

Variations and relationships of salinity, nutrients and suspended solids in Chelem coastal lagoon at Yucatan, Mexico

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Chelem lagoon is a typical sand barrier tropical coastal body of very shallow water located in the Gulf of Mexico side of Yucatan Peninsula characterized by strong anthropogenic activity including a seaport, urban and industrial development which affected its natural regime. The whole region is karstic with no rivers and groundwater circulation. Monthly observations of physical and chemical parameters were carried out during almost five years. Chelem lagoon has antiestuarine characteristics: the salinity increases toward the interior since there are not important inputs of fresh water, and the evaporation is high. The statistical analysis showed three different zones: west zone is characterized by high salinity values, high ammonium concentration and low human disturb; central zone has lot of water exchange between sea and lagoon that keep favorable conditions; and east zone has large variations in salinity, high ammonium and suspended materials and low oxygen, and is impacted by the human activities. Hurricane Gilbert affected the lagoon, decreasing the salinity and raising the silicate and nitrate concentrations. Salinity, ammonium, silicate and suspended solids presented annual periodicity.

Chelem lagoon, located in the Gulf of Mexico coast of Yucatan peninsula, is a typical tropical barrier island lagoon of III-A of Lankford's classification¹ (see Fig.1). The average annual air temperature is between 24 and 26°C, precipitation 444 mm, evaporation between 1364 and 2293 mm, with the maximum occurring between April and June². Low precipitation, high evaporation and insignificant fresh ground water discharges (related with the events of cretaceous period³⁻⁵), condition the Chelem lagoon's hydrology^{6,7}. It was an hypersaline body of water with temporal communication with the open sea through two natural mouths until 1969 when an artificial channel was opened for the construction of Yukalpeten Harbor, which considerably increased its interaction with open waters. The tide is diurnal with a range of 0.6 m, surface area of 15 km² and depths between 0.5-1.0 m except in the port, where dredging deepened it to 3.0 m. In the central and eastern zones there are patches of seagrass *Halodule wrightii*, the western part with red algae *Eucheuma* sp., while the sides not altered by human activities are covered by mangrove patches dominated by *Avicenia germinans* with *Rhizophora mangle* also present. Urban and industrial

developments around and through the lagoon affected seriously its circulation and water quality⁸. Bottom sediments showed the existence of nutrient recycling sites for the water column⁹. The whole region is of karstic nature. The above processes generate considerable temporal and spatial variations in salinity, nutrients and suspended solids in water. To know the magnitude of these variations, its periodicity and the relationships between them, were the principal objectives of this study. With these results, we have the "base line" needed for determine in the future if the natural and anthropogenic processes are changing the conditions of lagoon.

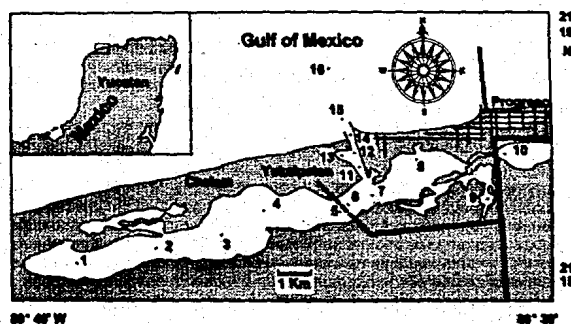


Fig. 1—Chelem lagoon, location of sampling stations.

Materials and Methods

Sixteen stations along the lagoon (Fig. 1) were sampled from January 1988 to October 1992, every month except in Dec./88, Dec./89, March/90, April/90, July/90, Oct./90, March/91, Oct./91, Jan./92 and Aug./92, making a total of 48. Water temperature was measured with a YSI-33 meter. Surface samples were taken with Van-Dorn bottles, pH with a Beckman Phi-32 pH meter, suspended solids by filtration of 1 liter of sample through a glass micro fibre filter Whatman GF/C¹⁰, chlorophyll *a*, *b* and *c* by filtration of 1 liter of

sample through a glass micro fibre filter Whatman GF/C, and extraction with 90% acetone¹¹, dissolved oxygen with the Winkler method¹², and saturation calculated with the equations of Garcia & Gordon¹³. Filtered water was analyzed for salinity with salinometer (Kahlsico RS-9); ammonium, nitrite, nitrate, phosphate, silicate, and particulate nitrogen was quantified¹² with a Shimadzu UV/VIS spectrophotometer.

