1.7 milligrams per liter, exceeding phosphorus in a weight ratio of 170:1. About 10 percent of the nitrogen and 40 percent of the phosphorus entering the lagoon is retained. The bottom sediments, with a volume of about 4.5 million cubic meters, average 0.8 and 0.014 percent nitrogen and phosphorus, respectively.

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March 1978

UNITED STATES DEPARTMENT OF THE INTERIOR

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In recognition of the general trend toward the adoption of the metric system of measurements (SI or System Internationale), metric units are used in this report. Within the Commonwealth of Puerto Rico, both the SI and English systems are used extensively. The following factors may be applied for conversion of metric values (SI) to English values:

	Multiply	By	To obtain
Length			
	millimeters (mm)	.03937	inches (in)
	meters (m)	3.281	feet (ft)
	kilometers (k)	.6214	miles (mi)
Area			
	square meters (m^2)	10.764	square feet (ft^2)
	square kilometers (km^2)	.3861	square miles (mi^2)
Volume			
	cubic meters (m^3)	35.31	cubic feet (ft^3)
Weight			
	grams (g)	.03527	ounces (oz)
	tonnes (t)	1.1025	tons (T)
Flow			
	cubic meters per second (m^3/s)	22.827	million gallons per day (Mgal/d)

L I M N O L O G Y O F
L A G U N A T O R T U G U E R O,
P U E R T O R I C O

by Ferdinand Quiñones-Márques and Luis A. Fusté

ABSTRACT

Laguna Tortuguero, located on the north coast of Puerto Rico, is the largest freshwater lagoon on the island. It has a surface area of 2.24 square kilometers with a volume of about 2.68 million cubic meters and a mean depth of 1.2 meters.

Water entering the lagoon from 1974-75 included 3.41 million cubic meters from precipitation and 19.7 million cubic meters from ground water and surface flows. About 20.1 million cubic meters was discharged to the sea through the north canal outlet and 2.85 million cubic meters was lost by evapotranspiration.

The quality of the water in the lagoon depends on the inflow of seawater and on circulation patterns. Seawater flows contribute about 5 percent of the water in the lagoon. Chloride and sodium are the most abundant ions, ranging in concentration from 300 to 700 and from 150 to 400 milligrams per liter, respectively. Among the nutrients, nitrogen concentrations average 1.7 milligrams per liter, while phosphorus average 0.01 milligram per liter. About 70 percent of the nitrogen is organic or ammonia nitrogen. Total nitrogen inputs to the lagoon were about 33.2 tonnes and about 34.0 tonnes was discharged to the ocean, suggesting a near equilibrium in the system.

Dissolved oxygen concentrations average 8.2 milligrams per liter, increasing toward the bottom as a result of high oxygen production by periphyton. Wind mixing contributes to maintain high oxygen concentrations throughout the lagoon.

The bottom sediments in the lagoon average about 2.0 meters deep, with a volume of about 4.5 million cubic meters, or twice the water volume. Organic

carbon in the sediment averages about 6.8 percent by weight while nitrogen and phosphorus average 0.8 and 0.014 percent by weight, respectively.

Bacteria counts throughout the lagoon are very low, indicating excellent sanitary conditions. Phytoplankton concentrations average 6,000 cells per milliliter. Of 47 genera of phytoplankton identified, 16 were diatoms and 12 blue-green algae. *Anacystis* was the dominant alga 90 percent of the time. Zooplankton concentrations average 100,000 organisms per cubic meter. A total of 17 species were identified, among which *Diaptomus dorsalis*, *Diaphanosoma brachyurum* and *Filinia opoliensis* are dominant.

The lagoon, as a whole represents a near steady-state system approaching natural eutrophic conditions. Water flows, nutrients and the dissolved-oxygen concentrations are the most important factors in the present steady-state conditions. The bottom sediments are a potential source of nutrients to the lagoon. Land-use changes in the immediate area of the lagoon could result in increases in the water and nutrient flows, which could shift the present equilibrium toward a more biologically productive system.

INTRODUCTION

Purpose and Scope

Laguna Tortuguero, located between the Río Cibuco and the Río Grande de Manatí, and about 35 km west of San Juan (fig. 1), is the largest natural freshwater lagoon in Puerto Rico. The lagoon is a valuable natural resource which has been maintained in a near natural condition. Except for a drainage channel dug by the U.S. Army in 1940, no other works have disturbed the lagoon. The lagoon and the immediate area around it are sanctuaries for a diversity of species of fish, other aquatic organisms, birds, and several endemic plants (Reyes de Ruiz, 1971). The area is a source of recreation for sportsmen and fishermen and provides additional sources of food and income to a number of dwellers in the vicinity. Recently a number of private and government interests have proposed developments in the immediate vicinity of the lagoon. Several major urban development projects have been proposed on its southern slopes. Plans for a power generating unit in the area are contemplated. A permit to extract sand for industrial uses from the area north of the lagoon was recently approved. The potential impact of these projects on the overall water quality and hydrology of the lagoon may be significant.

At the request of the Department of Natural Resources of the Commonwealth of Puerto Rico, the U.S. Geological Survey initiated a comprehensive study of the limnology of the lagoon. The purposes of the 1-year study were to obtain baseline information as to the overall chemical, physical and biological conditions in the lagoon and to analyze the hydrologic factors in the lagoon system. The investigation was conducted from July 1974 to June 1975 under the cooperative program between the Commonwealth of Puerto Rico and the U.S. Geological Survey.

BASE FROM U.S. GEOLOGICAL SURVEY, MANATI QUAD. 1969, SCALE: 1:20,000.

Figure 1.--Laguna Tortuguero and sampling stations.

We gratefully acknowledge the assistance of Juan Carvajal Zamora, Microbiologist, Department of Natural Resources of the Commonwealth of Puerto Rico, for his aid in the biological work of the study. We are also grateful to W. J. Byas, Division of Mollusks of the U.S. National Museum, in identifying mollusk specimens collected during the study. The hydrologic analysis of the lagoon could not have been performed without the data obtained by Roberto Ramírez, a hired observer.

Methods and Procedures

Sampling stations throughout the lagoon were established as shown in figure 1 and listed in table 1. Samples for chemical, physical, biochemical and bacteriological properties were collected monthly (except during December 1974) from stations 1 through 5. Station 1 (canal outlet) was also a flow-measuring station from which daily observations of gage heights were made. Discharge measurements were made at station 1 about once every 2 weeks. Continuous water-level recorders were installed at station 6 and in the vicinity of station 4. A standard rain gage and a recording class "A" evaporation pan were installed in the vicinity of station 6. Samples of rainfall were collected from the rain gage for chemical and physical analyses.

Nutrient samples were chilled to 4°C and analyzed within 4 days of collection. Samples collected for whole water chemical analyses of common ions, nutrients, pesticides, heavy metals and phytoplankton were analyzed at the U.S. Geological Survey Central Laboratory in Doraville, Georgia. Samples collected for determination of zooplankton, bacteria, and periphyton were analyzed at the U.S. Geological Survey Field Service Laboratory in San Juan. Chemical, physical, and biochemical analyses were performed in accordance with methods described by Brown and others (1970), and the American Public Health Association and others (1971). Biological (plankton) and bacteriological analyses were performed as described by Greeson and others (1973), Ward and Whipple (1959), and Smith (1950). Taxonomic keys described by Reimer (1966), Davis (1955), and Prescott (1970) were utilized in the periphyton analyses.

On site determinations at each station were made of the dissolved-oxygen concentration (DO), pH, specific conductance, temperature, and Secchi disk transparency. Vertical profiles were determined for the DO concentration and temperature.

Bottom sediment samples for the analysis of pesticides and heavy metals were collected at stations 2 and 5 once during the study. An Ekman dredge suspended from a line was used for the collection of the samples. Cores of the bottom sediments were collected with a PVC pipe piston-type core sampler. Bottom sediment samples were frozen prior to the analyses. Mollusks identified from the cores were removed from segments not exposed to freezing. Depths of bottom sediments were measured with a calibrated PVC pipe.

Table 1.--Sampling stations in Laguna Tortuguero, Puerto Rico.

Station number	Name	Latitude	Longitude
50038190	Laguna Tortuguero No. 6	18°27'46"	66°28'01"
50038191	Laguna Tortuguero No. 2	18°27'53"	66°27'50"
50038192	Laguna Tortuguero No. 3	18°27'50"	66°27'16"
50038193	Laguna Tortuguero No. 4	18°27'55"	66°26'40"
50038194	Laguna Tortuguero No. 5	18°27'52"	66°25'50"
50038200	Laguna Tortuguero No. 1 (Outlet near Vega Baja)	18°28'29"	66°26'50"

A diel study of the community productivity in the lagoon utilizing the oxygen evolution method was conducted November 26, 1974. Methods described by Slack and others (1973) were used during the study.

A bathymetric survey of the lagoon was conducted during May 1975. A fathometer coupled to an Ott current meter mounted on a moving boat was used to measure depths and distances (Smoot and Novak, 1969). Bearings were maintained with a compass and the use of land controls. Data from the bathymetric study were used for computations of the capacity of the lagoon (Eakin and Brown, 1939; and Heinemann and Dvorak, 1970).

LAGOON CHARACTERISTICS

Laguna Tortuguero is unique not only because of its near natural state, but also because it is fed from a series of freshwater and saline-water springs that make it slightly saline. Geologically, the lagoon is probably very recent. Meyerhoff (1933) and Bennett and Giusti (1972) suggest that "it is probably the arrested preliminary stage of a line of interconnected sinks and haystacks which are typical of the karst in the area." Test borings in the lagoon area indicate a sequence of peat, sand, and clay overlying an irregular limestone surface. The limestone surface in the lagoon proper is well below the general water table. There is no longer a downward movement of rainwater but an upwelling of water into the lagoon from the underlying aquifer. The upwelling is the sole reason for the existence of Laguna Tortuguero. Ground water in a coastal aquifer is not static but is part of a dynamic system. As freshwater moves toward the sea, there is a corresponding movement of seawater inland along the bottom part of the aquifer. Eventually the seawater moves upward and back toward the sea. The freshwater moving seaward is also carried upward, mingling with the seawater to form a mixing zone along the contact between freshwater and seawater. It is this upwelling of seawater which accounts for the slightly salty quality of Laguna Tortuguero (Bennett and Giusti, 1972). The lagoon is, in effect, a window through which part of the flow mechanism of freshwater and saltwater in a coastal aquifer can be observed.

At present the freshwater-seawater system can be considered to be in a dynamic balance. Bennett and Giusti (1972) indicate that prior to 1940, before the drainage canal was dug, the lagoon water level was probably 0.5 to 1 m higher. A balance similar to the present one but probably at a different point in the dynamic system, existed prior to the lowering of the lagoon level. Changes in the lagoon's natural system caused by the lowering in the canal should have been recorded in the lagoon itself.

The surface area of the lagoon is about 2.24 km^2, of which about two-thirds is on the east part. The lagoon is relatively shallow, averaging about 1.2 m in depth. A bathymetric map of the lagoon is shown in figure 2. The map shows that the east part is generally deeper than the west part. Equal depth lines for the canal that joins both parts of the lagoon are not shown because of the scale. The canal in this area is about 1.5 m deep. The deepest part of the lagoon (2.8 m) was measured near the west end of the canal.

The bathymetric map of the lagoon shows the depth from the water surface to the bottom sediment layer. It will be shown in a later section that the consistency and depth of the sediments may have a bearing on the actual depth.

The physical characteristics of the lagoon are summarized in table 2. The development of shoreline ratio (DL) is an index of the morphology of a lake, produced by the ratio of the length of the shoreline to the length of the circumference of a circle of area equal to that of the lake. The ratio gives an insight into the origin and behavior of lakes (Hutchinson, 1957). Irregular lakes or lagoons exhibit development of shoreline ratios higher than 1.5.

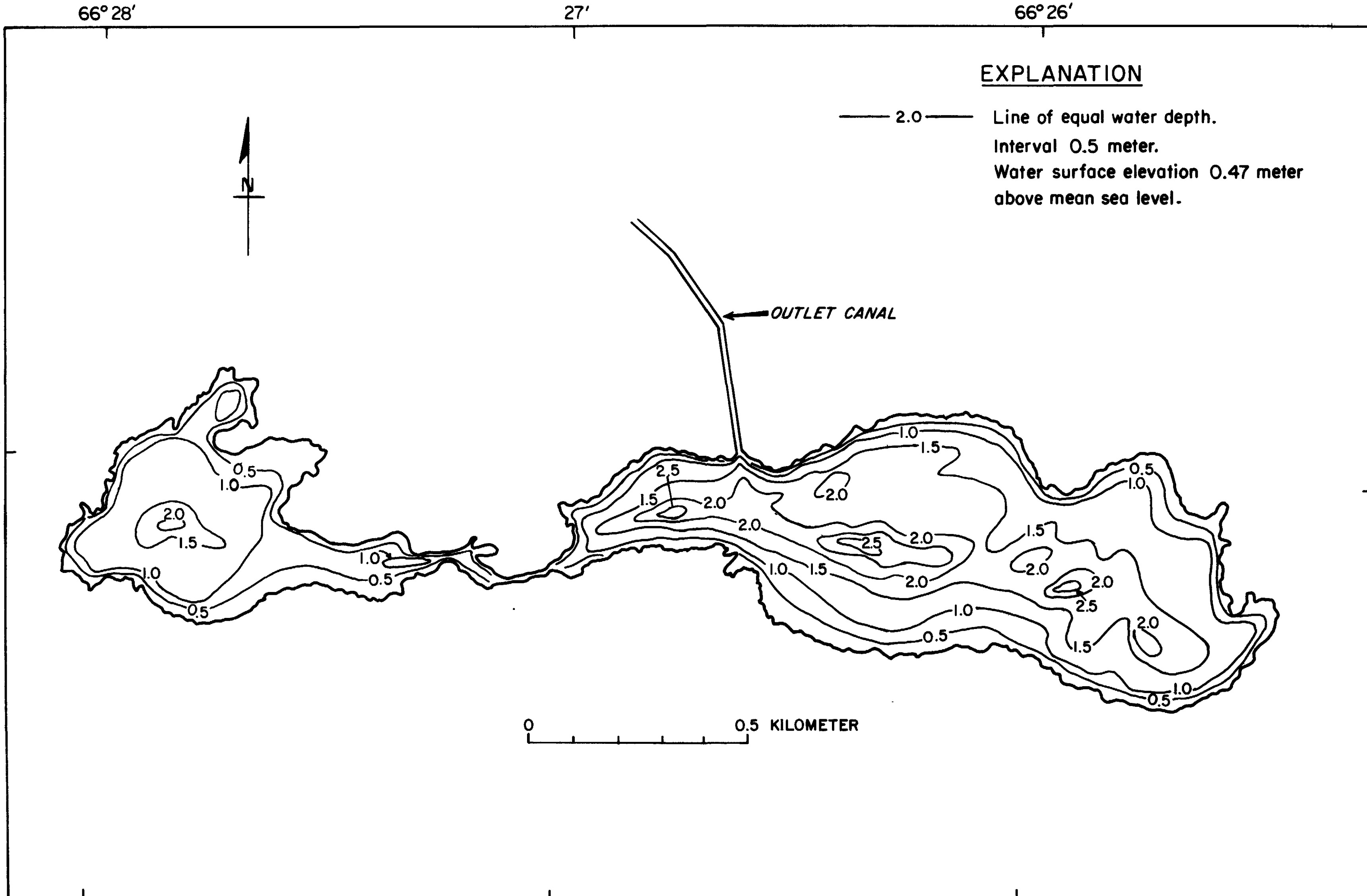

Figure 2.--Bathymetric map of Laguna Tortuguero. Surveyed May 1975.

Table 2.--Physical characteristics of Laguna Tortuguero.

Area (A)	2.24 km^2
Volume (V)	2.68 Mm^3
Mean depth $\frac{V}{A}$	1.2 m
Maximum depth	2.8 m
Maximum length (east to west end)	4.6 km
Maximum width (east end)	.9 km
Maximum width (west end)	1.0 km
Shoreline length (L)	15.3 km
Development of shoreline $D_L = \frac{L}{2\sqrt{\pi A}}$	2.9

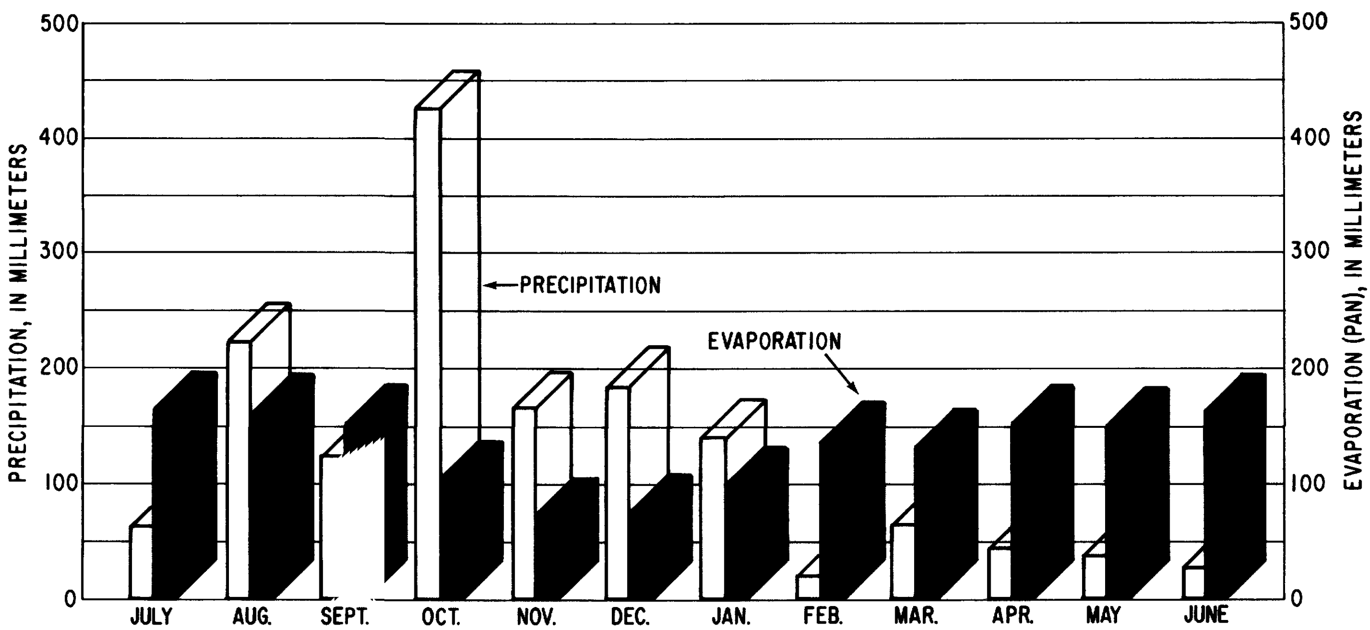

Figure 3.--Seasonal precipitation and pan evaporation near Laguna Tortuguero.

HYDROLOGY OF LAGUNA TORTUGUERO

Precipitation and Evaporation

Precipitation along the north coast of Puerto Rico is characterized by a drought period from February through March and increasing rainfall thereafter. The average precipitation in the vicinity of Laguna Tortuguero is about 1,600 mm per year (Colón, 1970).

A standard 8-in (203 mm) nonrecording precipitation gage was located on the western shore of the lagoon. Daily observations were made. Monthly totals of the amount of precipitation measured are shown in figure 3. A total of 1,521 mm of rainfall was recorded during the year of study, which contributed 3.41 Mm^3 to Laguna Tortuguero.

Evaporation data collected at the weather station are also shown in figure 3. A total of 1,592 mm of pan evaporation was recorded during the study period. If a pan-to-evapotranspiration (ET) coefficient for the lagoon of 0.8 is assumed (Pruitt, 1966), total evapotranspiration from the lagoon can be estimated as about 1,274 mm. This is equivalent to a volume of 2.85 Mm^3 evapotranspiration from Laguna Tortuguero during the study period.

The data in figure 3 show that through half of the year of study there was a deficit between precipitation and evaporation in the area. Even when evaporation rates are adjusted to reflect evapotranspiration, a deficit would be shown for most of the months after February 1975. The overall balance between precipitation and evapotranspiration shows a net input of 247 mm. Most of the excess precipitation occurred during October 1974, when a total of 245 mm was recorded.

Runoff

Runoff into Laguna Tortuguero occurs only during periods of intense storms. Whenever precipitation in the area exceeds percolation rates, some overland runoff, mainly from the southern slopes, may flow directly into the lagoon. Although no samples were collected during storms, areas in the vicinity of station 3 (fig. 1) showed some evidence that overland runoff had occurred.

Outflow from Laguna Tortuguero is only through the north canal outlet. The canal (fig. 4), reportedly dug by the U.S. Army in 1940, is about 0.6 km in length (to the ocean), about 8.5 m wide and about 1 m deep. Although the canal is affected by backwater from the ocean tide, it flows continuously. The common belief that seawater flows through the canal into the lagoon is not correct. There were no observations of flows in the direction of the lagoon, nor did specific conductance measurements indicate seawater encroachment during the study period.

Figure 4.--Canal outlet, looking south.

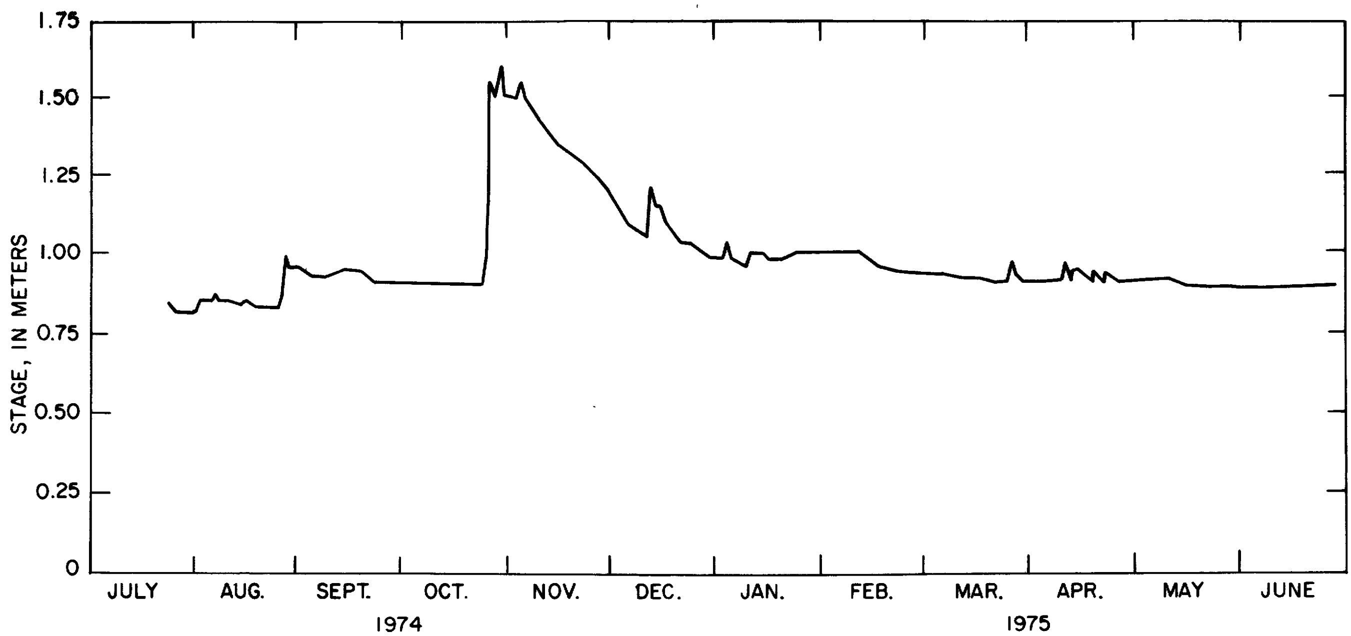

Figure 5.--Seasonal fluctuation in the water-surface elevation in Laguna Tortuguero (west end).

