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Evaluation of the health status of a coastal ecosystem in southeast Mexico: Assessment of water quality, phytoplankton and submerged aquatic vegetation

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ABSTRACT

The coastal environment of the Yucatan Peninsula (SE, Mexico) includes a wide variety of ecosystems ranging from mangroves to coral reefs, resulting in a heterogeneous landscape. Specifically, the marine system is characterized by environmental differences which respond to regional and local forcing functions such as marine currents and groundwater discharges (GD). Such functional characteristics were used here to define four subregions across the Yucatan coast and diagnose the health status of this coastal marine ecosystem. To achieve this goal, we conducted an analysis and integration of water quality variables, an eutrophic assessment, evaluated changes in submerged aquatic vegetation (SAV), and analyzed the community structure and distribution of harmful phytoplankton. The first step was to determine the reference values for each subregion based on data previously collected from 2002 to 2006 along the coast of Yucatan, 200 m offshore. The trophic index (TRIX) and Canadian index for aquatic life (CCMEWQI) were used to diagnose each subregion and then the ASSETS approach was conducted for Dzilam and Progreso, sampling localities on each end of the health status continuum (those with the best and worst conditions). Overall, results indicated that the marine coastal ecosystem of Yucatan is in good condition; however, differences were observed between subregions that can be attributed to local forcing functions and human impacts. Specifically, the central region (zone HZII, Progreso-Telchac) showed symptoms of initial eutrophication due to nutrient inputs from human activities. The eastern region (zone HZ III, Dzilam-Las Bocas) showed a meso-eutrophic condition linked to natural groundwater discharges, while the other two subregions western (zone HZI Celestun-Palmar) and caribbean (zone HZ IV Ria Lagartos-El Cuyo) exhibited symptoms of oligo-mesotrophic condition. These findings may be considered baseline information for coastal ecosystem monitoring programs in Yucatan, and the approach used could be replicated for other coastal areas.

1. Introduction

The biological richness of coastal ecosystems is recognized world-wide, and this is one of the main reasons they are attractive for the establishment and development of human communities; approximately 60% of the planet's population is found in coastal areas (Constanza et al., 1997). This situation has generated great pressure on these ecosystems resulting in a decrease of water quality and biodiversity, loss of critical habitats, and an overall decrease in the life-quality of local inhabitants. Such impacts are an urgent call for studies that characterize and diagnose the present condition of coastal environments. This task can be performed based on an ecosystem approach which analyzes the distribution, structure and dynamics of different components of the ecosystem in order to establish management policies for the sustainable use of coastal resources and environmental services.

The first step required to achieve sustainable use of coastal ecosystems is to assess the system's condition, which is a complex process due to natural gradients and variability intrinsic to coastal areas, as well as ongoing structural and functional changes occurring due to human impacts. In response to such complexity, scientists have sought to identify and select the most adequate parameters to define the ecological quality or health status of coastal waters. Previous studies have explored the use of a number of metrics, indices, and analytical frameworks to increase the credibility and robustness of coastal ecosystem health status determinations (Borja, 2005; Borja et al., 2004, 2000; Orfanidis et al., 2003; Dennison et al., 1993; Buchanan et al., 2005).

In the case of Mexico, the environmental protection law known as "Ley General del Equilibrio Ecológico y la Protección al Ambiente" or LGEEPA, suggests the use of a zoning approach as a tool to regulate human activities and to guide the sustainable use of coastal environments. Such zoning of coastal ecosystems must, at

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least, include an ecological characterization of the area and a diagnosis of its environmental conditions in order to develop adequate criteria for the regulation of human activities within each area. The desired result is the preservation, protection, and restoration of coastal ecosystem natural resources.