The statistical analysis was done with software CSS/STATISTICA¹⁴: data normal distribution with Kolmogorov-Smirnov test; multiple correlations

Table I—Average values by station and average for all the study in Chelem lagoon

		Station									
		1	2	3	4	5	6	7	8	9	10
Temperature	°C	27.3	27.6	27.6	27.6	27.7	27.6	27.4	27.6	30.7	28.9
Salinity	‰	40.0	36.8	37.0	36.5	36.3	36.4	36.2	36.2	38.0	43.3
Dissolved oxygen	ml/l	4.00	4.06	3.97	3.91	3.99	4.28	3.91	3.74	4.37	2.66
Oxygen saturation	%	90.8	84.9	83.2	81.9	83.6	89.8	80.9	78.2	97.5	62.0
pH		8.52	8.42	8.46	8.43	8.41	8.44	8.40	8.40	8.61	8.53
Ammonium	μM	9.9	10.6	10.8	10.7	7.7	7.1	7.0	7.0	8.5	10.4
Nitrite	μM	0.2	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.7
Nitrate	μM	2.8	3.8	3.0	3.2	4.1	3.1	2.6	2.7	1.8	3.9
Phosphate	μM	0.7	0.7	0.5	0.6	0.5	0.5	0.5	0.5	0.8	1.0
Silicate	μM	64.8	64.6	63.2	59.0	36.1	23.3	22.7	34.0	131.8	81.3
Chlorophyll <i>a</i>	μg/l	3.16	3.41	2.44	2.01	2.64	3.51	4.76	5.51	5.93	18.48
Chlorophyll <i>b</i>	μg/l	0.99	1.16	1.02	0.91	1.01	1.13	1.29	1.27	1.24	2.27
Chlorophyll <i>c</i>	μg/l	3.54	4.08	3.55	3.03	3.45	3.97	4.62	4.68	4.90	8.17
Particulate nitrogen	μM	5.8	3.5	2.5	2.3	2.3	2.5	3.4	5.3	10.0	30.9
Total suspended solids	mg/l	19.0	15.0	6.9	7.7	11.8	12.2	14.6	14.8	39.7	43.4
Inorganic suspended solids	mg/l	11.4	10.2	3.9	5.0	8.1	8.5	10.4	9.2	25.5	15.9
Organic suspended solids	mg/l	6.6	5.3	3.0	3.1	4.0	4.0	4.4	5.5	16.1	27.4

		Station						Average	Std.	Min.	Max.
		11	12	13	14	15	16				
Temperature	°C	27.5	27.2	27.5	27.2	27.3	27.3	27.7	2.6	22.0	37.0
Salinity	‰	36.3	36.4	36.3	36.5	36.9	37.3	36.9	5.3	10.1	71.3
Dissolved oxygen	ml/l	3.83	3.75	3.89	3.96	4.16	4.34	4.00	1.00	0.20	10.90
Oxygen saturation	%	79.9	78.4	81.1	82.6	86.7	90.5	84.0	26.3	5.1	288.7
pH		8.43	8.43	8.42	8.43	8.45	8.46	8.45	0.10	7.71	9.55
Ammonium	μM	6.3	5.8	9.3	5.9	5.5	4.4	7.8	5.9	< 0.1	54.0
Nitrite	μM	0.3	0.3	0.4	0.3	0.3	0.2	0.3	0.3	< 0.01	5.0
Nitrate	μM	2.6	2.5	3.3	2.4	1.9	1.7	2.8	2.8	< 0.05	24.0
Phosphate	μM	0.5	0.5	0.6	0.5	0.5	0.4	0.6	0.7	< 0.03	9.5
Silicate	μM	20.4	16.8	19.5	14.2	7.3	4.6	38.8	45.7	0.2	386.4
Chlorophyll <i>a</i>	μg/l	4.69	5.18	6.24	5.34	5.98	2.29	4.61	5.60	0.40	46.80
Chlorophyll <i>b</i>	μg/l	1.37	1.43	1.67	1.52	1.35	1.03	1.26	1.02	< 0.04	7.30
Chlorophyll <i>c</i>	μg/l	4.86	5.09	5.27	5.39	5.10	3.45	4.46	3.83	< 0.04	28.16
Particulate nitrogen	μM	3.0	2.7	3.1	3.1	3.9	2.2	5.4	8.4	1.0	68.4
Total suspended solids	mg/l	11.2	11.9	10.2	14.7	15.2	5.6	15.5	25.3	1.1	384.7
Inorganic suspended solids	mg/l	7.6	8.6	6.7	10.8	11.0	3.6	9.7	18.1	0.6	282.3
Organic suspended solids	mg/l	3.6	3.2	3.7	4.2	4.3	2.0	6.0	9.4	0.3	102.3