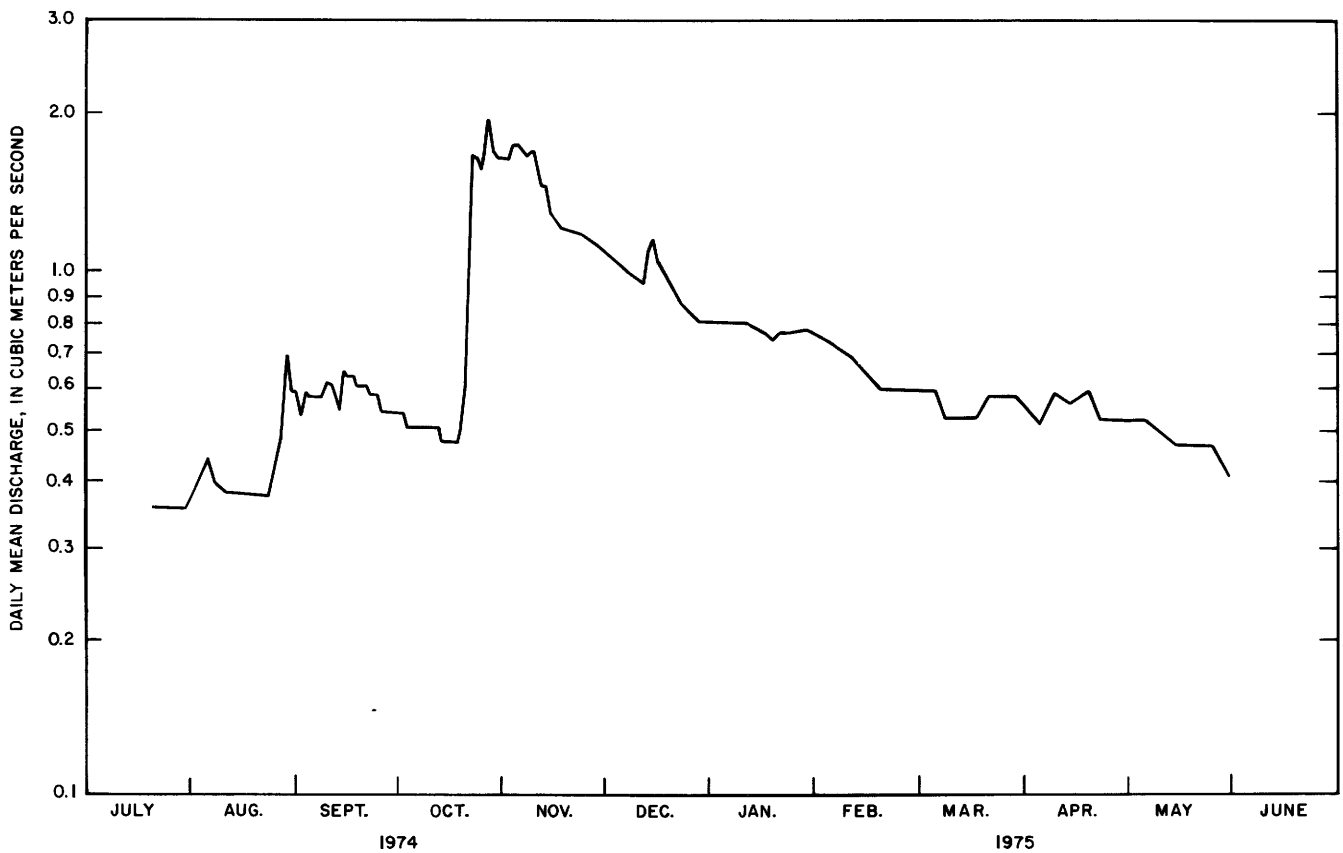

Figure 6.--Daily mean discharge at canal outlet.

Discharge measurements through the canal outlet ranged from 0.26 to 1.95 m^3/s. The lowest measurements were made in July 1974 when the study was initiated, while the highest were made during October 1974. The storm of October 24-25, 1974, resulted in a rapid increase in the water level throughout the lagoon. The water level, shown for the west end in figure 5, rose about 0.6 m during the storm. At the canal outlet, the water level increased about 0.4 m. Daily discharges increased at the canal outlet from 46,500 m^3 on October 23 to about 171,000 m^3 on October 29.

Daily mean discharges at the canal outlet are shown in figure 6. A total of 20.1 Mm^3 was discharged during the period of study; the equivalent to a mean daily discharge of about 0.64 m^3/s. This is in agreement with an estimated 0.6 m^3/s reported by Bennett and Giusti (1972) as the base flow from the lagoon to the sea.

Water Budget

The water budget for Laguna Tortuguero during the study period is summarized in figure 7. Ground- and surface-water inflows were computed on the basis of the other known flows. The overall change in storage in the lagoon was the result of a higher water level at the end of the study.

The volume of water discharged through the canal outlet results in a high flushing rate in Laguna Tortuguero. Flushing rates are an important aspect of lake hydraulics and the degree of eutrophication of lakes.

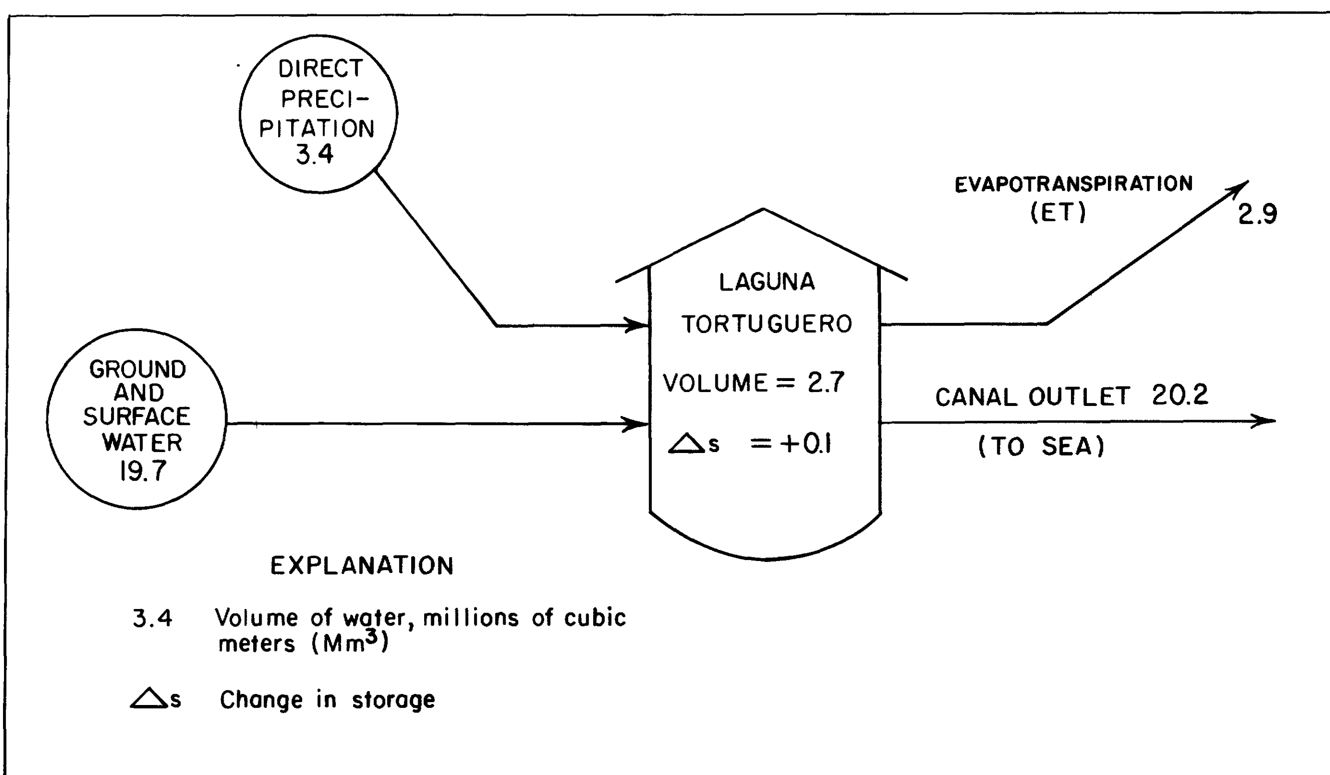

Figure 7.--Water budget, July 1974 to June 1975.

The flushing rate of Laguna Tortuguero during the study period was 7.5 per year. Dillon (1975) has reported that lakes with flushing rates higher than 1 per year are able to tolerate higher nutrient loadings. It will be shown later that this plays an important role in the limnology of Laguna Tortuguero.

CHEMICAL AND PHYSICAL CHARACTERISTICS

Common Ions and Related Physical Characteristics

Chemical analyses were made for calcium, magnesium, sodium, potassium, iron, manganese, chloride, sulfate, and bicarbonate, as well as physical measurements of pH, temperature, and specific conductance.

There are significant differences between the concentrations of some of the ions in samples collected from the eastern and those from the western parts of the lagoon. For common ions and other data in the report, stations 2 and 5 (fig. 1) are used as index stations as these represent the extremes of the conditions in the lagoons. Stations 4 and 5 in the east end and station 1 (canal) represent nearly similar water-quality conditions, and the average of these is reported at times. The average was assumed to represent the quality of water in the eastern part of the lagoon.

The seasonal fluctuation in the average of the main chemical and physical characteristics at stations 1, 4 and 5 is shown in figure 8. Concentrations and values for station 2 are shown in figure 9. With very few exceptions, the concentrations of the different ions declined significantly after the rains of October 1974. The large inflow of surface runoff, probably very low in the concentration of ions, diluted the concentration of those in the lagoon. Most of the concentrations of the different ions analyzed did not recover at the end of the study to the values measured at the beginning of it.

Chloride and sodium are the principal ions in the waters of Laguna Tortuguero. The concentration of chloride ranged from 300 to 700 mg/L, while that of sodium ranged from 150 to 400 mg/L. The ratio of sodium to chloride resembled that of seawater during the periods prior to the flood of October 1974 and after the recovery period.

The areal concentration of chloride during two periods is shown in figure 10. On November 14, 1974, after the flood of October, the average chloride concentration in the east part of the lagoon was about 400 mg/L, while in the west part it was about 540 mg/L. On June 24, 1975, at the end of the study and after the lagoon had recovered nearly to its normal stage condition, the average chloride concentration in the east part was about 640 mg/L, while in the west part it was close to 800 mg/L.

Comparison of the two surveys inciates a change in chloride concentration of about 250 mg/L throughout the lagoon. This change in the amount of chloride in the water, as well as other ions, could have a significant effect on some of the aquatic communities in the lagoon.

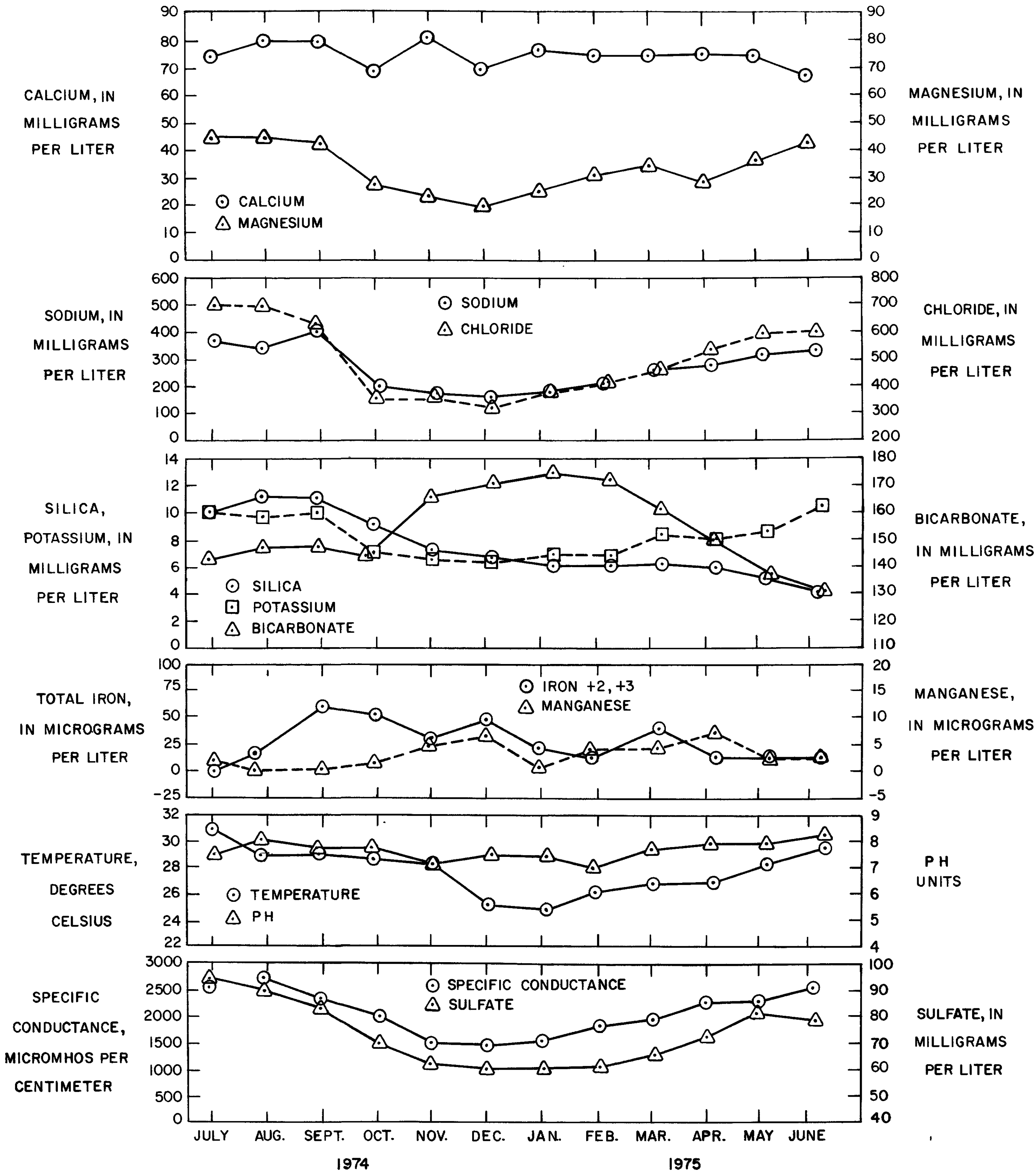

Figure 8.--Seasonal fluctuation in the main chemical and physical characteristics for the average of stations 1, 4 and 5 in eastern Laguna Tortuguero.

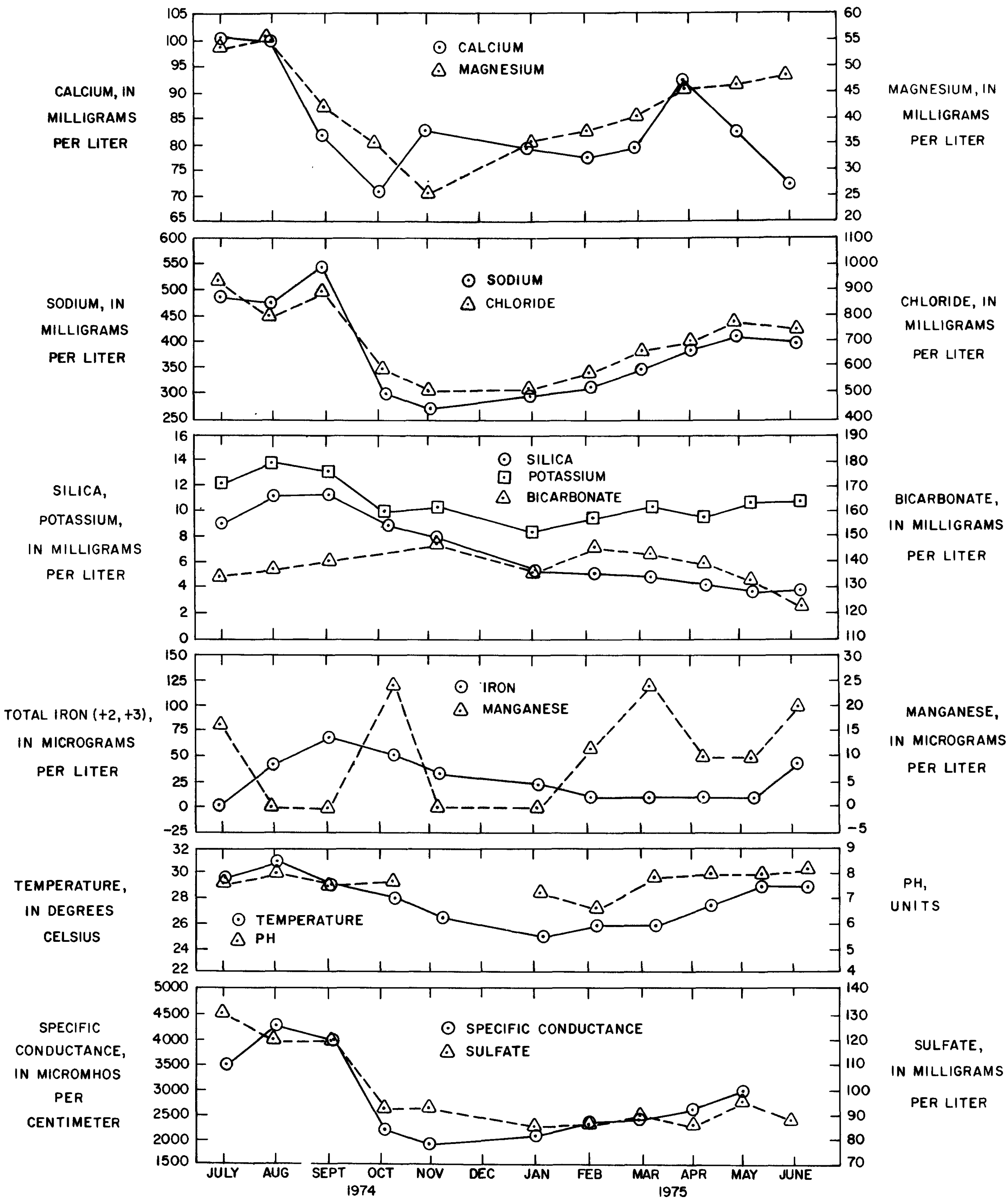

Figure 9.--Seasonal fluction in the main chemical and physical characteristics at station 2 in western Laguna Tortuguero.

Chloride and sodium are the principal ions in the waters of Laguna Tortuguero. The concentration of chloride ranged from 300 to 700 mg/L, while that of sodium ranged from 150 to 400 mg/L. The ratio of sodium to chloride resembled that of seawater during the periods prior to the flood of October 1974 and after the recovery period.

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Sulfate, calcium and magnesium follow in order of abundance among the ions in Laguna Tortuguero. The sulfate concentrations in the east part of the lagoon ranged from 60 to 95 mg/L, while those in the west part ranged from 85 to 130 mg/L. Magnesium concentrations ranged from 20 to 45 mg/L and 25 to 55 mg/L for the east and west parts, respectively.

The average ratio of sodium to sulfate ($Na^+/SO_4^=$) throughout the lagoon is about 4, which is similar to the ratio of these ions in seawater. This ratio and that of sodium to chloride indicate seawater input to the lagoon from the underlying aquifer.

The calcium concentration throughout Laguna Tortuguero fluctuated from 70 to 100 mg/L in the east part but remained nearly constant at about 75 mg/L in the west part. Seawater has a concentration of up to 400 mg/L of calcium (Hem, 1970). If only about 5 percent of the water in Laguna Tortuguero is of seawater origin (based on the percentage of chloride), and if there were no other source of calcium to the lagoon, a dilution in the calcium concentration to about 20 mg/L would occur. However, the primary source of water to Laguna Tortuguero is ground water from the Aymamón aquifer (Bennett and Giusti, 1972), which is either saturated or supersaturated with calcium (Giusti, 1974). The chemical equilibria of these waters maintain in solution concentrations of calcium of as much as 100 mg/L. Calcium plays an important role in the sediments in Laguna Tortuguero. This will be discussed in connection with the sediments in the lagoon.

The concentration of silica in Laguna Tortuguero ranged from 3 to 11 mg/L, decreasing from the beginning to the end of the study. There were no significant differences in concentration between the east and west parts of the lagoon.

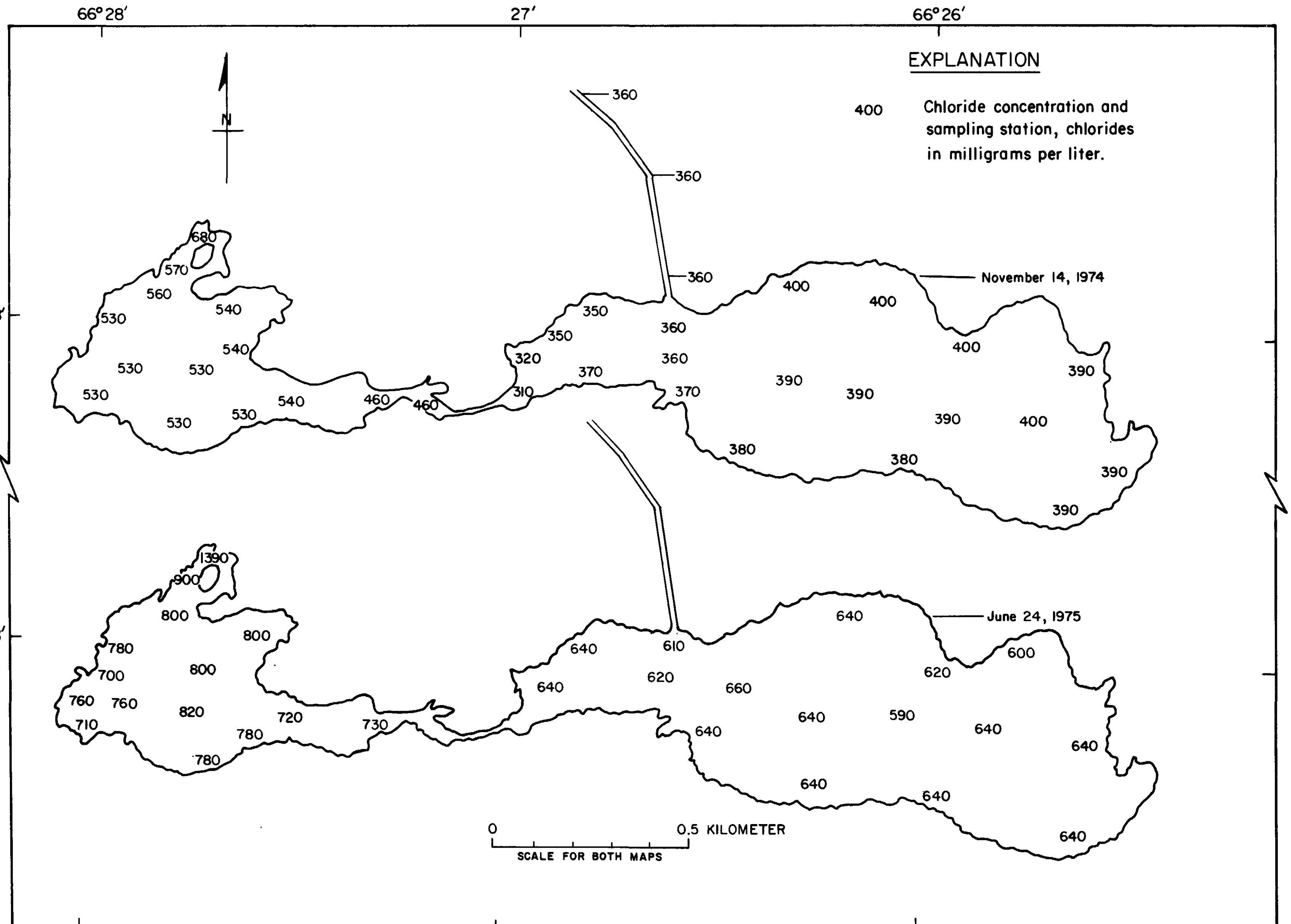


Figure 10.--Chloride concentrations throughout Laguna Tortuguero on November 14, 1974 and June 24, 1975.

Silica in ground waters along the north coast averages about 10 mg/L (Guisti, (1974). Prior to the flood of October 1974, silica concentrations in the lagoon were about 11 mg/L. Concentrations then declined steadily not only after the flood, but continued to decline during the period when recovery in the concentrations of other ions occurred. Bicarbonates in the lagoon followed a similar pattern. Silica plays an important role in the metabolism of diatoms. The decline in silica during the spring and summer could be related to the diatom populations in the lagoon. These interactions will be covered in the biological part of the report.

Specific conductance values at 25°C ranged from 1,500 to 2,800 μmho/cm in the eastern part of Laguna Tortuguero and from 2,000 to 4,300 μmho/cm in the western part (figs. 8 and 9). Higher values were recorded on the northern tip of the western part of the lagoon (6,500 μmho/cm), but these are not typical of the lagoon. The proximity of the ocean to this area accounts for the higher values.

The relation between the specific conductance and chloride concentration, their seasonal fluctuations and the comparisons between the two parts of the lagoon are shown in figure 11. A correlation between the two parameters shows that chloride concentrations throughout the lagoon may be estimated accurately by multiplying the specific conductance times 0.25. Because the field measurement of specific conductance may be accomplished with a high degree of precision, chloride ion concentrations in the lagoon may be monitored with minimum effort and expense.

The pH of the water in Laguna Tortuguero did not change significantly during the period of study. It ranged from 6.8 to 8.2 units; however, the mode was about 8.0 units. The high calcium and bicarbonate concentrations provide an alkaline buffer system that maintains the pH nearly unchanged.

Concentration of ions is higher in the western than in the eastern part of the lagoon (figs. 8 and 9). This difference may be caused by several factors. The west end of the lagoon does not have an open drainage system to the ocean such as the canal of the eastern part. As a result, flushing of the lagoon occurs principally in the eastern part, while in the western part the water is more "stagnant." Also, because the general wind pattern in Laguna Tortuguero is from east to west, the winds act as an additional force that reduces the flow from the western to the eastern end. With limited drainage in the west, evaporation further concentrates the ions. Upwelling of seawater into the western end is bound to occur at a higher rate than in the east because the western part of the lagoon is closer to the ocean.