The state of Yucatan is located in the SE portion of the Gulf of Mexico, and includes 365 km of coast which support 1,200,000 people with a population growth rate of 2% per year (greater than the state or national average; INEGI, 2000). In addition, this population doubles during the holiday season, when people from inland move to the coasts where they spend their vacation. As a result, coastal ecosystems of Yucatan, as in other parts of the world, are being heavily impacted by human activities such as: fishing, marine transportation, mining (salt and petreous extraction), cattle-raising, aquaculture and tourism, the last of which has exhibited its most rapid growth during the last five years. These activities require the construction and maintenance of infrastructure, which causes changes in coastal ecosystem structure and dynamics (Pare and Fraga, 1994). As a response to this situation, federal and state governments together with academic institutions designed the Yucatan Coastal Zoning Program (SEMARNAT-SECOL, 2007), legislation designed to achieve sustainable use of coastal ecosystem resources in the region. However, this document lacks a baseline diagnosis of health condition of such areas to be used to measure the success of regulatory performance. Thus, the main objective of the present work was to diagnose the condition of coastal marine waters of the state of Yucatan based on water quality and trophic indices, as well as submerged aquatic vegetation (SAV) and phytoplankton metrics. Given that the Yucatan Peninsula receives considerable freshwater inputs via groundwater discharges, inland human activities which pollute the aquifer will most likely play an important role in this diagnosis. Such diagnosis must also take into account the spatial distribution of human impact by type and intensity.

1.1. Study area

The study was carried out at the coast of the state of Yucatan (SE, Mexico), which is bordered by the Gulf of Mexico on the northwest side and by the Caribbean Sea on the southeast side (Fig. 1). The coastal system extends approximately 365 km which represents 3.3% of the total extent of Mexican coasts. Climate in the study area is dry and arid with a rainy season in summer and little rainfall during the rest of the year. Three well-defined seasons can be identified: dry (March–May), rainy (June–October) and a season of cold fronts referred to as “nortes” (November–February). The tide is mixed and semidiurnal with a range of approximately 0.6 m (Capurro, 2002).

Due to the karstic nature of the substrate in the region, the coastal marine system in Yucatan is highly influenced by submerged groundwater discharges (SGD), which are estimated to be around $8.6 \times 10^6\ \mathrm{m}^3\ \mathrm{km}^{-1}\ \mathrm{year}^{-1}$ (Hanshaw and Back, 1980). The aquifer recharge occurs during the rainy season (Herrera-Silveira et al., 1998; Herrera-Silveira and Comin, 2000). The SGD are characterized by low salinity, high nitrate and silicate concentrations, and may be classified based on the type of discharge as point (direct) or non-point (diffuse). In the first case, discharges occur mostly in the form of springs in the marine zone. In the second case, seepage input is produced by water infiltrations through fractures of the calcareous substrate (Troccoli et al., 2004; Back and Lesser, 1981; Perry, 1990). Other freshwater inputs are through surface runoff due to laminar flux from mangrove fringe areas, coastal lagoons and harbors. Finally, a coastal upwelling from Cabo Catoche (east of the Yucatan Peninsula) also results in nutrient supply to the study system, and its influence becomes more intense during spring (March to May) (Cochrane, 1969; Logan, 1969; Ruiz, 1979; Merino, 1997). Cold fronts (“nortes”) and hurricanes are also common in this area and intensify coastal currents and tides, favouring sediment resuspension, changes in water turbidity, and movement of organic and inorganic matter from coastal lagoons and swamps to the marine system resulting in a natural fertilization process of marine waters (Odum, 1972; Morales-Ojeda, 2004).

With respect to the differences along the coast, some are man induced and others are the result of morphology and edaphology of the area. The major human uses of this system include tourism, fisheries, salt extraction, port development, seasonal local tourism and cattleraising. The natural influencing characteristics include

