Gulf and Caribbean Research

Volume 17 | Issue 1

January 2005

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DOI: 10.18785/gcr.1701.14

Gulf and Caribbean Research Vol 17, 133–143, 2005 Manuscript received January 29, 2003; accepted December 7, 2004

SEASONAL AND SPATIAL PATTERNS IN SALINITY, NUTRIENTS, AND CHLOROPHYLL *a* IN THE ALVARADO LAGOONAL SYSTEM, VERACRUZ, MEXICO

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ABSTRACT Ten monthly collections, distributed among three seasons, were taken from July 2000 to June 2001 in the Alvarado lagoonal system, Veracruz, Mexico. Variables measured *in situ* included dissolved oxygen, salinity, and water temperature. Water samples were collected to determine concentrations of ammonium, nitrates, nitrites, orthophosphates, total phosphorus and chlorophyll *a*. Collections representing the rainy season were taken in September and October, those for the nortes season were taken in November, December, and January, and dry season collections were taken during February, March, May June, and July. There was seasonal and spatial variation in nutrient concentrations, and they were related to the discharge of the rivers; concentrations increased during the rainy and nortes seasons. Other factors affecting water quality included the constant discharge of organic materials into the system, resuspension of sediments during the nortes season and the biological activity within the system that assimilated the nutrients in the water. The Alvarado lagoonal system has three separate zones based on physicochemical characteristics; Camaronera Lagoon, Buen Pais Lagoon and the urban zone of Alvarado Lagoon, and the river zone in Alvarado Lagoon.

RESUMEN Se realizaron diez muestreos durante el periodo comprendido entre Julio de 2000 a Junio de 2001, distribuidos a lo largo de tres estaciones climáticas, en el sistema lagunar de Alvarado, Veracruz, México. Los parámetros que fueron registrados in situ incluyendo oxígeno disuelto, salinidad y temperatura de agua. Al mismo tiempo se colectaron muestras de agua para determinar en laboratorio las concentraciones de amonio, nitratos, nitritos, ortofosfatos, fósforo total y clorofila a. Los meses de colecta que abarcaron las temporada de lluvias fueron tomadas en Julio, Septiembre y Octubre, para Nortes Noviembre, Diciembre, y Enero, y por último, la temporada de secas que correspondieron los muestreos de Febrero, Marzo, Mayo, y Junio. Los nutrientes presentan una variación espacio-temporal presentando relación con: la descarga de los ríos, incrementándose su concentración durante la temporada de lluvias y Nortes; las constantes descargas de agua provenientes de diversas actividades humanas, como son la agricultura y los asentamientos humanos; la resuspensión de los sedimentos durante la temporada de Nortes; y la gran actividad biológica de estaos sistemas que permiten la rápida transformación de la materia orgánica en nutrientes. El sistema lagunar de Alvarado presenta tres zonas diferentes basadas en sus características fisicoquímicas: Laguna de Camaronera, Laguna de Buen País y la zona urbana de Laguna de Alvarado, y la zona de ríos en Laguna de Alvarado.

INTRODUCTION

Coastal lagoons are productive aquatic systems with a large amount of energetic input. They frequently show elevated concentrations of nutrients (Mee 1978), and many are considered eutrophic. Annually, the constant wind-driven movement of the water column resuspends sediments, which furnishes nutrients to the water column through the biogeochemical cycle and the transformation of materials that were in the sediments (Colombo 1977). Rivers and their drainages provide additional nutrients. These nutrients can exhibit large seasonal variation, with the highest concentration generally found following a rainy period. Minimal concentrations are detected after the spring phytoplankton bloom, although even in those months, the concentration of nutrients is higher than that in the adjacent coastal zone (De la Lanza and Arenas 1986).

In Mexico, estuarine lagoonal systems represent 30 to 35% of the coastal areas, and 42 of the 134 lagoons are found along the coast of the Gulf of Mexico (GOM) and the Caribbean Sea (Contreras 1985). The estuarine systems along the GOM are generally bordered by well developed marsh zones, and the ocean influence is accentuated (Kennish 1986). However, in the southern GOM, estuarine systems are generally bordered by mangroves and the degree of oceanic influence varies greatly. In these systems, many factors such as salinity show great seasonal variation. It is common to encounter a gradient where the salinity is higher near the inlets and decreases towards the rivers.

Typically, three seasons (rainy, dry and nortes) define the hydrological behavior of the southern GOM systems (Gómez 1974, Villalobos et al. 1975, Lankford 1977, Botello 1978, Contreras 1988). The rainy season usually occurs from June through September and is characterized by consistent rainfall and large terrestrial runoff, resulting in frequent floods, turbid waters and additional pressures due to the influence of drainage from the land (Contreras 1985). During this season there are brief times of calm weather, characterized by cessation of the rains, high temperatures and elevated rates of evapotranspiration. During these periods, extraordinary photosynthesis occurs, with values occasionally exceeding 700 mgC/m^3/h and elevated concentrations of chlorophyll *a* of 100 mg/m^3 (Contreras 1994). The dry season is typically from March through June and has minimal rainfall and river flow (Villalobos et al. 1975, Contreras 1983). The dry season is characterized by elevated temperature, clear water and relative stability in phytoplankton diversity, and the lagoon is generally affected by the dominance of ocean water mass. The higher salinity found during the dry season may be due to evaporation and the reduced influence of the rivers (Villalobos et al. 1966, Contreras 1983). During the nortes, or winter season (October–February), there are strong winds blowing from the north off the GOM and temperatures are low (Herrera and Comin 1995, Barreiro and Aguirre 1999). Autotrophic processes dominate over heterotrophic processes, and there is a considerable quantity of dissolved organic material including organic phosphorus.

The Alvarado lagoonal system is a typical coastal estuary along the southern GOM that supports a variety of different activities, such as fishing, transportation and urban development. A previous study on the hydrography and productivity of this system identified 5 distinct areas, determined by water temperature and chlorinity, within the lagoon: areas with marine influence, areas with freshwater influence, a gradient area, a calm area and the coastal adjacent area (Villalobos et al. 1966). These authors also established that the hydrological and biological characteristics of the lagoon were clearly defined by the rainy and dry seasons. The lagoon is polyhaline with a tendency towards being mesohaline during the dry season and becomes almost totally freshwater during the rainy season (Villalobos et al. 1975). The biological productivity in the system is high, and primary production and the number of phytoplankton cells are inversely related to the phytoplankton biomass and the postlarval stages of shrimp (Villalobos et al. 1975). More recently, Morán-Silva et al. (1996) reviewed the general hydrological behavior of the Alvarado lagoonal system. They concluded that the hydrological conditions are a direct result of the fluvial discharges and found the lagoon to be predominantly oligohaline. Higher salinity values were found only during the dry season or near the inlets and water temperature varied seasonally. The shallow depth throughout the system, in combination with the winds, allows mixing and aeration of the water column despite the high primary production observed. High nutrient concentrations were found near river mouths, mangroves, and submerged vegetation, presumably through degradation of organic material and resuspension of the sediments. However, the Moran-Silva et al. (1996) study did not examine the seasonal differences in nutrients in the system. Thus, the principal objective of this work is to describe, analyze and characterize the seasonal-scale patterns of the salinity, physicochemical and nutrient variables and their relationship with chlorophyll *a* during the dry, rainy and nortes seasons in the Alvarado lagoonal system, Veracruz, Mexico.

