COASTAL EUTROPHICATION IN THE YUCATÁN PENINSULA

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INTRODUCTION

It is well known that countries that are unable to plan their economic development in line with the conservation of natural resources and their management may not be able to maintain any kind of progress in the areas of health, food, housing, energy and other critical needs. Taking this into consideration Mexico faces a major challenge as a result of its wealth in natural resources, and the economic and social needs of its inhabitants. Therefore, it is imperative to develop a compatible economic, social and environmental strategy with the goal of achieving a better standard of living for the human population. Under this premise the researchers and experts in management have to face complex options for the study, use and administration of natural resources in the terrestrial and aquatic ecosystems of the country.

The coastal zone, which can be described as the area where marine, atmospheric, fluvial, subterranean and anthropomorphic processes interact, stands out among the systems that compose terrestrial and aquatic environments. These processes not only provide scenic variety, but are also responsible for high diversity and biological productivity, turning the coastal zone into an attractive location for new human settlements and development of economic activities.

Mexico is among the countries whose proportion of terrestrial and maritime territory is clearly inclined towards the sea, offering a series of opportunities for development. These impose a series of challenges in the sense that uses of marine resources have to be done in an environmentally friendly manner. Unfortunately this has not happened and there are cases of severe damage to fisheries, beaches, estuaries, coastal lagoons, mangroves and wildlife, among other resources (Merino *et al.* 1992; Rivera-Arriaga and Villalobos 2001; Euan-Avila and Witter 2002).

This tendency for environmental deterioration is not exclusive to Mexico. The country is making efforts to reverse it by using general concepts of integrated management of the coastal zone, with focus on its long term development. A series of tools is in use to obtain, analyze and integrate economic, social and environmental information, in order to establish guidelines that direct the sustainable development of the Mexican coast (Fig. 28.1).

Adopted development strategies must contemplate measures to monitor the consequences of human activity on the coastal environment, which will allow the establishment of programs to mitigate or reverse the cause of identified problems. Indicators have to be selected to provide information not only on the consequences, but the origin of the problems, thus guiding activities leading to sustainability of a resource and/or ecosystem.

Among the characteristics and indicators that have proven useful with this purpose are those related to the eutrophication of coastal aquatic ecosystems in other countries, both developed and developing. This has been identified as one of the main problems, having received the largest amount of economic resources, not only to understand, but to mitigate and solve the problem (Urban *et al.* 1996).

The process of eutrophication consists of the increase in the production of organic matter as a result of the increased introduction of nutrients, mainly nitrogen and phosphorus. It is a

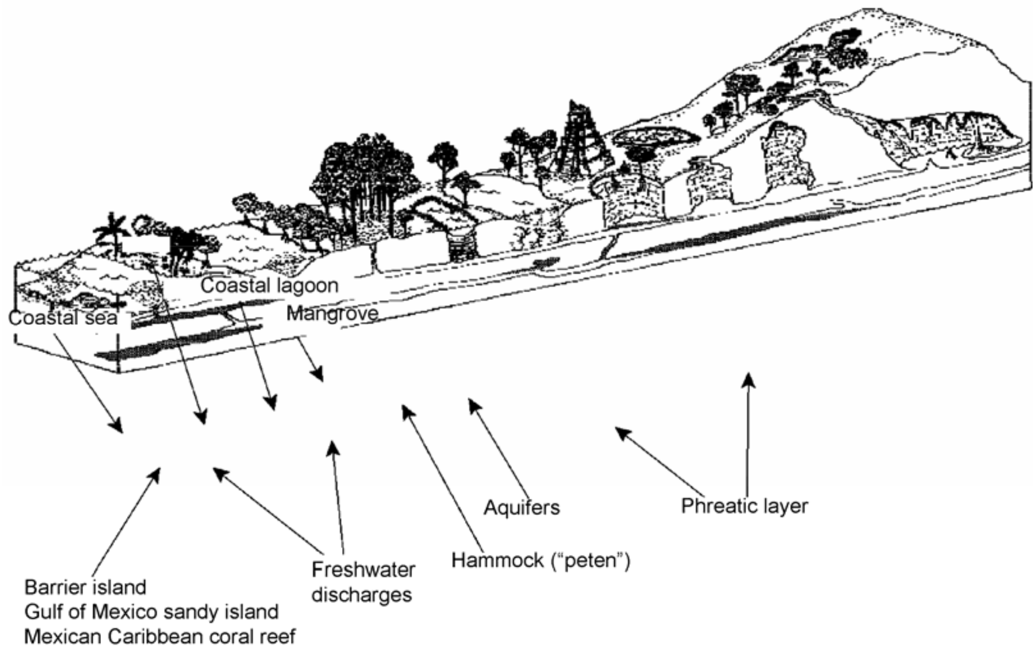


Fig. 28.1. Schematic diagram of a transversa section of the Yucatán Peninsula showing the main ecosystems, with emphasis on the coastal zone.

natural process that has been accelerated by human activity, and has been named cultural eutrophication. It is recognized by a larger accumulation of organic material in the form of algae.

Among the symptoms of the cultural eutrophication process that have been used as indicators of this problem are: concentration of chlorophyll-*a* (Chl-*a*) in the water column; frequency, spatial cover and toxicity of harmful algal blooms; decrease in seagrass cover; and decrease of the dissolved oxygen concentration in the water column, among others (Bianchi *et al.* 1999). The consequences of these symptoms include the loss of habitat with changes in biodiversity, impact on recreational and commercial fisheries, tourism, including human health, and on the ecosystems in general.

Although the process of eutrophication has been well documented for freshwater ecosystems for more than 20 years, it is still poorly understood for coastal environments, for which reason there are important research and monitoring programs on the coasts of the United States of America and the European Community. In both cases the process has been incorporated as an environmental diagnostic element for coastal ecosystems (Bricker *et al.* 1999; ICRAM 2000). This type of program and diagnosis is lacking in Mexico under a large-scale spatial context such as the Gulf of Mexico.

In order to evaluate the eutrophication problem and consider it as a diagnostic element which, through monitoring, will allow the assessment of the success of management strategies in coastal ecosystems of the Gulf of Mexico, it is necessary to develop scientific foundations that will ensure the sustainability of this large ecosystem. These foundations are based on the determination of spatial and temporal variability of eutrophication and the variables to which it is related.

In order to achieve this goal, the strategy has to begin with research to identify the indicators and the reference values of variables related to the trophic condition of coastal ecosystems, following a design of spatial and temporal variability at different scales. This will enable the elaboration of ad hoc monitoring programs to provide input for administrative decision-making for the management of natural resources in coastal ecosystems. However, due to the geological, climatic and geographic differences, among others, of coastal ecosystems, reference conditions are different among regions. Similarly, water bodies such as estuaries, marine coastal zones, bays and coastal lagoons often respond differently to nutrient inputs from different sources (rivers, runoff, groundwater discharges, among others). This means that the criteria have to be designed specifically for each type of water body and region.

Normatization regarding the risks of eutrophication to aquatic ecosystems and health is deficient in Mexico. This is due to the fact that norms applied to coastal ecosystems use reference values for aquatic life that are established based on the ecological criteria for water quality (CNA 2000). These criteria assume that all coastal water bodies (Pacific Coast, Caribbean Sea and Gulf of Mexico) are similar, since they do not establish a distinction among them. In addition, this same norm underestimates the eutrophication process as a problem, since it does not include variables or indicators of this process (Chl-*a*, water transparency, phytoplankton community, red tides, submerged aquatic vegetation), that are recognized as key for the diagnosis and monitoring of the problem (USEPA 1999).