between the parameters (confidence level of 95%, $p=0.05$); principal components analysis to check the grouping of sampling stations, from their correlations and covariances estimated with eigen values and vectors; variance analysis ANOVA to know if the stations groups were statistically different using the Post-Hoc test of Sheffé ($p=0.05$); time series of monthly averages after transforming the values with the damping method of filter 4253H were subjected to autocorrelation analysis for periodicity of the correlation coefficients.

Results and Discussion

Results of all parameters measured and their correlations are summarized in Tables 1 and 2.

Temperature of lagoon water showed moderate fluctuations with maximum and minimum values in June and January respectively (Fig.2).

Minimum salinity was recorded in September 1988 after hurricane Gilbert hit the region, and maximum in May 1992 (Fig. 3). Stations 1 and 10 presented the highest values and stations 7 and 8 the lowest ones. Station in the open sea had higher value than central zone of lagoon, suggesting influx of fresh water in that area. There is a clear salinity annual cycle (Fig.2), and its correlation with precipitation, evaporation and temperature are significant (Table 2), indicating a decrease with high precipitation and increase with high evaporation. The spatial distribution showed three zones: the western with 37.25 ‰, the eastern with

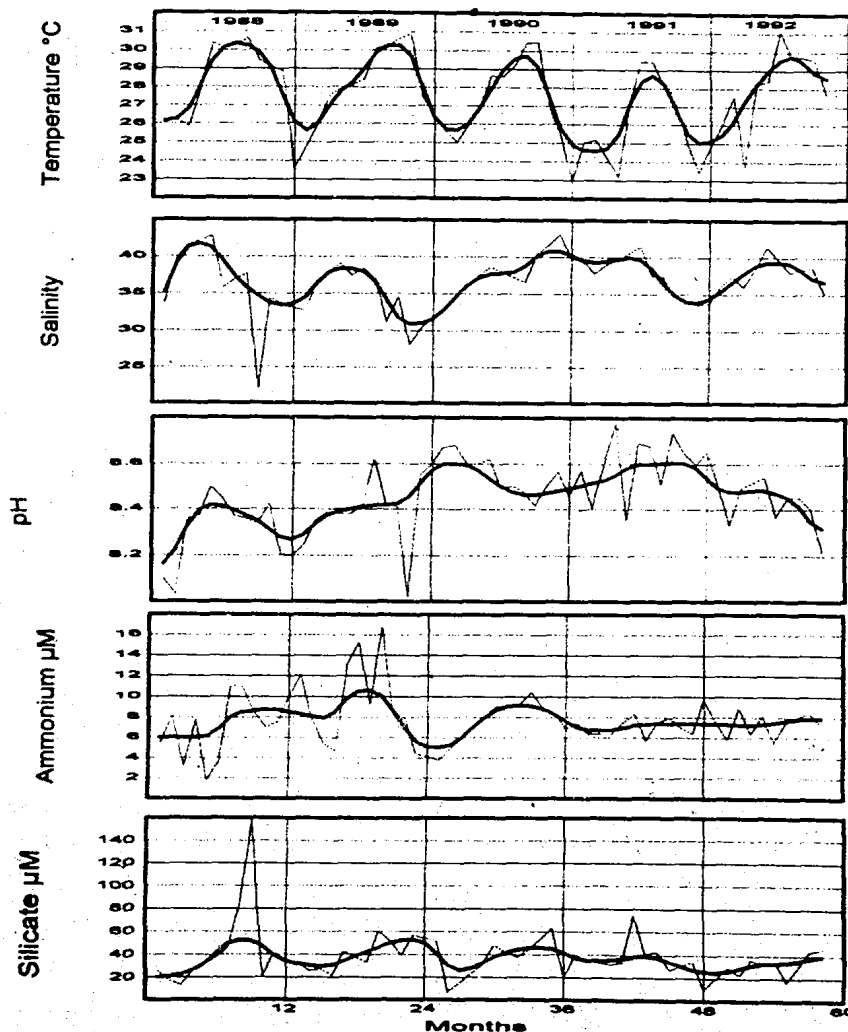


Fig. 2—Statistic analysis of monthly average surface temperature, salinity, pH, ammonium and silicate (----: real average; —: transformed average).

39.26 ‰, and the central with 36.48 ‰.

Distribution of dissolved oxygen was not homogeneous (Fig. 4) and below saturation (84 %), meaning that oxygen is consumed more than produced. Principal component analysis of their concentrations identified three zones, though the ANOVA did not show any significant differences among them. No cyclic pattern was found from the time series analysis, most probably due to many factors regulating its concentration.