Study Area

The Alvarado lagoon system is located in the coastal plain of the GOM, 63 km southeast of the port of Veracruz, between 18°46 and 18°42 N and 95°34 and 95°58 W (Figure 1). Lankford (1977) considered the system to be a drowned river valley. The lagoonal system consists of 3 smaller lagoons with a total length of about 27 km and a surface area of 6,200 ha. Alvarado Lagoon, the main body of water, continues to the west into Buen Pais Lagoon, which is connected to Camaronera Lagoon through a narrow channel to the west. The primary connection to the ocean is Alvarado Inlet, situated at the northeast of the system. A small, 400 m wide outlet to the ocean was constructed in 1982 in Camaronera Lagoon. The Papaloapan River discharges into Alvarado Lagoon from the southeast. Tidal influence does not diminish the outflow of this river, and mean daily flow into the lagoon is 40 million m^3 (Contreras 1985). This system is classified as a positive estuary, because the surface water evaporates at a lesser rate than water is added by the river flow (McLusky 1981). This characteristic is in contrast to many lagoonal systems that are hypersaline due to high evaporation and low freshwater input.

The climate of the area is tropical and humid, and precipitation during the summer ranges from 110 to 200 cm. The mean annual temperature varies between 22–26 °C,

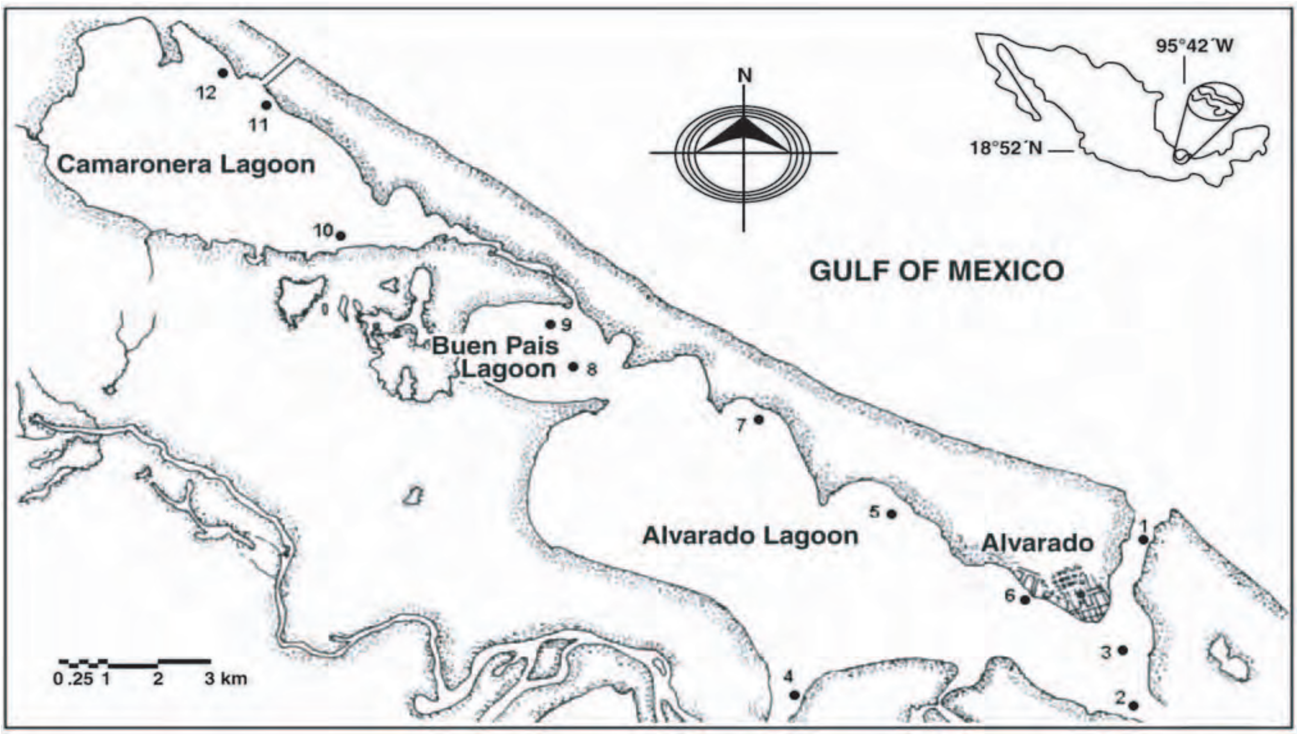

Figure 1. Map of sampling locations in the Alvarado Lagoon system, Mexico.

with temperature oscillations between 5–7 °C between each season (Garcia 1973). The prevailing southeast winds have a maximum velocity of 14.4 $msec^{-1}$, except for October, when winds from the north and northeast range from 90–129.6 $msec^{-1}$ (Contreras 1985).

The lagoon is almost entirely surrounded by mangroves with the typical zonation pattern of red mangrove, *Rhizophora mangle*, bordering the water and black mangrove, *Avicennia germinans*, and white mangrove, *Laguncularia racemosa*, immediately interior. Other sporatically occurring aquatic vegetations include wild celery, *Vallisneria americana*; cordgrass, *Spartina* sp.; and cattail, *Typha* sp.; while the dominant submerged aquatic vegetation (SAV) is *Ruppia maritima* (Morán-Silva et al. 1996). During the rainy season, the water lily, *Eichhornia crassipes*, invades the lagoon.

MATERIALS AND METHODS

Twelve stations were established throughout the Alvarado lagoonal system (Figure 1) to detect the influence of rivers, inlets, SAV and urban discharges. We defined groups for each system: Camaronera group includes stations 10–12; Buen Pais group includes stations 8–9; the Alvarado Lagoon group (urban dominated) includes stations 5–7; and finally the river dominated group includes stations 1–4 in Alvarado Lagoon. Sampling occurred at about 30 d intervals between July 2000 and June 2001. Water temperature (°C) was measured with a mercury thermometer, salinity (psu) with a YSI model 33 salinometer and dissolved oxygen (D.O., ml/l) with a YSI model 51b meter during each collection. Surface water samples were collected at each station for nutrient concentration determination. Methods follow Contreras (1994) for ammonium (NH_4, mg-at/l), nitrate (NO_3, mg-at/l), nitrite (NO_2, mg-at/l), phosphate (PO_4, mg-at/l), and total phosphorus (P-TOT, mg-at/l). Determination of chlorophyll *a* (chl *a*, µg/l) follows techniques in SCOR-UNESCO (1980). The samples were kept on ice for 48 h prior to analysis (Strickland and Parsons 1972, Wetzel and Likens 1990).