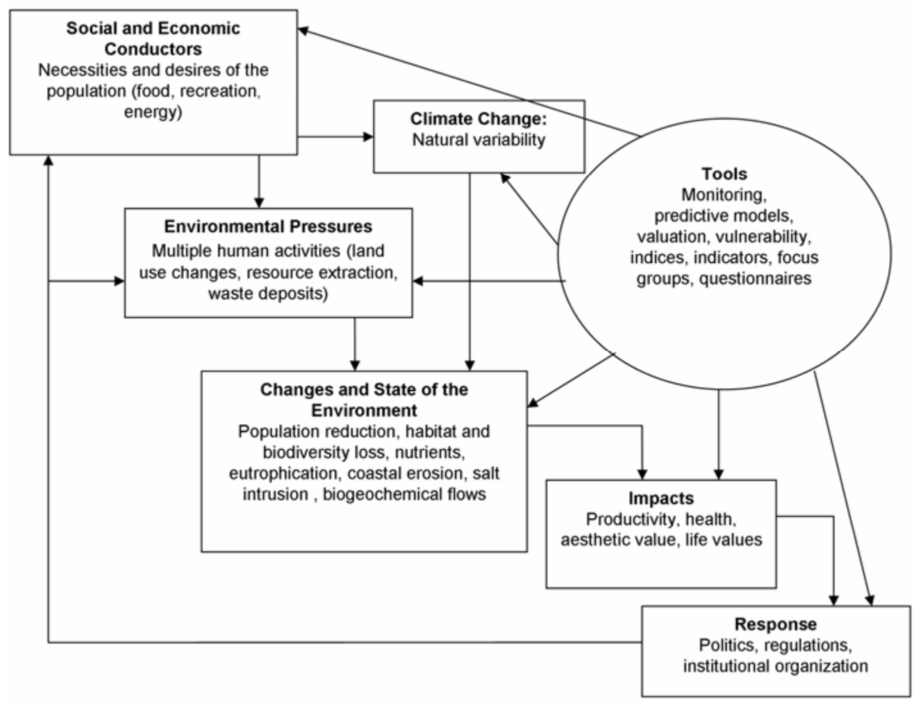
STUDY AREA

In the specific case of the Yucatán Peninsula the coastal environment is recognized as the most valuable natural resource, which emphasizes the need to identify indicators for the diagnosis and monitoring of the eutrophication process in its coastal ecosystems. This should include the type of soil (karstic), water discharges (groundwater and non point sources), dominance of farming activities, and the coastal development with predominance of tourism activities (Capurro *et al.* 2002).

It is important to point out that of the more than 4 million people that inhabit the Yucatán Peninsula, 90% live within 100 km from the coast. The birth rate (2.2%) is higher than the national average (1.7%). Immigration to the coast is high and its development is expected to receive official impulse through activities such as tourism, maritime transportation, port development, aquaculture and fisheries. Therefore, the population and human settlements will grow, leading to continued changes of land use and impacts on ecosystems such as mangroves, coastal lagoons, beaches, sand dunes, submerged vegetation and coral reefs. This will bring health problems, reduce the economic benefit, and lead to social unrest if coastal management strategies based on indicators and diagnostic tools that enable the identification of problems, followed by solutions, are not put into practice.

Among the environmental features that characterize the Yucatán Peninsula its hydrographic basin stands out due to its homogeneous topography, absence of rivers, and karstic soils. The latter favor rainwater infiltration into the aquifer, which is discharged into the coastal ecosystems through natural springs and non point sources (Fig. 28.2), which are estimated to have an input of 9-11 million/m^3/year/km of coastline.

This is particularly important since, as the water filters quickly and easily to the aquifer, so do all sorts of contaminants. Considering that the tourism industry, fisheries, salt production and urban activities are predominant in the area, it is easy to imagine that the main contaminants are organic (nitrogen and phosphorous). Considering that for more than 90% of these activities there are no wastewater treatment plants, and that for the other 10% the treatment plants are



Fig, 28.2. Conceptual model of interactions between components of the integrated management of the coastal zone.

deficient, it is no surprise that some symptoms and consequences of eutrophication are already observed in the coastal ecosystems of the Yucatán Peninsula, including frequent harmful algal blooms, decrease in seagrass cover, intoxication due to consumption of seafood, and even the closure of beaches to tourists (Reyes and Merino 1991; Merino *et al.* 1992; Herrera-Silveira *et al.* 2002b).

For this reason the Programa de Procesos y Manejo Costero (Coastal Processes and Management Program) of the Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional Unidad Mérida (CINVESTAV-IPN; Center for Advanced Studies and Research of the National Polytechnic Institute Merida Unit) began a research project to analyze the process of eutrophication in the coastal ecosystems of the Yucatán, with the objective of understanding the causes and consequences of the process in terms of water quality, and to develop indicators and monitoring programs according to the environmental problems of the area. These will enable the diagnosis of the present situation and the vulnerability of the different coastal ecosystems of the Yucatán Peninsula to the eutrophication process, as well as give support to water management policies and, therefore, to measure the success of conservation, rehabilitation/restoration or sanitation measures.

This study presents results concerning water quality diagnosis in the different coastal ecosystems of the Yucatán Peninsula using indicators of trophic condition. The chapter intends to identify the key variables and processes related to eutrophication, and provide technical support for the implementation of coastal water management policies.

METHODOLOGICAL APPROACH

The methodological approach has to consider a range of aspects, from the geohydrology of the area to the type and intensity of human activities on the coast. The study area includes coastal lagoons, bays and the marine coastal zone from Campeche to Chetumal, covering a broad spectrum of types and intensity of uses (Table 28.1, Fig. 28.3).

Collection activities in all locations included at least one annual cycle with monthly sampling. Data for some sites includes more than 10 years of monitoring. Samples were collected in at least 15 stations per site, covering areas ranging from 20 to 900 km^2. The sample collection employed conventional and non-conventional techniques and equipment, specifically the use of synoptic maps of hydrological variables known as "DataFlow IV" (Madden and Day 1992). The spatial heterogeneity of fresh water discharges to coastal ecosystems in this region of the Gulf of Mexico is difficult to establish, since it is predominantly from groundwater sources and, therefore, new technologies need to be employed.

Physical and chemical characteristics of the water (temperature, salinity, dissolved oxygen, nitrate, nitrite, ammonia, phosphate and silicate) were measured following the techniques and recommendations made by Parsons *et al*. (1984), phytoplankton community (Chl-*a*, composition and density by groups) where measured using techniques developed by Jeffrey *et al.* (1997), and seagrass and macro-algae cover were assessed according to Fourqurean *et al.* (2002). However, not all the variables were measured at all sites (Table 28.1), and much research remains to be done for the ad hoc implementation of monitoring programs.

For the analysis of the information on Chl-*a*, physical and chemical variables in the water column, data was grouped by site in the systems: lagoons/bays and coast, in the Gulf and the Caribbean Sea regions (Table 28.1, Fig. 28.3). This division relates to differences that were identified between the waters of these two large as well as between semi-closed and open ecosystems (Troccoli 2001; Herrera-Silveira *et al.* 2002a).

The analysis of the information consisted of determining the reference values and intervals of the Chl-*a*, physical and chemical variables in the water column by region. In order to do this, USEPA (2001a) recommendations were followed, which are based on the calculation of the median of the dataset; this takes into consideration the order of the data rather than its magnitude and, therefore, is not affected by extreme values. The upper and lower quartiles were calculated as a measure of variability, which in its turn establishes the lower and upper limits within which any data is considered normal.

In order to establish statistical differences among the variables analyzed by region, box plots were employed (Fig. 28.4). These plots evaluate the presence of differences among groups of medians of a dependent variable that is based on one factor: the regions. The horizontal line in each box corresponds to the median and next to it is the mean (symbolized by a cross). The upper and lower portions of each box represent the 25^{th} and 75^{th} percentiles (quartiles interval), whilst the extremes of the bars represent the 5^{th} and 95^{th} percentiles. The lateral notch on the boxes corresponds to 95% of the confidence interval of the median. Therefore, when the notches between two boxes do not overlap it is assumed that the medians are significantly different (Boyer *et al.* 1997).

The trophic condition of each type of ecosystem and region was obtained by integrating information on chemical, phytoplankton and submerged aquatic vegetation (SAV) variables from each location (Table 28.1), and applying the criteria and recommendations of diagnostic studies

Table 28.1. Locations on the Yucatán Peninsula where information was collected for physical, chemical and chlorophyll-*a* (V/P-C-CHL*a*) variables, as well as phytoplankton and/or submerged aquatic vegetation (V/Pt-SAV) communities.