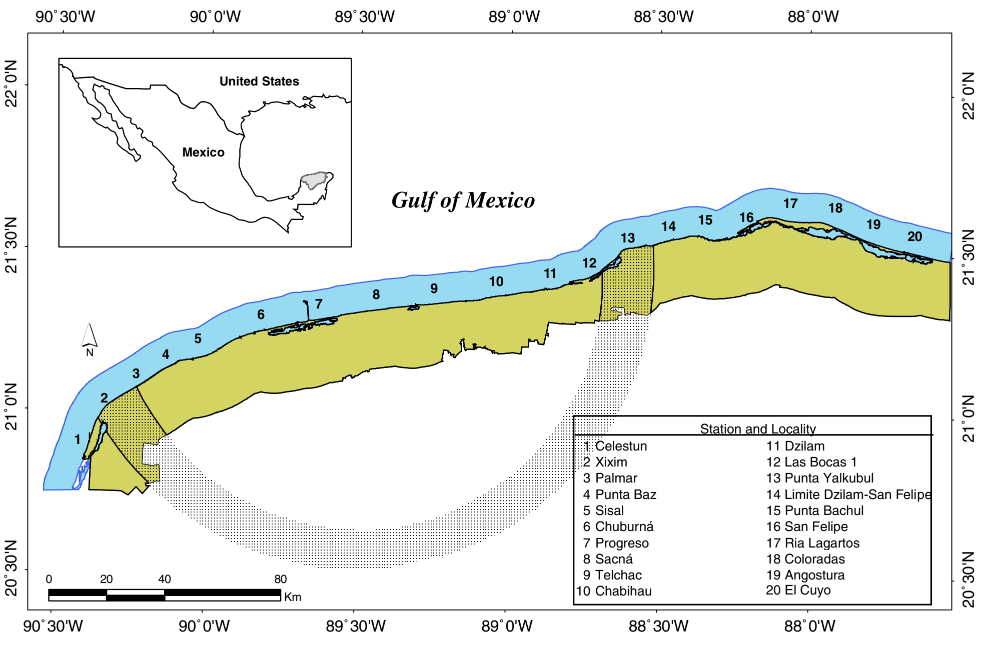

Fig. 1. Study area and location of sampling sites.

the nearshore area known as the “ring of sinkholes” related to the Chicxulub crater. The sinkhole area is characterized by large levels of underground water flow and importantly, the dominant freshwater inputs to the coastal zone are linked to areas where the sinkholes ring area meets the coastal line (i.e., localities of Celestun and Dzilam) (Pacheco Martinez and Alonzo Salomon, 2003). Thus, the sinkhole areas have an important influence on hydrochemical and biological characteristics along the coast of Yucatan (Morales-Ojeda, 2007).

2. Material and method

From February 2002 to November 2006, data were collected from three transects parallel to the coast line, and at three different distances from shore (50, 100 and 200 m) which were used as replicates after a preliminary analysis showed no statistically significant differences among water quality measures among the three replicates. Each transect consisted of 20 sampling stations separated by about 16 km from each other (of 360 km of coast) (Fig. 1). A total of 60 sampling stations were sampled systematically three times a year (during each season: dry, rainy, and “nortes”). A total of 1800 samples were taken to conduct water quality and phytoplankton analyses, (respectively $n = 1800$ each), and for SAV $n = 900$.

Measurements of water quality parameters (temperature, dissolved oxygen and salinity) were conducted “in situ” by means of a YSI-6600 multiparameter probe. Sample processing involved collecting 1 l of surface-water with dark polyethylene bottle, of which 500 ml were stored in a freezer immediately after filtration for analyses of dissolved nutrients (nitrite, NO_2^-; nitrate, NO_3^-; ammonium, NH_4^+; soluble reactive phosphate, SRP; and soluble reactive silicate, SRSi) according to the method reported by Parsons et al. (1984). The remaining 500 ml were used for chlorophyll-*a* analysis using the method of acetone (90%) extraction and Jeffrey and Humphrey’s equation (1975). The light coefficient extinction was measured using a spherical sensor LI-COR and Li-1000 data logger and calculated with the following expression:

$$K = \frac{LN(\mathrm{Io}/Iz)}{Z}$$

where K is the extinction coefficient m^{-1}, Io is the incident light, Iz is the light at 0.5 m, Z is the 0.5 m depth.

A qualitative analysis of phytoplankton community structure consisted of collecting additional 250 ml water samples which were preserved with lugol acetate. Taxonomic identification of phytoplankton species was carried out using an inverted Zeiss microscope (Axiovert 100) and selecting 20 fields per sample following the Utermöhl technique (Hasle, 1978). Phytoplankton species abundances were used to calculate species richness (Krebs, 1985; Whittaker, 1975), Shannon–Weaver diversity index (1963), and Pielou evenness (1966).

Submerged aquatic vegetation (SAV) data were analyzed “in situ” by estimating vegetation cover according to Braun-Blanquet modified methods (Fourqurean et al., 2001). In addition, three replicates were taken with a 0.122 m^2 core-sampler using standing-crop methods for composition and biomass (Zieman et al.,1999).