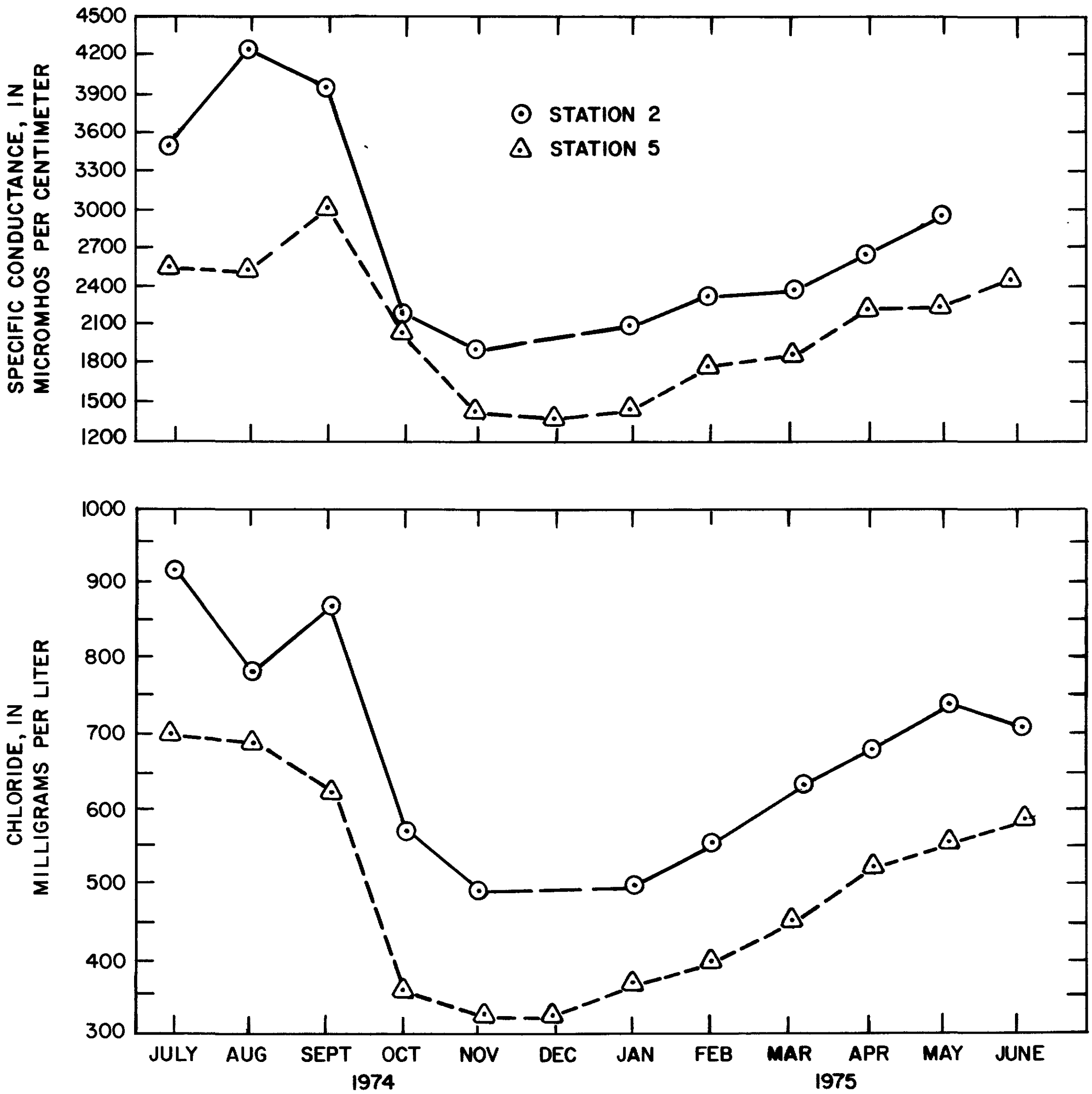


Figure 11.--Seasonal fluctuation in the chloride concentration and specific conductance at stations 2 and 5.

Nutrients and Nutrient Budget

Nutrients, among which nitrogen and phosphorus are accepted as the most significant, include a large number of elements and compounds which are essential to plant life (Hutchinson, 1973). A list of the nutrients which are important in aquatic systems is shown in table 3. With increased nutrient concentrations, plant growth may accelerate, and certain species which are adapted to higher nutrient concentrations may become dominant.

The enrichment of natural waters with plant nutrients is part of the process of eutrophication. In relatively undisturbed drainage basins, nutrients are transported to lakes and reservoirs where they are utilized by plants, accumulated in the sediments or discharged downstream. Human activities in a basin may accelerate the rate of eutrophication. For example, fertilization of cropland combined with poor soil conservation practices, feedlot activities, and human wastes all can contribute nutrients to water, leading to "cultural eutrophication."

Criteria have been established as to what concentrations, in terms of nitrogen and phosphorus, constitute limits beyond which nuisance effects of the eutrophication process may take place. Sawyer (1947) suggested that above a concentration of 0.01 g/m^3 of phosphorus (P) and 0.3 g/m^3 organic nitrogen (N), lakes would become eutrophic. Vollenweider (1968) developed criteria based on areal loading and mean depth, estimating that lakes with an average depth of 5 m receiving up to 1.0 g/m^2 per year N and 0.07 g/m^2 per year P would not be affected by algal blooms and other effects of eutrophication. Lakes receiving more than 2.0 g/m^2 per year N and 0.13 mg/m^2 per year P would be considered "critically loaded." Brezonik and Shannon (1971) revised Sawyer and Vollenweider's estimates. On a volumetric basis, they reported that up to 0.12 g/m^3 P and 0.86 g/m^3 N would be permissible before nuisance effects due to eutrophication occur. On an areal basis, permissible levels would be 0.28 and 2.0 g/m^2 per year P and N, respectively. Brezonik and Shannon's study suggests that Florida lakes can asssimilate more nutrients than those in Vollenweider's analysis (in Europe and throughout the United States). According to Dillon (1975), lakes with high turnover times will tolerate higher loading rates before showing the effects of eutrophication.

The seasonal fluctuations in the concentration of the principal forms of nitrogen and phosphorus in Laguna Tortuguero are shown in figures 12 and 13. Organic nitrogen constitutes about 60 percent of the total nitrogen in the lagoon. Concentration ranged from 0.5 to 1.1 mg/L, and averaged about 0.9 mg/l. Concentrations were lowest following the heavy rainfall in October 1974.

Ammonia and nitrate nitrogen follow in order of abundance among the nitrogenous forms in Laguna Tortuguero. Ammonia is produced from the breakdown of organic nitrogen by bacteria. Nitrate is the higher oxidation state among the common nitrogen forms. Both ammonia and nitrate are important forms in the growth of phytoplankton. Their concentrations are related not only to each other but also to the phytoplankton activity.

Table 3.--Nutrients essential to algal life (modified from Greeson, 1971).

Element	Minimum requirement (mg/L)
(?) Aluminum	Probably trace quantities.
Boron	0.1
Calcium	20
Carbon	Quantities always sufficient in surrounding medium.
Chlorine	Trace quantities.
Cobalt	0.5
Copper	0.006
Hydrogen	Quantities always sufficient in surrounding medium.
Iron	0.00065 - 6.0
Magnesium	Trace quantities
Manganese	0.005
Molybdenum	Trace quantities.
Nitrogen	Trace quantities - 5.3
Oxygen	Quantities always sufficient in surrounding medium.
Phosphorus	0.002 - 0.09
Potassium	Trace quantities.
Silicon	0.5 - 0.8
Sodium	5.0
Sulfur	<5.0
Vanadium	Trace quantities.
Zinc	0.01 - 0.1

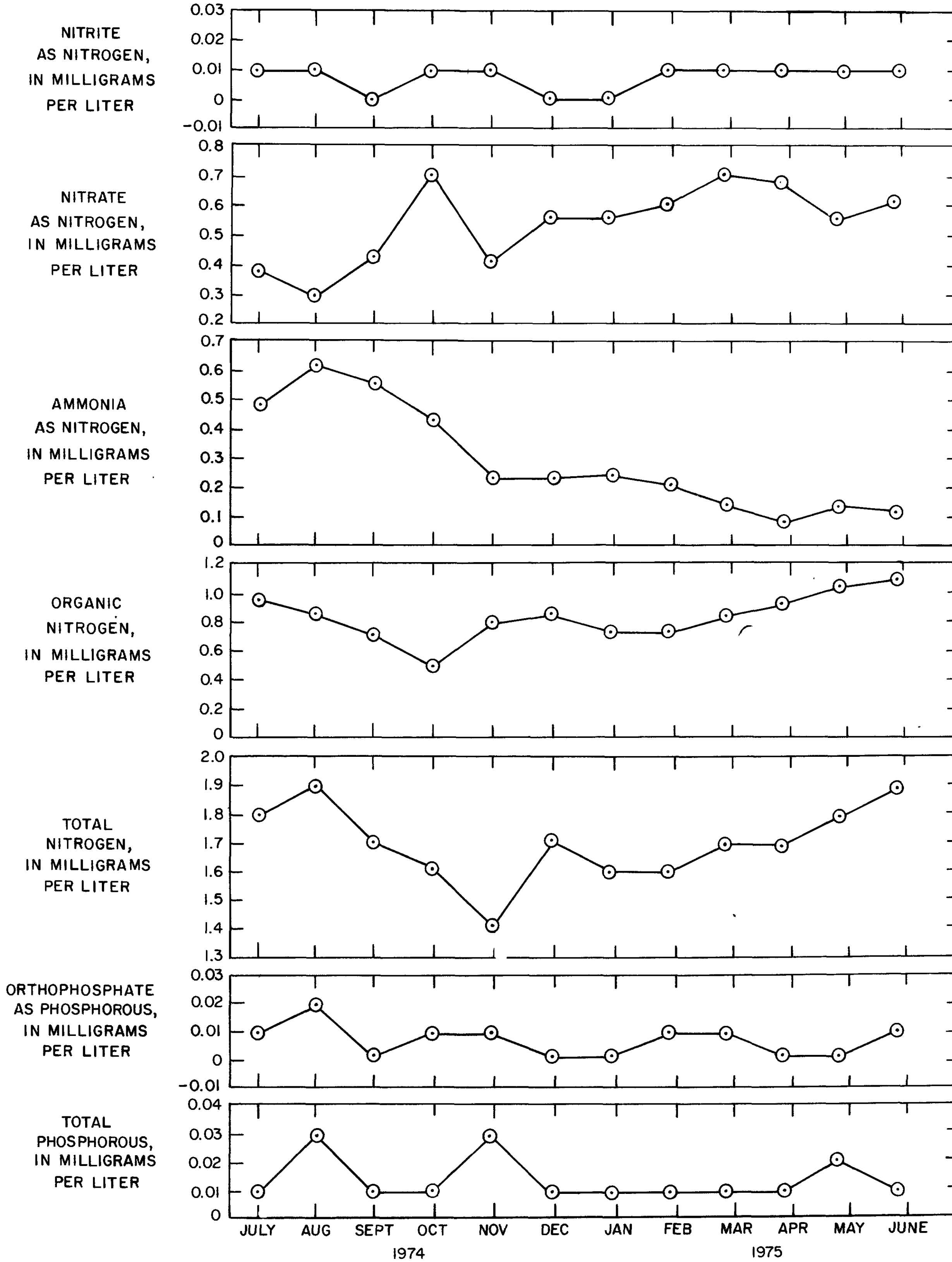


Figure 12.--Seasonal fluctuation in the concentration of the principal nitrogen and phosphorus forms at the east part of Laguna Tortuguero for the average of stations 1, 4, and 5.

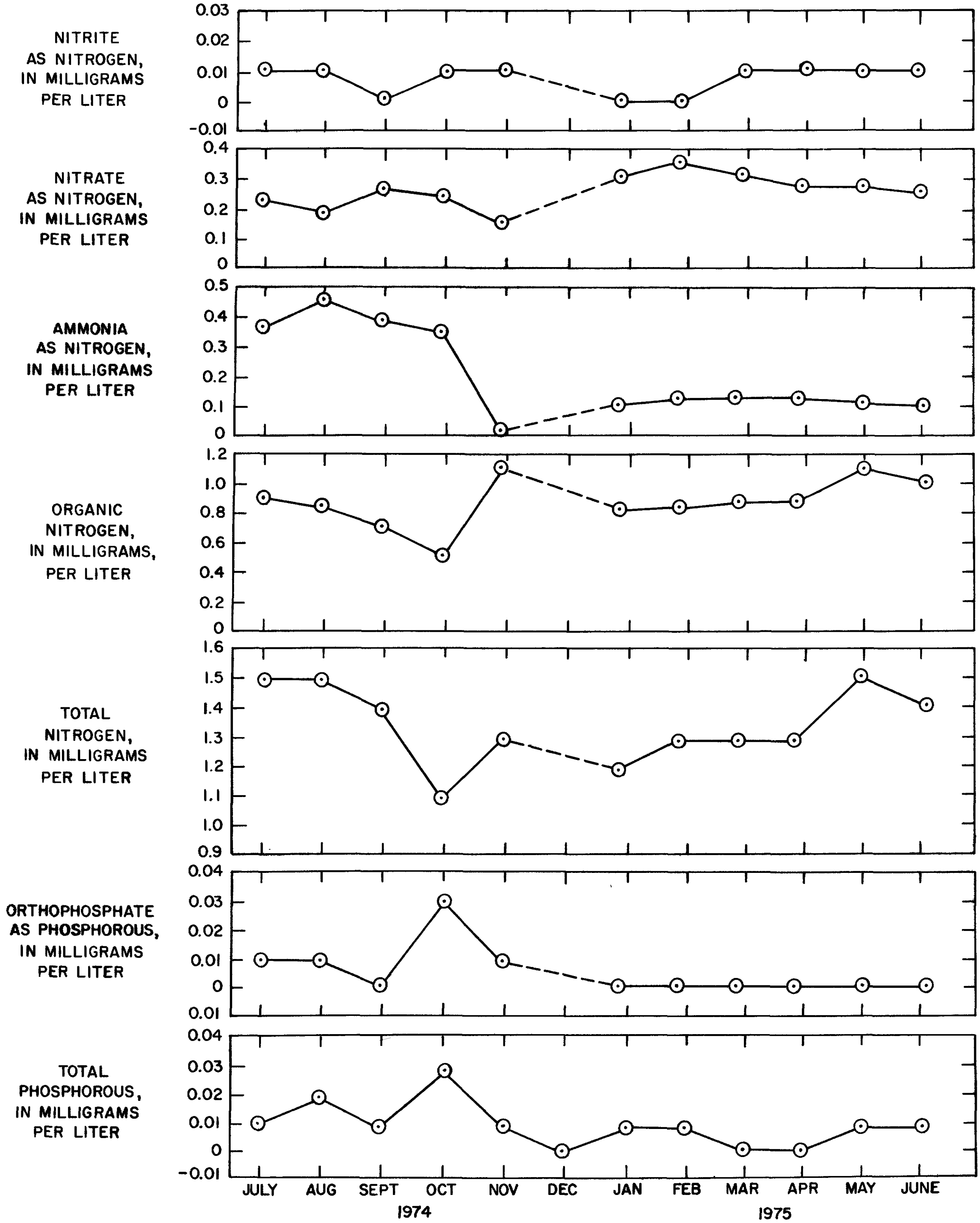


Figure 13--Seasonal fluctuation in the concentration of the principal nitrogen and phosphorus forms at station 2 in the west part of Laguna Tortuguero.

The concentrations of ammonia in Laguna Tortuguero were generally higher in the eastern than in the western part (figs. 12 and 13). Peak concentrations of 0.60 mg/L in the eastern part and 0.45 mg/L in the western part occurred during August 1974. Concentrations decreased to less than 0.2 mg/L after the October flood, and remained below 0.2 mg/L during the remaining 8 months of the study. Examination of the other nitrogen forms shown in figures 12 and 13 shows that the initial reduction in ammonia concentration was due to a general reduction in the total nitrogen in the system.

Also shown in figures 12 and 13 are seasonal fluctuations in the total nitrogen concentration. This is perhaps a better index of nutrient concentration because the various nitrogen species are in a constant state of change as they are utilized, stored or transformed by plants and animals. The total nitrogen value provides the overall nitrogenous level of the system.

The total nitrogen concentration ranged from 1.1 to 1.9 mg/L throughout the lagoon. The concentrations were generally higher in the eastern part. The average concentration in the east was about 1.7 mg/L and in the west about 1.3 mg/L. At the canal outlet (station 1) the average concentration was 1.7 mg/L.

The seasonal changes in the concentrations of orthophosphate and total phosphorus in Laguna Tortuguero are also shown in figures 12 and 13. In a way similar to total nitrogen, total phosphorus is a preferred variable over other phosphorus forms as an index of eutrophication. Orthophosphate is probably more readily available to algae for their metabolism, but many organisms are capable of decomposing organic phosphates into forms suitable to their needs.

The total phosphorus concentration in Laguna Tortuguero ranged from 0 to 0.03 mg/L and averaged about 0.01 mg/L. This concentration is on the threshold of detection by the analytical methods. These values are below those described by Brezonik and Shannon (1971) as "permissible" in terms of nuisance effects of algae.

The overall weight ratio of total nitrogen to total phosphorus (TN/TP) in Laguna Tortuguero ranged from 100 to 190 and averaged about 170. Vollenweider (1968) suggests a TN/TP which exceeds 15 indicates phosphorus is the limiting factor for the phytoplankton growth. It could be, however, that a micronutrient, and not phosphorus, is the limiting factor in Laguna Tortuguero.

The balance of the nutrients' inflow and outflow to Laguna Tortuguero is an important aspect of the system. A shift in the present flows could induce changes in some of the lagoon communities which could have an overall effect on the entire system.

Nutrient sources to Laguna Tortuguero include rainfall, surface runoff and ground-water flows. Sinks or outflows include the canal outlet and interchanges with the sediments. The sediments, under certain conditions, may also act as a source of nutrients.

Rainfall and dry fallout contribute a significant amount of nutrients to Laguna Tortuguero. The analyses (table 4) represent total concentration and include dry fallout. The samples were composites between the dates indicated in table 4. Total nitrogen concentration in rainfall ranged from 0.32 to 1.2 mg/L and averaged 0.62 mg/L (1.2 mg/L of August 27 sample not included in the average). Total phosphorus concentration ranged from 0.01 to 0.53 mg/L, with an average of about 0.15 mg/L. These concentrations of N and P are higher than those in many streams throughout Puerto Rico, and the average total phosphorus is higher than the modal concentration in the lagoon. If the monthly composite concentrations of total nitrogen and total phosphorus are applied to the monthly precipitation (and estimating the months for which analyses were not made), the contribution of rainfall to the lagoon area (fig. 6) is about 1.92 metric tons of nitrogen and 0.35 metric tons of phosphorus.

The role of surface runoff as a source of nutrients to Laguna Tortuguero is not known. During heavy storms, precipitation that does not infiltrate into the ground will flow as overland runoff. Some nutrients will be dissolved and transported in particulate matter into the lagoon. Measurements of nutrients during these conditions were not made.

However, an estimate of the overall nutrient loads from ground and surface water can be made if the assumption is made that the mean concentration of nitrogen and phosphorus in the combined surface- and ground-water flows is equal to the concentration prevailing in the lagoon. This is a reasonable assumption as the total nitrogen and total phosphorus in the lagoon did not change significantly during the year. With a flushing rate of 7.5 times a year, it would be expected that unless the source of nutrients is nearly constant, significant variations would be shown throughout the year.

About 70 percent of the nitrogen in the lagoon is present as organic plus ammonia nitrogen. These low oxidation states suggest recent input to the lagoon or a source within the lagoon itself such as the decaying aquatic plants and animals. Ground-water discharge is the predominant inflow to the lagoon. Nitrogen in the ground water, however, is predominantly as nitrate. Therefore, it appears that the nitrate in the ground water utilized initially by plants and the low oxidation states of nitrogen which predominate in the lagoon are results of decaying of the plants and animals.

The contribution of nitrogen and phosphorus from ground and surface waters to Laguna Tortuguero is about 3.13 metric tons of nitrogen and 0.31 metric ton of phosphorus. These values were computed from the monthly concentrations of total nitrogen and total phosphorus and an estimate of the total volume contributed from each part of the lagoon. The volume estimate was adjusted by the proportion of the area and the specific conductance on each part of the lagoon. These computations result in a 25 percent volume contribution from the western part and 75 percent from the eastern part.

Table 4.--Selected physical and chemical characteristics of rainfall near Laguna Tortuguero. [Values in milligrams per liter, except specific conductance in micromhos per centimeter at 25°C; pH in units]

	Specific conduc.	pH	Sodium	Potassium	Silica	Chloride	Sulfate
1974							
Jul 31		6.4					
Aug 1		6.4					
Aug 5	49	6.8	2.0	0.3	0.5	4.3	5.3
Aug 27	96	-					
Aug 28	83		6.3	.9	.4	1.3	11
Aug 30					.4	13	4.2
Sep 15	35		7.0	.4	.4	1.9	-
Sep 28							
Sep 30							
Oct 6							
Oct 24							
Oct 25							
Oct 31	45		3.3	.6	.5	1.3	5.0
Nov 26	45						
1975							
Mar 5	75	6.4					
Mar 30			5.5	2	1.4	1.8	21
May 31							
Jun 30							
Jul 22							

Sea water Cl/Na = 1.8
Mg/SO_4 = 4.9

Table 4.--Selected physical and chemical characteristics of rainfall near Laguna Tortuguero. [Values in milligrams per liter]--Continued.

	Bicar-bonate	Total nitrogen as N	Total nitrate as N	Total orthophos-phorus as P	Total phos-phorus as P
1974					
Jul 31		0.88	0.17	0.44	0.53
Aug 1					
Aug 5	12	.56	.18	0	.35
Aug 27		1.2	.21	.12	.32
Aug 28	20	.59	-	.01	.02
Aug 30	10	.32	-	.01	-
Sep 15	-	-	-	.01	-
Sep 28				-	.07
Sep 30				0	.09
Oct 6				-	.09
Oct 24				.01	.07
Oct 25			.07	.34	.41
Oct 31	14	.47	.08	.01	.01
Nov 26					
1975					
Mar 5					.06
Mar 30					
May 31		.58			.08
Jun 30		.56			.08
Jul 22					

Sea water Cl/Na = 1.8
Mg/SO_4 = 4.9

At the canal outlet, the average total nitrogen and phosphorus concentrations ranged from 1.4 to 1.9 mg/L and from 0.01 to 0.09 mg/L, respectively. Computations prorated on the basis of the seasonal concentrations show that a total of 34.0 metric tons of nitrogen and 0.42 metric ton of phosphorus was discharged to the sea.

The overall nutrient budget of Laguna Tortuguero is summarized in figure 14. The change in storage represents a gain from the difference in concentrations and volumes in the lagoon at the beginning and end of the study. If a mass balance is made, a total of -0.6 metric ton of nitrogen and 0.24 metric ton of phosphorus is not accounted for. These amounts are probably being exchanged with the bottom sediments in the lagoon, but could also be errors due to the accuracy of the procedure used.

According to the nutrient budget (fig. 14), a total of 33.2 metric tons of nitrogen and 0.6 metric ton of phosphorus entered Laguna Tortuguero during the 1-year study period. These loads are equivalent on an areal basis to about 15 g/m^2 of nitrogen and 0.3 g/m^2 of phosphorus. These values exceed loading rates described by Vollenweider (1968) and Brezonik and Shannon (1971) as critical; above which the nuisance effects of eutrophication are likely.

The nuisance effects of eutrophication include heavy algal blooms which discolor the water and often result in anaerobic conditions. Heavy algal blooms were not observed in Laguna Tortuguero. The flushing rate of the lagoon system appears to be the principal factor in controlling the present steady state. If the flow of water out of the lagoon were to be restricted, short-circuiting the removal of nutrients from it, one would expect that eventually some of the eutrophication effects would be more evident.

Heavy Metals and Pesticides in Water

Concentrations of arsenic, cadmium, nickel, copper, lead, mercury, and other heavy metals, at levels greater than those found in natural waters, are well documented by the National Academy of Sciences-National Academy of Engineering (1972), among others. Certain of these heavy metals such as arsenic, cadmium, lead, mercury, etc., are extremely toxic to humans and animals even in very small concentrations. Cadmium produces the infamous "Itai-itai" disease, painfullly deforming bones and other human structures. Others, such as nickel, are suspected of being capable of inducing cancer.

Heavy metals are introduced into the hydrologic environment from industrial, agricultural and domestic effluents. As examples, mercury is widely used in the wood preservative industry; nickel, cadmium and chromium in the electroplating industry; lead was used extensively in the paint industry and continues to enter the hydrologic environment by leaching from old houses and other structures.