Location	System and Region[a]	V/P-C-CLA	V/PT-SAV	Intensity of Use[b]			
				U	T	F	P
Campeche	GC	X		+	+	-	+
Celestún	LB/G	X	X	+/-	+/-	+	-
Laguna Celestún	LB/G	X	X	-	+/-	+	-
Sisal	GC	X	X	+/-	-	+/-	+/-
Progreso	GC	X	X	+	+	+	+
Laguna Chelem	LB/G	X	X	+	-	-	+
Dzilam	GC	X	X	+	-	+	+
Mouth of Dzilam	LB/G	X	X	-	-	-	-
Río Lagartos	LB/G	X		+/-	+/-	+	+/-
Holbox	LB/G	X		+/-	+/-	+	+/-
Cancún	CC	X	X	+	+	-	+
Nichupté/Bojórquez	LB/C	X		+	+	-	-
Isla Mujeres	CC	X	X	+	+	+/-	+
Playa del Carmen	CC	X		+	+	-	+
Bahía de la Ascensión	LB/C	X	X	-	-	+	-
Chetumal	LB/C	X		+	+/-	-	+/-

[a] Lagoons and Bays of the Gulf (LB/G), Lagoons and Bays of the Caribbean (LB/C), Gulf Coast (GC), Caribbean Coast (CC)
[b] Main uses: Urban (U), Tourism (T), Fisheries (F), Port (P). Use intensity: low (-), intermediate (+/-), high (+)

on the eutrophication state of estuaries in the USA (Bricker *et al.* 1999), and oligotrophic coastal waters (Karydis *et al.* 1983).

ANALYSIS

The median and interquartile values that represent the reference value and its natural variability for each type of ecosystem and region are presented in Table 28.2. The temperature was highest on the Caribbean Coast (CC) and lowest in the Gulf (GC), but it was more variable in the Lagoons and Bays of the Gulf (LB/G). Significant temperature differences can be observed among regions (Fig. 28.4a), with generally higher temperatures in the Caribbean.

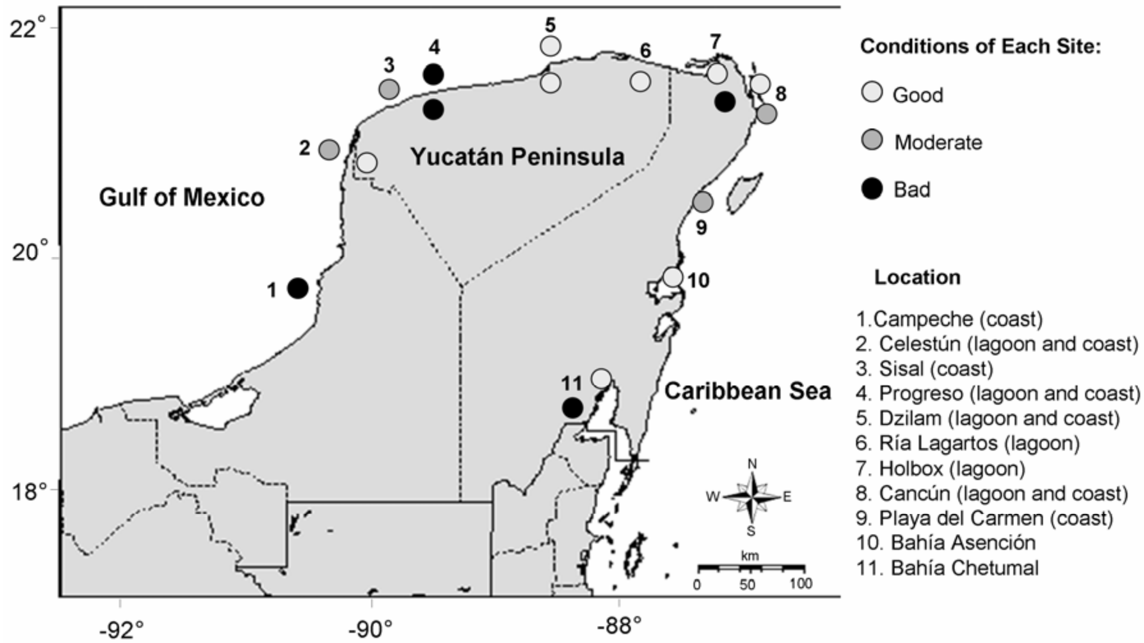


Fig. 28.3. Location of the sites selected for the diagnosis of the level of eutrophication in the ecosystems of the Yucatán Peninsula, based on chemical, phytoplankton and submerged aquatic vegetation variables.

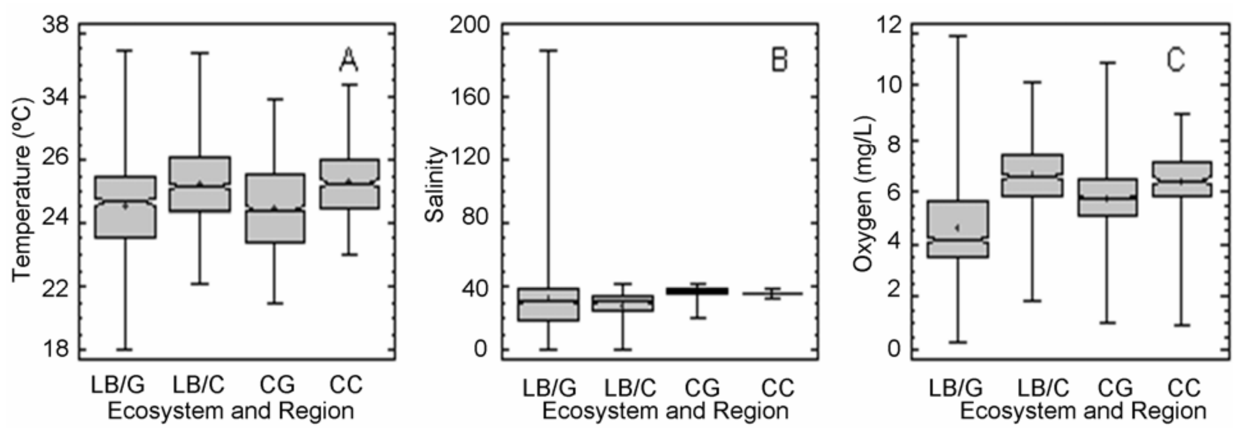


Fig. 28.4. Comparison of mean concentrations and variability of temperature, salinity and dissolved oxygen among types of ecosystems of regions from the Yucatán Peninsula. Lagoons and Bays of the Gulf (LB/G), Lagoons and Bays of the Caribbean (LB/C), Gulf Coast (GC), Caribbean Coast (CC).

Table 28.2. Reference values (median) and variability intervals (lower and upper quartile) of physical, chemical and chlorophyll-*a* variables in coastal regions of the Yucatán Peninsula.

Variable	**Region**[a]			
	LB/G	**LB/C**	**GC**	**CC**
Temperature (°C)	27.3	28.3	26.8	28.4
	25.0-29.0	26.7-35.1	24.8-29.1	26.8-29.9
Salinity (ppt)	30.6	30.3	36.9	34.9
	18.4-37.4	24.6-34.0	35.4-38.2	34.7-35.4
Dissolved Oxygen (mg/L)	4.4	6.5	5.7	6.4
	3.4-5.6	5.8-7.4	5.0-6.4	5.8-7.0
Nitrite (µmol/L)	0.39	0.47	0.57	0.21
	0.16-1.04	0.26-0.86	0.23-0.97	0.05-0.42
Nitrate (µmol/L)	2.6	1.8	2.8	1.9
	1.1-7.0	0.8-3.7	1.3-6.0	1.0-9.1
Ammonia (µmol/L)	4.7	3.7	3.7	2.4
	2.5-8.5	2.0-6.6	2.1-6.2	1.9-3.4
Phosphate (µmol/L)	0.5	0.7	0.4	0.6
	0.15-1.10	0.36-1.00	0.3-0.8	0.4-0.9
Silicate (µmol/L)	62	18.0	7.0	4.0
	23.0-118.0	10.0-35.0	4.0-12.0	3.0-8.0
Chlorophyll-*a* (µg/L)	3.8	0.59	2.3	0.35
	2.2-6.0	0.34-1.10	1.2-5.0	0.25-0.5

[a] Lagoons and Bays of the Gulf (LB/G), Lagoons and Bays of the Caribbean (LB/C), Gulf Coast (GC), Caribbean Coast (CC)

Salinity was highest in GC and lowest in LB/G, although the latter had greater variability for both high and low salinities. The CC ecosystems exhibited very low variability. Significant differences were observed between the Gulf and Caribbean ecosystems (Fig. 28.4b).

