Water Quality Effects on Fish Larvae in a Tropical Coastal Lagoon of the Gulf of Mexico

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Abstract

Human settlements and industrial activities located along rivers and coastal lagoon margins have led to the discharge of untreated waste effluents into proximate waters, a situation that has affected the biota, fisheries and man himself. Many examples of this phenomenon exist throughout the world, including along the coast of Mexico. This study analyzed the physicochemical water quality parameters of a coastal lagoon in the northwest Gulf of Mexico during four sampling seasons in 2009 and 2010 that included dry, rainy and north-wind seasons; results were compared to conditions of the lagoon in 1983. Anthropogenic discharges along rivers and lagoons in the study area were correlated with slight increases in ammonium, total nitrogen and phosphorus starting 30 years ago, with concentrations remaining stable during this time period. Intermittent decreases in these nutrients occurred during heavy rains. Residence time of these nutrients varied from 19–40 days and depended on the depth of the lagoon. Results suggest that water quality does not differ greatly between historic and present times, suggesting that these fluvial-lagoon systems do not currently require environmental management. However, controlling urban discharge, as the human population increases will be necessary to minimize the impact of anthropogenic discharges. Fish larvae were only affected by the variation of temperature and salinity of the lagoon water.

Keywords

Tropical costal lagoon · Water-quality behavior · Estuarine physicochemistry · Fish larvae · Gulf of Mexico

2.1 Introduction

Wetlands and the environmental services they provide have attracted humans and their activities, which has resulted in environmental runoff and unintended nutrient inputs. It is for these reasons that many ancient ethnic groups settled along the margins of both inland water bodies like lakes and rivers, and coastal systems such as lagoons, estuaries, salt marshes and bays. Monitoring water quality in coastal wetlands, including riverine lagoon systems, is fundamental to discriminating between natural changes in physicochemical characteristics and those changes generated by human activities. This information can then be used to establish management recommendations and guide decision making, with conservation as the ultimate goal.

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Water quality monitoring programs in countries around the world have led Mexico to analyze basic parameters to determine the productivity and trophic state associated with phytoplankton in both inland and coastal waters. Aquatic environments provide food and refuge to a great variety of organisms as a result of both functional and biochemical traits. These organisms represent a greater and more diverse array of species than in terrestrial systems, as wetlands provide a greater number of habitats as well as a buffer against extreme climate variations (Sánchez-Santillán and de la Lanza-Espino 2012).

There are slightly more than 600 coastal water bodies in Mexico (Contreras Espinosa 2010). The chemical composition of the freshwater that flows into these water bodies is determined by the geochemical composition of the lands through which the rivers flow, and typically results in the high productivity of coastal eco-systems. However, agricultural activities occurring within these basins may increase nutrient concentrations to levels that could have profound impacts on the historic food web.

Laguna Tampamachoco, in the state of Veracruz, is a prime example of a coastal lagoon that has been impacted by anthropogenic modification and monitored through time. The lagoon has been studied since 1980 when the first physicochemical attributes were measured (Contreras-Espinosa 1983, 1985). Several years later an environmental impact study was conducted (CFE 1994). Calva and Torres-Alvarado (2000) evaluated the organic-matter content of three lagoons in Veracruz and recorded the greatest content of nitrogen in the sediments of Laguna Tampamachoco. Further, de la Lanza-Espino et al. (1996) completed a temporal and spatial analysis on the content of silicates in the lagoon. In 2009, as part of an interdisciplinary project, de la Lanza-Espino et al. (2012) carried out three surveys to determine the water quality of Laguna Tampamachoco by analyzing basic physicochemical parameters during one dry season (March 2009) and two rainy seasons (August 2009 and September 2010). The aim of the current study was to compare the changes in water quality of Laguna Tampamachoco since the original study in 1980; a period of more than 30 years. Notably, human population abundance has grown considerably along the margins of Laguna Tampamachoco and consequently, anthropogenic nutrient inputs to this coastal system have also increased.