We used correlation analysis to examine the relationship between nutrient concentration and chl *a* (Daniel 1977). Dendrograms were constructed of temporal and spatial classification with Euclidian distance (values range from 0, when entities are identical, to infinity) using the monthly salinity data from each station. Classification of the system using salinity followed the procedure of Carriker (De la Lanza 1994). For all analyses we used the Community Analysis Program (ANACOM) 3.1 (De la Cruz, 1994), and results were considered significant if $P < 0.05$.

RESULTS

Physicochemical variables

Salinity varied among all stations from 14.2 psu during the dry season in June to 0.0 psu during the rainy season in September. The lowest salinity values were always associated with the rivers (0–7.1 psu), whereas the highest values were found in Camaronera and Buen Pais Lagoons (Figure 2a). Salinities at the Alvarado Lagoon stations showed the highest values in March.

Dissolved oxygen varied from 12.8 ml/l in Camaronera Lagoon to 4.13 ml/l in the stations of the river group. The highest D.O. values were found during the dry season, and values for all stations peaked in May (Figure 2b). The D.O. values at the Alvarado Lagoon group stations fluctuated more than those from the other stations.

Water temperature varied seasonally, with annual variation ranging from 21.6 °C during the nortes season to 32.2 °C during the rainy season (Figure 2c). Water temperature tended to be higher in the Alvarado Lagoon zone and lower in the stations with river discharge throughout the year.

Nutrients

Ammonium was the dominant form of inorganic nitrogen, representing 60.98 to 88.3 % dissolved inorganic nitrogen (DIN). The highest ammonium concentration was 42.43 µg-at/l during the dry season in Buen Pais Lagoon, and the lowest was 2 µg-at/l during the dry season in Camaronera Lagoon (Figure 3a). In general, the highest ammonium values were found at the river group stations and in Buen Pais Lagoon. The highest nitrite concentration was 3.54 µg-at/l during the dry season at the river stations. Undetectable amounts of nitrite were found during the dry season in Buen Pais and during the rainy season in the Alvarado Lagoon group (Figure 3b). Nitrite peaked in the Alvarado Lagoon group (urban zone) at the end of the nortes season. Nitrates were highest during the nortes season in the urban and rivers zones (7.9-10.6 µg-at/l), and lowest (0.67 µg-at/l) in Camaronera Lagoon during the nortes season (Figure 3c). A smaller peak of nitrate was evident in all stations at the end of the dry season.

Camaronera Lagoon had the greatest range in total phosphorus, with highest values during the rainy season (18.8 µg-at/l) and lowest values during the nortes season (3.5 µg-at/l; Figure 4a). Highest values for all stations occurred during the rainy periods (Figure 4a). The values of orthophosphates were highest at the end of the dry season (4.5–6.2 µg-at/l) and lowest during the rainy season (0.37–0.48 µg-at/l) at all stations (Figure 4b).

Chlorophyll *a*

Chlorophyll *a* values fluctuated during the annual cycle, with lowest values during the dry season (4.3–18.8 µg/l) and highest values in the nortes season (11.5–92.6 µg/l). Buen Pais Lagoon exhibited the greatest fluctuation in chl *a* (Figure 4c). Overall, the river group stations had the lowest chl *a* values (5.1–32.1 µg/l). Correlations between chl *a* and the physicochemical and nutrient measurements differed seasonally, but there were no significant correlations between chl *a* and any other variable measured (Table 1). During the rainy season, there was a moderately positive correlation between chl *a* and salinity and D.O., and a strong negative correlation with ammonium and nitrite. During the nortes season, total phosphorus showed a strong, negative correlation with chl *a*. Salinity had a moderately positive correlation with chl *a* during the dry season, while total phosphorous and phosphates were moderately negatively correlated.

Spatial-temporal variation

The variability of most of the parameters was reflected principally in salinity, which was rapidly modified by the rain and tidal influence. Using salinity in a cluster analysis, three principal groups were evident (Figure 5a). Group 1 consists of the months of September and October, representing the rainy season, when the system was oligohaline with salinities ranging from 0 to 3.8 psu. Group 2 consists of the months November, December, January and February, corresponding to the nortes season when the salinity begins to increase, ranging from 0 to 11.5 psu. The third group corresponds to the dry season (March, May and June 2001), with the highest salinity values (2 to 14.5 psu), resulting in a mesohaline system. However, July is isolated from the other groups. This month corresponded to the rainy season, while June 2001 was more similar to the dry season due to a lack of rain during that year.

When cluster analysis was applied to the collection stations, the analysis resulted in three groups separated by marine or freshwater influence (Figure 5b). The first group consisted of stations located in Camaronera Lagoon (12 and 11) that receive direct tidal influence through the inlet and had the highest salinities (up to 21 psu). The second group has stations separated into 2 sub-groups, with stations 8–10, representing the eastern portion of Camaronera Lagoon and Buen Pais Lagoon, as one sub-group and stations 5–7, the urban dominated stations, as the second subgroup. The first sub-group receives some tidal influence and had mean salinities ranging from 6.33 to 8.75 psu, while the second sub-group consisted of lower salinity stations located along the eastern shore of Alvarado Lagoon with a marked influence from urban zones. The final major