The highest dissolved oxygen reference values were observed in the Caribbean ecosystems and highest variability occurred in the LB/G systems. Significant differences in the median concentrations were seen between the Gulf and Caribbean systems (Fig. 28.4c).

In terms of nutrients, the nitrite concentration was highest in the GC region and lowest in the CC region, with higher variability in the ecosystems of the LB/G region. Significant differences were registered between CC and the other regions (Fig. 28.5a). The median

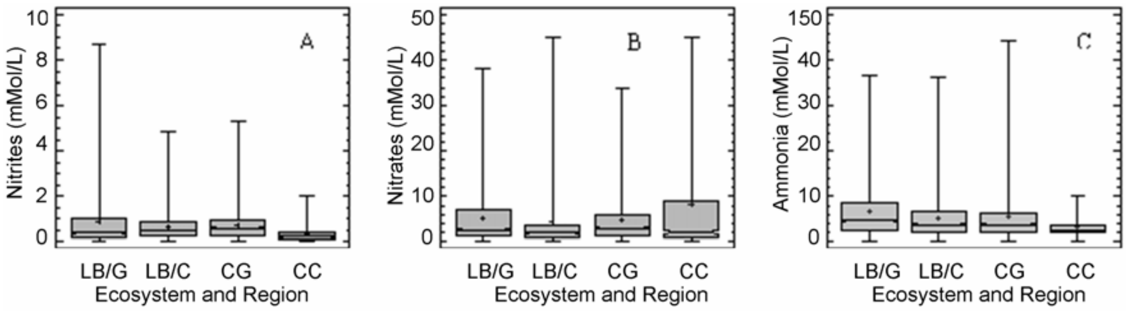


Figure 28.5. Comparison of mean concentrations and variability of nitrite, nitrate and ammonium among types of ecosystems of regions from the Yucatán Peninsula. Lagoons and Bays of the Gulf (LB/G), Lagoons and Bays of the Caribbean (LB/C), Gulf Coast (GC), Caribbean Coast (CC).

concentration of nitrate was highest in the CC region and lowest in the GC region, with greater variability in the Lagoons and Bays of the Caribbean (LB/C) ecosystems (Fig. 28.5b). The highest median concentration of ammonia was registered in the LB/G systems and the lowest in CC. The highest variability was in the GC region. Significant differences occurred between CC and the other types of ecosystems (Fig. 28.5c). Phosphate exhibited highest reference concentration and variability in the LB/C ecosystems, with significant differences between the Gulf and Caribbean regions (Fig. 28.6a). Lastly, the highest reference value and variability for silicates were registered in the LB/G systems, whilst the lowest occurred in CC. Significant differences were observed between the types of systems (lagoons/bays higher than the coast) (Fig. 28.6b).

The highest reference values of Chl-*a*, as well as the highest variability, were registered in the Gulf ecosystems. Significant differences in Chl-*a* concentrations occurred between the Gulf and Caribbean ecosystems (Fig. 28.6c).

The diagnosis of other eutrophication variables, such as phytoplankton and SAV, was concentrated in four locations of the northern Yucatán (Celestún, Sisal, Progreso and Dzilam), where these variables have been measured regularly during recent years.

In terms of phytoplankton, diatoms dominate the Celestún community, followed by dinoflagellates and cyanobacteria. Inter-annual changes are reflected in the increase of species of dinoflagellates and cyanobacteria (Fig. 28.7a). In Sisal the relative abundance is dominated by diatoms; however, inter-annual changes are observed, with increase in the numbers of dinoflagellates and chlorophytes (Fig. 28.7b). In Progreso the community is dominated by dinoflagellates, followed by diatoms, and significant inter-annual differences are not observed (Fig. 28.7c). In the case of Dzilam, the community is dominated by diatoms, followed by dinoflagellates; however, a larger number of phytoplankton groups is observed in this location, such as cyanobacteria, chlorophytes and cryptophytes, and inter-annual changes are not observed (Fig. 28.7d).

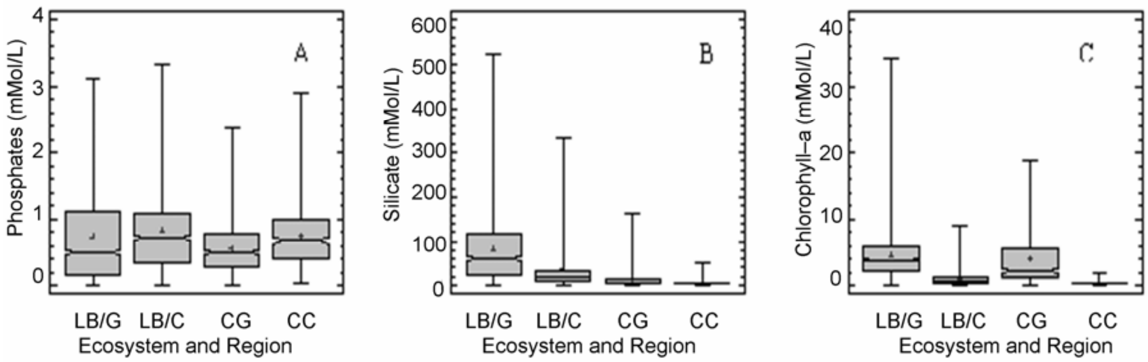


Fig. 28.6. Comparison of mean concentrations and variability of phosphate, silicate and chlorophyll-a among types of ecosystems of regions from the Yucatán Peninsula. Lagoons and Bays of the Gulf (LB/G), Lagoons and Bays of the Caribbean (LB/C), Gulf Coast (GC), Caribbean Coast (CC).