2.2 Study Area

Laguna Tampamachoco is located north of the city of Veracruz at 20°18′-21°02′ N and 97°19′-97°22′ W. It has an area of 1,500 ha and its main source of freshwater is the Tuxpan River. The lagoon has an average depth of 0.6–0.8 m; the estuary inlet is about 3-m deep in March and 5-m deep in

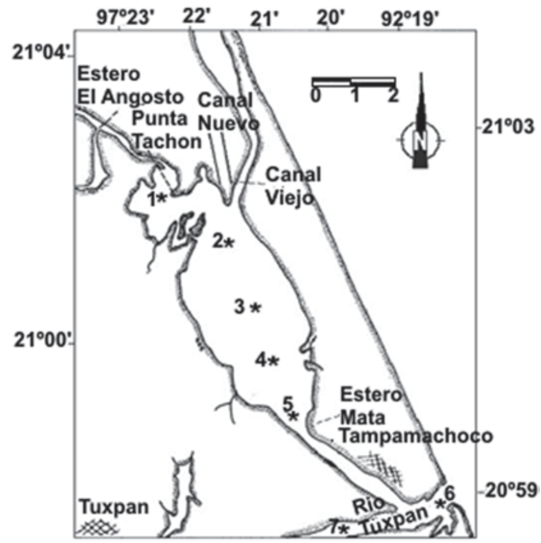

Fig. 2.1 Sampling stations in Laguna Tampamachoco, Veracruz

August, and the depth of the channel between the mouth of the Tuxpan River and the lagoon inlet varies from 6 to 20 m wide. Tide height varies throughout the year with ±0.54 m in March and ±1.09 m in December (CFE 1994). The climate is sub-humid and warm and summer rains are typical (García 1988). Mean annual rainfall totals about 1,900 mm; the driest month is January and the rainiest month is September. The average annual temperature is 25 °C. The lagoon contains several vegetated islands that are populated by *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove) and patches of *Conocarpus erectus* (button mangrove).

2.3 Materials and Methods

Sampling took place in the morning between 1,000 and 1,100 h during the dry (March) and rainy (August) seasons of 2009, and in the rainy season of 2010 (September). Surface and bottom water samples were collected from seven stations covering the lagoon, the estuary and the river mouth-lagoon inlet (Fig. 2.1). The following parameters were recorded in situ: temperature (°C), depth (m), salinity (psu), dissolved oxygen concentration (mg/L), dissolved oxygen saturation (%), and pH using a YSI 556 MPS sensor. The samples were frozen and later analyzed in the laboratory for concentrations of nitrates, nitrites, ammonium, total nitrogen, orthophosphates and total phosphorus according to Strickland and Parsons (1972). Samples were also analyzed to measure Chemical Oxygen Demand (COD; APHA 2005). To determine nitrogen balance, the Land Ocean Interactions in the Coastal Zone (LOICZ) methods were used and included inputs and outputs between terrestrial and marine materials, as well as Ecological Net Metabolism (MNE).

2.4 Results and Discussion

2.4.1 Temperature

Water temperature in tropical coastal lagoons varies throughout the day between approximately 18 and 32 °C, depending on the season and the geographic location. Sampling in Laguna Tampamachoco took place only during the day therefore the temperature range was small. In March 2009, water temperature varied from 25.94 to 27.63 °C at the surface and 24.40 to 27.41 °C at the bottom. In August 2009 the temperature varied from 26.10 to 29.79 °C at the surface and slightly less at the bottom at most of the stations. However, a difference in temperature between the surface and the bottom of 4.36 °C and 4.32 °C was recorded at stations 6 and 7, respectively. This temperature difference was likely due to stratification of the relatively cool and dense freshwater entering from the Tuxpan River and the warm and less-dense sea water entering with the tide. In September 2010, the temperature difference between the surface and bottom layers was small (< 1 °C) at stations 1, 2, and 3. Only surface temperatures were recorded at stations 4, 5 and 6 in September 2010; strong bottom currents inhibited bottom temperature measurements. In March, surface temperatures were slightly lower than those recorded in August. Contreras-Espinosa (1983) in a monthly study carried out in 1979, recorded a wide range of temperatures with a minimum in February (19–23 °C) and a maximum in May (31–32 °C), which included sampling areas in both the estuary and the lagoon. However, an unpublished study carried out in 1985 by CFE (1994) recorded the warmest month in September with a maximum of 33.5 °C and the coldest in February with a minimum of 17 °C, which coincided with the 1979 study. The maximum surface water temperature recorded in the present study was 29.79 °C in August during the rainy season. The temperature difference between the current study and the 1979 study may be an effect of interannual variability or due to the presence of strong meteorological events like the occurrence of La Niña in 2010, which generated low temperatures (NOAA 2013).