2.1. Characterization of affinity zones

A characterization of Yucatan’s coastal marine water, including phytoplankton and SAV measurements, was previously conducted by Morales-Ojeda (2007) who identified affinity zones for each ecosystem component. Specifically, cluster analyses were performed for each component using the median value per station. In the case of water quality, K, DO, salinity, nitrite (NO_2^-), nitrate (NO_3^-), ammonium (NH_4^+), inorganic phosphorus (SRP), silica (SRSi), and Chlorophyll-*a* (chl-*a*) were used in an hierarchical joining tree method based on measurements of the square Euclidean distance similarity, and using a complete linkage (furthest neighbor) amalgamation algorithm. Groundwater discharges and the contribution of salinity, nitrite and ammonia (discriminate variables) were statistically relevant to the cluster formation, which was evaluated using a canonical variates analysis (CVA). The resulting zones were characterized and then reference values were determined for each one (see determination of reference values section). With respect to phytoplankton, the medians of the phytoplankton abundance were used in a hierarchical agglomerative complete linkage method (furthest neighbor) using the Sorensen coefficient to identify similar phytoplankton zones.

2.2. Water quality parameters and indices as environmental indicators

Dissolved inorganic nutrients (NO_3^-, NO_2^-, NH_4^+ and SRP) have been used as indicators of eutrophication (US EPA, 2001; EEA, 1999), whereas Chl-*a* has been used as an early indicator of deviations in marine water health status (e.g., Assessment of Estuarine Trophic Status-ASSETS; Bricker et al., 2003). In the specific case of the coastal marine system of Yucatan, special emphasis has been given to soluble reactive phosphate (SRP) and soluble reactive silicate (SRSi), the reason for this being that in karstic regions such as the Yucatan Peninsula, SRP could be a limiting nutrient due to its precipitation in presence of calcium carbonate to form apatite (Coelho et al., 2004; Slomp and Van Cappellen, 2004); SRSi on the other hand, may be used as a tracer of groundwater discharges (Smith et al., 1999). Based on this, continental water discharges caused by anthropogenic activities could produce pulses of high SRP concentrations, which could have an impact on phytoplankton species composition, leading to an increase in the abundance of opportunistic species which are responsible of harmful algal blooms (HABs; Lee et al., 2005).

2.3. The TRIX assessment method

A water quality index provides a convenient means of summarizing complex water quality data and facilitating its communication to a general audience. In order to identify the trophic condition of the Yucatan coast, the water quality TRIX index (Vollenweider et al., 1998) was calculated. This index is a linear combination of four state variables related to primary production (chlorophyll-*a* and oxygen) and nutritional condition (dissolved inorganic nitrogen, inorganic phosphorus) (Melaku et al., 2003). This index was calculated as follows:

$$TRIX = \frac{[\log(Chl\text{-}a * |\%\mathrm{DO}| * \mathrm{DIN} * P + k)]}{m}$$

where P is the mineral or inorganic phosphorus (P-PO_4 μmol l^-), DIN is the mineral nitrogen: dissolved inorganic nitrogen (μmol l^{-1}), Chl-*a* is the chlorophyll-*a* concentration, as μg l^{-1}, %DO is the absolute value of the oxygen saturation deviation from the oxygen calculated as $|100 - \%\mathrm{DO}|$. Parameters $k = 1.5$ and $m = 1.2$ are scale coefficients which were included to fix the lower limit value of the index and the length of the related trophic scale from two to eight the meaning of values are shown in Table 1.

2.4. The Canadian index assessment method

An additional index was calculated which describes the water status for aquatic life. Here we call it the Canadian Index (CI), as it was developed by British Columbia’s Ministry of Environment, and modified by the Canadian Council of Ministers of the Environment. Like other indices, the CI essentially reduces the multivariate

Table 1
General ranking for TRIX assessment (take from Penna et al., 2004).

TRIX value	Tropic status	Environmental meaning	Condition	Reorganization for this study
2–4	Low	Low production	High	Good
4–5	Medium	Moderate production	Good	(combines high and good of original TRIX)
5–6	High	Between moderate and high production	Bad	Fair
6–8	The highest	High production	Poor	Poor

Table 3
Reference values used for the calculation of CI. The values correspond to the Q1 and Q3 of the total dataset ($n = 1800$).