Water samples were collected in Laguna Tortuguero on June 24, 1975 for analyses of selected heavy metals (table 5). Except for cadmium and selenium,

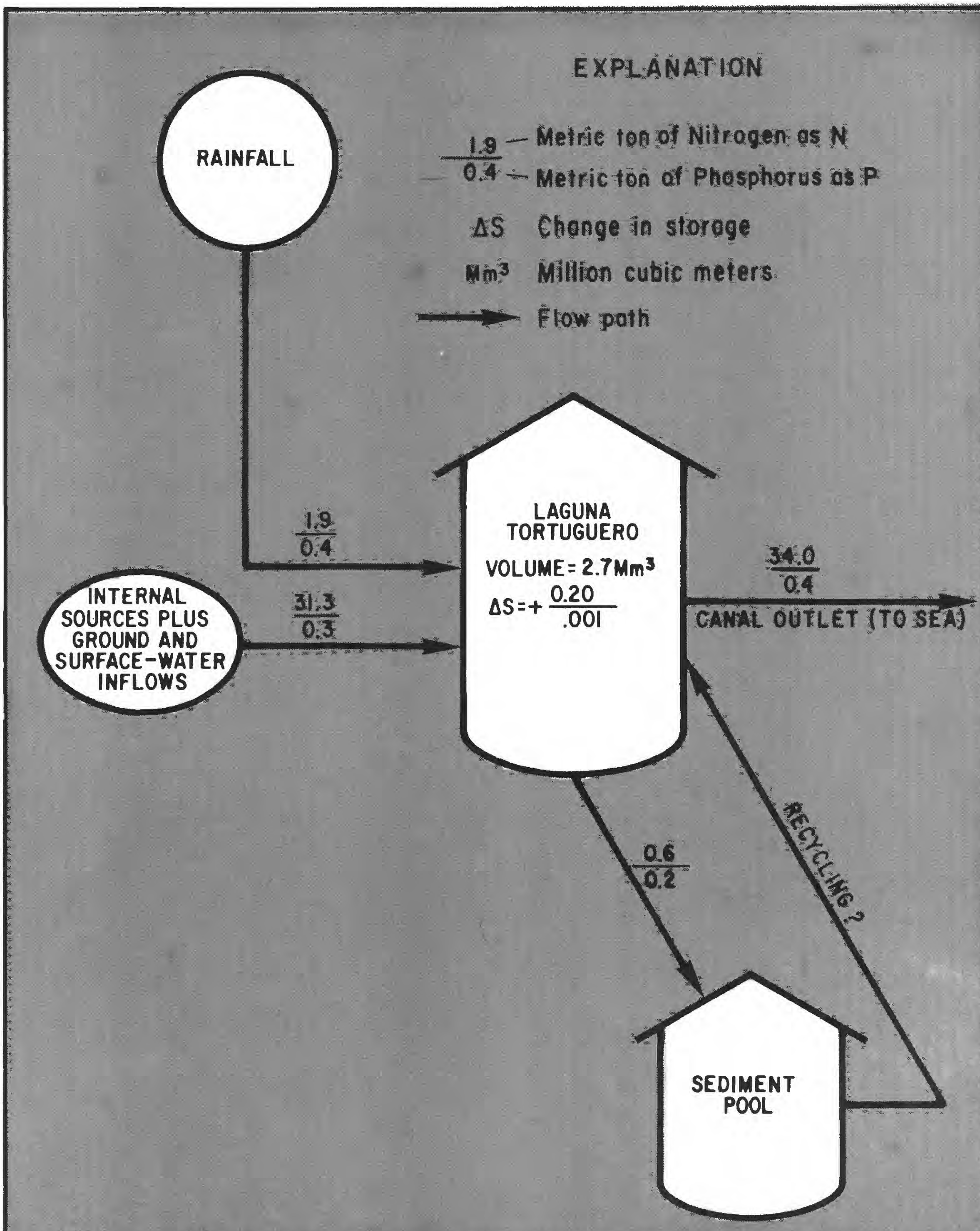


Figure 14.--Nutrient budget of Laguna Tortuguero, July 1974 to June 1975.

the concentration in one or more of the samples exceeded values normally found in waters throughout Puerto Rico (U.S. Geol. Survey unpub. data). An additional sample collected at station 1 in October 1975 indicated a near absence of the metals detected in June. Monitoring of heavy metals in the lagoon should continue until the source and fate of these metals is determined. Because many of these metals are accumulated in plankton and fish, which may eventually be consumed by the population, it is essential that the sources and sinks of these be determined.

Monitoring in Laguna Tortuguero included determinations of selected pesticides. Pesticides are organic compounds which include three major groups on the basis of their use. These are the insecticides, herbicides, and fungicides. The group of insecticides is the most important one from the environmental point of view because of the persistence and toxic characteristics of some compounds. The properties and interactions of pesticides and the environment are discussed in depth by Gould (1966, 1972), among others.

No pesticides, polychlorinated biphenyls (PCB's) or polychlorinated naphthalenes (PCN's) were detected in three water samples from the lagoon (table 6).

Table 5.--Concentration, in micrograms per liter, of selected heavy metals in the waters throughout Laguna Tortuguero. Samples collected on June 24, 1975.

Station	Cadmium (Cd)	Chromium (Cr)	Lead (Pb)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
1	1	<10	27	0.2	69	2	20
2	1	10	23	.2	66	9	80
3	1	50	23	.2	72	8	40
4	0	<10	1	.2	17	6	20
5	1	50	27	.2	66	6	20
USGS unpub. data	0-10	<10	5-10	0.1-0.2	0-20	0	0-100

Table 6.--Concentration, in micrograms per liter, of selected pesticides and organic chemicals in the water at stations 1, 2, and 5. Samples collected November 14, 1974.

Parameter	Station		
	1	2	5
Aldrin	0.0	0.0	0.0
Chlordane	.0	.0	.0
DDD	.0	.0	.0
DDE	.0	.0	.0
DDT	.0	.0	.0
Dieldrin	.0	.0	.0
Heptachlor	.0	.0	.0
Heptachlor epoxide	.0	.0	.0
Lindane	.0	.0	.0
PCB	.0	.0	.0
PCN	.0	.0	.0
Toxaphene	.0	.0	.0

Dissolved Oxygen

The concentration of dissolved oxygen is one of the most studied and important properties of lake waters. Oxygen determinations provide an insight into the chemical and biological interactions in a lake.

The solubility of oxygen in water is regulated by the atmospheric pressure, salinity, and temperature. It is directly proportional to the partial pressure in the gas phase and decreases nonlinearly with increasing temperature.

The concentration of oxygen in lake waters is influenced by several factors. The oxidation of water by wind blowing across the water surface is an important factor. Biological activity by algae produces oxygen which may be retained in the water. Consumers such as fish and zooplankton utilize some of the available oxygen. Organic matter is oxidized exerting an oxygen demand which on occasion may deplete all the oxygen available in the water.

It is commonly accepted that dissolved oxygen lower than 5.0 mg/L may be unfavorable to aquatic life, particularly to fish. However, many species of fish can survive at almost zero oxygen concentrations. The organism may continue to survive, but the ability of the species to cope with the demands of the environment and reproduce is reduced. A dying out of the species may then follow. Accordingly, recommendations to establish levels of protection instead of arbitrary numbers have been proposed recently (National Academy of Sciences, 1972). For maximal protection of fish and other aquatic organisms, it is recommended that the minimum dissolved oxygen concentration should not be lower than the natural seasonal minimum of the particular body of water. To establish the natural minimum requires a near-natural system which is a difficult proposition in many places. The importance of the criterion is that it recognizes the vital role of adequate dissolved oxygen concentrations to protect fish and aquatic life.

Seasonal fluctuations in the dissolved oxygen concentration at stations 2 and 5 are shown in figure 15. Vertical profiles of other stations in the lagoon were similar to those shown. The profiles in figure 15 are representative of daylight hours, mostly from 1000 to 1200 hours. Dissolved oxygen concentrations also fluctuate diurnally as a reslt of biological activity in the system. Diurnal changes in oxygen throughout Laguna Tortuguero are shown in figure 16.

During the day the dissolved oxygen (DO) concentration in the lagoon is at, near, or above saturation levels (fig. 16).

Diel fluctuations in the dissolved oxygen concentration are related to the community productivity and wind action. Oxygen is produced by plants during the day and utilized by plants and other organisms at night. Under normal conditions a buildup in the dissolved oxygen concentration should start after the sun is up. The process should reverse after sunset when photosynthetic

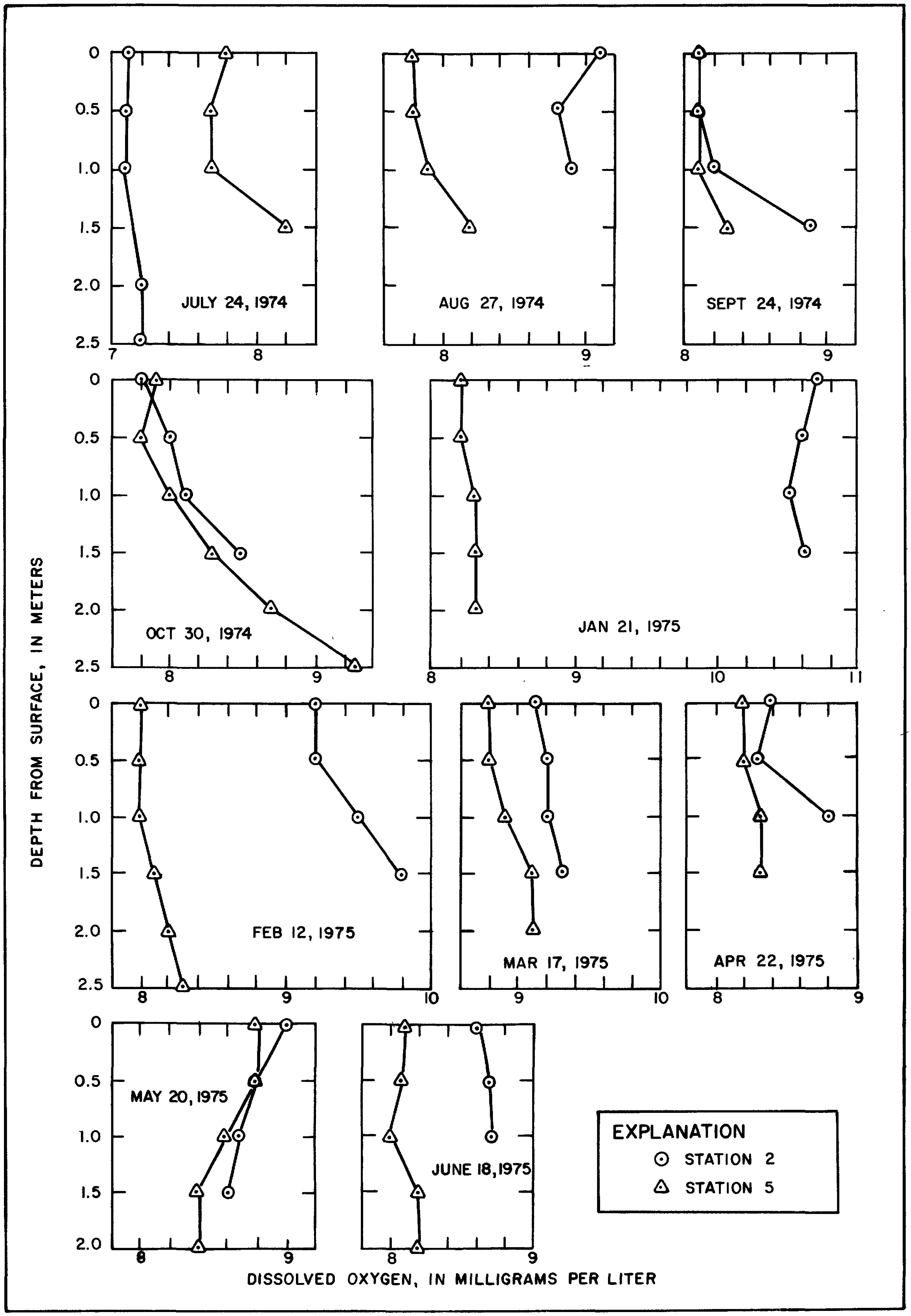


Figure 15.--Seasonal fluctuation in the dissolved oxygen concentration at stations 2 and 5.

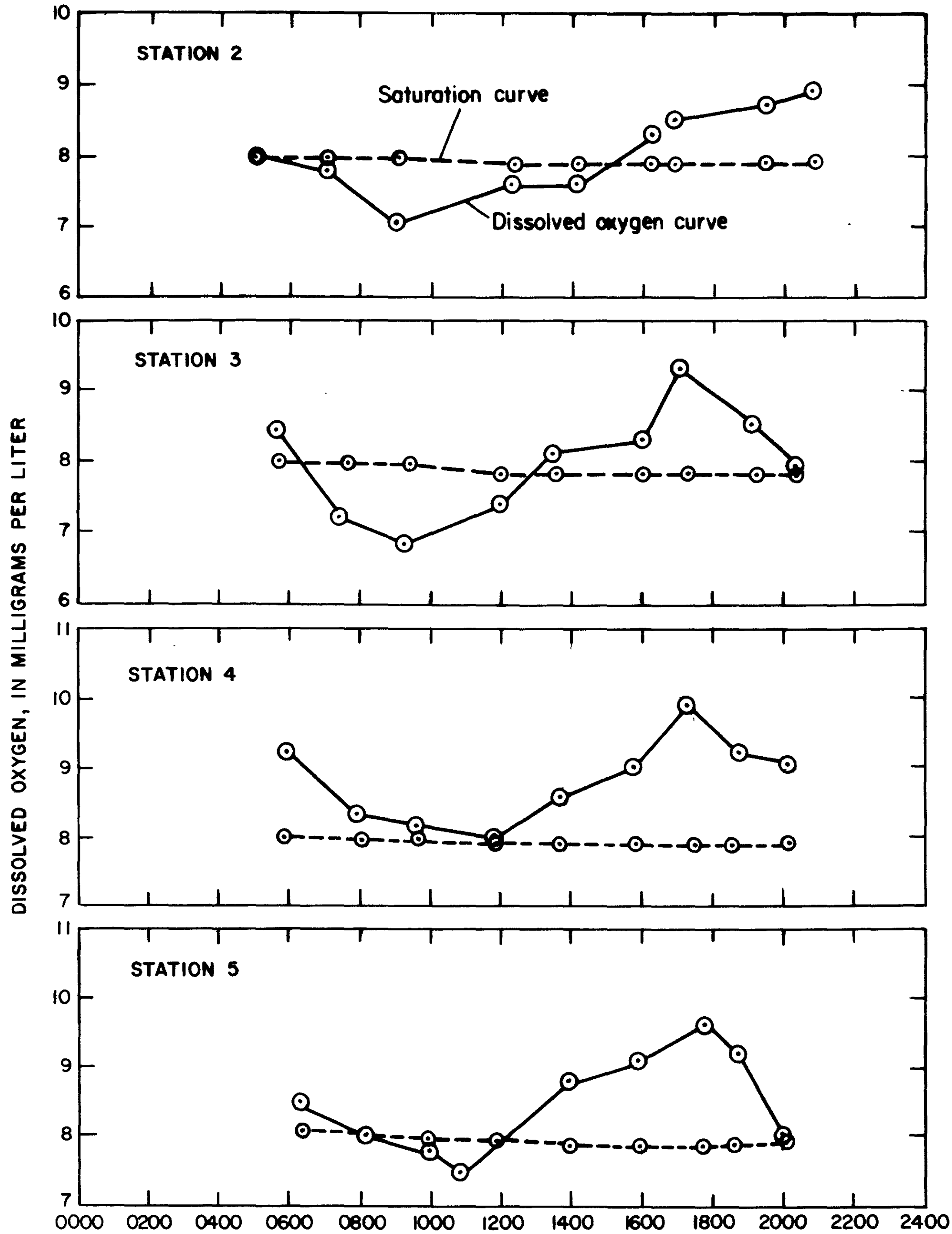


Figure 16.--Diurnal fluctuation in the dissolved oxygen concentration at 0.5 meters depth. Data for November 26, 1974.

production of oxygen ceases and consumers continue utilizing the oxygen in the water. Diel fluctuations in DO in Laguna Tortuguero were on the order of 2 to 3 mg/L on November 26, 1974 (fig. 16).

Wind plays an important role in the dissolved oxygen concentration throughout Laguna Tortuguero. The wind blows predominantly from the east, peaking in force in the early afternoon. The coastal area where the lagoon is located is largely unprotected and the wind creates standing waves and crests of up to 2 feet (fig. 17). In essence, this acts like a huge mixer, helping to saturate the water with air and oxygen.

Temperature

Temperature profiles throughout Laguna Tortuguero were determined concurrently with the dissolved oxygen measurements. These also were made during daylight hours. Almost uniform conditions were found in the lagoon, with a slight difference between the eastern and western parts. The profiles for stations 2 and 5 are shown in figure 18.

The data show that temperature stratification in the lagoon is minimal, with near uniform conditions in the water column. This is the result of the shallow nature of the lagoon and the mixing effect of the wind. The small temperature differential between the two parts of the lagoon is due to the smaller volume of the western part. The larger volume of water in the eastern part is capable of absorbing and diffusing more energy with a smaller change in temperature.

Seasonally there is a small fluctuation in temperature. From summer to winter a change of about 5 degrees Celsius occurs in the water column.

Sediments

The bottom sediments play an important role in the chemical and biological interactions of a lake system. They usually act as a sink, but sometimes are a source of chemical components to the water. Bottom dwelling organisms derive most of their food from organic matter and nutrients in the sediments. Chemical and biochemical reactions that affect the entire lake commonly occur in the sediments.

The bottom sediments in Laguna Tortuguero are unique. They are composed of a soft, carbonaceous muck-type material that in the upper layers may be as much as 75 percent water. The thickness of the sediments throughout the lagoon is variable. A map of the generalized thickness of the bottom sediments is shown in figure 19. A maximum thickness of about 6 m was recorded, while an average of about 2 m is probably representative of the lagoon.

Figure 17.--Waves on the east part of Laguna Tortuguero.

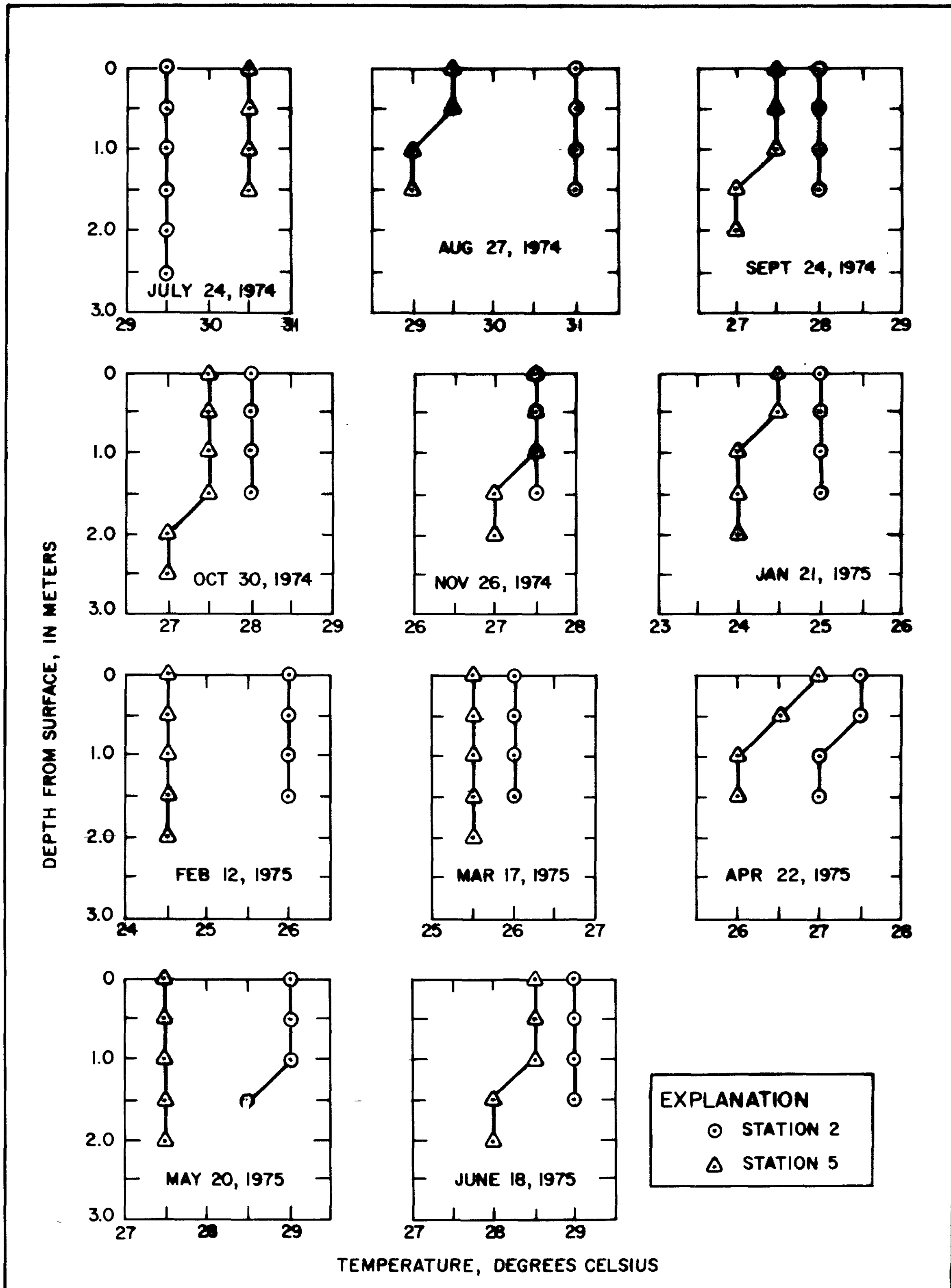


Figure 18.--Seasonal fluctuation in temperature at stations 2 and 5.

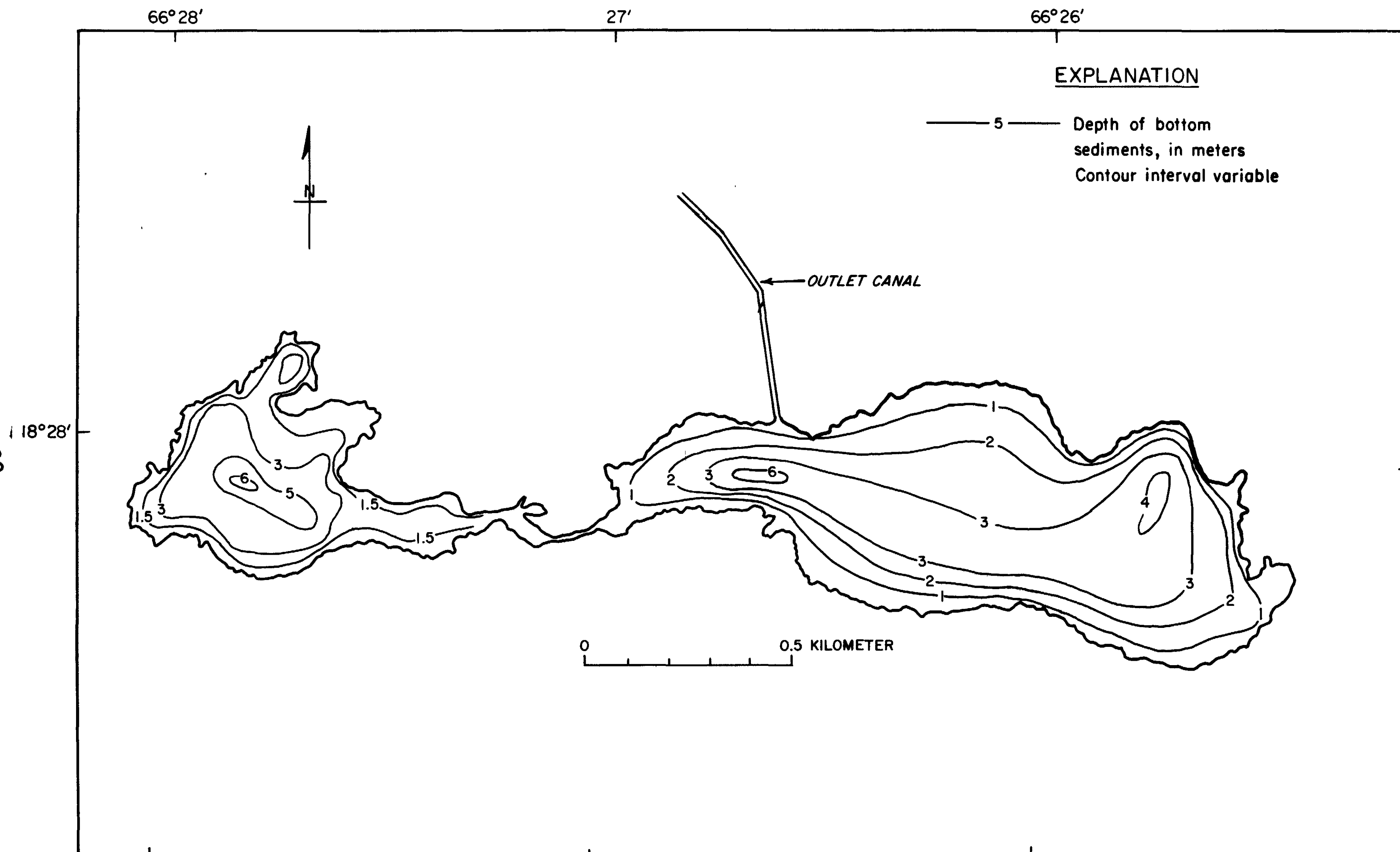


Figure 19.--Generalized thickness of bottom sediments.