2.4.2 Salinity

In the March sampling period, salinity varied between 23.49 and 36.24 psu at the surface and between 32.30 and 36.26 psu at the bottom. This distribution was due to the gradient between the freshwater and seawater inputs resulting in a salt wedge at stations 6 and 7 and a weak salt wedge at stations 4 and 5 (Figs. 2.1 and 2.2). The highest salinities were recorded in the lagoon as a result of high evaporation and shallow depth. In August, and in spite of the rainy season, surface salinity at stations 1–5 was high with values of

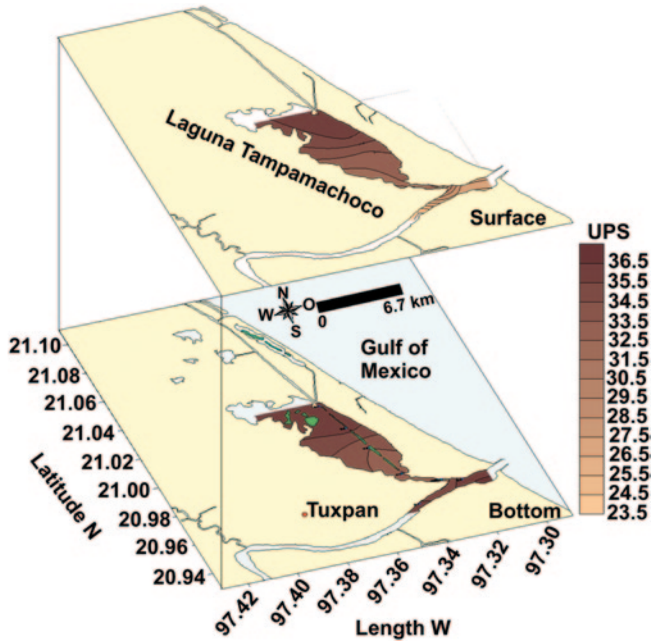

Fig. 2.2 Salinity distribution in Laguna Tampamachoco, Veracruz in March 2009

37.34–37.42 psu and bottom salinity was similar with values of 32.7 to 37.6 psu. In contrast, the estuarine stations (6 and 7) registered salinity values of 28.4 psu at the surface and 32.01 psu at the bottom and 16.80 at the surface and 25.82 psu at the bottom, respectively, in response to the salt wedge located between the river mouth and the lagoon inlet. In September 2010, salinity decreased more than 50 % at all the stations, particularly at the river mouth and the lagoon inlet where the surface water was oligohaline and the bottom water was mesohaline (Fig. 2.3). This marked decrease was in response to heavy rains associated with the presence of a medium to strong La Niña event in 2010. Contreras-Espinosa (1983) recorded similar salinity values more than 30 years ago.

2.4.3 Dissolved Oxygen

The concentration of dissolved oxygen in water varies on a diel cycle due to photosynthetic respiration by primary producers and can be modified by human activities. Dredging and canal construction increase the amount of suspended sediment and organic matter within the water column, which can cause low oxygen levels due to decomposition. Runoff from urban settlements along the margins of lagoons and estuaries, inland agricultural areas, and port activities also increase sediment, organic matter, and nutrients that can cause varying dissolved oxygen. Acceptable oxygen levels were recorded during all three survey periods during the present study, except for sporadic cases in August 2009 when near-