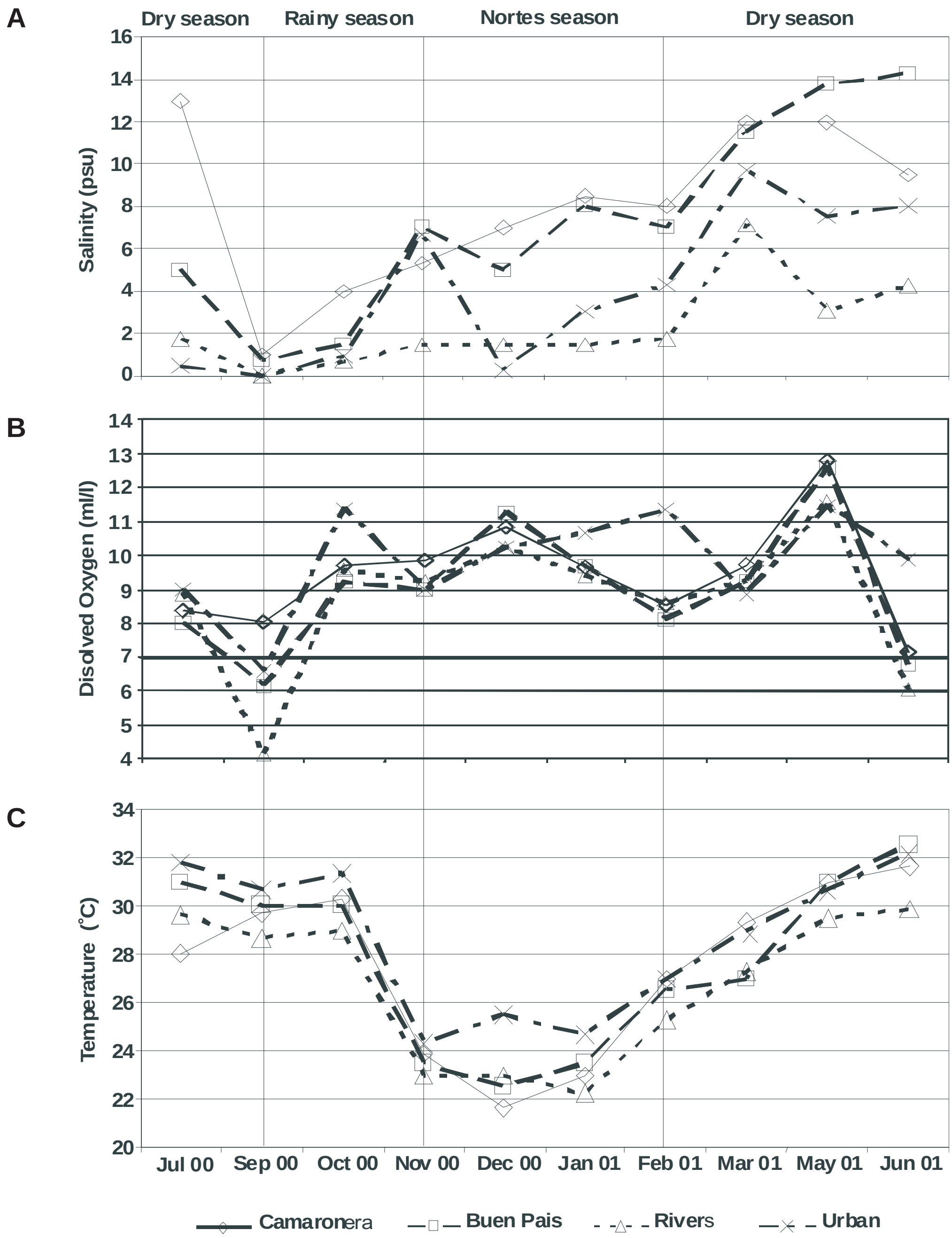

Figure 2. Plot of mean monthly salinity (A), dissolved oxygen (B), and water temperature (C) over the course of the study pooled by sampling stations within each of the four groups.

group contained all the stations associated with the river group (1–4) and can be defined as an oligohaline zone.

DISCUSSION

It is well known that the variability of the hydrological variables and nutrients is especially marked in lagoonal systems. This is due to many factors, like the dynamics in the circulation of the lagoon as affected by the tides, the winds, and the shallow depth. Furthermore, constant resuspension of sediments, regeneration processes originated by microbial activity in the sediments, river flow, and human activities contribute to nutrient variation (Colombo 1977, Snedaker and Brown 1982).

As expected, the low salinity values found during the rainy season were a result of the increased freshwater inflow into the lagoonal system (Botello 1978). Similarly, the months corresponding to the dry season (March, May and June in this study) had the highest salinity throughout the system, due to reduced river flow. However, the months

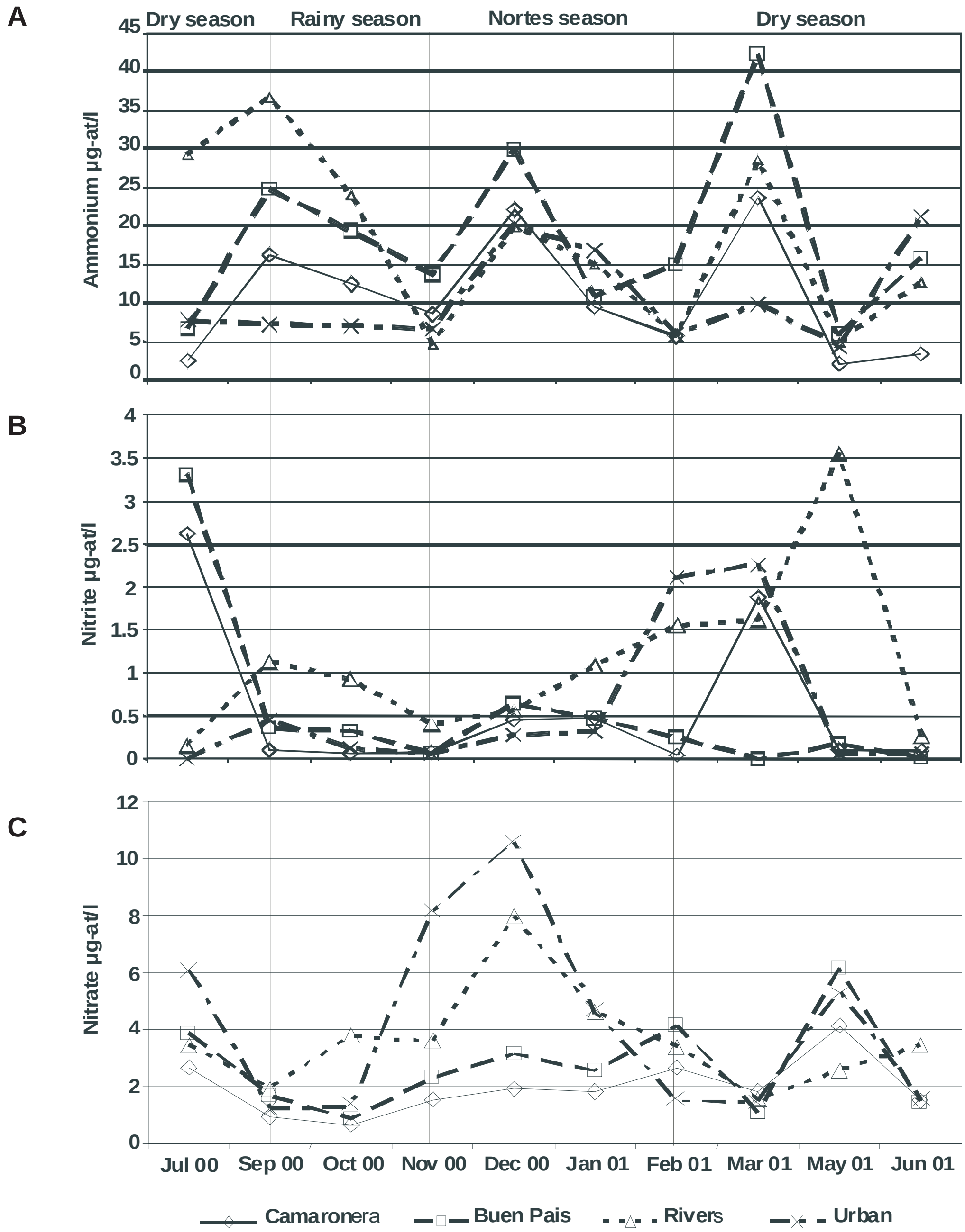

Figure 3. Plot of mean monthly ammonium (A), nitrite (B), and nitrate (C) over the course of the study pooled by sampling stations within each of the four groups.

during the nortes season (December, January and February) had salinity values similar to the dry season. Thus, the Alvarado lagoonal system can be considered oligohaline during the rainy season and mesohaline during the nortes and dry seasons. However, the stations close to the river mouth remained oligohaline during the dry season, indicating a weak marine influence in the lagoon (Morán-Silva et al. 1996). Seasonal differences in salinity have been noted previously in other Mexican lagoons, such as the Celestum Lagoon (Herrera-Silveira and Comin 1995) the Tampamachoco Lagoon (De la Lanza et al. 1998), and the Alvarado lagoonal system (Morán-Silva et al. 1996).