The pH values had a similar behavior like salinity; in the east and west ends of the lagoon they were high, while the center had the lowest ones. Principal components analysis showed three zones: east and west high, central low, and the mouth with intermediate values. The pH (average by station) had a direct correlation with salinity and temperature, due to the relation of pH with the system CO_2 -carbonates, and the dependence of their equilibrium constants with salinity and temperature.

Ammonium concentration was higher than the published values for other lagoons and bays (Lake

of Tunis in Mediterranean Sea has between 4 and $16 \mu\text{M}$, and Abu-Kir Bay in Alexandria amount $8 \mu\text{M}^{15}$). Principal components analysis grouped stations in three zones: east and west sides with average concentration of $10.0 \mu\text{M}$; central with $7.2 \mu\text{M}$; and the mouth with $5.6 \mu\text{M}$; ANOVA confirmed it. Monthly averages denoted an annual pulse (Fig. 2), low concentrations in the first months of the year (January-May), and higher values in summer (July-October). Inverse correlation was found between ammonium and dissolved oxygen suggesting ammonium production from organic material decomposition.

Nitrite was low ($<0.5 \mu\text{M}$), except at station 10 where it reached the maximum value. Good correlation with salinity and dissolved oxygen suggest that nitrite was produced mainly in stations of high salinity and low dissolved oxygen.

Nitrate was variable (Fig. 5), with station 16 having the lowest value, station 5 the highest and stations 2, 10 and 13 also with high averages ($> 3.3 \mu\text{M}$), suggesting production of nitrate by