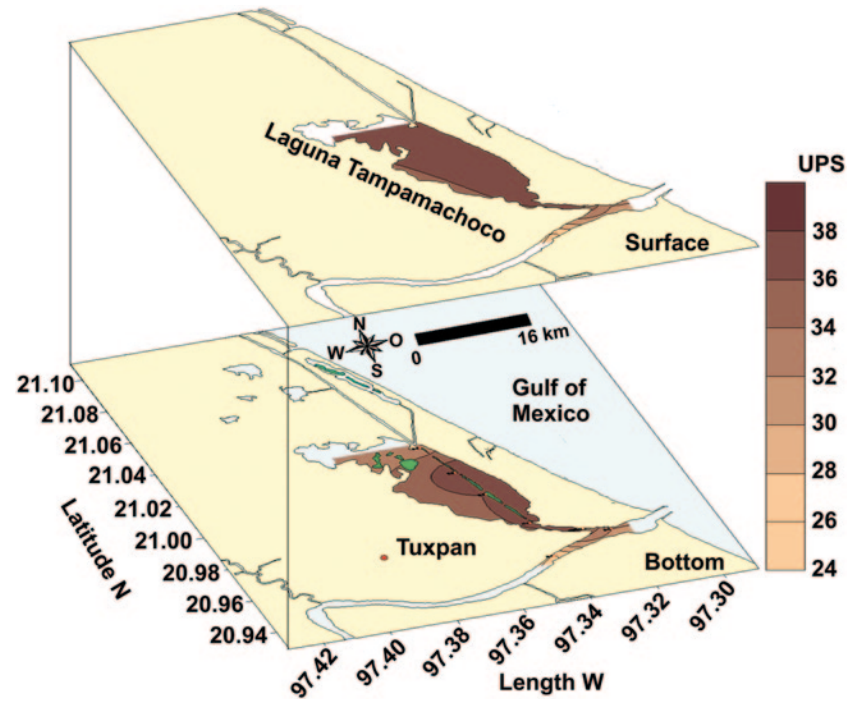

Fig. 2.3 Salinity distribution in Laguna Tampamachoco, Veracruz in August 2009

hypoxic conditions were recorded both in the lagoon and the estuary, and in bottom waters where there was possibly a predominance of organic-matter decomposition (Table 2.1). Despite these sporadic low dissolved oxygen levels, oxygen saturations were acceptable for the survival of benthic organisms. Supersaturation (> 100 %) of dissolved oxygen also occurred due to high photosynthetic activity in some survey periods and water-column locations (Table 2.1).

It is important to mention that lower dissolved oxygen concentrations in August and September in the bottom water coincided with the low-salinity river stations. This may be due to a low tide (see tide prediction table in González 2009) occurring simultaneously with high organic-matter discharge coming from the port and the urban settlements along the river margin. de la Lanza-Espino et al. (1996) characterized this phenomenon both temporally (in dry, rainy and north-wind seasons) and spatially (based on the content of silicates) and defined three characteristic areas within the Tampamachoco lagoon-marine ecosystem with correspondence to a gradient of dissolved oxygen concentrations from high to low: the estuarine-marine, the lagoon proper and the inner region of the lagoon. This distribution of dissolved oxygen is similar to the values recorded in the present study. Contreras-Espinosa (1983) also recorded hypoxic conditions in various seasons in Laguna Tampamachoco, as did the CFE (1994) in its environmental impact study. CFE (1994) documented low concentrations of dissolved oxygen at the lagoon inlet and the river in the same season. These results demonstrate that hypoxia has been a characteristic of this coastal system for more than 30 years, and varies depending on the hydrodynamics, geomorphology, depth, season, and urban activities.

2.4.4 pH

The pH varied from neutral to alkaline among the three sampling periods as a result of the input of river (September) and marine (March and August) waters (Table 2.1). These conditions are normal in coastal riverine-lagoon systems during daylight when photosynthesis is greatest as a result of CO_2 assimilation.