The volume of bottom sediments in Laguna Tortuguero is significant. Based on the computed area of 2.24 km^2, and an average thickness of about 2 m, the volume would be about 4.48 Mm^3. This volume is about 1.7 times the computed volume of water in the lagoon. Field observations indicate that the sediments may have an average water content of about 25 percent, by volume, or equivalent to an additional water volume of about 1.6 x 10^6 m. This is about 40 percent of the estimated volume of the lagoon.

The principal component of the bottom sediments in Laguna Tortuguero is precipitated calcium carbonate. Chemical analyses of the water show that the average dissolved calcium concentration is about 75 mg/L in the eastern end and about 100 mg/L in the western end, other than during storm periods when dilution occurs. The concentration of calcium in solution is regulated by the calcium-bicarbonate equilibria (Garrels and Christ, 1965). Equilibrium constants for carbonate and bicarbonate ions are as follows (Hem, 1961):

$$\frac{[HCO_3^-]\ [H+]}{[H_2CO_3]} = 4.16 \times 10^{-7}$$

$$\frac{[CO_3^{-2}]\ [H+]}{[HCO_3^-]} = 4.84 \times 10^{-11}$$

The final calcium concentration is regulated by the equilibrium

$$Ca^{+2} + HCO_3^- = CaCO_3 + H^+$$

The concentration of calcium in equilibrium can be obtained from a manipulation of the above equations, application of equilibrium constants, activity coefficients and analytical results (Hem, 1961; Back, 1961). The dominant factor in the equilibrium is the pH of the water. The following expression can be used for the computation of the amount of calcium in equilibrium, beyond which precipitation occurs:

$$mCa^{+2} = \frac{KCaCO_3}{CO_3^{=} \cdot \gamma Ca^{+2}} ,$$

where m = molality, in moles per liter,

K = equilibrium constant of $CaCO_3$,

α = activity of a particular ion, equal to the activity coefficient (γ) times the molality

$$CO_3^{-2} = \frac{mHCO_3 \cdot \gamma HCO_3 \cdot KHCO_3^-}{\alpha H+}$$

For a pH of 8.0 and a bicarbonate concentration of 143 mg/L, the calcium concentration at equilibrium would be about 36 mg/L. If the pH is about 7.8 units, the calcium at equilibrium would be about 58 mg/L. These computations show that whenever the calcium concentration in solution at a pH of 7.8 exceeds 58 mg/L, precipitation of calcium carbonate theoretically occurs. Supersaturation may shift the theoretical equilibrium maintaining in solution more calcium carbonate.

Additional calculations show that whenever the pH exceeds 7.6 units, under average calcium and bicarbonate concentrations of 75 and 143 mg/L, calcium precipitation may occur. The data in figures 8 and 9 show that most of the time these conditions are exceeded, indicating that precipitation probably occurs nearly all the time. Unless equilibrium conditions are shifted dramatically, deposition of the calcium carbonate will continue, slowly decreasing the volumetric capacity of the lagoon.

Chemical analyses show near uniform concentrations among the most important metals, organic carbon, and nutrients in the bottom sediments throughout the lagoon (table 7). Organic carbon, the principal component of the sediments other than calcium, averages about 6.8 percent by dry weight. The principal source of carbon is probably from decaying littoral plants that abound in the lagoon. Remains of fish and plankton also contribute to the organic load of the bottom sediments.

Table 7.--Concentration of selected metals, organic carbon and nutrients in the bottom sediments. Average of samples collected on January 21 and April 22, 1975. [Concentrations in micrograms per gram of sediment.]

Parameter	Station			
	2	3	4	5
Organic carbon	68,000	66,000	74,000	64,000
Iron	2,100	6,600	850	800
Manganese	90	45	38	54
Zinc	10	20	10	<10
Total nitrogen, as N	9,200	12,000	8,100	3,700
Total phosphorus, as P	140	310	170	130

Iron, manganese and phosphorus are interrelated in aquatic systems. The concentration of phosphorus in solution is related to its reactive power with available iron and manganese, as well as to the oxidation state of these ions and the pH of the media. At the pH found in Laguna Tortuguero, orthophosphates ($H_2PO_4^-$ and $HPO_4^{=}$) are the dominant forms (Stumm and Leckie, 1970). The higher oxidation states of iron and manganese (ferric and manganic) are highly insoluble. Their oxidation or reduction is controlled by the redox potential. Under aerobic conditions, the oxidation potential is high, resulting in a shift toward the higher oxidation states. Nearly quantitative precipitation of ferric and manganic phosphates occur. The opposite occurs in systems where the dissolved oxygen concentration is low, resulting in the release of phosphates from the sediments. Aerobic conditions promote the removal of phosphorus from solution. A high oxygen concentration in water therefore acts as a servomechanism for the control of algal blooms by limiting the phosphorus available in the water for photosynthesis. The conditions in Laguna Tortuguero are an example of the desirable point of these steady state conditions. Dissolved-oxygen concentrations are high, phosphates in the water are low while being about 0.014 percent by weight of the bottom sediments. It is probable that any reduction in the dissolved-oxygen concentration in the lagoon would promote solution of the precipitated phosphates and possibly an increase in the algal biomass.

Analyses of the bottom sediments of Laguna Tortuguero also included cores collected at stations 4 and 5. The analyses from the cores do not show any marked stratification of the principal nutrient-related components (table 8). It would be reasonable to conclude that nearly uniform conditions exist in the bottom sediments. Identification of mollusks recovered from different depths in the sediment cores (table 9) showed mostly freshwater species which are presently found in the lagoon (Reyes de Ruiz, 1971).

Chemical analyses of the bottom sediments in Laguna Tortuguero also included determinations of the most common pesticides, polychlorinated biphenyls (PCB's), polychlorinated napthalenes (PCN's) and toxaphene. Results from samples collected on November 14, 1974, are shown in table 10.

The data in table 10 show that residues from DDT, the most common insecticide, are present in the bottom sediments. Lower concentrations of DDD, one of the metabolites of DDT, were also detected at both stations. DDD is the major product of DDT oxidation under anaerobic conditions (Gould, 1972). The half-life of DDT has been estimated by Gould to be from 10 to 20 years. Because DDT is at a higher concentration than its metabolite, one may conclude that DDT in the two bottom sediment samples is of very recent origin.

Dieldrin, a common chlorinated insecticide and an oxidation product of aldrin, was detected in low concentrations at station 2. Dieldrin has a half-life of 8 to 10 years (Gould, 1972). There is no information as to whether both compounds were used in the area. If only aldrin was used, dieldrin in the lagoon could be from aldrin's oxidation, indicating it is of recent origin in the lagoon.

Table 8.--Concentration of organic carbon, iron, manganese, total nitrogen and total phosphorus in sediment cores from stations 4 and 5. [Concentrations in micrograms per gram of sediment.]

Core depth, in meters	Carbon, organic		Iron		Manganese		Nitrogen, total as N		Phosphorus, total as P	
	Station 4	Station 5	Station 4	Station 5	Station 4	Station 5	Station 4	Station 5	Station 4	Station 5
0.25	116,000	4,900	7,900	-	100	-	3,500	1,900	160	75
.50	124,000	18,000	13,000	-	60	-	-	15,000	110	120
.75	-	11,000	6,900	-	20	-	-	9,200	100	71
1.00	2,000	4,000	580	-	90	-	-	5,900	92	140
1.25	-		4,300	-	80	-	-	-	130	-
1.50	96,000		-	-	-	-	9,300	-	-	-

Table 9.--Species of mollusks identified from a bottom sediment core from Laguna Tortuguero. [Identifications courtesy of the Mollusks Division of the U.S. National Museum, Washington, D.C.]

Assiminea spp

Amnicola spp

Cerithium atratum Born

Cerithium lotosum Menke

Melanoides tuberculata Muller

Neritina virginea Linneaus

Physa cubensis Pfeiffer

Table 10.--Concentration of selected pesticides and organic chemicals in the bottom sediments at stations 2 and 5. Samples collected November 14, 1974. [Micrograms per kilogram of sediment.]

Parameter	Station 2	Station 5
Aldrin	0.0	0.0
Chlordane	.0	.0
DDD	.7	.7
DDT	3.2	11
DDE	.0	.0
Dieldrin	2.6	.0
Endrin	.0	.0
Heptachlor	.0	.0
Heptachlor epoxide	.0	.0
Lindane	.0	.0
PCB	.0	.0
PCN	.0	.0
Toxaphene	.0	.0

Although the concentration of the reported insecticides detected in the bottom sediments in Laguna Tortuguero are relatively low, components of the food chain are capable of concentrating these compounds. Bottom dwellers, such as snails, worms and certain species of fish are capable of concentrating these compounds in their muscle tissues. Further work is needed on the fate of the pesticides in the food chain in Laguna Tortuguero.

BIOLOGICAL CHARACTERISTICS

Bacteria

Bacteriological conditions are important indicators of the sanitary quality of waters. Among bacteria, the coliform group is the most widely used indicator of sanitary conditions. The presence of pathogenic organisms such as salmonella is indicated most of the time when high concentrations of some of the components of the coliform group are present in water (National Academy of Sciences, 1972). Fecal coliform bacteria are preferred indicators over the total coliform bacteria count. Total counts may reflect bacteria of origin other than from the intestinal tract of warmblooded animals, including man. However, high total coliform bacteria counts may still be used as a gross indicator of poor sanitary quality.

The seasonal fluctuation in the number of total coliform, fecal coliform and fecal streptococcal bacteria at stations 1, 2 and 5 in Laguna Tortuguero is shown in figure 20. Similar concentrations of bacteria were observed at stations 3 and 4.

In general, the number of bacteria throughout Laguna Tortuguero is very low. Concentrations never exceeded maximum recommended values for use of the lagoon water for contact sports (National Academy of Sciences, 1972). Fecal coliform and fecal streptococcal bacteria were undetected on many occasions. An analysis of the ratios of fecal coliform to fecal streptococcal bacteria throughout the lagoon shows that these are usually less than one. These ratios indicate that the source of bacteria in the lagoon is predominantly nonhuman (Geldreich, (1967). Most of the area around the lagoon is used for pasture. Wastes from cattle in those areas leach into the lagoon, transporting bacteria. Populations of fish, birds and other species within the lagoon also contribute small numbers of bacteria.

Phytoplankton and Periphyton

The phytoplankton are the assemblage of microscopic plant organisms which perform the greatest part of the photosynthetic activity in most lakes. Periphyton properly refers to plants and other small organisms that grow upon submerged solid surfaces. The phytoplankton react to stresses imposed on their habitat. In systems where stresses are minimal, a diverse population in terms of numbers of species is usually found. Systems subject to environmental stresses are characterized by the dominance of a few species.

The phytoplankton studies in Laguna Tortuguero included determinations of cell concentrations, identification of the most important genera and the seasonal fluctuation in their dominance. Shortly after the studies were initiated it became apparent that the phytoplankton populations in Laguna Tortuguero are virtually all periphytic organisms that are freed from the substrate by the mixing of the lagoon due to the wind effects.

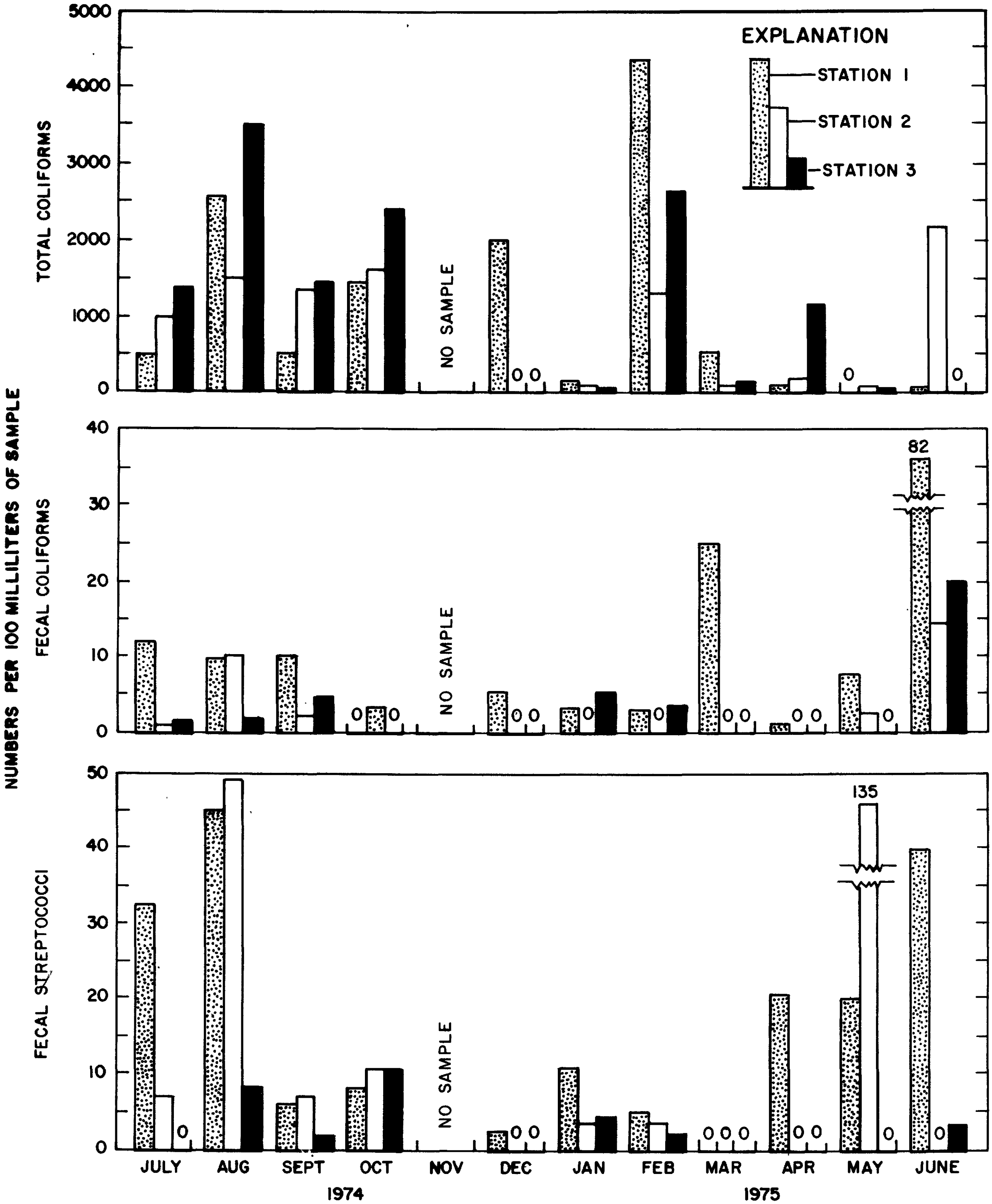


Figure 20.--Seasonal fluctuation in the number of total coliform bacteria, fecal coliform bacteria, and fecal streptococcal bacteria at stations 1, 2 and 5.

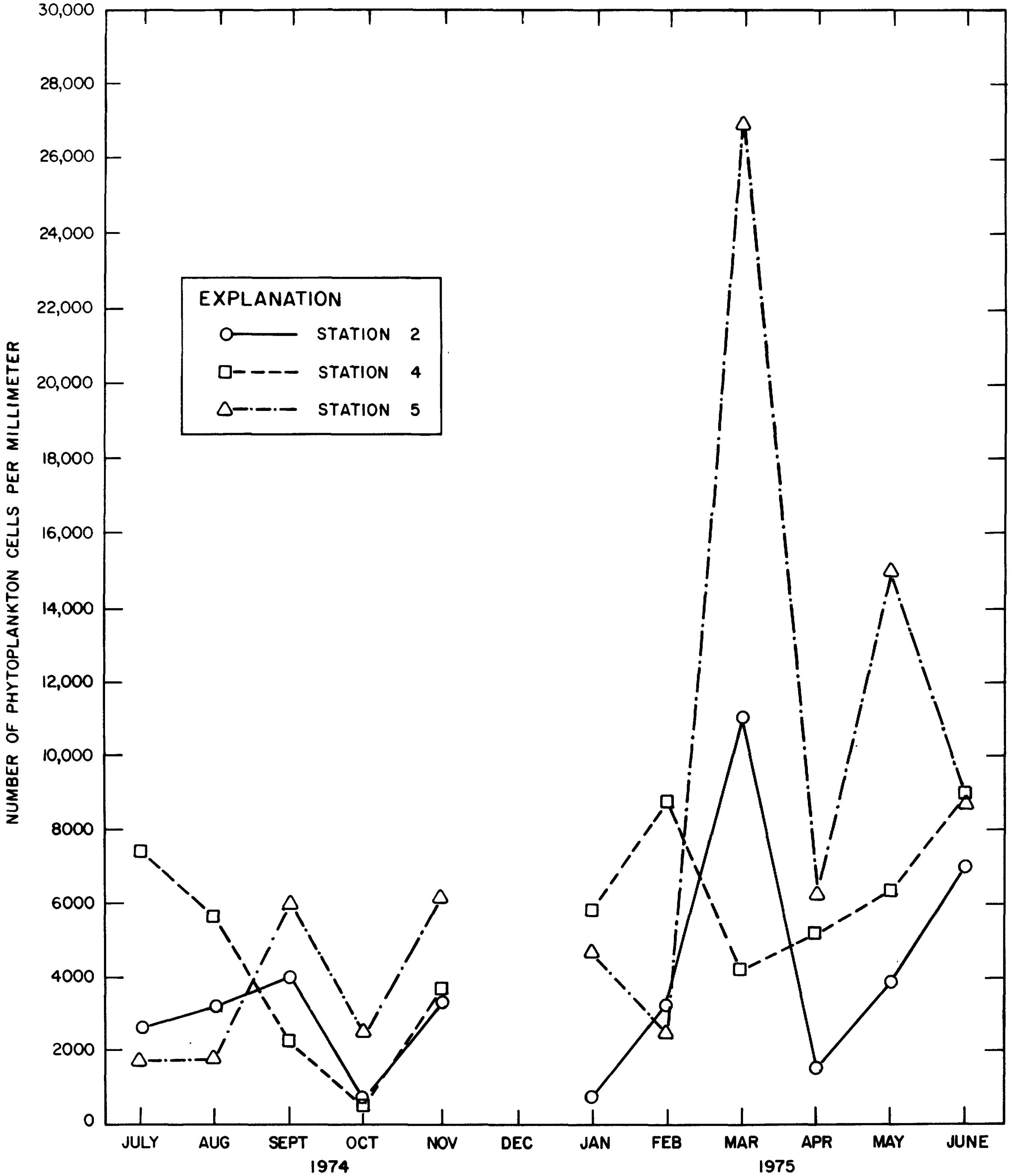


Figure 21.--Seasonal fluctuation in the number of phytoplankton cells at stations 2, 4 and 5.

The seasonal fluctuation in the number of phytoplankton cells at stations 2, 4 and 5 is shown in figure 21. In general, station 5 had the highest concentration, followed by station 4 and station 2. However, the differences between all the stations are small. The data show a general increase in the number of cells after January 1975. The increase in the number of cells is typical of aquatic systems in Puerto Rico at this time of the year.

The number of phytoplankton cells in Laguna Tortuguero is relatively low compared with other lakes and lagoons in Puerto Rico. An average of about 6,000 cells/mL is probably representative throughout the lagoon. In San José Lagoon, a very eutrophic brackish-water lagoon near San Juan, Puerto Rico, cell concentrations range from 50,000 to 900,000 cells/mL, while in Lake Loíza phytoplankton concentrations exceed 12,000 cells/mL most of the time (U.S. Geol. Survey unpub. data).

The genera of phytoplankton identified throughout Laguna Tortuguero are shown in table 11. Of the 47 genera identified, 16 were Cyanophyta (blue-green), 9 were Chlorophyta (green) and the remaining of different Divisions. The large number of genera differs from the findings of Candelas (1974), who reported only 16. The systematic sampling during the year of study, as well as seasonal pulses, are probably the reasons for the differences.

Seasonal fluctuations in the percent of dominance of the principal genera at stations 2 and 5 are shown in figures 22 and 23. Anacystis was dominant throughout the lagoon. At station 2, Anacystis was dominant during 6 of the observations and codominant during 4 other occasions. At station 5 Anacystis was dominant during 9 of the 11 samplings.

Anacystis is a blue-green algae typical of productive systems as well as shallow tropical lakes such as Laguna Tortuguero (Hutchinson, 1957). Constant high temperatures and an ample supply of nitrogen and phosphorus are the necessary conditions to maintain a constant bloom of blue-green algae such as Anacystis. Although in Laguna Tortuguero phosphorus is to some extent limiting, it is available in ample concentrations in the bottom sediments. The present conditions check the blooms of Anacystis at low levels. If phosphorus or other limiting components were to be supplied, massive blooms of Anacystis probably would occur.

The Anacystis populations dominate not only in terms of frequency but also in the percentage of the populations. It averages about 75 percent of the cells identified, indicating a low diversity among the phytoplankton. Distinct dominance by a single population is characteristic of stressed ecosystems. We have shown that there are no external stresses in Laguna Tortuguero promoting the dominance of a single group of organisms. However, the low phosphorus concentration may constitute an internal constraint that creates conditions favorable to the more adaptable blue-green algae.

Among the other genera of phytoplankton in Laguna Tortuguero, pennate diatoms are the most abundant. Pennate (noncentric) diatoms are characteristic of oligotrophic systems (Hutchinson, 1967). Among these, Cymbella, Nitzchia and Navicula (fig. 24) are the most common in the lagoon.

Table 11.--Genera or phytoplankton identified throughout Laguna Tortuguero.

Genera	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
			1974						1975			
Amphriprora 2					x	- - No samples						
Amphora 2		x	x	x	x		x	x	x	x	x	x
Achnanthes 2		x	x				x					x
Anabaena 1	x	x	x	x	x			x	x		x	
Anacystis 1	x	x	x	x	x		x	x	x	x	x	x
Ankistrodesmus 3	x		x	x			x					
Agnemellum	x	x						x	x			
Borzia 1					x							
Cymbella 2	x	x		x	x		x	x	x	x	x	x
Chlamydomonas 3	x	x		x					x			
Cyclotella 2	x		x	x	x			x			x	x
Coelastrum 3									x	x		
Chlorella 3				x								
Cymatopleura 2											x	
Cryptomonas 4				x	x			x				
Chodatella 4								x				
Coccochloris 3	x											
Dactylococcopsis 1	x											
Dinobryon 4					x							
Diatoma 2	x								x			
Dictyosphaerium 3							x					
Denticula 2							x		x	x		
Euglena 4									x			

1 blue-green algae 2 diatoms 3 green algae 4 other

Table 11.--Genera or phytoplankton identified throughout Laguna Tortuguero--Continued.