Water quality parameter	Non-compliance if:	Q1 (P25)	Q3 (P75)	Unit
K	<>	0.67	1.63	m^{-1}
Salinity	<>	35.72	37.2	
DO	<>	3.7	7.08	$mg\,l^{-1}$
Chl-*a*	<>	1.86	6.06	$\mu g\,l^{-1}$
NO_3^-	<>	0.71	2.25	$\mu mol\,l^{-1}$
NO_2^-	<>	0.07	0.65	$\mu mol\,l^{-1}$
NH_4^+	<>	0.1	3.48	$\mu mol\,l^{-1}$
SRP	<>	0.06	0.38	$\mu mol\,l^{-1}$
SRSi	<>	5.75	15.1	$\mu mol\,l^{-1}$

nature of water quality data. It incorporates three elements: *scope* – the number of variables not meeting water quality objectives; *frequency* – the number of times these objectives are not met; and *amplitude* – the amount by which the objectives are not met. The index computes a number between 0 (worst water quality) and 100 (best water quality), and the results are divided into five descriptive categories in order to simplify representation (Table 2). Due to regional levels of variation in marine water parameters in the study area, and since the 1st quartile denotes an excellent condition, we used it as the reference values for the variables required by the index (*k*, salinity, DO, Chl-*a*, NO_2^-, NO_3^-, NH_4^+, SRP and SRSi) (the reference values used are shown in Table 3).

2.5. Biological indicators

2.5.1. Phytoplankton

Phytoplankton community descriptors such as total abundance, species richness and diversity were considered indicators of the system's health condition. High phytoplankton concentrations could decrease the amount and quality of light along the water column and serve as an indicator of conditions. Likewise, richness and diversity have been useful descriptors of the environmental condition of aquatic ecosystems and of changes in coastal hydrodynamics and water quality patterns (Margalef, 1961; Brander et al., 2003; Heiskanen et al., 2005; Washington, 1984). Due to an HAB incident in 2001 caused inshore by *Cylindrotheca closterium*, a double HAB event in 2003 caused inshore by *C. closterium* and offshore by *S. trochoidea*, as well as the coastal population growth which has increased nutrient inputs to seawater, we consider that results of phytoplankton community structure will serve to evaluate the vulnerability of the coastal system and identify potential species and areas which may act as reservoirs of HAB species.

The HAB monitoring program, established in 1998, as well as previous experience from the 2001 and 2003 events, have been useful in determining criteria for evaluating system condition. Both the number of incidents and the density of individuals of species such as *C. closterium* and *S. trochoidea* which caused high levels of fish mortality are used as criteria. The total species number associated with HABs has been previously selected as an indicator of the risk level an area has to develop an HAB event. The rationale is that a high number of species at a given locality could act as a reservoir which could increase the probability of a HAB event given changes in nutrient dynamics or water circulation patterns (CEC, 1991). The spatial extent and duration of HAB events depends on water quality, turbulence and stratification along the coast (Smayda, 2002).

2.5.2. Submerged aquatic vegetation (SAV)

Measurements of SAV cover are the most common data available in coastal marine systems. Negative SAV cover changes, as well as changes in species composition from seagrasses to macroalgae are generally associated with eutrophication (Orth and Moore, 1983; Stevenson et al., 1993). Overgrowth of macroalgae and epiphytes are known to suffocate bivalves and cause SAV die-off (Dennison et al., 1993). There is no standard measure or threshold value above which macroalgae and/or epiphytes are considered harmful for an ecosystem, and quantitative information is rarely available in the literature. However, Bricker et al. (2003) considered that the condition determination could be made heuristically in the absence of a standard measure, by examining the percent change in spatial coverage over time.

This study was based on the regionalization of physicochemical, phytoplankton and SAV components following multivariate data analysis. Cluster analyses were conducted in order to determine different zones along the coast based on water quality and phytoplankton data, while the SAV zoning was performed via non-metric multidimensional scaling analysis (NMDS) (Clarke and Warwick, 2000).

2.5.3. Determination of reference values

Water quality, phytoplankton and SAV reference values were established based on a modified approach from the US EPA (2005). According to this approach, values which fall within the 25th percentile (or its equivalent 1st quartile) or lower values give an idea of the least impacted water quality conditions (except for DO and phytoplankton diversity and richness where the

Table 2
General ranking for CI assessment (take from CCME, 2001).