2.4.5 Total Nitrogen, Ammonium, Nitrites and Nitrates

Both nitrates and nitrites were low in the three sampling periods and ammonium varied. Nitrates and nitrites varied from 0–0.7 µM with a slight predominance of nitrites. These low concentrations were similar to values recorded in 1979 by Contreras-Espinosa (1983). High values of ammonium were recorded in March 2009 (12.14–15.71 µM) and September 2010 (20.00–25.71 µM). The approximate 60 % increase in ammonium from March to September was likely caused by increased runoff during the rainy season in September (Fig. 2.4). Contreras-Espinosa (1983) sampled ammonium throughout the year and recorded maximum values in May (at the start of the rainy season) with 52 µM, which corroborate values recorded in the present study during the rainy season. In August 2009, the concentration of ammonium was markedly low throughout the system and varied from 0 to 2.86 µM; this nutrient was particularly low in the Rio Tuxpan. This difference in ammonium could be to normal interannual variability in river discharge (Fig. 2.4).

Table 2.1 Descriptive statistics of physicochemical parameters of the Laguna Tampamachoco, Veracruz, Mexico in March and August 2009 and September 2010

Parameter	Statistic	March 2009		August 2009		September 2010	
		Surface	Bottom	Surface	Bottom	Surface	Bottom
Temperature °C	Max	27.63	27.41	29.79	29.14	27.96	27.42
	Min	25.94	24.4	26.10	23.26	25.45	25.99
	Mean	26.83	25.98	27.74	26.00	26.67	26.61
	SD	0.61	1.19	1.28	1.80	0.86	0.60
Salinity (psu)	Max	36.24	36.55	37.43	37.60	27.39	19.79
	Min	23.49	32.76	16.80	25.84	3.40	1.77
	Mean	31.66	34.83	33.49	34.12	16.14	10.65
	SD	4.32	1.66	7.41	4.31	8.55	7.40
Dissolved Oxygen (mg/L)	Max	10.48	7.90	9.65	6.12	7.58	6.53
	Min	3.38	3.10	5.08	3.15	3.63	5.69
	Mean	6.03	5.28	7.35	4.18	5.63	6.01
	SD	2.34	1.86	1.61	1.27	1.35	0.41
Oxygen Saturation (%)	Max	150.30	119.90	140.40	88.80	100.00	93.50
	Min	51.10	47.60	81.90	43.80	53.60	72.60
	Mean	88.98	77.43	111.67	60.14	75.15	80.20
	SD	31.88	24.43	20.76	20.02	15.64	9.64
Ammonium (µM)	Max	15.71	15.71	11.43	4.29	23.57	35.00
	Min	12.14	12.14	1.43	0.71	19.29	20.00
	Mean	14.02	14.59	3.37	1.94	21.7	25.00
	SD	1.07	1.22	3.60	1.29	1.61	4.77
Total Nitrogen (µM)	Max	37.86	35.71	22.86	11.43	38.57	38.57
	Min	16.43	19.29	5.00	7.14	30.00	30.00
	Mean	26.79	27.24	10.09	8.76	33.93	33.87
	SD	7.35	5.90	5.39	1.58	3.10	3.00
Orthophos-phates (µM)	Max	1.61	2.58	3.55	3.23	6.77	4.19
	Min	0.65	0.97	0.32	0.00	0.65	0.97
	Mean	1.13	1.57	1.74	1.24	2.58	2.39
	SD	0.30	0.54	0.91	1.48	2.02	1.42
Total Phosphorus (µM)	Max	6.13	5.48	6.77	7.74	28.06	24.84
	Min	2.58	2.58	3.23	3.23	9.35	4.19
	Mean	3.63	3.46	4.68	4.80	14.67	13.54
	SD	1.39	1.00	1.10	1.97	7.43	8.45
Chemical Oxygen Demand (mg/L)	Max	2.99	2.99	5.98	5.98	7.62	5.71
	Min	1.63	1.63	5.44	5.44	4.08	3.54
	Mean	2.24	2.25	5.51	5.18	5.31	4.39
	SD	0.65	0.70	0.19	0.20	1.31	0.77