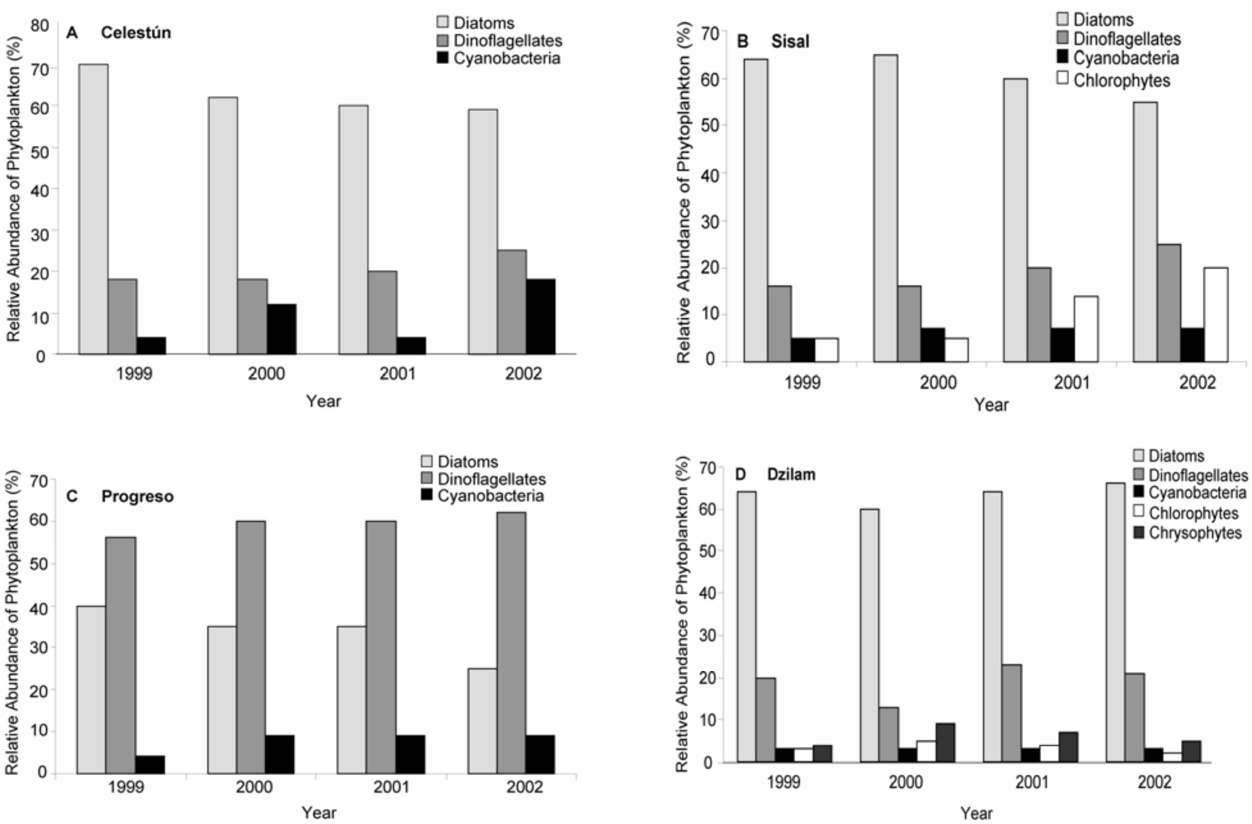


Fig. 28.7. Composition and inter-annual changes of phytoplankton groups in four locations of the northern Yucatán Peninsula.

Seagrasses represent the dominant group of submerged aquatic vegetation, with *Thalassia testudinum* as the most common species (Aguayo 2003). This community presents differences among sites, as well as inter-annual changes (Fig. 28.8). Seagrasses represent the dominant group in Celestún, but inter-annual changes exhibit reduction in their cover and increase of filamentous algae. In the Sisal region red algae are the dominant group, and its increase can be observed inter-annually. In Progreso the filamentous algae are the dominant cover, and inter-annual changes are observed with an increase in this group and decrease of other SAV components. In Dzilam seagrasses dominate the cover, but an inter-annual decrease is observed.

One of the challenges of research and monitoring in the coastal ecosystems of the Yucatán Peninsula is the spatial variability of hydrological characteristics, due to the way freshwater penetrates the coastal ecosystems (groundwater springs) and the differences between these discharges from those of rivers, in terms of their low temperature and sediment load (Herrera-Silveira 1994).

Synoptic mapping equipment, which is designed to detect different variables (temperature, salinity, transparency and fluorescence) through a continuous flow system in a moving research vessel, has been used for water quality assessment. This method allows the collection of large amounts of information at very short time intervals. Although information is available for most locations mentioned in Table 28.1, the analysis of one location is presented here, due to its importance not only for its coastal ecosystems, but also for its geographic location and economic repercussions. The location is the polygon of the Parque Marino Costa Occidental de Isla Mujeres (Marine Park of the West Coast of Isla Mujeres), Punta Cancún and Punta Nizuc, on the coast of Quintana Roo (Herrera-Silveira *et al.* 2002b).

The data collected using Dataflow IV during 2001 and 2002 is presented in Figs. 28.9-28.12. The sampling frequency was every 10 seconds (at approximately every 50 m). The first observed aspect is the high spatial variability of some characteristics, demonstrating that the coastal waters in these locations (reef zones), which were considered environmentally stable, are more spatially heterogeneous than it was believed.

The temperature fluctuated between 21.60°C and 36.34°C (Fig. 28.9). The site with highest variability at a spatial microscale was Punta Cancún, whereast the lowest variability was at Punta Nizuc. Salinity ranged from 28.2 to 36.8 (Fig. 28.10), exhibiting higher microscale spatial heterogeneity in the Punta Nizuc polygon. Transparency varied between 1.01 and 4.29 in a scale that ranges from 0 (totally turbid water) to 5 (completely clear water) (Fig. 28.11). This variable was more heterogeneous in the Isla Mujeres polygon and inter-annual differences were observed. Fluorescence, used as a measure of Chl-*a* in vivo, ranged from 0.09 and 0.59 (Fig. 28.12), in a scale of 0 to 5 units of fluorescence in vivo. These results confirm the oligotrophic tendency of these waters. However, their spatial heterogeneity is very high, mainly in the Isla Mujeres polygon, where inter-annual differences were also observed.

The results of the diagnosis of the nutritional condition of the coastal ecosystems of the Yucatán Peninsula show the induced, or cultural, condition of each site, and not the natural condition of this process. Fig. 28.3 shows the condition of lagoons and bays that exhibit natural mesotrophic or eutrophic conditions, classified as good as a result of the diagnosis. Poor sites are considered as those which, despite being in waters of oligotrophic nature, exhibited eutrophication indicators, which placed them as poor in the diagnostic classification. The intermediate state was classified as regular.

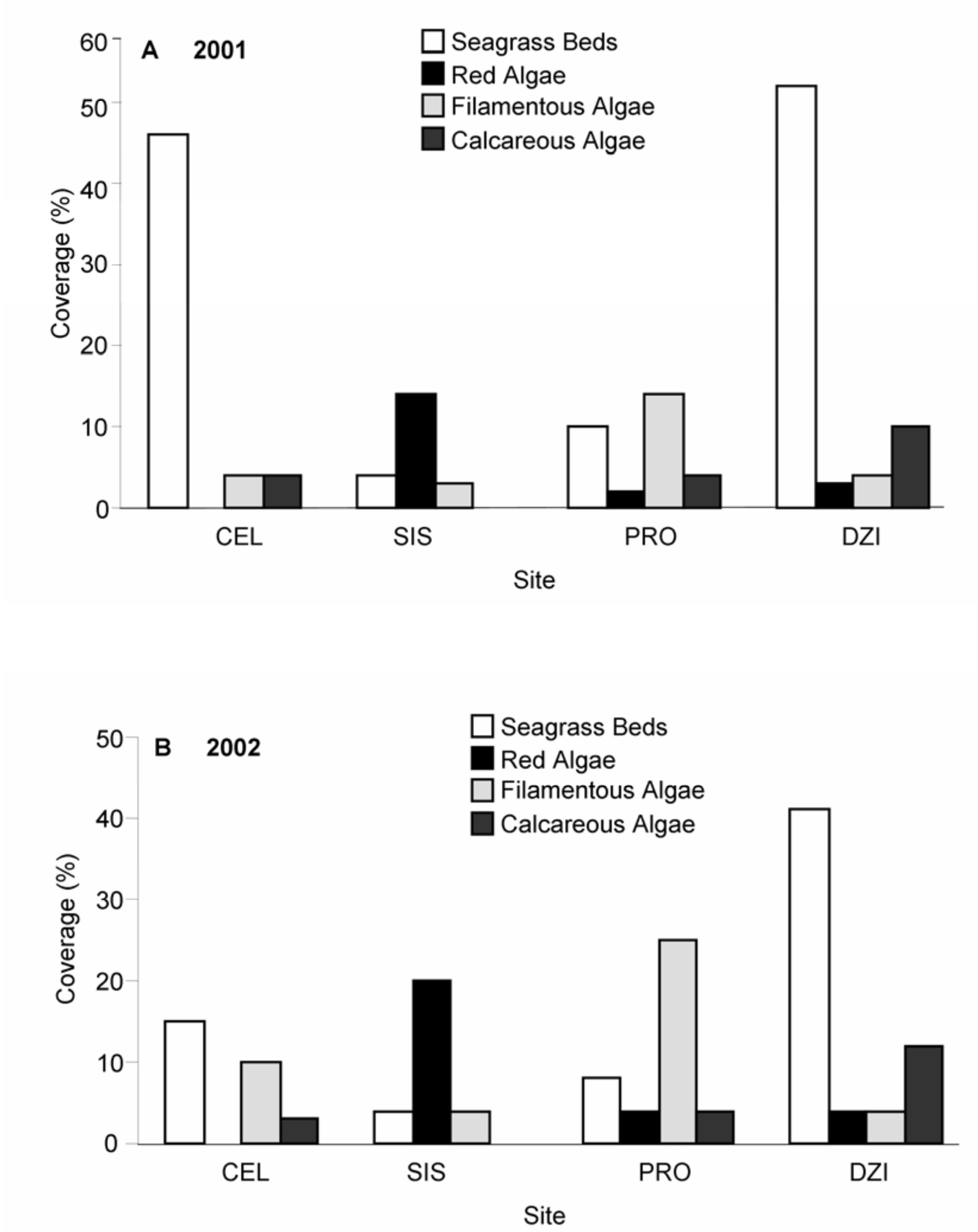


Fig. 28.8. Coverage of submerged aquatic vegetation and inter-annual changes at locations of the northern Yucatán. Celestún (CEL), Sisal (SIS), Progreso (PRO) and Dzilam (DZI).