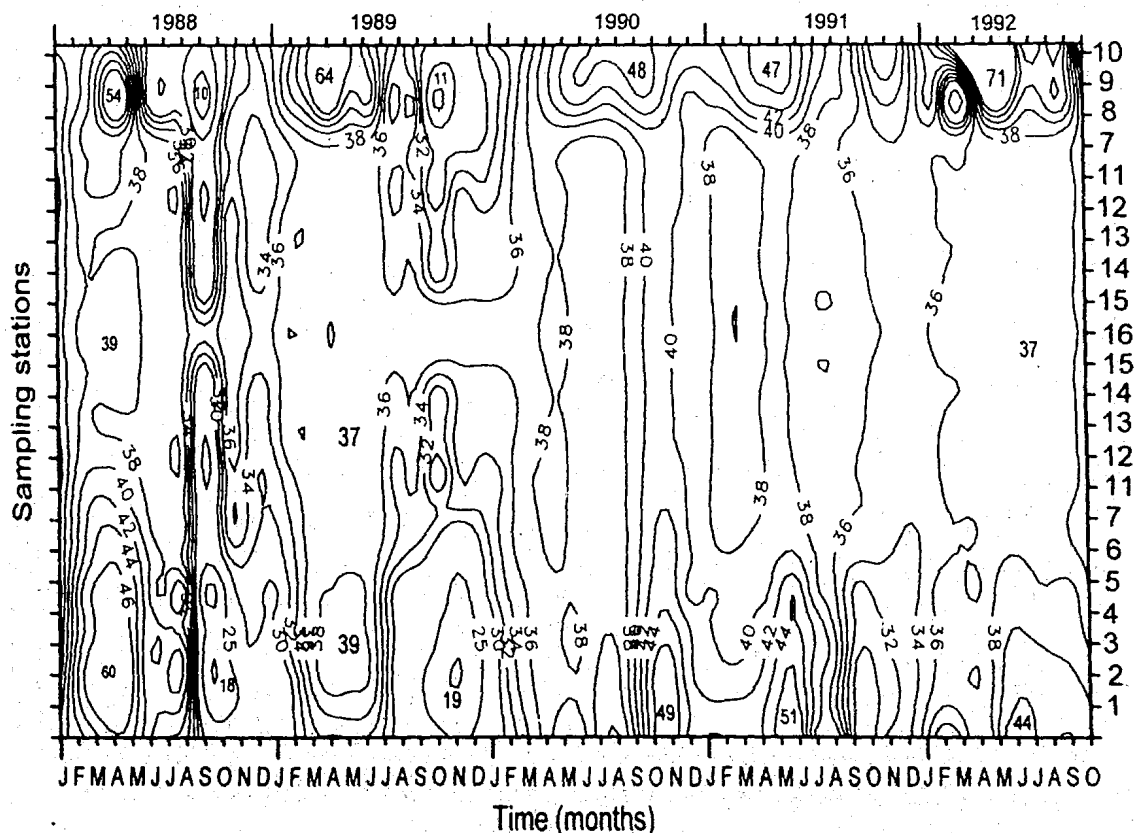


Fig. 3—Salinity in Chelem lagoon.

nitrification⁷. An increase was observed ($6.6 \mu\text{M}$ in September 1988), immediately after Gilbert hurricane and $3\frac{1}{2}$ months later ($14.7 \mu\text{M}$ in January 1989), likely the result of rain associated with the storm¹⁶.

Phosphates increased toward both east and west ends, but in general showed low concentrations except at station 10 near Progreso which had the highest value (probably due to eutrophication). This nutrient had significant correlation with salinity, temperature, pH, ammonium, nitrite, chlorophyll and suspended solids. Principal components analysis showed two zones with significant differences. During strong northern winds it reached high values suggesting that re-suspension of sediments by waves is an important process in recycling phosphates.

Silicate concentration was higher in the eastern region, reaching its maximum at station 9, western stations also presented high values (around $60 \mu\text{M}$), suggesting an influx of silicate rich

groundwater from a natural source like the high salinity spring found once in the lagoon (Table 3), or by discharges of domestic or industrial waste water. Statistical analysis showed two zones, and good correlations with salinity, ammonium, phosphate and pH, meaning that high silicate stations were also high in salinity, ammonium, phosphate, and pH, suggesting that silicate is conservative (like salinity), and increasing with evaporation. Time series showed annual periodicity, with higher concentrations at the beginning of autumn (September-October) and after hurricane Gilbert (Fig. 2).

Temporal variation of chlorophyll *a*, *b* and *c* were high, suggesting an important variability in the abiotic parameters that limit phytoplankton biomass. The values were considerably higher than those found in other coastal lagoons and estuaries. Lowest concentrations were in the west zone, and highest in Yukalpeten harbor (station 13) and in the east end (stations 9 and 10). These three last