The lowest D.O. concentrations were encountered in September, which corresponds to the end of the rainy season, when there is an increase in suspended organic material. When organic material is resuspended, microorganisms begin decomposition, removing oxygen from the water column (Kennish 1986). The highest D.O. concentrations were found associated with seagrass beds, similar

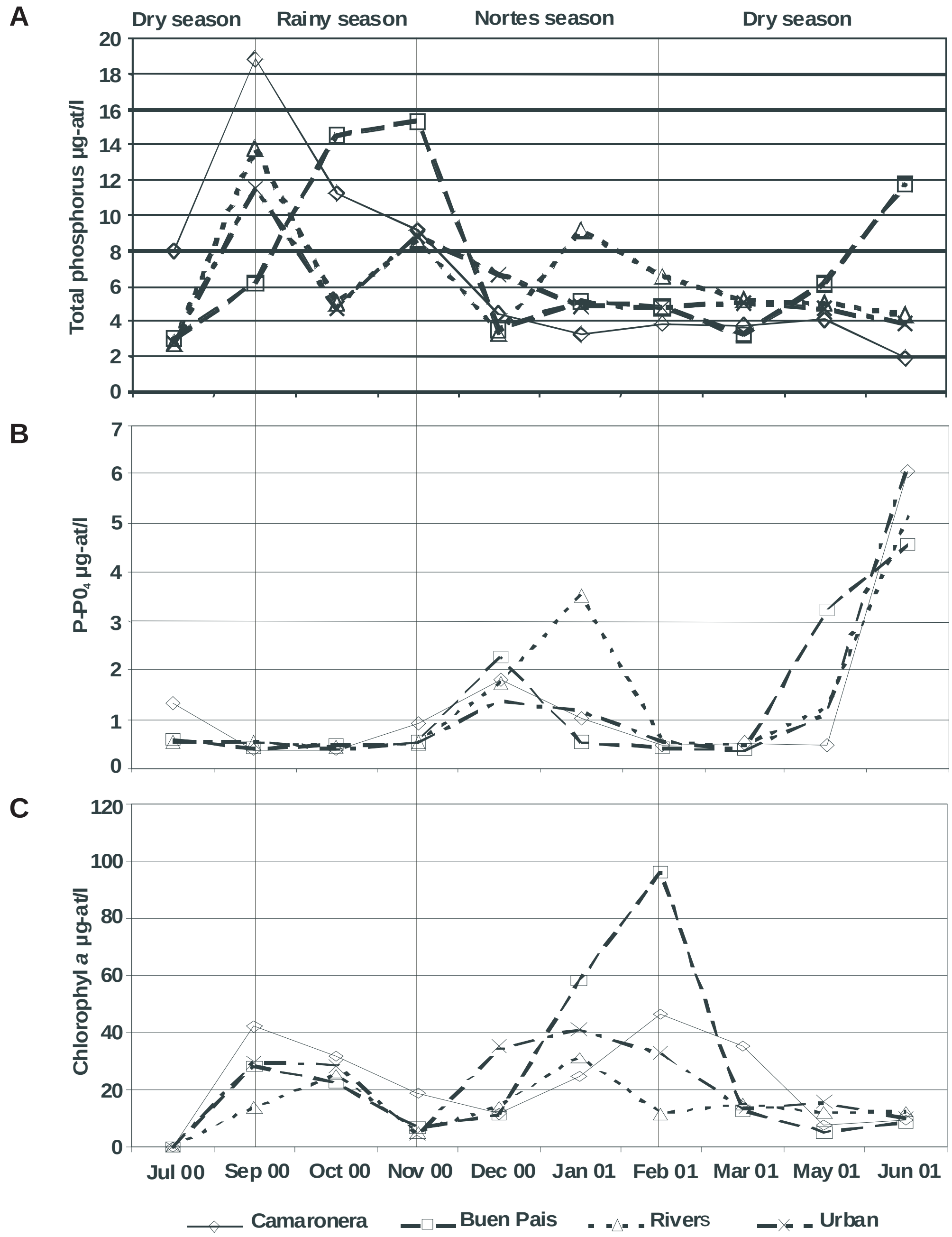

Figure 4. Plot of mean monthly total phosphorus (A), orthophosphate (B), and chlorophyll *a* (C) over the course of the study pooled by sampling stations within each of the four groups.

to reports by Contreras and Gutierrez (1989) for other systems in the state of Veracruz. Overall, D.O. concentrations remained relatively heterogeneous and could be related to photosynthetic activity, seasonality, mixing of water and tidal activity (Botello 1978, De la Lanza and Cantu 1986), or to the presence of SAV throughout the system.

With respect to nutrients, the form of ammonia in this type of system comes from degradation of organic material, submerged vegetation and waste from organisms (Tiejten 1968, Botello 1978, De la Lanza and Arenas 1986). Ammonium was the predominant form of inorganic nitrogen during all the seasons. Similarly, Kennish (1986) found that ammonium was the predominant form of inorganic nitrogen in estuarine waters. This agrees with reports by Contreras and Castañeda (1992) and Contreras (1983) for the Tampamachoco Lagoon and the lagoonal system of Carretas-Pereyra, respectively. Maximal ammonium values were observed in Buen Pais Lagoon during the dry season, no doubt enhanced by the increasing temperature that favors a greater degradation of organic mate-