Genera	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Elakatothrix 3						- - No samples				x		
Glenodinium 4			x	x							x	
Gomphonema 2	x							x				x
Gomphosphaeria 1	x				x			x	x			x
Gymnodinium 4												x
Johanesbaptistia 1	x		x	x				x				
Kirchneriella 3	x				x		x		x			
Lyugbya 1	x	x	x	x	x		x		x		x	
Mastogloia 2				x								
Melosira 2	x	x	x	x				x				
Mallomonas 4					x							
Mouegeotia 3										x		
Navicula 2	x	x	x	x	x		x	x		x	x	x
Nitzchia 2	x	x	x	x	x		x	x	x	x	x	x
Oocystis 3			x		x		x			x		
Oscillatoria 1				x	x		x	x		x		x
Phacus 4				x								
Phormidium 1					x				x	x		
Peridinium 4								x		x		x
Pinnularia 2	x		x									x
Rhoicosphenia 4			x									
Scenedesmus 3	x		x	x				x				x
Synedra 2		x	x	x	x			x	x	x	x	
Tetraedron 3	x	x										

1 blue-green algae   2 diatoms   3 green algae   4 other

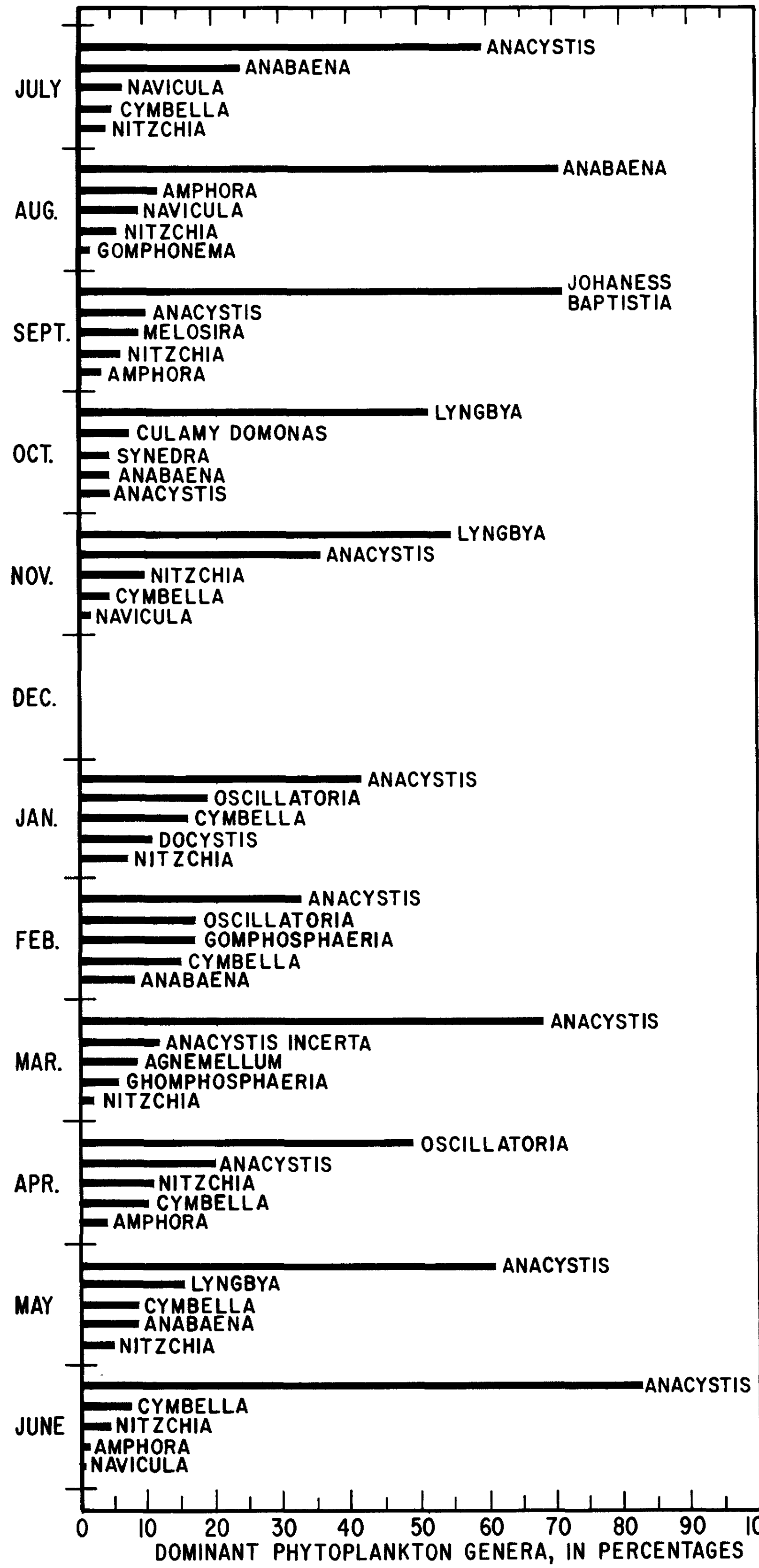


Figure 22.--Seasonal fluctuation in the percent dominance of phytoplankton genera at station 2.

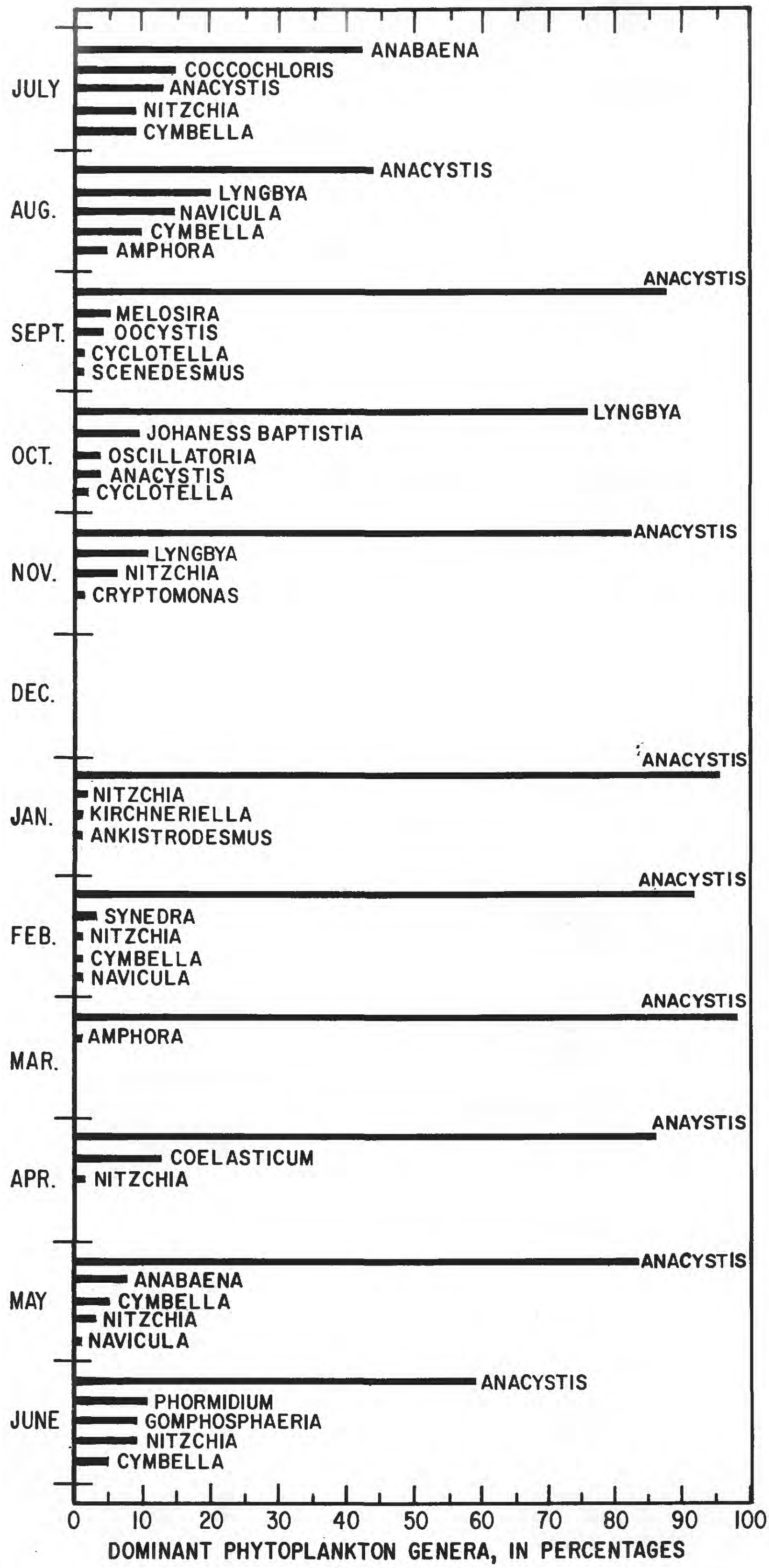


Figure 23.--Seasonal fluctuation in the percent dominance of phytoplankton genera at station 5.

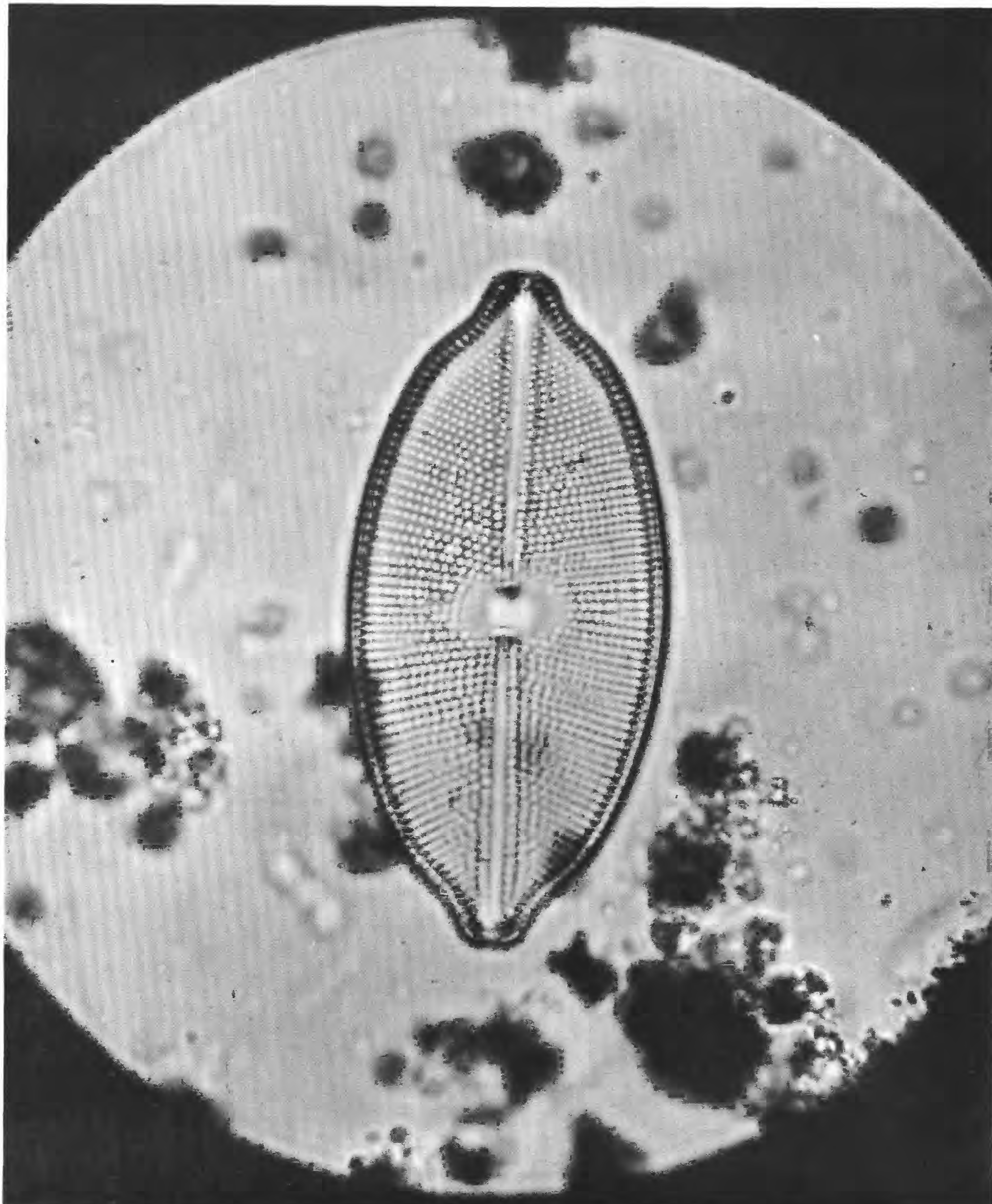


Figure 24.--Navicula sp.

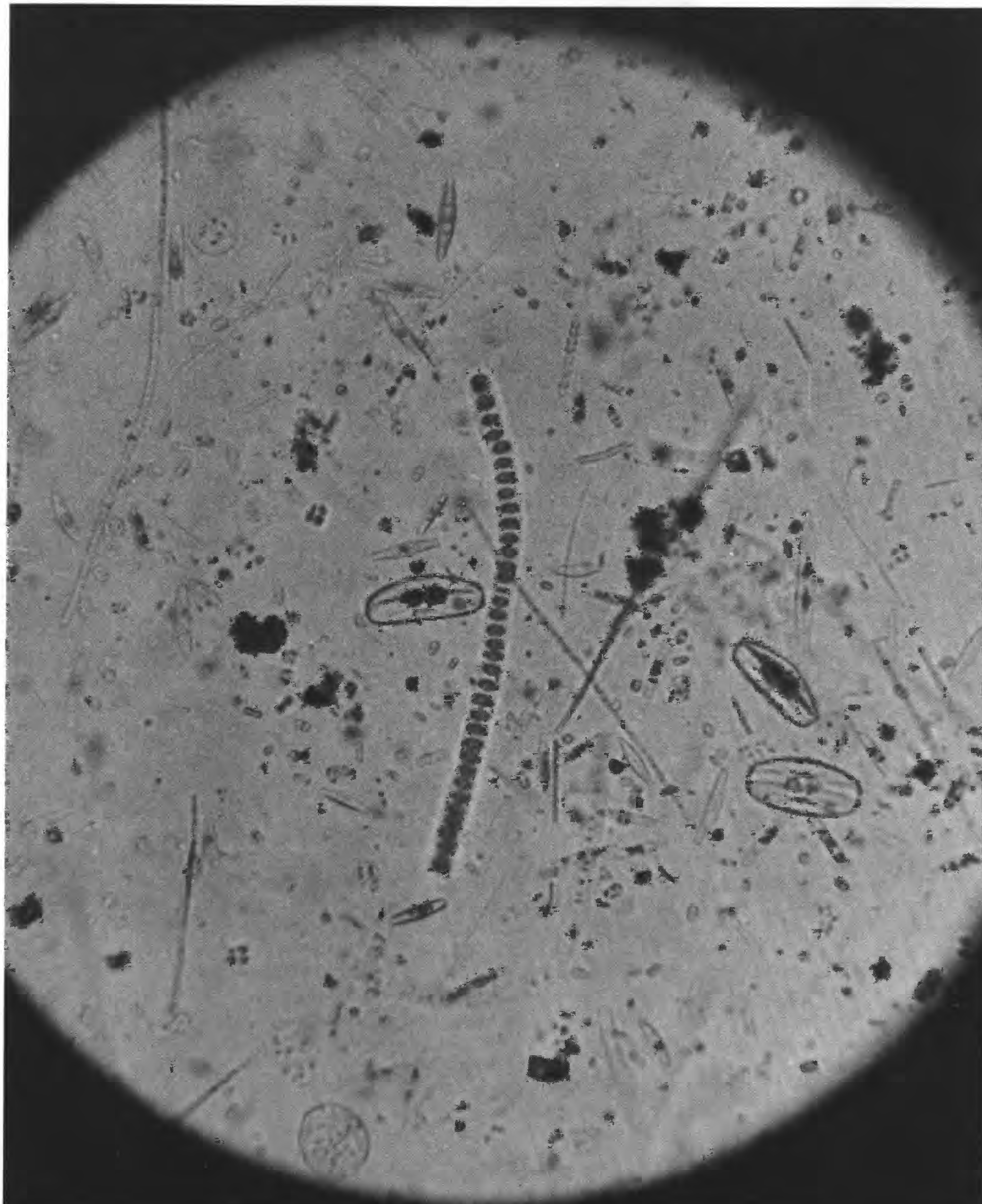


Figure 25.--Periphyton.

The periphyton of Laguna Tortuguero is closely associated with the phytoplankton but it is much more abundant and diverse. The entire bottom of the lagoon is covered by a thick layer of periphytic algae. As previously shown, these algae are responsible for the higher dissolved oxygen concentrations near the bottom as compared with the upper layers in the water column. These mats also may have an effect on redox reactions and possibly pump nutrients from the sediments into the water.

The species of periphyton identified from the lagoon are shown in table 12. Sixty-five species were identified, of which 44 were Chrystophyta (diatoms) and 20 were Cyanophyta (blue-green). An example of the density and diversity of these populations is shown in figure 25. In addition to the diatom species identified, there were many subspecies that could not be identified. Although only qualitative analyses were made of the periphyton, it is obvious that a high diversity exists among these organisms. The pennate diatoms comprise more than 75 percent of all the organisms observed. Future studies in Laguna Tortuguero should include a more detailed investigation of the periphyton.

Zooplankton

The zooplankton are the animal component of the plankton. Zooplankton feed on bacteria, smaller organisms, detritus and algae. They are a link in the food chain, grazing on other organisms and being consumed by fish. Large populations are characteristic of productive systems. High diversity is typical of ecologically balanced systems, while low diversity implies stresses.

The zooplankton studies in Laguna Tortuguero included identification of most of the species collected, determination of population densities, dominance and seasonal fluctuation. Only those species in the water (swimming or floating) were investigated, although composites of vertical hauls were also collected.

The different zooplankton species identified in Laguna Tortuguero are shown in table 13. Seventeen species were observed, of which 12 were properly identified. Some of the zooplankters shown in table 13 were observed only during short periods during the study. Only *Diaptomus dorsalis*, *Diaphanosoma brachyurum* and *Filinia opoliensis* were collected during each sampling (no samples were collected during December 1974).

The number of zooplankton species identified by Candelas (1974) was 10. Candelas further concluded that the diversity of zooplankton in the lagoon was low. The opposite is shown from this study, more specifically upon consideration of the percent dominance of the principal species.

The number of zooplankton organisms per unit volume is shown in figure 26. Concentrations ranged from 20,000/m^3 to 380,000/m^3, averaging about 100,000/m^3. There are no significant differences between stations 2, 4 and 5. The concentrations increased slightly after February 1975, as did the phytoplankton populations (fig. 21). Zooplankton also increased after October.

Table 12.--Species of periphytic algae identified in Laguna Tortuguero.

Chrysophyta (diatoms)

Navicula

Navicula palpebralis
Navicula braunii
Navicula viridis
Navicula pupula var. *capitata*
Navicula inaculata
Navicula circumtexta
Navicula decurrens
Navicula radiosa
Navicula scutum
Navicula pseudo. *sentiformis*

Cymbella

Cymbella lanceolata
Cymbella cymbiformis
Cymbella pusilla

Denticula

Denticula thermalis

Asterionella spp.

Amphora

Amphora proteus

Dipeoneis

Dipeoneis elliptica

Cyclotella

Cyclotella meneghiniana

Terpsinoe

Terpsinoe musica

Coratoneis

Coratoneis arcus

Cyptopleura

Cyptopleura gibba

Gomphonema spp.

Stauroneis

Stauroneis anceps

Scoliopleura spp.

Eunotia

Eunotia paralella

Anomoeoneis

Anomoeoneis sphaerophora

Mastogloia

Mastogloia smithii
Mastogloia smithii var. *lacustris*

Neidium

Neidium dubium

Pinnularia

Pinnularia rupestris
Pinnularia spp.

Synedra

Synedra tabulata
Synedra ulna
Synedra delicatissima
Synedra fasciculata
Synedra minuscula
Synedra spp.

Table 12.--Species of periphytic algae identified in Laguna Tortuguero.--
Continued.

Chrysophyta (diatoms)

Homocladia (Nitzchia)

Homocladia linearis
Homocladia anuphioxys
Homocladia fasciculata
Homocladia spp.

Fragilaria

Fragilaria crotonensis
Fragilaria spp.

Amphiprora spp.

Cyanophyta (Blue-green)

Gomphosphaeria spp.
Eucapsis spp.
Oscillatoria forosa
Oscillatoria geminata
Aphonothece spp.

Symploca thermalis
Coclosphaerium spp.
Glocothece spp.
Synechococcus spp.
Anacystis dimidiata

Anacystis cyanea
Chroococcus spp.
Borzia trilocularis
Aphanoupsa spp.
Spirulina princips

Glococapsa spp.
Arthrospira khanuae
Arthrospira gomontiana
Phormidium subfuscum
Johanesbaptistia pellucida

Chlorophyta (Green algae)

Staurastrum furcigerum

Table 13.--Species of zooplankton identified in Laguna Tortuguero.

	1974						1975					
Species	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Brachionus stylifer	x				x	-- No samples --					x	
Calanoida spp.	x	x	x	x								
Ceriodaphnia reticulata				x	x		x		x		x	
Cladocera spp.	x				x			x	x		x	x
Diaptomus dorsalis	x	x	x	x	x		x		x	x	x	x
Diaptomus purpureus		x	x	x	x		x		x	x	x	x
Diaphanosoma brachyurum	x	x	x	x	x		x	x	x	x	x	x
Filinia opoliensis	x	x	x	x	x		x	x	x	x	x	x
Halicyclops spp.					x		x	x		x		
Hexartha mira				x	x		x	x	x		x	x
Huntemannia lacustris	x	x	x	x					x		x	x
Keratella americana	x	x	x	x	x			x	x			x
Keratella cochlearis	x	x	x	x	x		x	x	x		x	x
Latonopsis occidentalis		x	x		x		x	x	x	x	x	x
Ostracoda spp.	x	x		x	x		x	x	x	x	x	x
Paracyclops fimbriatus				x					x			
Paracyclops sp.								x				

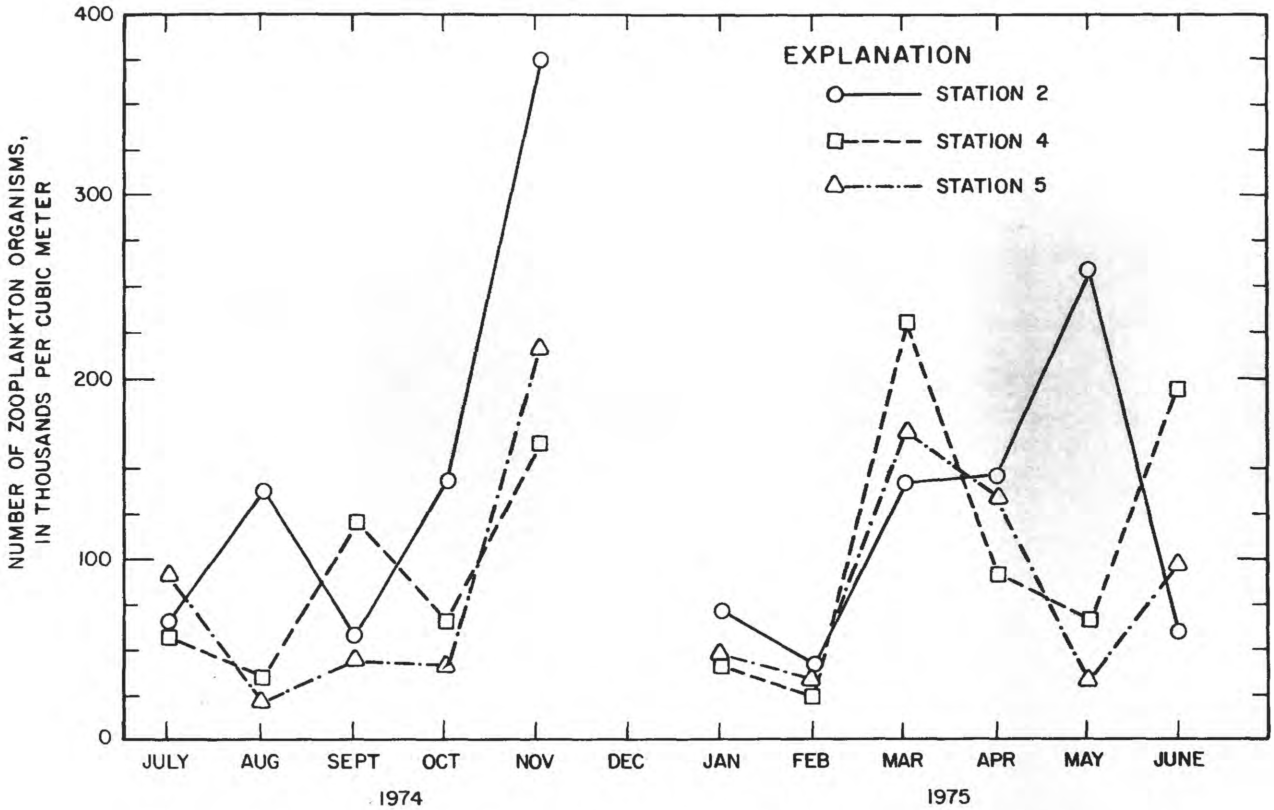


Figure 26.--Seasonal fluctuation in the number of zooplankton organisms at stations 2, 4, and 5.

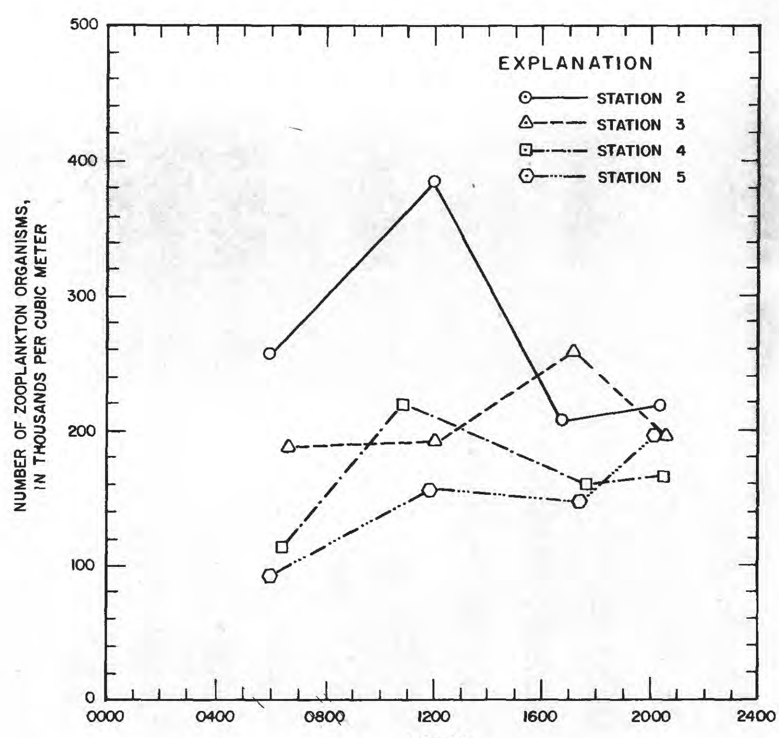


Figure 27.--Diurnal fluctuation in the number of zooplankton at stations 2, 3, 4, and 5, Nov. 26, 1976.