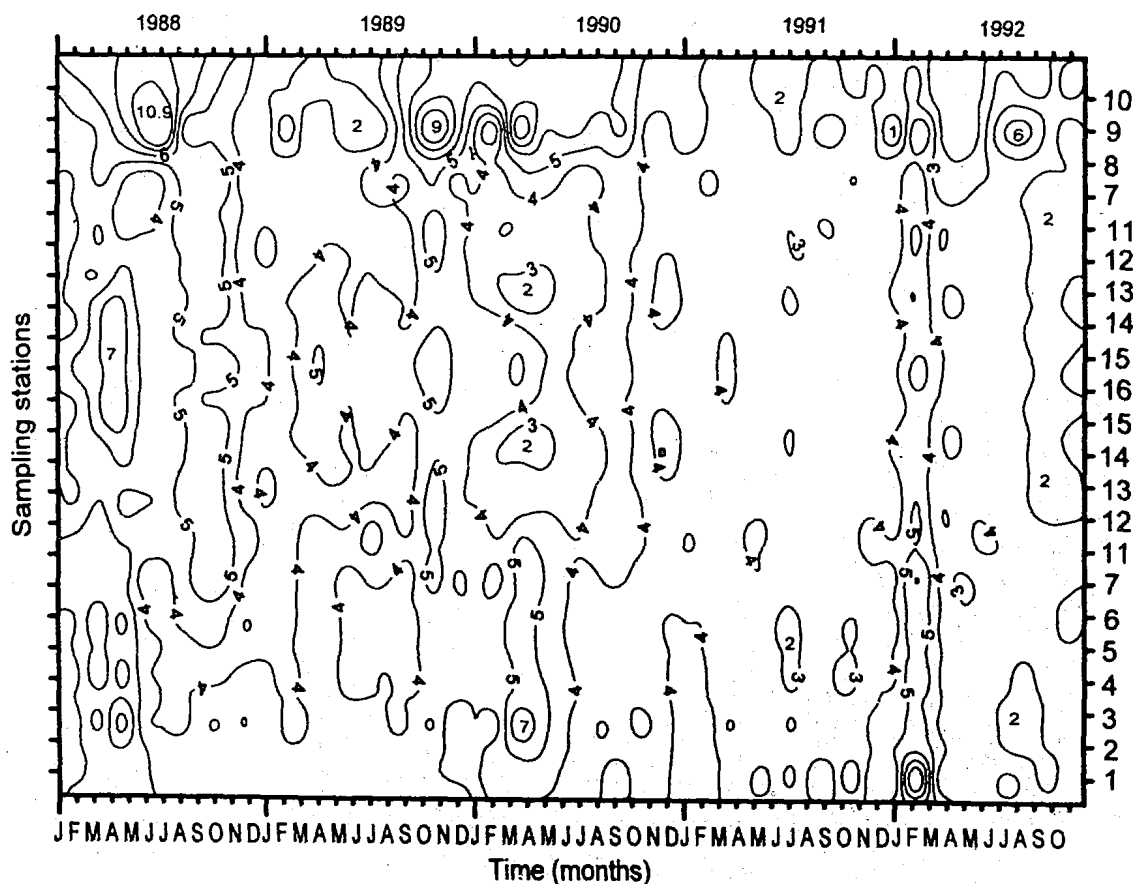


Fig. 4—Dissolved oxygen (ml/l) in Chelem lagoon.

stations showed eutrophication signs, especially station 10 reaching a maximum around $50 \mu\text{g l}^{-1}$, which according to UNESCO corresponds to an altered zone¹⁵. The statistical analysis showed direct correlations with salinity, nitrite, and phosphate, inverse with oxygen, and confirmed that stations 8, 9, 10 and 13 were different from the rest. Chlorophyll *a*, *b* and *c* ratios (4.61:1.26:4.46), indicated the existence of algal groups containing chlorophyll *a* and *c*¹⁷.

Particulate nitrogen was in the normal range of estuarine systems, except station 10 ($68.4 \mu\text{M}$), which was higher. Statistical analysis showed one

zone normal with low concentrations and one disturbed with higher values, and significant correlations with salinity, nitrite, phosphate, pH, dissolved oxygen, chlorophyll *a*, *b* and *c*, total, inorganic and organic suspended solids.

Suspended solids displayed alternative values: high at the end of north wind season and low at the beginning of the rainy one, indicating a clear relationship of suspended solids and wind. Time series analysis confirmed this annual pulsation which is a common pattern in most of coastal systems. Statistics showed difference between east and the rest. Inorganic and organic fractions had

Table 3—Values of the parameters measured in the spring sampled once at Chelem lagoon and the corresponding average values for the lagoon stations and the mouth (station 15)