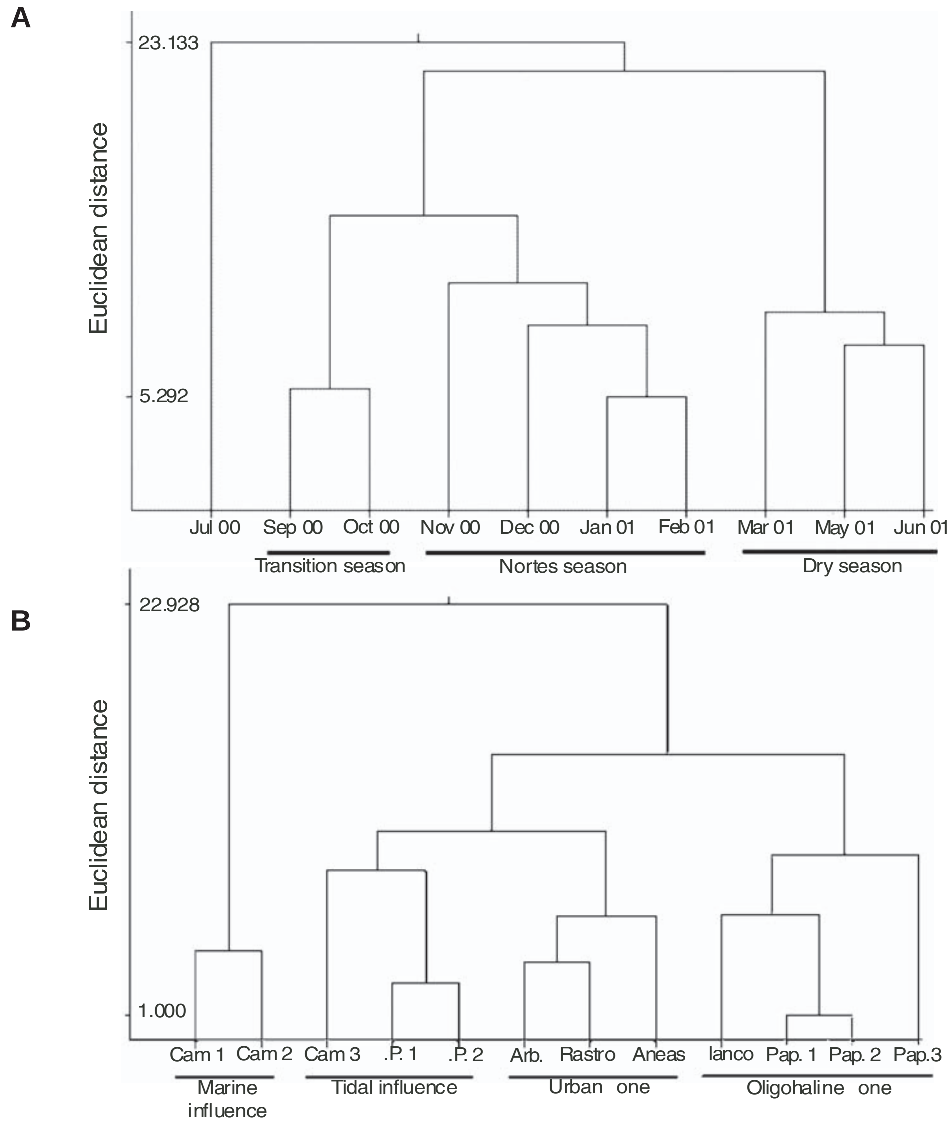

Figure 5. Dendogram based on Euclidean distance of monthly (A) and station (B) salinity values. Station numbers correspond to stations in Figure 1. Cam-Camaronera Lagoon; B.P.-Buen Pais Lagoon; Arb., Rastro, Aneas—urban areas on the north side of Alvarado Lagoon; Blanco-Blanco River, Alvarado Lagoon; Pap.-Papaloapan River, Alvarado Lagoon

rials found in the sediments as well as increased waste from organisms in the water column. However, Kennish (1986) indicated that the concentrations of the nitrogenous components can be augmented with the river flow. We observed a similar increase in the river group stations during September, a time of high river flow in Alvarado Lagoon. Day et al. (1998) reported a similar situation in Terminos Lagoon, showing augmentation of nutrient concentrations during times of high discharge from the rivers.

Buen Pais Lagoon had generally higher values of ammonium than the other two lagoons within the system, with a peak in March. This may be due to slower water circulation in this lagoon relative to the others in the system (Villalobos et al. 1975). In contrast, the urban areas of Alvarado Lagoon did not have an increase in nitrogen in March, although there were peaks in June and December. Alvarado Lagoon is impacted by urban discharges from the Port of Alvarado, which tend to increase the nitrogen concentration in the water (Barreiro and Aguirre 1999). This was particularly evident for nitrate during the nortes season.

The Lagoon showed notable hydrological variation on spatial as well as temporal scales. For instance, eutrophication was noted in semi-isolated areas such as within canals, which had minimal effects of circulation, yet the rest of the Lagoon was not eutrophic. On a temporal scale, the dry and wet seasons result in changes in salinity and nutrients with consequent variation in the habitat during the annual cycle.

TABLE 1

Seasonal correlation coefficients (Pearson's r) between chlorophyll *a* and various water chemistry variables in the Alvarado lagoonal system. No values were significant at *P* < 0.05.

Variables	Rainy	Nortes	Dry
Salinity (psu)	0.55	–0.04	0.43
Dissolved oxygen (ml/l)	0.59	–0.15	0.02
Temperature (ºC)	0.35	–0.24	0.29
Ammonium (µg-at/l)	–0.65	0.29	0.10
Nitrite (µg-at/l)	–0.14	0.27	–0.20
Nitrate (µg-at/l)	–0.74	–0.13	0.15
Phosphate (µg-at/l)	–0.15	0.14	–0.37
Total phosphorous (µg-at/l)	–0.20	–0.62	–0.47

The nutrient concentrations reached during the rainy season were more elevated than during the dry season.

The Alvarado lagoonal system had the highest phosphorus concentration during the rainy season. While this nutrient comes principally from organic material, it is also produced through autochthonous processes such as bioturbation and remineralization of the sediments and remixing by currents (Groen 1969). Total phosphorus was highest during September throughout the lagoonal system, no doubt due to the effects of increased river runoff and resuspension of the sediments (Groen 1969). Concentration decreased gradually to the lowest point during the dry season. A peak of orthophosphates in June may be related to the decrease in chl *a* concentration during this month, as phytoplankton utilize orthophosphates (Contreras and Castaneda 1992). Overall, Camaronera Lagoon had the lowest concentration of phosphates, probably because currents are minimal, resulting in little resuspension of the sediment where the majority of phosphates are stored (De la Lanza 1996). In Alvarado Lagoon, phosphates were higher during the nortes and dry seasons compared to the rainy season, and variation was not as great as in the other lagoons. The variation in phosphate that was observed is probably a direct result of river input. The agricultural land and associated fertilizers within the drainage basin of the Papaloapan River are important sources of phosphates (Correll et al. 1992), which can be transported into the lagoon through erosion and runoff.