Core CI value	Condition	Environmental meaning	Reorganization for this study
95–100	Excellent	Water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels.	Good
80–94	Good	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.	(combines excellent and good of original CI)
65–79	Fair	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.	Fair
45–64	Marginal	Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.	Poor
0–44	Poor	Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.	

Table 4
Reference values for water quality variables calculated from all data collected from 2002 to 2006, where excellent/good = 1st quartile to median value, fair = median to 3rd quartile, poor = above 3rd quartile. For DO the estimations are inverse.

	k (m^{-1})	DO (mg l^{-1})	Chl-*a* (μg l^{-1})	NO_2^- (μmol l^{-1})	NH_4^+ (μmol l^{-1})	SRP (μmol l^{-1})
HZI n = 720						
Good	<0.7–1.3	6.0–>7.3	<2.3–3.7	<0.07–0.16	<0.1–0.82	<0.06–0.24
Fair	1.3–1.8	4.4–6.0	3.7–6.0	0.16–0.4	0.82–2.81	0.24–0.36
Poor	>1.8	<4.4	>6.0	>0.4	>2.81	>0.36
HZII n = 450						
Good	<0.65–1.03	5.05–>6.7	<1.72–2.72	<0.1–0.3	<0.1–0.54	<0.05–0.14
Fair	1.03–1.45	2.2–5.05	2.72–5.36	0.3–0.78	0.54–2.39	0.14–0.3
Poor	>1.45	<2.2	>5.36	>0.78	>2.39	>0.3
HZIII n = 270						
Good	<1.07–1.37	5.57–>6.78	<3.09–4.81	<0.04–0.24	<0.72–2.23	<0.06–0.23
Fair	1.37–1.72	3.27–5.57	4.81–7.36	0.24–0.75	2.23–6.46	0.23–0.38
Poor	>1.72	<3.27	>7.36	>0.75	>6.46	>0.38
HZ IV n = 360						
Good	<0.4–0.8	5.8–>7.1	<1.1–1.9	<0.06–0.28	<0.53–2.06	<0.1–0.32
Fair	0.8–1.2	3.7–5.8	1.9–4.1	0.28–0.57	2.06–5.08	0.32–0.44
Poor	>1.2	<3.7	>4.1	>0.57	>5.08	>0.44

estimations were inverse) and thus represent excellent conditions, values located between the first quartile and the median indicate a good condition, (here we join the excellent and good condition for a combined classification of good); values between median and 3rd quartile indicate a fair conditions, and finally, values higher than the 3rd quartile indicator poor or bad conditions. Tables 4–6 show the reference values used respectively for water quality, phytoplankton and SAV. Those values were used to determine the coast condition applying the criteria detailed in Table 7 to a specific area and then the results were represented as a map.

Table 7
Decision rules or criteria used for the overall analysis of all four coastal zones. The 16 indicators are divided in the following way: six for water quality, five for phytoplankton community and five for SAV.

Good	Fair	Poor
<= 50% of the 16 indicator variables along all the stations included in the zone are fair and the rest are good but none are fair	Bad and fair constitute <= 50% of the 16 variables, along all the stations included in the zone but the rest are good	Bad and fair constitute >50% is poor of the 16 variables, along all the stations included in the zone

2.5.4. The ASSETS assessment method

Finally, the ASSETS methodology was used to assess the trophic status of systems that by Trix and CI results were determined to have the best and worst conditions along the continuum. These results were compared with the results determined by TRIX and the Canadian Index. In brief, the ASSETS eutrophication assessment method examines nutrient related water quality problems using a Pressure-State-Response approach (for details see Bricker et al. (1999, 2003, 2007); Ferreira et al. (2007); Scavia and Bricker (2006), <www.eutro.org>, <www.eutro.us>).

Table 5
Reference values for phytoplankton of the coastal marine ecosystem of Yucatan all data collected from 2002 to 2006 where excellent/good = 1st quartile to median value, fair = median to 3rd quartile, poor = above 3rd quartile just for Shannon diversity index For the rest of variables the estimations are inverse.