Total nitrogen was highest in September 2010 (range 30.00–38.57 µM) and coincided with the rainy season and the period of maximum runoff. The estuarine sampling areas (stations 6 and 7) and those located at the pier and near the shoreline villages (station 5) were especially high in total nitrogen due to human-waste discharge. Values of total nitrogen were also high in March 2009, although unevenly distributed as evidenced by the large standard deviations (Table 2.1). These concentrations are uncommon in Mexican coastal lagoons and may be relatively high due to the decomposition of organic matter from urban runoff, decomposition of dead organisms and their excreta, suspension of sediments generated by continuous boat traffic, and ammonium inputs from other anthropogenic sources (Campos-Villegas 1996). The high content of ammonium recorded in September 2010 was associated also with the high concentration of total nitrogen due to generation of ammonium from the decomposition of organic matter (i.e., ammonification). Considering data from Contreras-Espinosa (1983), the concentration of ammonium has been high for more than 30 years, with values about 60 % greater in September 2010 in the current study.

Despite the low concentration of nitrates and nitrites and the high concentration of ammonium, a nutrient that is assimilated in photosynthesis by some phytoplanktonic species, the Margalef Index of community diversity for most of the stations studied by Sánchez-Santillán in 1989 (unpublished data)

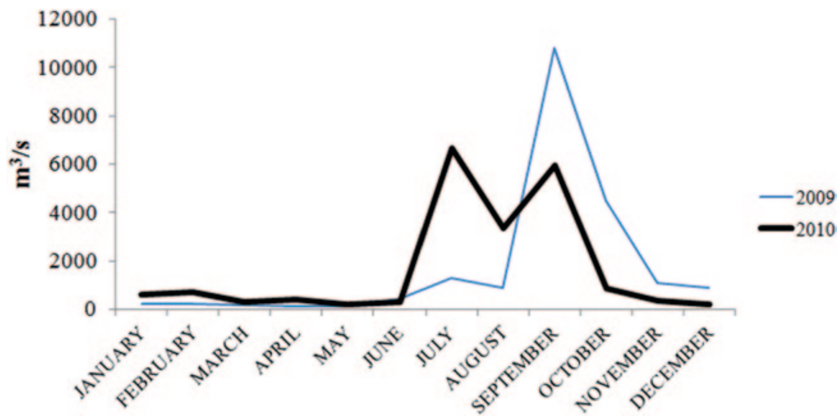

Fig. 2.4 Rio Tuxpan flow in two different years

Table 2.2 Land Ocean Interactions in the Coastal Zone (LOICZ) balance of inorganic nitrogen of Laguna Tampamachoco, Mexico. Acronym abbreviations are: dissolved inorganic nitrogen balance (ΔNID), dissolved inorganic phosphorus balance (ΔPID), and ecological net metabolism (MNE)

ΔNID (mmol/m²day)	ΔPID (mmol/m²day)	MNE	Balance of N
0.11	0.03	−2.9	−0.330
−0.07	−0.02	2.3	0.280
0.24	0.02	−1.6	−0.003

indicated a condition of generalized succession of Laguna Tampamochoco with values from 3 to >5.1. In this trophic state, fast-growing species dominate more static species, which may result in a bloom (high reproductive rate) of the dominant primary producers. The high abundance of primary producers will then die, causing an increase in the organic nitrogen load, which was observed in the current study. Margalef (1975) calculated trophic values of 3.4–5.5 in Laguna de Alvarado (located approximately 1,500 km to the south on the Gulf of Mexico coast), indicating a relatively active phytoplankton community with scarce chlorophyll. Similarly, the physicochemical characteristics and high trophic level of Laguna Tampamachoco are likely related.