A global characteristic of lagoonal phytoplankton is their high productivity. For this reason, we consider coastal lagoons as ecosystems with characteristics intermediate between the ocean and the rivers (Margalef 1969). Since algae are the only organisms that remain constant with respect to other cellular components that are ecologically important, chl *a* concentration can be used to better understand the dynamics of the system (Marshall 1987). Unfortunately, the coefficients of correlation did not show a significant relation between the concentration of chl *a* and the physicochemical variables. There is usually a strong relationship between nutrient concentration and chl *a* concentration, as has been previously discussed (Contreras 1994). We found an increase from undetectable chl *a* in July to moderate levels (14–42 µg/l) in September and October, similar to findings in other Mexican lagoonal systems (Contreras et al. 1992, Contreras and Castaneda 1992, Barriero and Aguirre 1999). Interestingly, the highest correlation between D.O. and chl *a* was found during this time, when chl *a* began to increase from a dry season low, suggesting an increase in productivity. During November and December, chl *a* again decreased in most areas of the lagoon, and chl *a* values were higher from January through March, with a peak in February. The high chl *a* values in Buen Pias Lagoon during February (96.2 µg/l) indicate a hypereutrophic system at that time. The February peak corresponds to the end of the nortes season, a time when Li et al. (2000) found an association of phytoplankton blooms with a peak of nutrients. The decrease in chl *a* during May and June may be related to the increase in phosphates and inorganic phosphorus during this time.

Barreiro and Aguirre (1999) found that an increase in nitrate during the rainy season is necessary for a phytoplankton bloom to commence during the dry season. Our data show a dramatic increase in nitrate during November and December, which may be related to the bloom, and a subsequent increase in chl *a* in February. The predominance of blooms during the dry season may also be related to calmer water conditions during this time (Marshall 1987).

Overall, the pattern of chl *a* was relatively similar among stations and lagoons, with peaks and low points occurring during similar times. Spatial patterns of chl *a* respond to local conditions (Barreiro and Aguirre (1999), and the estuarine currents can distribute the phytoplankton biomass asymmetrically (Li et al. 2000). For instance, phytoplankton populations from the ocean may enter the lagoon on incoming tides (Revilla et al. 2000), which may explain the increased chl *a* concentration near the inlet in Camaronera Lagoon during September, January and February. On the other hand, Revilla et al. (2000) found that the major concentration of chl *a* in estuaries was found in discharge areas that did not receive a direct tidal influence. Similarly, Day et al. (1998) found a major concentration of chl *a* in Estero Pargo (mean annual value 8 µg/l) in comparison to Terminos Lagoon (3 µg/l). However, our data show that the chl *a* concentration was low at stations located at the Papaloapan and Blanco rivers, where there is major discharge but minor tidal influence.

In terms of spatial distribution, it is possible to distinguish areas directly influenced by terrestrial sources due to elevated quantities of phosphorus. These are interpreted as areas within the lagoonal system with a greater density of primary producers, compared to other zones where different factors, such as circulation, river influence, or winds do not permit the accumulation of phytoplankton. The persistence of these phytoplankton overloaded areas is the direct cause of natural eutrophication or eutrophication originated by urban activities. Natural eutrophication is a result of geographic properties, accumulation of sediment, etc., while anthropogenic eutrophication is a result of uncontrolled use of fertilizers, deforestation, and addition of contaminants and human wastes to the lagoonal system. The continued urban development along the internal coast of the Alvarado Lagoon exacerbates the anthropogenic inputs to the system. Finally, there has been a change in the bottom use in the discharge area of the Papaloapan River that has altered the hydrological dynamics.

Our results suggest that habitats within the lagoonal system have high heterogeneity that is driven by variation in salinity and water temperature. This variation is the result of the influence of river discharge and tidal exchange. In addition, these difference may also relate to the bathymetry, the presence of SAV or the proximity of mangroves. However, our results do not correspond to those reported by other authors. Villalobos et al. (1966) described 5 natural areas based on the influence of the rivers and the ocean, whereas in this work, we define only 3 such areas, which are a function of river discharge, proximity to ocean inlets and the influence of urban discharges. Our findings concur with Lozano (1993) who found that an increase of anthropogenic activities, in conjunction with poor planning, contributed to local and regional changes in hydrological characteristics of the freshwater sources to the Alvarado lagoonal system.

Salinity characteristics of the Alvarado lagoonal system vary seasonally. Our work has reinforced the observations of Villalobos et al. (1975) who described the seasonal salinity variation. Furthermore, two earlier studies on the Alvarado lagoonal system found that salinity varied more than other variables (Sevilla and Chee 1974) and was lowest during the rainy period (Sevilla and Chee 1974, Chee 1981). It appears that the amount of rainfall and subsequent river discharge is one of the forces driving the variability of the system. Thus, to better understand the hydrology of the Alvarado lagoonal system this information is required.

ACKNOWLEDGEMENTS

We thank the students from the Ecology Laboratory at FES-Iztacala as well as the fishing community at Alvarado Port, Veracruz, Mexico, for their assistance with this project. The authors thank Dr. W. Boynton of Chesapeake Biological Laboratory for comments on an earlier version of this manuscript.

LITERATURE CITED

Barreiro, G.M.A. and L.A. Aguirre. 1999. Distribución espacio-temporal de la biomasa fitoplánctonica en el sistema lagunar Pom-Atasta, Campeche, México. Revista de Biología Tropical 47 (Supplement 1) 27–35.

Botello, V.A. 1978. Variación de los parámetros hidrológicos en la época de sequía y lluvia (Mayo y Noviembre de 1974) en la Laguna de Términos, Campeche, México. Anales del Centro de Ciencias del Mar y Limnologia. Universidad Nacional Autónoma de México 5(1):159–178.

Chee, B.A. 1981. Aspectos hidrológicos en la Laguna de Alvarado, Veracruz. Tesis Profesional. Universidad Autónoma de Baja California. Ensenada, Baja California. 160 p.

Colombo, G. 1977. Lagoons. In: R.SK. Barnes, ed. The Coastline. Wiley Interscience, New York, NY USA, p. 63–81.

Contreras, E.F. 1983. Variaciones en la hidrología y concentraciones de nutrientes del área estuarino—lagunar de Tuxpan Tampamachoco, Veracruz, México. Biotica 8(2):201–213.

Contreras, E.F. 1985. Lagunas Costeras Mexicanas; Centro de Ecodesarrollo, Secretaria de Pesca. México D.F., 253 p.

Contreras, E.F. 1994. Manual de Técnicas Hidrobiológicas. Editorial Trillas. México D.F., 141 p.

Contreras, E.F. and F.M. Gutiérrez. 1990. Hidrología, nutrientes y productividad primaria en lagunas costeras. In: Rosa-Velez, J. de la and F. González-Arias, eds. Temas de Oceanografía Biológica en México. Universidad Autónoma de Baja California. Ensenada, p. 57–78.

Contreras, E.F. and L.O. Castañeda. 1992. Contribución del nanofitoplancton en la cantidad de clorofila “a” de dos sistemas lagunares del estado de Chiapas, México. Investigaciones Marinas CICIMAR 7:61–73.

Contreras, E.F., A. Garcia, and O. Castañeda. 1992. Hidrología, nutrientes y productividad primaria en el sistema lagunar-estuarino de Carretas-Pereyra, Chiapas, México. Universidad y Ciencia 9(17):43–51.