	S‰	pH	Oxygen ml/l	Ammonium μM	Nitrite μM	Nitrate μM	Phosphate μM	Silicate μM
Spring	43.4	7.3	4.2	5.9	1.7	56.1	1.9	157.5
Lagoon	37.3	8.5	3.5	7.9	0.3	2.9	0.6	41.5
Mouth	36.9	8.5	3.5	5.5	0.3	1.9	0.5	7.3

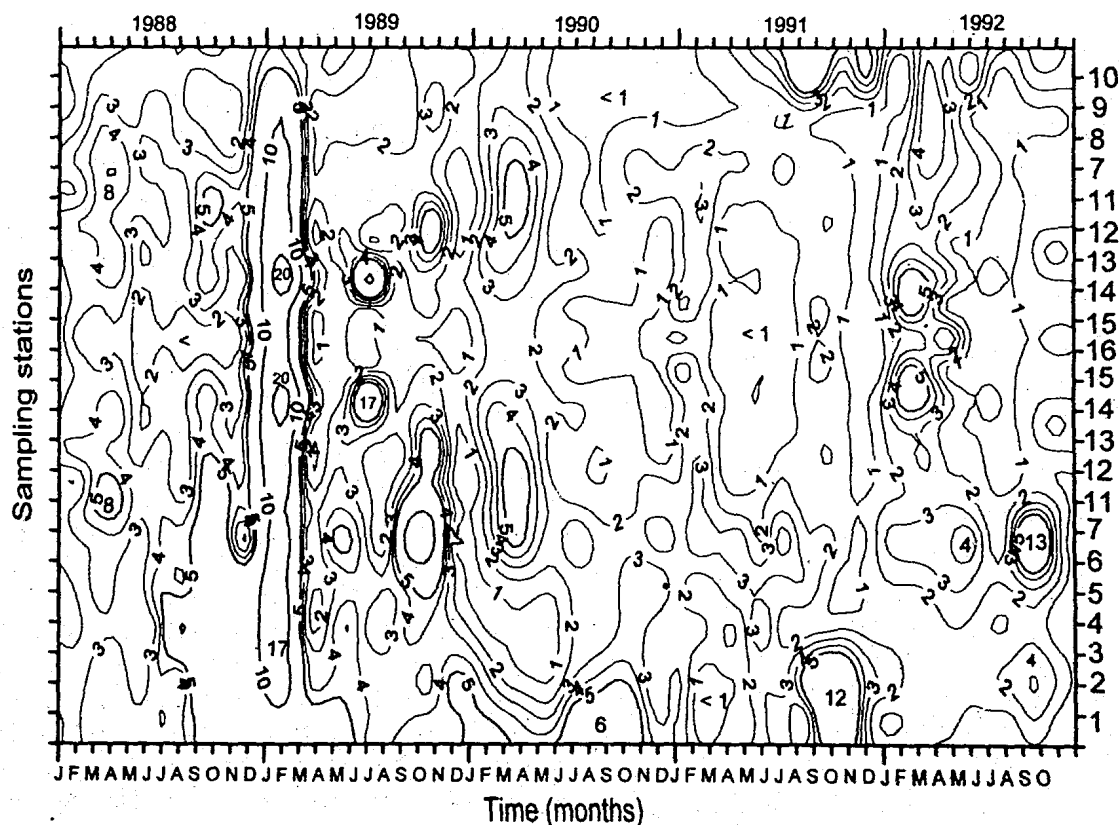


Fig. 5—Nitrate concentration (μM) in Chelem lagoon.

same behavior like total suspended solids.

With this study we found that Chelem lagoon has antiestuarine characteristics: the salinity increases toward the interior, and also that salinity is regulated mainly by the precipitation and the evaporation. We identify three zones in the lagoon: west zone is characterized by high salinity values, high ammonium concentration and low human disturb; central zone has lot of water exchange between sea and lagoon that keep favorable conditions; and the east zone has large variations in salinity, high ammonium and suspended materials and low oxygen, and is impacted by the human activities. Hurricane Gilbert affected the lagoon, decreasing the salinity and raising the silicate and nitrate concentrations. Salinity, ammonium, silicate and suspended solids presented annual periodicity. Ammonium and phosphate concentrations suggest that decomposition of organic matter in the sediments of the lagoon is important. Public and private efforts must be done to avoid more deterioration of the lagoon.

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