2.4.6 Orthophosphates and Total Phosphorus

The orthophosphate content recorded during the three survey periods was within the normal range of values for non-impacted lagoons in Mexico (de la Lanza-Espino 1994). For example, values in September 2010 at the river mouth (station 6; 2.58 µM at the surface and 0.97 µM at the bottom) and in the lagoon near the pier (station 4; 0.97 µM at the surface and 3.87 µM at the bottom) were similar to de la Lanza-Espino (1994). However, the concentration of total phosphorus was high at station 4 (9.35 µM at the surface and 15.48 µM at the bottom) and station 6 (28.06 µM at the surface and 28.84 µM at the bottom) and is indicative of eutrophication. High total phosphorous concentrations are likely due to inputs by the urban settlements, high river discharge and a consequent suspension of sediments due to the rainy

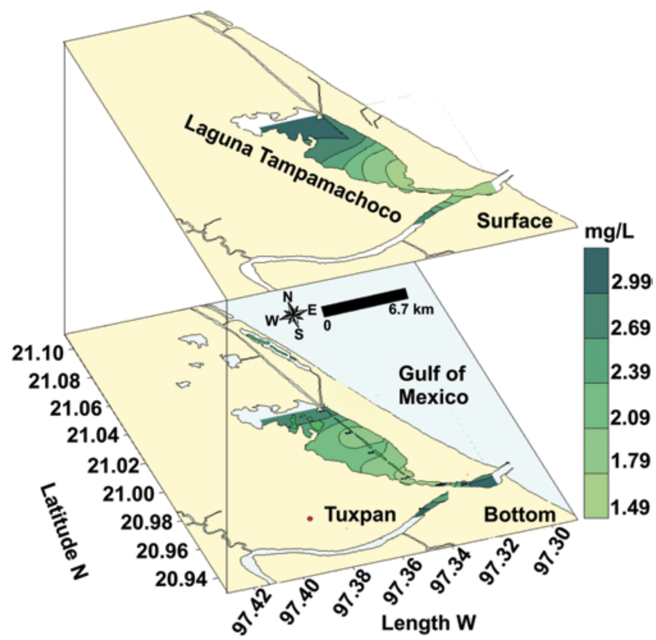

Fig. 2.5 COD distribution in Laguna Tampamachoco, Veracruz in March 2009

season, and the movement of small and large vessels. Total phosphorus in March 2009 and August 2009 was about 20% lower than September 2010, with levels considered normal for this coastal system (de la Lanza-Espino 1994) (Table 2.1).

In relation to LOICZ nitrogen balance, the Laguna Tampamachoco showed similar export-import processes (Table 2.2) as other coastal lagoons in Mexico (e.g., Laguna El Yucateco in the southern Gulf of Mexico), a process that

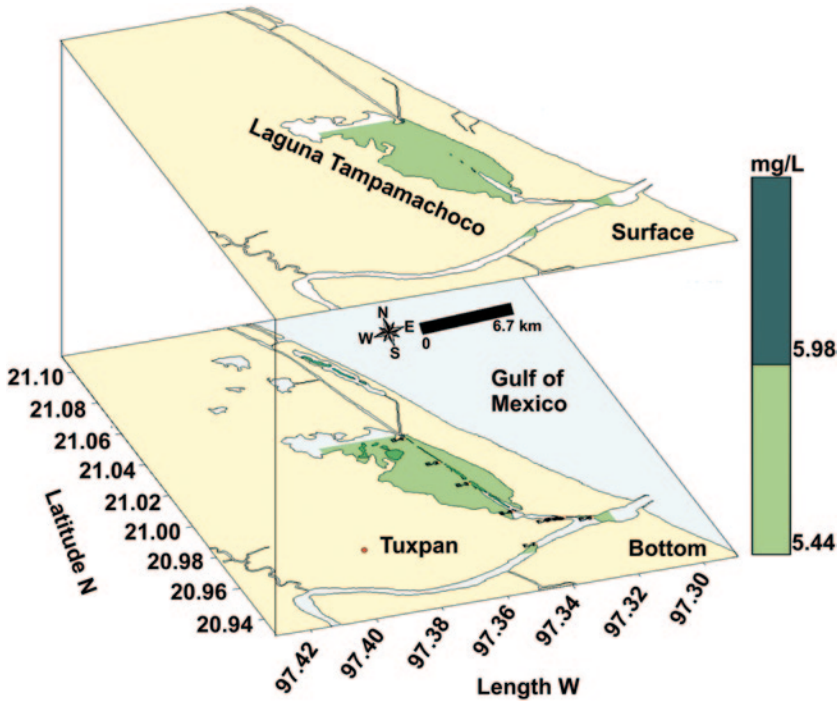

Fig. 2.6 COD distribution in Laguna Tampamachoco, Veracruz in August 2009

depends on tide, meteorological effects, circulation dynamics, differential runoff, and human activities. The Ecological Net Metabolism (MNE) was a state of heterotrophy.