Contreras, E.F., A. García, and O. Castañeda. 1994. La clorofila como base para un índice trófico en lagunas costeras mexicanas. Anales del Instituto de Ciencias del Mar y Limnología. Universidad Nacional Autónoma de México. Volumen 2. Número 21, 1–15.

Correl, D.L., T.E. Jordan, and D.E. Weller. 1992. Nutrient flux in a landscape: Effects of coastal land use and terrestrial community mosaic on nutrient transport to coastal waters. Estuaries 15:431–442.

Daniel, W. 1977. Bioestadistica. Limusa. México D.F., 485 p.

Darley, W. Marshall. 1987. Biología de las algas: Enfoque fisiológico. Editorial Limusa México D.F., 236 p.

Day, J.W., F. Ley-Lou, C.J. Madden, R.L. Wetzel, and A. Machado. 1988. Aquatic primary production in Terminos Lagoon. In: A. Yanez-Arancibia and J.W. Day, eds. Ecology of Coastal Ecosystems in the Southern Gulf of Mexico: The Terminos Lagoon Region. Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México. Editorial Universitaria, México, D.F., p. 221

De la Cruz, G. 1994. ANOCOM. Sistema para el análisis de comunidades. Ver 3.1. Manual del ususario. Cinvestav-IPN, Mexico. 99 p.

De la Lanza, E.G. 1994. Química de las lagunas costeras y el litoral mexicano. In: E.G. De la Lanza and M.C. Cáceres, eds. Lagunas costeras y el litoral mexicano. Universidad Autónoma de Baja California Sur. La Paz, Baja California Sur, p. 129–190.

De la Lanza, E.G. 1996. Importancia ecológica de los ciclos biogeoquímicos en los sistemas lagunares costeros. In: T.M.G. Figueroa, S.C. Alvarez, H. Esquivel, and M.E. Ponce, eds. Fisicoquímica y biología de las lagunas costeras mexicanas. Universidad Autonoma Metropolitana, Iztapalapa. División de Ciencias Biológicas y de la Salud. México, D.F., p. 7–15.

De la Lanza, E.G. and F.V. Arenas. 1986. Disponibilidad de nutrimentos a partir de materia orgánica en un sistema lagunar. Ciencia 37:247–254.

De la Lanza, E.G. and R.M. Cantú. 1986. Cuantificación de clorofilas y aplicación del índice de diversidad de pigmentos (D430/D665) para estimar el estado biótico de la laguna de Pueblo Viejo, Ver. Universidad y Ciencia 3 (5): 31–43.

Føyn, E. 1967. Waste disposal and pollution in coastal lagoon. In: Memorias Simposio Internacional de Lagunas Costeras. UNAM-UNESCO México D.F., p 281–290.

García, E. 1973. Modificaciones al sistema de clasificación de climática de Köppen. Instituto de Geografía. Universidad Nacional Autónoma de México. México, 522 p.

Gómez, A.S. 1974. Reconocimientos estacionales de hidrobiología y plancton en la laguna de términos, Campeche, México. (1964–1965) Anales del Centro de Ciencias del Mar y Limnología. Universidad Nacional Autónoma de México 1(1):61–82.

Groen, P. 1969. Physical hydrology of coastal lagoons. In: A. Ayala-Castañares and F.B. Phleger, eds. Lagunas Costeras, un Simposio. Memoria del Simposio Internacional Lagunas Costeras. Universidad Nacional Autónoma de México-UNESCO México D.F., 28–30 Nov 1967, p 275–280.

Herrera-Silveira, J.A. and F.A. Comin. 1995. Nutrient fluxes in a tropical coastal lagoon. Ophelia 42:127–146.

Kennish M.J. 1986. Ecology of Estuaries. Vol. 1, Physical and Chemical Aspects. CRC Press; Boca Raton, FL, USA, 254 p.

Lankford, R.R. 1977. Coastal lagoons of Mexico, their origin and classification. In: M.L. Wiley, ed. Estuarine Processes. Academic Press, New York. Vol. 2, p. 182–215.

Li, M., A. Gargett, and K. Denman. 2000. What determines seasonal and interannual variability of phytoplankton and zooplankton in strongly estuarine systems? Application to the semi-enclosed estuary of Strait of Georgia and Juan de Fuca Strait. Estuarine, Coastal and Shelf Science 50:467-488.

Lozano, M.H.M 1993. Comparación hidrológica entre la laguna de Alvarado, Veracruz y Términos, Campeche durante el ciclo anual de 1987. Tesis profesional. Facultad de Ciencias. Universidad Nacional Autónoma de México.

Margalef, R. 1970. Comunidades planctónicas en lagunas litorales. In: A. Ayala-Castañares and F.B. Phleger, eds. Lagunas Costeras un Simposio. Memorias del Simposio Internacional en Lagunas Costeras. Universidad Nacional Autónoma de México-UNESCO México D.F., 28–30 Nov 1967, p 275–280 .

McLusky, D.B. 1981. The Estuarine Ecosystem. Blackie Glasgo, Scotland, 150 p.

Mee, J.D. 1978. Coastal lagoons. In: J.P. Riley and R. Chester, eds. Chemical Oceanography. 2nd ed. Academic Press. New York, NY, USA, p. 441–490.

Morán-Silva, A.,.J. Franco-López, R. Chávez-López, A.T. Altamirano, and M.A.De Sucre. 1996. Aspectos generales del comportamiento hidrológico del Sistema Lagunar de Alvarado, Veracruz, México. Revista de Zoología, Numero Especial 2:1–16.

Revilla, M., A. Iriarte, I. Madariaga, and E. Orire. 2000. Bacterial and phytoplankton dynamics along a trophic gradient in a shallow temperate estuary. Estuarine, Coastal and Shelf Science 50:297–313.

Sevilla, M.L. and A.B. Chee. 1974. Contribución al conocimiento hidrográfico de la laguna de Alvarado, Veracruz, México. Memorias del V Congreso Nacional de Oceanografía:612–634.

Smith, N.P. 2001. Seasonal-scale transport patterns in a multi-inlet coastal lagoon. Estuarine, Coastal, and Shelf Science 52:15–28.

Snedaker, S.C. and M.S. Brown. 1980. Primary productivity of mangroves. In: O.R. Zaborsky, ed. CRC Handbook on Biosolar Resources, Volume 1. CRC Press, Boca Raton, FL, USA, p. 477–485.

Villalobos, F.A., C.J. Suárez, G. De la Lanza, F.M. Aceves, and J. Cabrera. 1966. Considerations on the hydrography and productivity of Alvarado Lagoon, Veracruz, México. Proceedings of the Gulf and Caribean Fisheries Institute 19:75–85.

Villalobos, F.A, S. Gómez, V. Arenas, J. Cabrera, G. De la Lanza, and F. Manrique. 1975. Estudios hidrobiologicos en la Laguna de Alvarado (Febrero–Agosto 1966) Anales del Instituto de Biologia. Universidad Nacional Autonoma de Mexico. Serie Zoología (1):1–34.