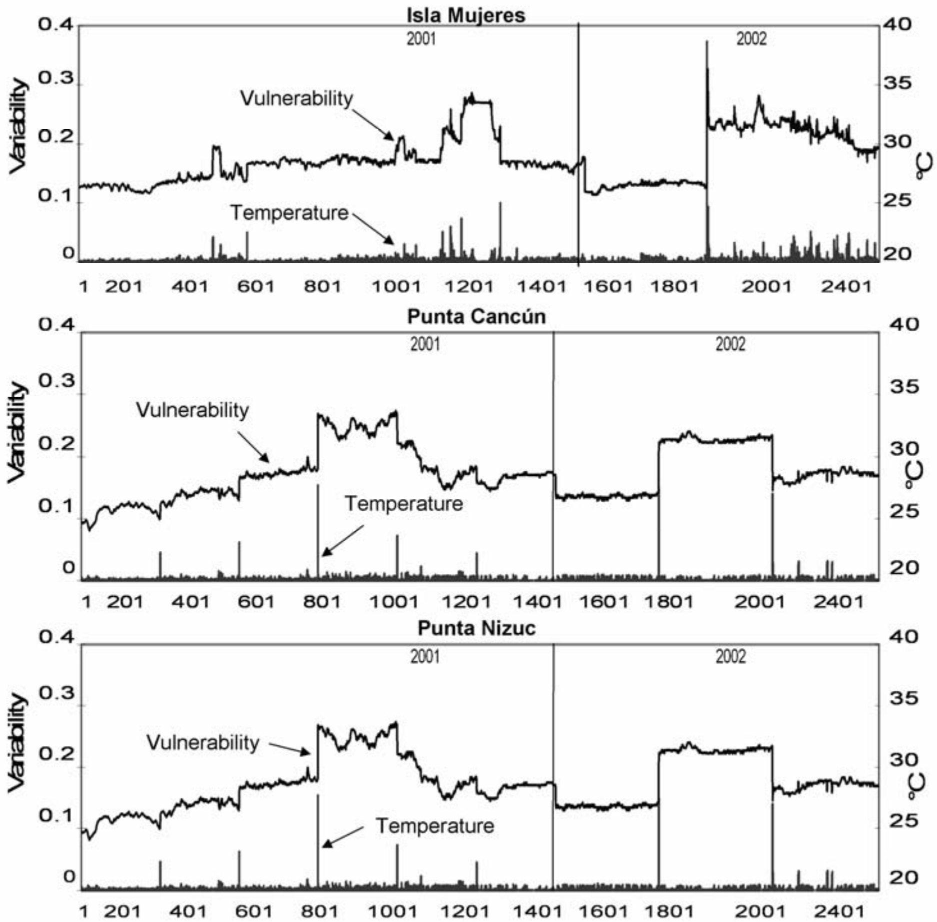


Fig. 28.9. Temporal comparison of micro-scale spatial temperature variability in the polygons of the western coast of Isla Mujeres Marine Park, Punta Cancun and Punta Nizuc.

The results indicate that the coastal systems of the Yucatán Peninsula are threatened by cultural eutrophication. This process is observed in both the lagoons and bays, and at the coast.

The concentration of phosphates, ammonia and Chl-*a* are the most evident symptoms of the initial stage of eutrophication in Campeche and, therefore, its condition is classified as poor. In Celestún the lagoon is in good condition despite its natural mesotrophic state. However, the symptoms of eutrophication along the coast can be observed in the phytoplankton community and seagrasses, for which reason its mesotrophic condition allows the classification of this ecosystem as regular. In Sisal the water column concentrations of ammonia, phosphate, silicate and Chl-*a* are the symptoms that indicate a mesotrophic condition, leading to its classification as regular. The hydrological conditions, phytoplankton and SAV of Progreso show that the lagoon and the coast are at the initial stages of eutrophication, for which reason they are classified as in poor condition. Although Dzilam is recognized as an area of high biological productivity, the information collected on different components indicates that there are no symptoms of cultural eutrophication on the coast or in the lagoon. Its condition is considered good. In the hyper-saline lagoon system of the Río Lagartos and the Holbox marine-estuarine system cultural eutrophication indicators are low. Therefore, they are considered in good condition.

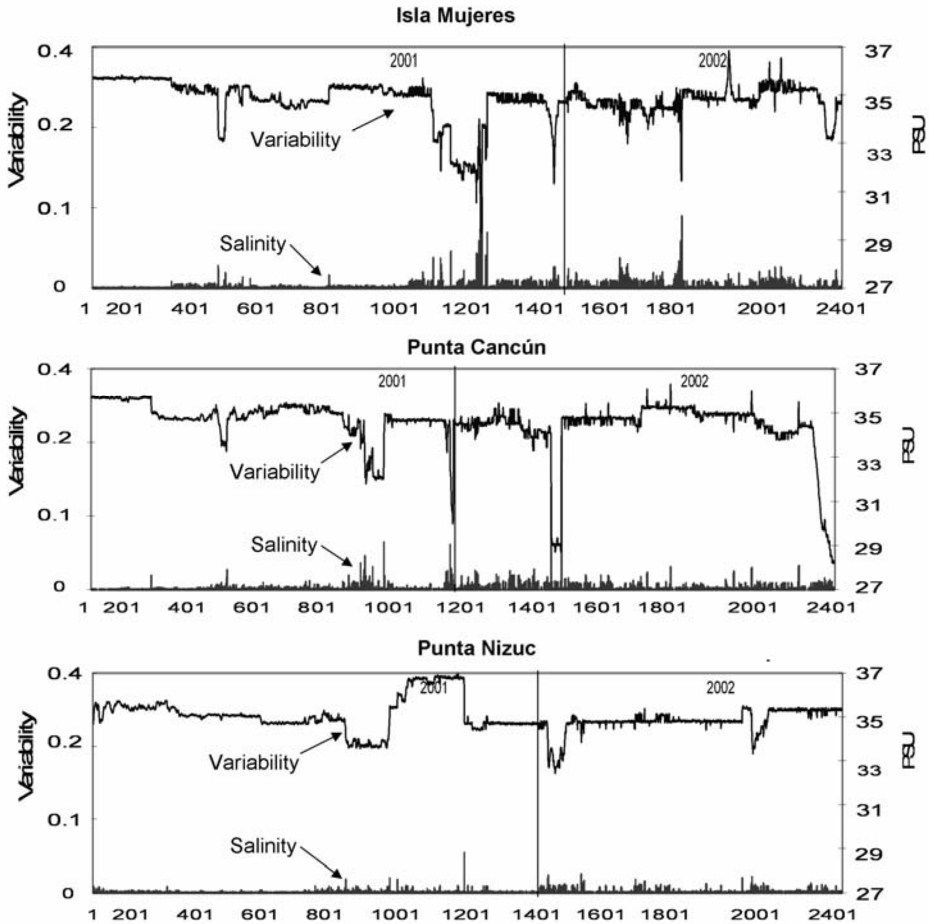


Fig. 28.10. Temporal comparison of the micro-scale spatial salinity variability in the polygons of the western coast of Isla Mujeres Marine Park, Punta Cancun and Punta Nizuc.