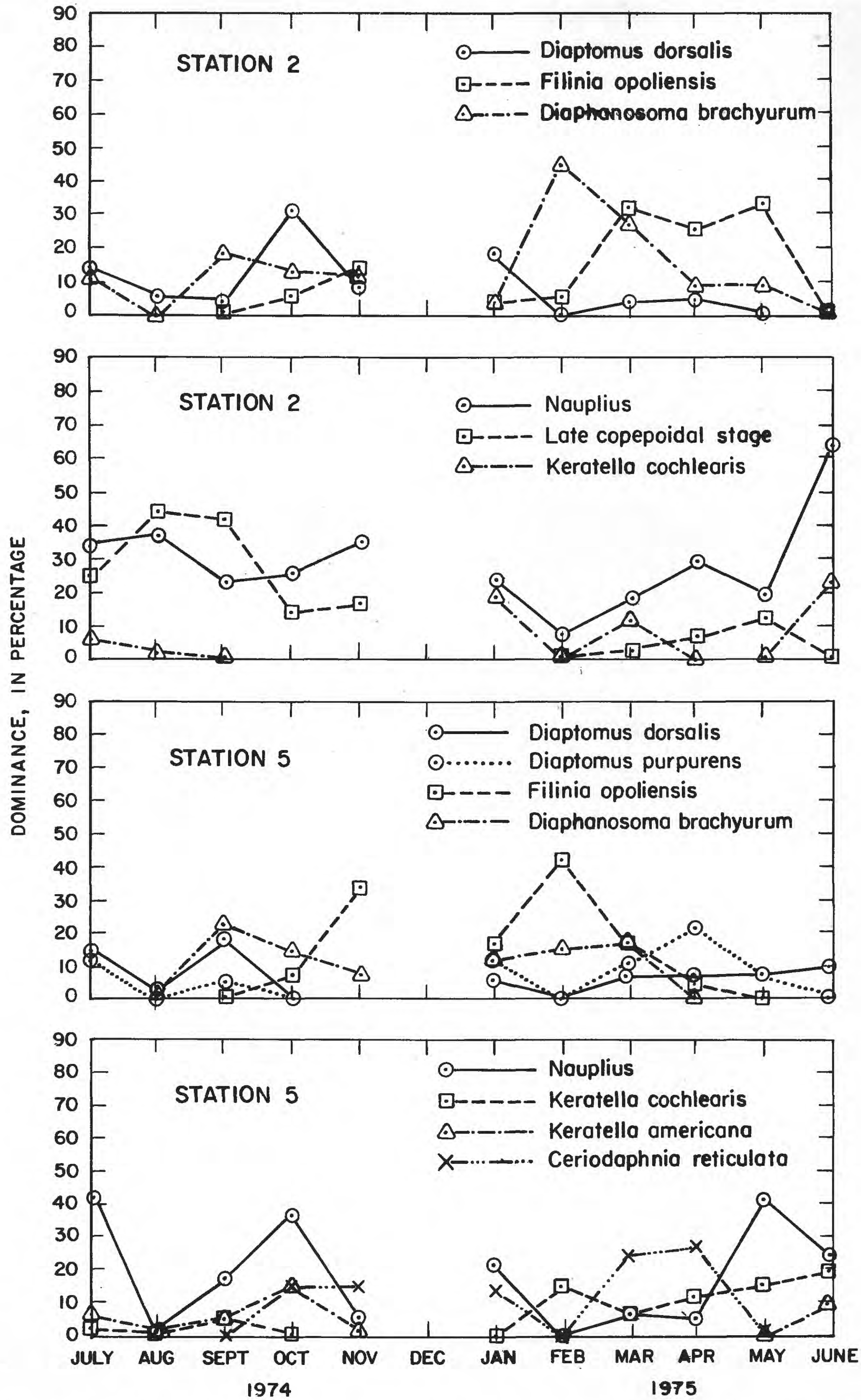


Figure 28.--Percentage dominance of the principal species, nauplius and copepoidal stages of zooplankton at stations 2 and 5.

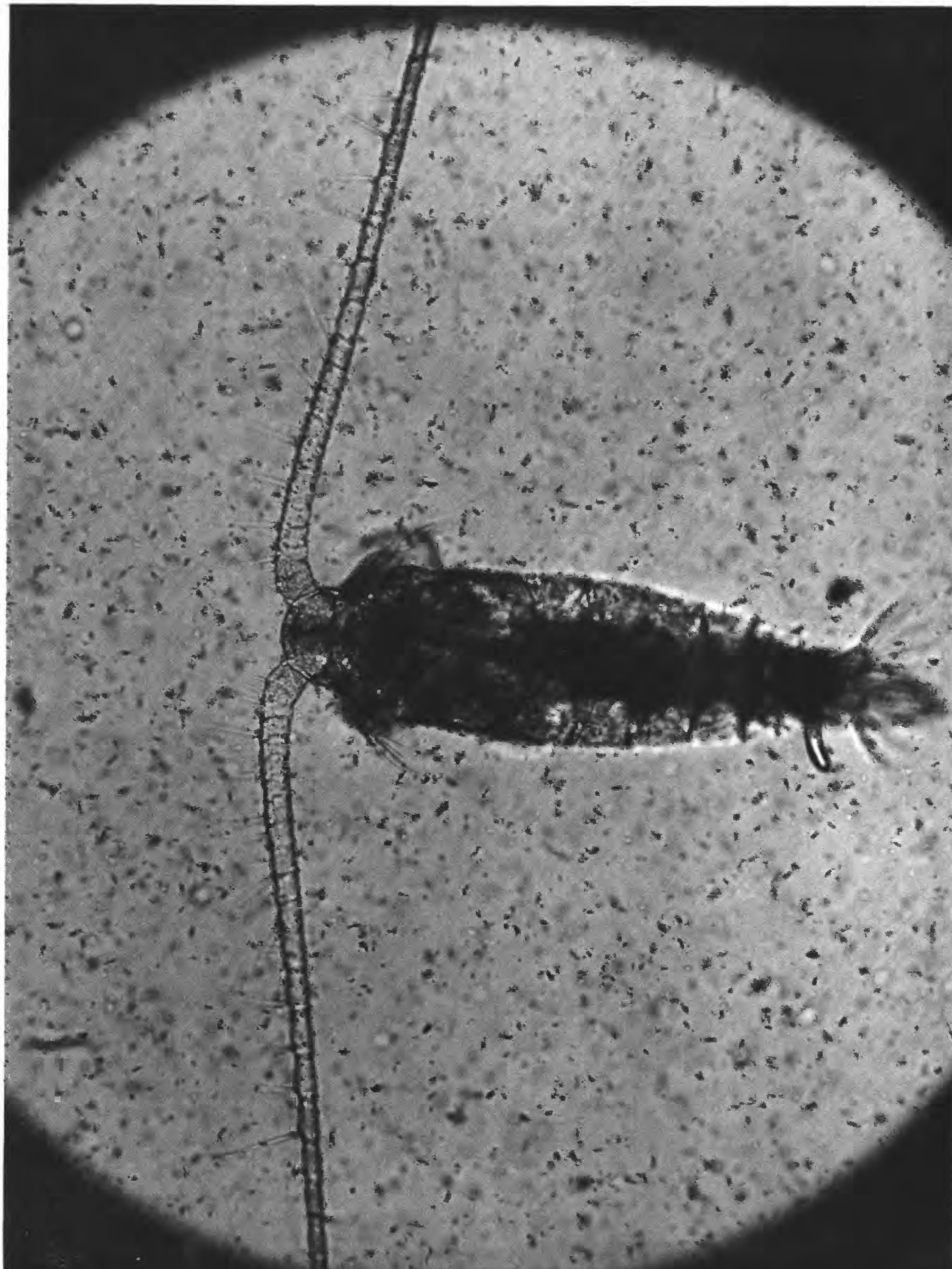


Figure 29.--Diaptomus sp.

Figure 30.--Diaphanosoma brachyurum.

The zooplankton concentrations in Laguna Tortuguero are typical of productive systems. Similar studies in Lago Loíza, Puerto Rico (written commun., Quiñones, 1976) a very eutrophic lake, showed that the zooplankton concentrations averaged about 1 million/m^3, ranging from 200,000/m^3 to 3.7 million/m^3. Although the concentrations in the lagoon are lower than in Lake Loíza, they are much higher than those reported in oligotrophic systems by Brinson (1973).

Of the species shown in table 13, the rotifers comprise nearly one-half of the organisms observed. Rotifers feed mainly on small organic matter particles that are captured by the action of their coronal cilia. The abundance of organic matter in Laguna Tortuguero probably benefits the rotifer population.

Diurnally there were no significant changes in the density of zooplankton throughout the lagoon on November 26, 1974 (fig. 27). In general, higher concentrations were observed at station 2. Although the study did not include the main night hours, a general increase in the number of organisms occurred from the early morning hours to the first night hours. Vertical migrations probably do not occur due to mixing of lagoon water by the wind.

Several species of zooplankton dominate in the lagoon. The percentage dominance of the principal forms is shown in figure 28. None of these were dominant during the entire study period. Only on rare occasions did more than 30 percent of the total population consist of a single species. This suggests a high index of diversity among the zooplankton.

The data in figure 28 show that more species were dominant or codominant in the east part (station 5) than in the west part (station 2). Some species identified in the eastern part were not present in the western part of the lagoon. Throughout the lagoon, *Filinia opoliensis* and the two species of *Diaptomus* (fig. 29) are the dominant zooplankters. *Filinia*, a rotifer, is cosmopolitan in distribution. *Diaptomus*, a calanoid copepod, includes a large number of species of worldwide distribution. Both *Filinia* and *Diaptomus* are characteristic of warm waters, mainly undisturbed systems (Hutchinson, 1967). A specimen of *Diaphanosoma brachyurum*, also a common cladoceran, is shown in figure 30.

Fish

The fisheries of Laguna Tortuguero were studied by Reyes de Ruiz (1971), and more recently a reconnaissance was conducted by the Department of Natural Resources of the Commonwealth of Puerto Rico (unpub. rept., 1976). Both studies are qualitative, indicating only the species collected during short runs.

In her 1971 study, Reyes de Ruiz identified 18 species in the lagoon. These are shown in table 14. Some of these (*Micropterus salmoides* and *Tilapia mossambica*) were introduced to the lagoon by the Commonwealth Department of Agriculture.

Table 14.--Species of fish identified in Laguna Tortuguero in 1971.

Species	Common name
Anguila rostrata	Anguila
Belonidae spp.	Agujón
Megalops atlantica	Sábalo
Mugil curema	Jarea
Mugil trichodon	Jarea
Agonostomus monticola	Dajao
Centropomus undecimalis	Róbalo
Caranx latus	Jurel ojón
Eleotris pisonis	Morón
Gobiomorus dormitor	Guavina
Dormitatur maculatus	Mapiro
Eucinsotomus pseudogula	Muniama
Gerres cinereus	Rayado
Diapterus rhombeus	Mojarreta
Diapterus plumeri	Mojarra
Micropterus salmoides	Lobina
Lepomis microlophus	Chopa
Tilapia mossambica	Tilapia

The species identified during the 1975-76 reconnaissance are shown in table 15. A total of 14 species were positively identified in the lagoon during the recent reconnaissance. *Gerres cinereus* was the most common species, accounting for about 93 percent of the fish captured with nets.

Large numbers of fish were not observed during the reconnaissance. The dominance by the *Gerres* spp. does not indicate a low diversity among the fish, but probably reflects conditions created by continuous fishing with large nets in the lagoon. The overall picture is that there has been no significant change in the fish populations in Laguna Tortuguero since the study in 1971 by Reyes de Ruiz. Some specimens captured by local fishermen during one of our field runs are shown in figure 31.

Aquatic Plants

The aquatic plants around Laguna Tortuguero were studied in detail by Reyes de Ruiz (1971). During this study only a reconnaissance of the most important plants was made.

Typha domingensis Pers ("enea," or cattail) is the dominant aquatic plant around the lagoon (fig. 32). Large colonies occupy almost the entire perimiter and even isolated "islands." *Typha* probably contributes most of the organic matter to the lagoon. Decaying plants abound in the bottom, not only near the shore but throughout the lagoon.

Blechum indicum and *Chara* spp. were observed in between the *Typha* colonies. In terms of abundance these were minor compared with the *Typha*.

The water hyacinth (*Eichornia crassippes*), common to most of the lakes in Puerto Rico, was not observed in Laguna Tortuguero. In her study, Reyes de Ruiz reported growing colonies of *Eichornia* and expressed concern for the possibility that the hyacinth could spread over the lagoon. *Eichornia* spp. is known to proliferate in systems of high nitrogen and phosphorus concentrations and low salinities. Perhaps the low phosphorus and relatively high chloride concentrations in Laguna Tortuguero check the development of blooms of *Eichornia* spp. Algal assays to determine the growth potential of *Eichornia* spp. in waters from Laguna Tortuguero should be made during future studies.

Community Productivity

The metabolism of plant and animal organisms in an aquatic system produces changes in the concentration of dissolved substances, primarily oxygen and carbon dioxide. The amount of oxygen produced, or organic carbon fixed, may be used as an indicator of the degree of productivity of the system and indirectly as a measure of the extent of eutrophication (Hooper, 1969 and Odum, 1971).

Gross primary productivity of the lagoon community was computed following the methods described by Greeson and others (1970) using the diel data shown in

Table 15.--Species of fish observed in Laguna Tortuguero during December 1975-January 1976.

Species	Common name
Awaous taiasica	Saga
Caranx latus	Jurel ojôn
Dormitator maculatus	Mapiro
Diapterus plumieri	Mojarra
Gerres cinereus	Rayado
Gobiomorus dormitor	Guavina
Lepomis microlophus	Chopa
Lophogobius cyprinoides	Morón
Lutjamus apodus	Pargo rubio
Megalops atlantica	Sâbalo
Mugil liza	Liza
Mugil cúrema	Jarea
Pimephales promelas	Mino
Tilapia rendalli	Tilapia

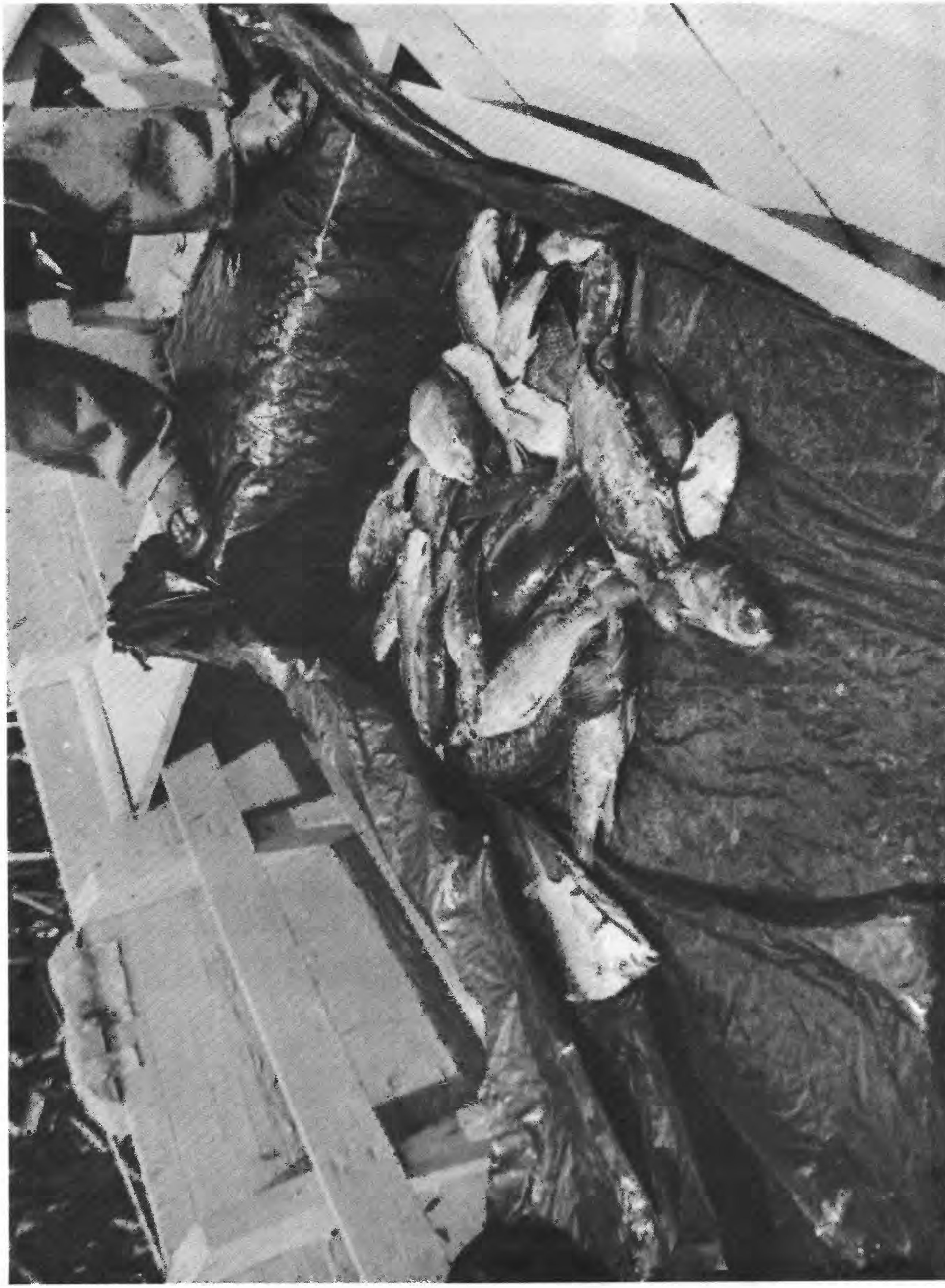


Figure 31.--Fish from Laguna Tortuguero.

Figure 32.--Typha dominguensis Pers, the dominant aquatic plant in Laguna Tortuguero.

figure 16. On the basis of field observations during the study, a gas transfer coefficient (K) of 2 $(g/m^2)/h$ was estimated. No corrections were made to the computations for the salinity of the lagoon because this was considered small. Parts of the night hours not included in the study were estimated on the basis of measurements after sunrise and before sunset. Respiration during those hours was estimated as an average between the observed sunrise and sunset hours, or about 0.35 $g/m^3/hr$. The data for station 5, including the dissolved oxygen, temperature and oxygen rate curves are shown in figure 33. Computations were based on principles described by Odum and Hoskins (1958) and Greeson and others (1977). Similar results were obtained at stations 2, 3, and 4.

The computations in figure 33 show that respiration on November 26, 1974 in Laguna Tortuguero exceeded gross production by a factor of almost 2. The difference between the oxygen produced and consumed must be supplied from the air by diffusion and air-water mixing due to the wind effect.

CHEMICAL, PHYSICAL AND BIOLOGICAL INTERACTIONS IN LAGUNA TORTUGUERO

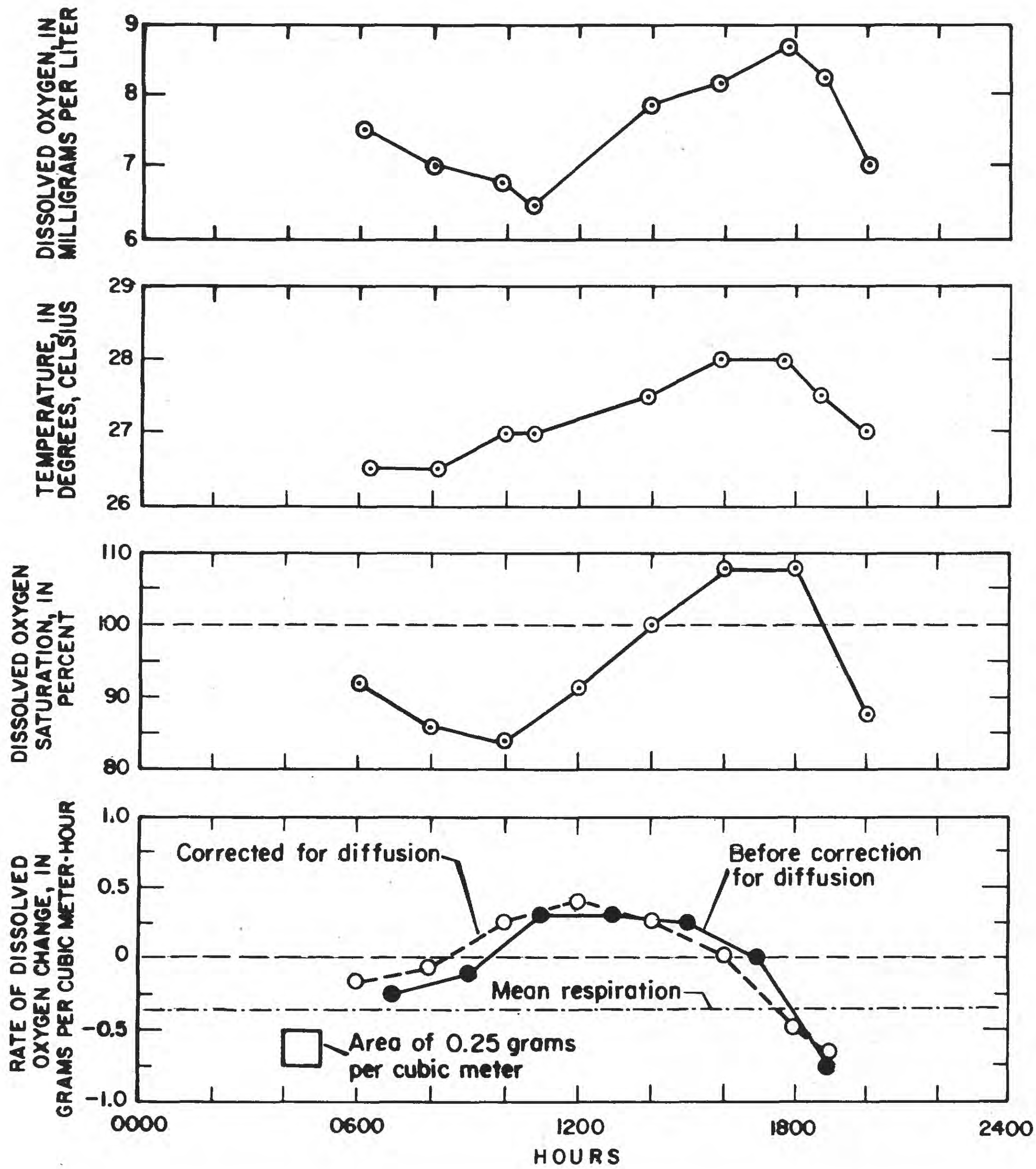
Laguna Tortuguero is a very complex system reacting to a series of chemical, physical and biological factors. In order to understand these interactions a systems analysis approach must be applied. The scope of this report does not include a complex systems analysis of the lagoon. However, a conceptual model of the most important interactions can be developed as a first step in a possibly more complex model that could be used as a management tool.

A simplified model of the Laguna Tortuguero system is shown in figure 34. The model is based on concepts described by H. T. Odum (1971). Only the most important flowpaths are shown; otherwise the model would become too complex.

The model shows that the principal external factors that influence Laguna Tortuguero are the wind, solar energy, and flows of water and materials. The wind is an important factor in maintaining a high dissolved-oxygen concentration in the lagoon and in mixing nutrients and organisms. High respiration by the consumers (zooplankton and nekton) and oxygen required to oxidize organic matter would deplete the dissolved oxygen in the lagoon unless replenished by diffusion.

The wind is also an important element in the lagoon's circulation. It blows most of the time in a westerly direction, restricting the movement of water from the western to the eastern part of the lagoon.

The sun provides the necessary energy to maintain the lagoon's producers in constant activity. Although the lagoon has a low phytoplankton population, periphyton is abundant and diverse. The transparency of the waters in the lagoon allows light transmission to the periphyton layer, promoting high productivity.



Depth=2.0 meters
Gross productivity=9.8 grams of oxygen per cubic meter per day
Respiration=16.8 grams of oxygen per cubic meter per day

Figure 33.--Dissolved oxygen curve and complementary information used for community primary productivity computations at station 5. Data for Nov. 26, 1974.