CONDITION	Phytoplankton community			HAB's species	
	Richness (No. of species')	Abundance (Cel/ml)	Shannon Div. index H′ (bit/ind)	Richness (No. of species)	Abundance (Cel/ml)
GOOD	>20	<129	>0.78	<2	<166
FAIR	12–20	129–349	0.51–0.78	3–4	166–220
POOR	<12	>349	<0.51	>4	>220

Table 6
Reference values for SAV of the coastal marine ecosystem of Yucatan were estimated from all data collected from 2002 to 2006. Where excellent/good = 1st quartile to median value, fair = median to 3rd quartile, poor = above 3rd quartile. For Seagrasses coverage (%SC), the estimations are inverse.

Condition	Seagrasses coverage (%SC)	Filamentous green algae (%FGA)	(SC:FGA) ratio	Seagrasses coverage change %
Good	>50	<5	<5	<10
Fair	20–49	5–10	5–15	10–50
Poor	<20	>10	>15	>50

The Pressure or Influencing Factors are determined by a matrix that combines the magnitude of nutrient inputs from the watershed with a measure of the system's ability to dilute or flush the nutrient inputs (i.e., susceptibility). The magnitude of loads is determined by a model that compares anthropogenic loading, from monitoring data or model estimates with natural background concentrations. The model factors in possible oceanic sources providing insight to the success of potential watershed-based management measures.

The state component or overall eutrophic condition assessment is based on five variables that are divided into two groups: (1) *primary symptoms* that indicate early stages of eutrophication (chlorophyll-*a* (Chl-a) and macroalgae); and (2) *secondary symptoms*, indicative of well-advanced problems (low dissolved oxygen (DO), losses of submerged aquatic vegetation (SAV), and occurrence of nuisance and/or toxic algal blooms (HABs)). An area-weighted-estuary-wide value for each variable is determined based on concentration, spatial coverage, and frequency of occurrence of problem conditions. The overall OEC, falling into one of five categories (i.e., High, Moderate High, Moderate, Moderate Low or Low) is determined by a matrix that combines the average score of *primary symptoms* and the highest score (worst impact) of the three *secondary symptoms*, thus giving the *secondary symptoms* a higher weighting in a precautionary approach.

The expected Response or Future Outlook (i.e., that conditions will worsen, not change, or will improve) is determined by combining susceptibility of the system with expected changes in nutrient loads. Expected changes in loading are based on predicted changes in population and watershed uses, mitigated by planned management actions.

Finally, the three components detailed above are combined into a single rating for a system of bad, poor, moderate, good or high for a system called the ASSETS Synthesis. The ASSETS method is available for download as a desktop program from <http://www.eutro.us/register>.

3. Results and discussion

3.1. Water quality zoning

The coast of Yucatan exhibited four discrete hydrochemical affinity zones (i.e., HZI–HZIV) (Fig. 2), which showed specific water quality characteristics that depended on the relative importance of regional/local, land/marine controls, as well as the type and intensity of human activities conducted at each zone (Lapointe et al., 2004).

Hydrochemical zone I (HZI) included stations which were not spatially distributed in a continuous manner; one sampling area was located in the western region of the study region from Celestun to Punta Baz (S1–S4), while the other was in the eastern portion of the system from the San Felipe-Dzilam limit to the locality of San Felipe (S14–S16). High salinity and relatively low nutrient concentrations characterized this region. This zone is influenced by waters from the Gulf of Mexico and nutrient inputs from coastal lagoons with a high organic matter concentrations. In addition, this zone is characterized by a low level of human impacts and population density, which result in it being considered a well-conserved marine area of the Yucatan coast.

Hydrochemical zone II was also spatially discontinuous and included the locality of Sisal (S5) and a stretch of coast from Progreso to Telchac (S7–S10). It was characterized by low concentrations of dissolved oxygen (Fig. 2b), relatively high salinities, high nitrite, nitrate and SRSi concentrations (Figs. 2a, d, c, and g), and the range in values for SRP concentration was higher than in other areas (Fig. 2f). This zone is considered the most impacted by human activities for the entire system (Herrera-Silveira et al., 2004; Aranda-Cirerol et al., 2006), and this is largely due to artificial inlets that connect the mangrove swamp with the coastal sea (Telchac-Chabihau) and play an important role in the determination of water quality. In this sense, coastal systems are not isolated, as they exhibit a varying degree of connectivity with inland processes which have been to a large extent responsible for producing strong