Some of the Caribbean ecosystems exhibit symptoms of cultural eutrophication. In the Cancún zone, which includes Isla Mujeres, the water and seagrasses condition shows symptoms of initial eutrophication stages at sites like Laguna Bojorquez and Laguna Makax in Isla Mujeres, whereas the coastal zones of higher tourism affluence, such as Punta Nizuc and some parts of Isla Mujeres present regular conditions. Lastly, some areas of these same polygons and 90% of Punta Cancún are considered in good condition. The coast of Playa del Carmen exhibits initial symptoms of eutrophication and is considered in regular condition. The area of Bahía de la Ascensión presents good hydrological and seagrasses conditions. However, some of the areas adjacent to the continental margin, fisheries areas and populated centers, present the initial symptoms of change of the natural trophic state. Finally, Bahía Chetumal exhibits both good and poor conditions with respect to cultural eutrophication indicators. In areas near the city of Chetumal and the mouth of the Río Hondo, the nutrients, dissolved oxygen and Chl-*a* reflect a state of initial eutrophication, whereas further away the variables indicate good conditions.

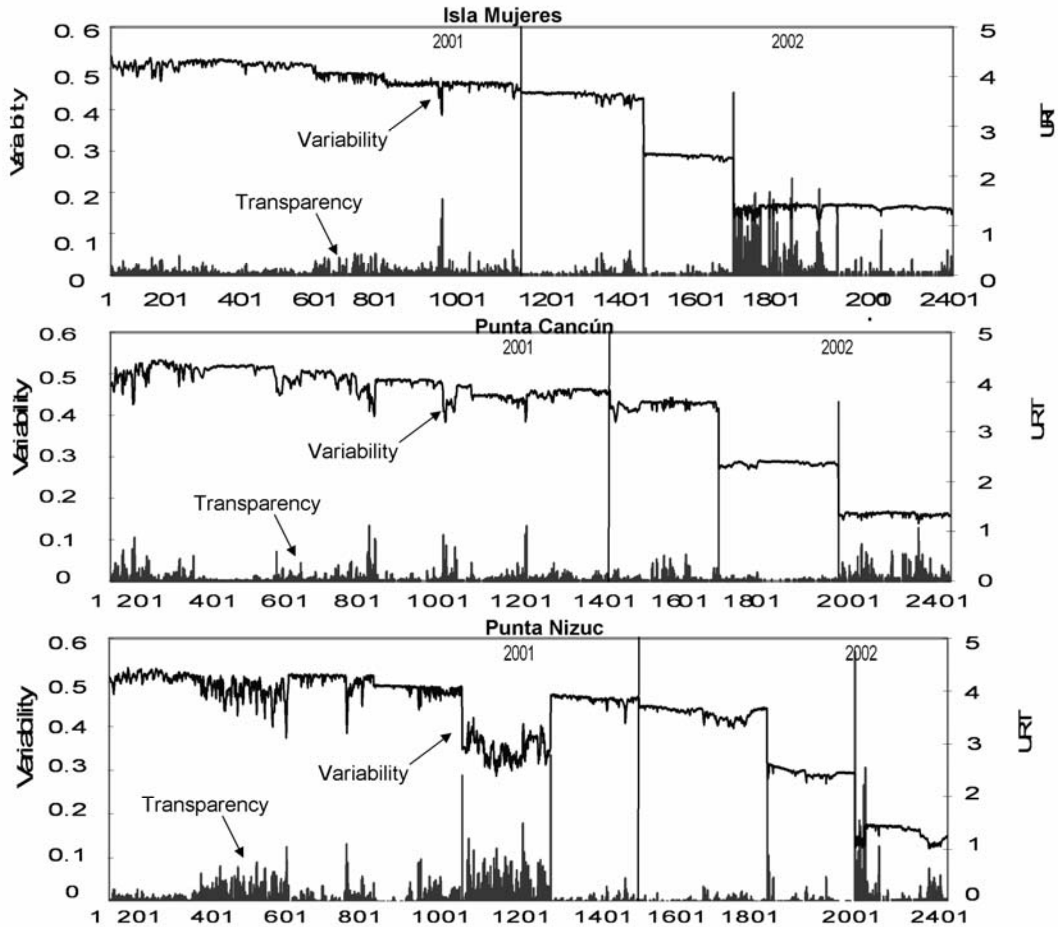


Fig. 28.11. Temporal comparison of the micro-scale spatial transparency variability in the polygons of the western coast of Isla Mujeres Marine Park, Punta Cancun and Punta Nizuc.

DISCUSSION

The data shows that the symptoms of the eutrophication process in the coastal ecosystems of the Yucatán Peninsula are reflected in different components of coastal ecosystems, as well as at different spatial and temporal scales. Therefore, long term research and monitoring strategies are required to keep identifying the conditions of the ecosystems, based on the analysis of the best indicators for each.

The main causes of eutrophication of the coastal ecosystems of the Yucatán are related to the wastewater effluents from urban and tourism development, aquaculture, and very importantly, the lack of treatment systems for agricultural wastewaters (Reyes 2001; Herrera-Silveira *et al.* 2002b). Moreover, modifications of the hydrology and hydrodynamics of coastal ecosystems due to construction of port infrastructure have a severe impact on the changes of their trophic condition. Although these causes are not specific to the coastal ecosystems of the Yucatán Peninsula, management problems in this region of the Gulf of Mexico are intensified by the manner which contaminated freshwater reaches the coastal zone, through non point sources of groundwater, which make corrective measures particularly difficult (Herrera-Silveira *et al*. 2000; Medina-Chan 2003).

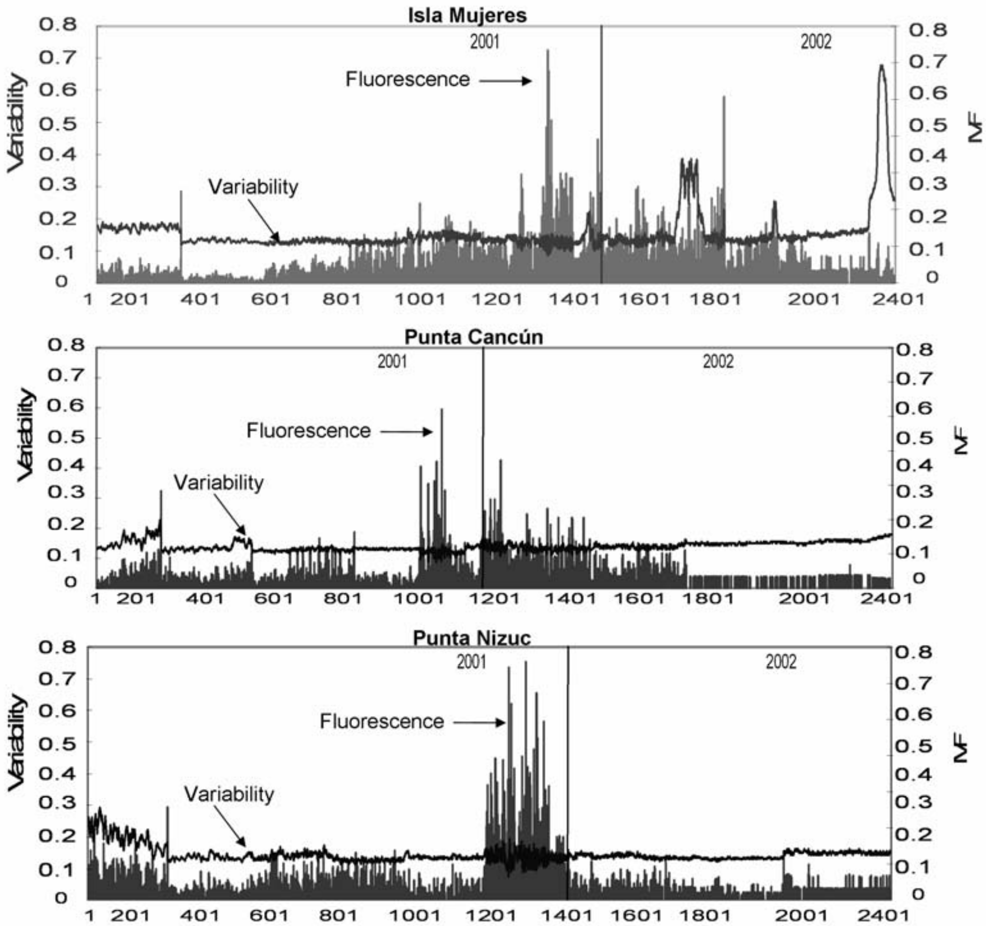


Fig. 28.12. Temporal comparison of the micro-scale spatial fluoresce variability in the polygons of the western coast of Isla Mujeres Marine Park, Punta Cancun and Punta Nizuc.