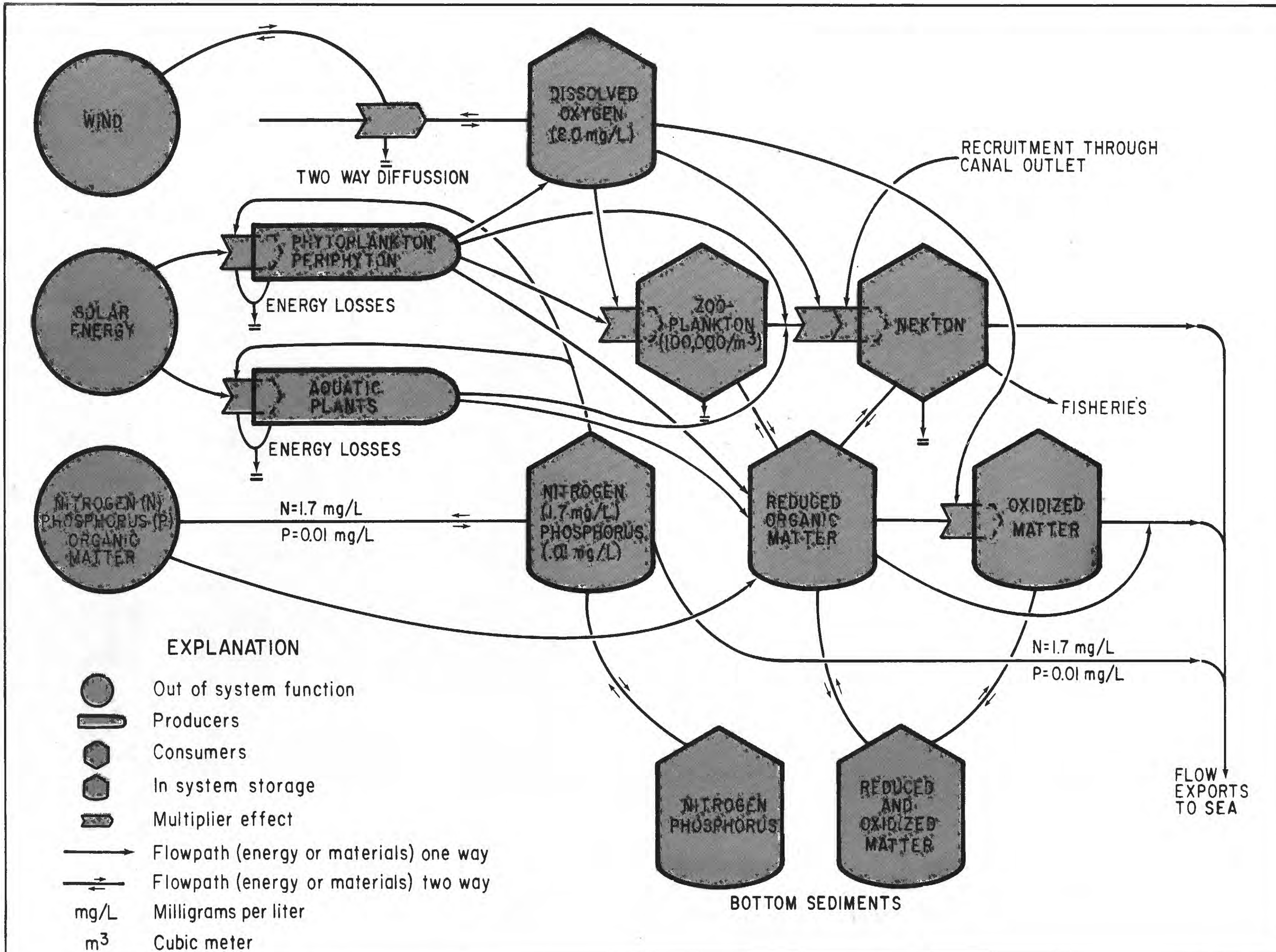


Figure 34.--Simplified model of the principal interactions in the lagoon.

The flow of materials into and out of Laguna Tortuguero is regulated by other factors not shown in the model, such as precipitation, ground-water flow, and so forth. The water-budget model shown in figure 7 details some of these components.

The external forces on Laguna Tortuguero interact to maintain the present system. Nutrients flowing into the lagoon maintain high nitrogen but low phosphorus concentrations in the water. The nutrients are utilized by the phytoplankton, periphyton and macrophytes. Some of the nutrients in the water precipitate and are stored in the sediments. The model shows a two-way flow between the water and the sediments. This exchange between water and sediments can be prompted by several conditions, among which are the availability of reactive cations (iron and manganese), their oxidation state, biochemical reactions, and so forth. The oxidation states of the ions may be regulated by the dissolved oxygen concentration in the water. The model does not show the interaction between dissolved oxygen and nutrients exchange with the sediments. Details of this mechanism are discussed by Stumm and Leckie (1970). The sediments constitute a nutrient sink that, under the proper conditions, can be triggered to release these to the water.

Most of the nutrients flowing into Laguna Tortuguero are discharged to the ocean and the concentration in the "nutrient pool" is maintained nearly constant. Short-circuiting of this flowpath, or the one providing nutrients to the plankton or macrophytes would most likely cause an increase in the nutrients in the water. This would in turn probably promote rapid increase in the algal populations. Community productivity would then increase, but so would the consumer populations. The fish population would also increase as a result of the more abundant plant and animal food sources. These potential developments are checked by a factor limiting the system's productivity. Phosphorus is probably the limiting factor. A more detailed model would show the present phosphorus concentration connected to a threshold sensor which in turn would operate a "switch" in the system. The threshold would be the phosphorous concentration beyond which increased productivity occurs. Concentrations exceeding the threshold value would prompt the switch to activate and induce the changes outlined.

The dissolved-oxygen subsystem of the model is important to our understanding of the conditions in the lagoon and aids in the prediction of what may happen if changes are induced. Oxygen flows into the lagoon from the air and is produced on site by phytoplankton and periphyton. Zooplankton (in large numbers) and fish (in relatively small numbers) are the primary consumers. The dissolved oxygen "tank" is connected to the organic matter subsystem. Oxygen is utilized to oxidize the organic matter in the lagoon deposited by macroscopic aquatic plants. At present, the amount of organic matter in the water is low. Biochemical oxygen demands (BOD-5) average less than 2.0 mg/L. However, the oxygen demand may be higher than what the BOD tests indicate. Respiration rates measured during the BOD tests do not account for high turnover rates.

Total organic carbon (TOC), a measure of the amount of carbonaceous material in the water, averages about 10 mg/L. Systems with high organic loading from sewage exceed TOC concentrations of 50 mg/L (Colston, 1974). The amount of dissolved oxygen, therefore, required to oxidize the organic matter is proportionally low.

A combined balance around the dissolved-oxygen pool in the lagoon would show that the wind is the primary source and the consumers are the primary sinks. If the organic loading to the lagoon were increased, a shift in the "level" in the oxygen "tank" would occur. If the organic-matter oxygen requirements were to reach a disproportionally high level, the wind "subsidy" would not be adequate to supplement the on site production. Instead of an average of 8.0 mg/L of dissolved oxygen, the system would attain a steady state at a lower level. If the organic loading is high enough, the equilibrium dissolved oxygen concentration can be lower than the minimal required for certain organisms. Dominance of the most tolerant ones, with loss of diversity would then follow. Low dissolved-oxygen concentration would also trigger the release of nutrients from the sediments as the oxidized insoluble precipitates were reduced to more soluble forms.

The nekton in the lagoon are affected by imports and exports through the canal outlet. Species capable of high tolerance in the nearly fresh waters in the lagoon migrate from and to the ocean. They graze on the plant communities (phytoplankton, periphyton and aquatic plants) and zooplankton. Insects and small organisms, also a source of food to the nekton, are not shown in the model.

The impact of other changes in the lagoon and its vicinity could be analyzed from the model. If considerable land around the lagoon were disturbed, increasing the amount of suspended sediment flowing into it, several changes could occur. Turbidity would increase in proportion to the amount of particles suspended. The transparency of the lagoon's water would be reduced, decreasing the transmission of light and the productivity of the periphyton. The "oxygen pool" could be lowered, affecting all the other communities in the lagoon.

The model does not consider the interrelation of the ground water and drainage system, but a separate model could be designed and coupled to it. Changes in the drainage system could have a severe impact on the lagoon. If the outlet channel were to be deepened (as proposed by a now defunct harbor project for the lagoon) seawater would flow in large quantities into the lagoon. The entire system would change from a nearly fresh to a brackish environment. Only the most tolerant freshwater species would survive and a succession of marine organisms (or those adapted to brackish systems) would dominate the lagoon. During intense storms, salinities would probably change drastically, exposing the organisms in the lagoon to nearly freshwater. Only a few organisms are capable of adapting rapidly to these changes. Species diversity would undoubtedly be reduced.

Only major interferences with the ground-water system in the lagoon would cause a significant impact on it. The magnitude of the ground-water discharges into the lagoon is large enough to withstand some disturbances. But if interception is large enough, the salinities in the lagoon would increase in proportion to the reduction in freshwater inflow. The changes already described would probably occur.

Proposed urban developments in the vicinity of Laguna Tortuguero could also trigger drastic changes in the lagoon's subsystems. Urban developments are characterized by increases in runoff. Fertilizers applied to lawns are partially leached and carried away by runoff. Colston (1974) reported average total phosphorus concentrations ranging from 0.3 to 1.5 mg/L in urban runoff in North Carolina. As previously shown, phosphorus is probably limiting the algal growth in the lagoon. If urban runoff from proposed developments is discharged into the lagoon, the potentially ample phosphorus supply could induce the development of algal blooms to nuisance levels. The water hyacinths, now absent from the lagoon environment, likely could proliferate with the added nutrients.

Finally, the model does not include the impact of chemical pollutants, such as organics or heavy metals. Discharges of organics or heavy metals into the lagoon would have an impact proportional to the concentration of the pollutants. Both organics and heavy metals accumulate in living tissue. Death of some organisms occurs due to extremely high concentrations of these components (National Academy of Science, 1972).

SUMMARY AND CONCLUSIONS

A comprehensive study of the limnology of Laguna Tortuguero was conducted from July 1974 to June 1975 by the U.S. Geological Survey in cooperation with the Commonwealth of Puerto Rico.

The lagoon has a surface area of 2.24 km^2, with a volume of about 2.68 Mm^3 (water-surface elevation of 0.47 m above mean sea level) and mean depth of 1.2 m. The shoreline length is about 15.3 km while the maximum length is 4.6 km and the maximum width 1.0 km.

During the study period a total of 1,521 mm of precipitation was recorded near the lagoon, contributing about 3.41 Mm^3 of water to it. Evapotranspiration from the lagoon was estimated as 1,274 mm, or about 2.85 Mm^3.

The lagoon is drained through a canal on its north side. The canal, about 0.6 km long, 8.5 m wide and 1.0 m deep discharges an average of 0.64 m^3/s. Total discharge during the year of study of 20.1 Mm^3 is equivalent to a flushing rate of 7.5/yr. The high flushing rate is a factor in the export of nutrients and organic matter from the lagoon.

Chemical analyses throughout the lagoon show higher concentrations of ions in the western part than in the eastern part. Poor circulation in the west as compared with the east, as well as evaporation, results in the concentration of ions.

Chloride and sodium are the principal ions in the water. Seawater flowing into the lagoon from the zone of diffusion contributes most of the chloride and sodium, as well as sulfate and magnesium. The chloride concentration ranged seasonally from 300 to 700 mg/L, while that of sodium ranged from 150 to 400 mg/L. The large fluctuations were due to extreme dilution during the storm of October 1974. Specific conductance values, a measure of the dissolved solids, ranged from 1,500 to 2,800 µmho/cm at 25°C in the eastern part and from 2,000 to 4,300 µmho/cm in the western part. The pH of the water in the lagoon fluctuated seasonally from 6.8 to 8.2 units.

Nitrogen is the principal nutrient in the water in Laguna Tortuguero, exceeding phosphorus by a weight ratio of about 170:1. Total nitrogen concentrations averaged 1.7 mg/L, while phosphorus averaged 0.01 mg/L, suggesting that phosphorus is probably the limiting factor in the phytoplankton growth in the lagoon.

The nutrient budget of the lagoon shows that precipitation contributed about 1.9 tonne of nitrogen and 0.35 tonne of phosphorus. A total of about 31.3 tonne of nitrogen and 0.31 tonne of phosphorus was contributed to the lagoon from ground and surface-water flows. The lagoon exported to the sea 34.0 tonne of nitrogen and 0.42 tonne of phosphorus.

Concentrations of selected heavy metals in the lagoon fluctuated during two samplings from zero to a maximum of 67 micrograms per liter for nickel. Pesticides were not detected in the waters, but residues of DDT, DDD and dieldrin were detected in the sediments.

The dissolved oxygen concentration throughout the lagoon exceeds saturation values most of the time. Monthly measurements ranged from 7 to 11 mg/L, averaging about 8.2 mg/L. The dissolved-oxygen concentration increases toward the bottom as a result of oxygen production by periphyton. Diurnally, concentrations fluctuated from 6 to 11 mg/L. The wind plays an important role in diffusing oxygen into the lagoon's water.

Temperatures throughout the lagoon fluctuate seasonally from about 24 to 31 degrees Celsius. There are no vertical temperature gradients.

The bottom sediments in Laguna Tortuguero occupy a volume of about 4.5 Mm^3, or 1.7 times the water volume. The sediments are composed primarily of calcium carbonate precipitated from ground water flowing from the Aymamón aquifer. Organic carbon averages about 6.8 percent by weight of the sediments. Decaying littoral plants are the primary source of organic material to the sediments. Among the nutrients, nitrogen comprises about 0.8 percent of the sediments, while phosphorus averages about 0.014 percent. The sediments constitute a sizable nutrients storage area.

Bacterial counts among the coliform group are very low throughout the lagoon, indicating excellent sanitary conditions. Small numbers of fecal coliform and fecal streptococci are contributed from cattle grazing in the vicinity of the lagoon.

Phytoplankton concentrations throughout the lagoon are low compared with other systems in Puerto Rico. Concentrations average about 6,000 cells/mL. A total of 47 genera of phytoplankton were identified, 16 of which were diatoms and 12 blue-green algae. Anacystis, a blue-green algae typical of eutrophic systems is the principal algae, dominating or codominating during about 90 percent of the observations.

Periphyton covers the entire lagoon bottom. A total of 65 species of periphyton were identified. Among these 44 were pennate diatoms, while 20 were blue-green algae.

The zooplankton in the lagoon are characterized by average concentrations of 100,000 organisms/m^3, mostly rotifers. A total of 17 species were identified, among which Diaptomus dorsalis, Diaphanosoma brachyurum and Filinia opoliensis are dominant. A high diversity among the zooplankton was indicated from relative percent dominance studies.

Data from the Commonwealth Department of Natural Resources show a high diversity among the fish in the lagoon. Fourteen species were identified during December 1975, although a single species (Gerres cinereus) dominated the populations.

Typha dominguensis Pers ("enea") is the dominant emergent aquatic plant throughout the lagoon, occupying about 90 percent of its shoreline. Typha contributes most of the organic load to the lagoon.

Community productivity studies indicate that the lagoon's total respiration exceeded gross productivity by a 2 to 1 factor on November 26, 1974. Prevailing east to northeast winds promote diffusion of oxygen into the lagoon's water. The overall productivity of the lagoon is comparable to that of eutrophic systems. Most of the productivity is from the periphyton layer.

A systems analysis of the lagoon shows that many factors are interacting in it. Water flow, nutrients, and the dissolved oxygen concentration are the most important factors. Changes in the hydraulic system, increases in the phosphorus load, or reduction of the dissolved oxygen concentration could cause dramatic changes in the lagoon's populations. To maintain its present steady state, disturbances of the lagoon should be kept to a minimum.

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GLOSSARY

Alga, algae (n), algal (adj).--A group of plants, mostly aquatic, single-celled, colonial, or multicelled, containing chlorophyll and lacking roots, stems and leaves.

Algal bloom (n).--A large number of a particular algal species, often amounting to 0.5 to 1 million cells per liter.

Allochthonous (adj).--Originating outside the area under consideration. See also Autochthonous.

Amino acid (n).--A class of nitrogen-containing organic compounds, large numbers of which become linked together to form proteins.

Anaerobe (n), anaerobic (adj).--An organism living or growing in the absence of free oxygen.

Aquatic (adj).--Pertaining to water; aquatic organisms, such as phytoplankton or fish, live in or on water.

Average flow.-- The average yearly discharge at a particular station, obtained from the sum of the annual total discharges of n years divided by the same number of years.

Bacterium, bacteria (n), bacterial (adj).--Microscopic unicellular organisms, typically spherical, rod-like, or spiral and thread-like in shape, often clumped into colonies. Some bacteria cause disease, others perform an essential role in the recycling of materials; for example, by decomposing organic matter into a form available for reuse by plants.

Biochemical oxygen demand (BOD).--The amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions. BOD-5 is a 5-day determination of the oxygen requirement for a known volume of water.

Biology (n), biological (adj).--The science or study of organisms.

Bloom (n).--See Algal bloom.

Carnivore (n).--An organism that obtains its nourishment by consuming other animals; includes many fishes and aquatic insects.

Clinograde.--The stratification curve of temperature or of a chemical substance in water that exhibits a sloping profile from the surface downward into deeper water.

Coliform bacteria (n).--A particular group of bacteria used as indicators of possible sewage pollution. They are formally characterized as aerobic, and facultative anaerobic, gram-negative, nonspore-forming, rod-shaped bacteria which ferment lactose with gas formation within 48 hours at 35°C.

Convective.--Flow originated by heat differentials. Climatologically it implies precipitation which originates when warm air rises against the windward side of a mountain, and upon contact with the colder upper layers.

Cultural eutrophication.--The acceleration of the natural process of nutrient enrichment in a lake as a result of man's activities.

Detritus (n).--Fragmented material of inorganic or organic origin.

Diatom (n).--A unicellular or colonial alga having a siliceous shell.

Diel (adj).--Relating to a 24-hour period that usually includes a day and the adjoining night.

Diurnal (adj).-- Relating to daytime or something recurring every day, often used as a synonym for diel.

Diversity.--The abundance in numbers of species in a specified location.

Drainage basin.--A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or a body of impounded surface water together with all tributary surface streams.

Ecology (n), ecologic(al) (adj).--The science or study of the relation of organisms or groups of organisms to their environment.

Ecosystem (n).--The community of plants and animals interacting together with the physical and chemical environment.

Environment (n).--The sum of all the external physical, chemical, and biological conditions and influences that affect the life and development of an organism.

Epilimnion (n).--The upper, relatively warm, circulating zone of water in a thermally stratified lake.

Euphotic zone (n).--That part of the aquatic environment in which the light is sufficient for photosynthesis; commonly considered to be that part of a water body in which the intensity of underwater light equals or exceeds 1 percent of the intensity of surface light.

Eutrophication (n), euthrophic (adj).--Enrichment of water, a natural process that may be accelerated by the activities of man; pertaining to waters in which primary production is high as a consequence of a large supply of available nutrients. See also Oligotrophic.

Evapotranspiration.--Water withdrawal from the soil, a body of water, etc., by evaporation and plant transpiration.

Fecal coliform bacteria (n).--That part of the coliform group that is present in the gut or the feces of warmblooded animals; they are indicators of possible sewage pollution.

Fecal streptococcal bacteria (n).--A particular group of bacteria found in the gut of warmblooded animals; their presence in natural waters is considered to verify fecal pollution. They are formally characterized as gram-positive, cocci bacteria which are capable of growth in brain-heart infusion broth either at 45°C and 10°C (the enterococci species) or at 45°C only (Streptococcus bovis and S. equinus).

Flushing rate.--The ratio between the annual discharge into a lake (or other water body) and the lake volume.

Genus, genera (n), generic (adj).--The taxonomic categories below family, consisting of species; the first part of the scientific name of organisms. See also Taxonomy.

Gross primary productivity (n).--The total rate at which organic matter is formed by photosynthesis, including the organic matter used up in respiration within the period of measurement. The term is synonymous with gross primary production, total photosynthesis, and total assimilation.

Habitat (n).--The place where an organism lives.

Herbicide.--Chemical or a mixture of chemicals intended to control or destroy vegetation.

Hypolimnion (n).--The lower, relatively cold, noncirculating water zone in a thermally stratified lake.

Limnology (n).--The area of science concerned with the characteristics of inland waters, the forces and procedures which mold and maintain the integrity of these waters, the interrelationship between water and basin, and the community of living organisms inhabiting the environment.

Macrophyte (n).--Large plants that can be seen without magnification, includes mosses and seed plants.

Mean annual flow.--The average daily discharge at a particular station, obtained from the sum of the daily discharges in a year divided by the number of days in the same year.

Mean depth.--The volume of the lake divided by its area.

Membrane filter (n).--A thin microporous material of specific pore-size used to filter bacteria, algae, and other very small particles from water.

Metabolism (n).--The chemical processes of living cells by which energy is derived and material is assimilated.

Net community productivity (n).--The rate of storage of organic matter not used by the organisms in the environmental area under study during the period of measurement; net primary productivity minus heterotrophic utilization.

Niche (n).--The location and ecological function of an organism in the environment.

Nutrient (n).--Any chemical element, ion, or compound that is required by an organism for the continuation of growth, for reproduction, and for other life processes.

Periphyton (n).--The entire community of microorganisms that are attached to or live upon submerged solid surfaces. Includes algae, bacteria, fungi, protozoa, rotifers and other small organisms.

Pesticide.--Any substance used to kill plants, insects, algae, fungi, and other organisms; includes herbicides, insecticides, algalcides, fungicides, and other substances.

pH.--The negative logarithm of the hydrogen-ion concentration, expressed as a number from 0 to 14. A pH of 7 is neutral, a pH of less than 7 is acidic, and a pH of greater than 7 is basic.

Photosynthesis (n), photosynthetic (adj).--A biochemical synthesis of carbohydrates from water and carbon dioxide in the chlorophyll-containing tissues of plants in the presence of light.

Phytoplankton (n), phytoplanktonic (adj).--The plant part of the plankton.

Plankter (n).--An individual planktonic organism.

Plankton (n), planktonic (adj).--The community of suspended or floating organisms which drift passively with water currents.

Pollution (n).--"an undesirable change in the physical, chemical, or biological characteristics of our air, land, and water that may or will harmfully affect human life or that of other desirable species, our industrial process, living conditions, and cultural assets; or that may or will waste or deteriorate our raw material resources." (Natl. Research Council, Comm. on Pollution, 1966, p. 3).

Population (n).--A group of interacting and interbreeding individuals of the same type living in a common habitat and having little reproductive contact with other groups of the same species.

Primary productivity (n).--The rate at which radiant energy is stored by photosynthetic and chemosynthetic activity of producer organisms (chiefly green plants) in the form of organic substances which can be used as food materials (Odum, 1971, p. 43). See also Gross primary productivity and Net community productivity.

Production (n).--The total amount of living matter produced in an area per unit time regardless of the fate of the living matter.

Respiration (n).--A life process in which carbon compounds are oxidized to carbon dioxide and water and the liberated energy is used in metabolic processes.

Sample (n).--A small separated part of something that is representative of the whole.

Secchi disk.--A circular metal plate, 20 centimeters in diameter, the upper surface of which is divided into four equal quadrants painted black and white. Variations in size and painted only in white are used. (The disk is lowered into the water and the average depth at which it is no longer visible is denominated as the "secchi disk transparency.")

Sediment (n).--Fragmental material, both mineral and organic, that is in suspension or is being transported by the water mass or has been deposited on the bottom of the aquatic environment.

Species (n, sing. and pl.).--The basic unit for the classification of organisms; the taxonomic category below genus, and the second part of the scientific name of an organism. See also Taxonomy. The biological concept of species, in contrast to the purely taxonomic concept, has been defined by Mayr (1940) as ". . . a group of actually or potentially interbreeding organisms reproductively isolated from other such groups of interbreeding organisms."

Suspended sediment (n).--Fragmental material, both mineral and organic, that is maintained in suspension in water by the upward components of turbulence and currents or by colloidal suspension.

Taxonomy (n).-- The division of biology concerned with the classification and naming of organisms; synonymous with systematic biology. The classification of organisms is based upon a hierarchial scheme beginning with the species at the base. The higher the classification level, the fewer features the organisms have in common. See also Species. As an example, the taxonomy of the common stonefly, Pteronarcys californica is as follows:

Kingdom	Animal
Phylum	Arthropoda
Class	Insecta
Order	Plecoptera
Family	Pteronarcidae
Genus	Pteronarcys
Species	californica
Scientific name	Pteronarcys californica

Thermal stratification (n).--A temperature distribution characteristic of many lakes in which the water is separated into three horizontal layers: a warm epilimnion at the surface, a metalimnion in which the temperature gradient is steep, and a cold hypolimnion at the bottom.

Trophic level.--A scheme of categorizing organisms by the way they obtain food from primary producers or organic detritus involving the same number of intermediate steps.

Tuff (n).--Volcanic ash usually more or less stratified in various states of consolidation.

Water quality (n).--Kinds and amounts of matter dissolved and suspended in natural waters, the physical characteristics of the waters, and the ecological relationships between aquatic organisms and the environment.

Zooplankton (n), zooplanktonic (adj).--The animal part of the plankton.

Looking north across the west end of Laguna Tortuguero.

Typical plant community along the shores of Laguna Tortuguero.