2.4.7 Chemical Oxygen Demand (COD)

In March 2009, COD values varied from 2.99 to 1.63 mg/L of O_2 indicating low concentrations of organic matter and a rapid and efficient remineralization, (Table 2.2, Fig. 2.5). In August, COD was homogeneous and approximately twice the value recorded in March, with no high values and/or an efficient decomposition that used the excess oversaturated dissolved oxygen. Low COD concentrations were recorded at only a few stations and at the bottom of the water column (Fig. 2.6).

2.4.8 Ichthyoplankton

The high concentration of ammonium, total nitrogen and total phosphorus that has caused eutrophication of Laguna Tampamachoco over the past few decades has likely not affected the fish larvae. Adult fishes that are found in Laguna Tampamachoco spawn at sea; eggs and larvae then enter the lagoon during the tidal cycles (Román-Hernández et al. 2006). Ocaña-Luna and Sanchez-Ramirez (2000) estimated the effect of temperature and salinity on the spatial and temporal variation of ichthyoplankton in Laguna Tampamachoco. Fish larvae were relatively abundant at night and were likely feeding during a period of low predation probability; larvae concentration varied from 54 to 307 org/100 m^3 in spring and summer, respectively. In November 1987 and August 1988, fish larvae densities varied between 100 and 153 larvae/100 m^3, respectively, and up to 188 larvae/100 m^3 were recorded in February of 1988 (Ocaña-Luna and Sanchez-Ramirez 2000). The fish larvae densities are within the range recorded by Flores-Coto et al. (1986). Román-Hernández et al. (2006) quantified a maximum average abundance of 1308 larvae/100m^3 in December 2003 and a low abundance of 192 larvae/100 m^3 in April 2004; abundance increased in May to 639 larvae/100 m^3. Based on the current and previous studies, larval densities were likely associated with variations in temperature and salinity. This suggests that the water quality of Laguna Tampamachoco since 1979 has likely not affected ichthyoplankton density. Additionally, Ponce et al. (in press) recently found no contamination of heavy metals and hydrocarbons in oysters and sediments of Laguna Tampamachoco

2.5 Conclusions

Laguna Tampamachoco has three distinct morphologic regions: the estuarine area where the river discharges near the lagoon inlet, the lagoon area proper and the more inner and shallow lagoon area with a complex bathymetry. Since the study by Contreras-Espinosa (1983), several studies have documented seasonal hypoxia in the lower part of the water column and high levels of ammonium in some areas of this riverine-lagoon system. However, total nitrogen content has decreased more than 50 % from the Contreras-Espinosa (1983) study to the present study, particularly in the rainy season. Therefore, year to year variability in physicochemical or water quality must be considered, including meteorological events of different magnitude and influences such as La Niña. Also, increases in the human population established along the margins of the lagoon and agricultural activities along the river basin should be considered for their pollutant discharges. However, the data for the physicochemical variables presented here and referenced in other studies have remained within the same range since Contreras-Espinosa (1983). It was observed that the tide might reduce the effect of the anthropogenic sewage coming from the settlements along the margins, from the agricultural activities in the river basin, and of the discharges from the port into areas near the confluence of the lagoon, river, and ocean. The low water residence times of 19 days from the river mouth to the estuarine-lagoon area, 40 days for the main body of the lagoon and 50 days for the whole system including its inner shallow areas, have helped to prevent an increase in the concentrations of ammonium contributed by the adjacent populated areas since Contreras-Espinosa (1983). The low oxygen concentrations at the bottom of the water column are likely compensated by significant photosynthetic activity from an active phytoplankton community. Based on the LOICZ model, nutrients are both exported to and imported from the sea, and the Ecological Net Metabolism (MNE) of Laguna Tampamachoco was calculated to be in a heterotrophic state.

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