On the other hand, the high spatial and temporal variability of the results indicate the importance of developing reference values for specific eutrophication indicators of each ecosystem, based on time series data. For this reason the norms for coastal water quality need to be revised and adjusted. The development of specific criteria at the state level is suggested. This strategy is applied in the U.S.A. and the European Community (ICRAM 2000; USEPA 2001b). Table 28.2 can be used as a reference point to define *ad hoc* criteria for each type of ecosystem. It is suggested that the conceptual and methodological framework take into account the surface hydrological basin, and integrates the groundwater system to the ecological characteristics that define the functioning of each type of ecosystem, so that the eco-hydrology could be used as the reference for a theoretical foundation.

The analysis of the results of micro-scale spatial variability (Figs. 28.9-28.12) shows that, despite the relative small size of the polygons of the Cancún Marine Park, the hydrological variables monitored by DataFlow IV can detect spatial, seasonal and inter-annual differences. This indicates that the sampling approach and the use of this type of technology are appropriate to measure micro-scale spatial variation. Moreover, the type and quantity of data generated enable geospatial analyses and test the hypotheses related to the processes that influence the spatial distribution of physical, chemical and biological variables. For example, the extent of the influence of freshwater discharges (estuarine plume, sediment plume, spatial reach of contaminants), as well as the size of phytoplankton blooms, including harmful algae, could be measured; on the other hand, it would help the selection of monitoring sites.

This type of information and analysis facilitates the interpretation of the relationship between water quality parameters and the characteristics of the area or drainage basin, as well as monitoring the success of management and water sanitation measures. It could also guide the design of new experiments and planning of new hypotheses.

The analysis of the results among types of ecosystems and regions indicates that the lagoons and bays have higher hydrological variability (Figs. 28.4-28.6) due to the interaction between their semi-closed characteristics and freshwater discharges, favoring salinity gradients both of estuarine and hypersaline type. Therefore, the import/export and storage of nutrients are highly variable (Smith *et al*. 1999).

An outstanding aspect is that the concentrations of nitrate and phosphate in the ecosystems in the Caribbean are higher than in those of the Gulf of Mexico region of the Yucatán Peninsula, although the salinity and the concentration of silicates in the latter indicate that they are mostly influenced by groundwater (Figs. 28.5 and 28.6). This suggests that the groundwater inputs carry a higher load of nutrients and put the ecosystems of the region under a higher risk of eutrophication. Questions emerge regarding the origin of the nutrients and the trajectory of the water in the aquifer. These should be analyzed immediately by the application of novel methodological approaches, such as the use of stable isotopes and techniques for the measurement of physiological stress (Ralph and Burchett 1995; Fourqurean *et al*. 1997; Durako and Kunzelman 2002). These new approaches offer the opportunity of performing diagnosis and monitoring aiming at the adaptive management of natural resources.

Both the phytoplankton and SAV variables demonstrated their usefulness as they reflect hydrological differences at sites with different types and intensity of use of coastal ecosystems (Table 28.1). This is why they have been included in coastal ecosystems monitoring programs at different latitudes (Hemminga and Duarte 2000; Livingston 2001).

Although Laguna Celestún is in good environmental condition, the artificial modification of hydrodynamics as a result of a bridge-dam could favor an accelerated eutrophication of the internal area. The coastal zone exhibits high concentrations of nitrate and phosphate, suggesting that the groundwater input is probably enriched with wastewaters, which could influence changes in the phytoplankton communities (Fig. 28.7a). Seagrasses have been reduced (Fig. 28.8), which could reflect natural inter-annual variations (Zieman *et al*. 1999) or be induced by the impact of fisheries activities in shallow areas (<2m), which cause renewed resuspension of sediments and physical damage.

In Sisal the higher depth of the coast (>4m) leads to higher cover by red algae (Fig. 28.8), but changes in nutrient concentrations as a result of shrimp production are producing effects in areas nearby tourist beaches. The shrimp industry discharges untreated wastewater on the coast, which is reflected in higher concentrations of nitrate, ammonia, phosphate, silicate, particulate matter and Chl-*a* (Reyes 2001). As a consequence the phytoplankton community exhibits an increase in dinoflagellates and chlorophytes (Fig. 28.7b).

The SAV in Progreso is composed mainly of filamentous algae (Fig. 28.8), suggesting a more advanced degree of eutrophication than the previous sites. The dominance of dinoflagellates in the phytoplankton and the presence of species typical of harmful algal blooms, on the other hand, are another symptom of a change in the trophic condition. These events have become more frequent on the Yucatán coast in recent years.

Although the general situation in Dzilam suggest that it is in good condition (Figs. 28.7 and 28.8), the factor associated with the inter-annual changes in the cover of seagrasses should be researched and monitored, in order to establish if the changes are the result of natural or anthropogenic factors.

Some measures should be taken to improve or conserve the quality of coastal waters and not stimulate the process of eutrophication in the coastal ecosystems of the Yucatán Peninsula, including: establishment of conventional wastewater treatment plants or improvement of existing plants; the use of natural or constructed wetlands according to the organic load; prevention of direct clandestine discharges into the ecosystems; use of coastal engineering to improve the hydrodynamics in the zones that have been severely altered.

There is much research left to be done. Firstly, it is necessary to apply the methodological approaches described herein at locations where there is a complete lack of information. In terms of monitoring, it is time to establish long-term research programs in coastal ecosystems, as there are for terrestrial ecosystems. These programs, designed for specific ecosystems, offer the opportunity of establishing the behavior and processes that act at different time scales, through different time-series which are responsible for the functioning of the ecosystem. Lastly, it is suggested that for both, research and monitoring, new analytical technologies are integrated into the data collection and analyses, such as stable isotopes, morphometric and physiological biomarkers in seagrasses, and geo-spatial analyses, among others.

Recent information indicates that the coastal ecosystems of the Yucatán Peninsula are controlled by hydrological discharges of groundwater and coast-ocean interaction, which makes them hydrologically heterogeneous. This is related to local factors such as:

a) Number and distribution of groundwater discharges
b) Frequency and intensity of natural events (northerlies, hurricanes, storms)
c) Frequency and intensity of rainfall (pulse discharges of fresh water)
d) Type and intensity of anthropogenic activities (urban wastewaters, agricultural and industrial activities, fisheries, aquaculture, as well as modifications of the hydrodynamics and changes in water residence times).

All these factors are related to the vulnerability of the ecosystems as their trophic condition is changed, thus triggering different eutrophication symptoms. This is the reason why the analysis and monitoring of this process have to integrate physical and chemical variables of the water, as well as phytoplankton and SAV characteristics, considering aspects ranging from physiological to community characteristics. These factors enable the identification of the health of the ecosystems and the necessary measures to maintain or improve it.

The information presented herein shows that the coastal ecosystems of the Yucatán Peninsula are already bearing the ecological consequences of cultural eutrophication. The recommendations are to recognize the existence of the problem and begin long term programs for the conservation and use of the natural resources on the coastal fringe. If management, research and monitoring measures are not taken shortly regarding the eutrophication of the ecosystems of the Yucatán Peninsula, consequences would include impacts rather than conservation, remediation rather than prevention, exploitation rather than use, distancing the objective of an integrated management of the coastal zone of the Gulf of Mexico.

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