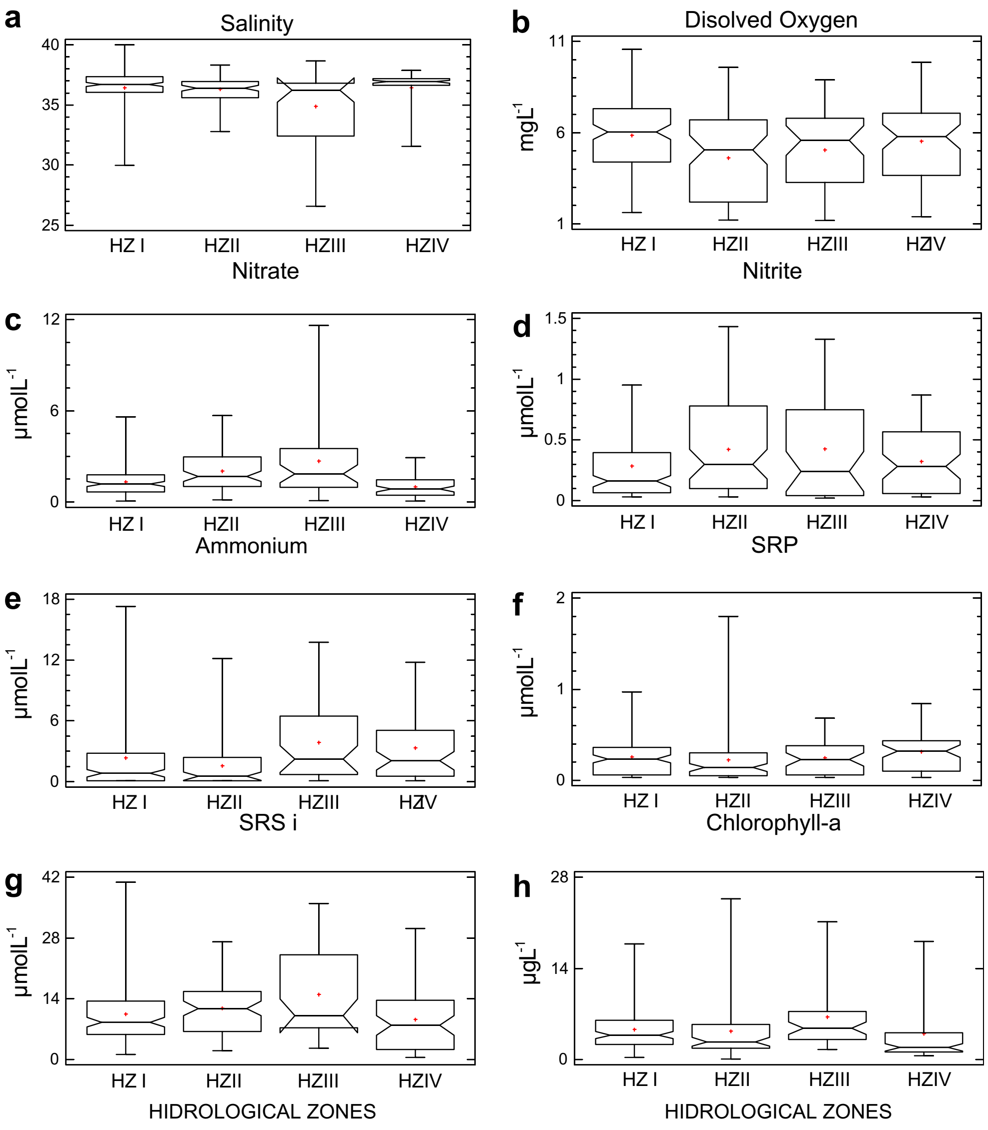

Fig. 2. Comparison between zones using water quality variables. (a) salinity, (b) dissolved oxygen (DO), (c) nitrate (NO_3), (d) nitrite(NO_2), (e) ammonium (NH_4), (f) Soluble reactive phosphorus (SRP). Boxes show the 25th, 50th and 75th percentiles. The 10th and 90th percentiles are shown with whiskers.

changes in N and P loads in this zone. These changes are related mainly to the geology, land use, degree of urbanization, source of wastewater, and nutrient exchanges with coastal ecosystems such as salt marshes, mangroves, and coral reefs (Tappin, 2002).

Hydrochemical zone III included a group of sampling stations located in the Dzilam region (S11–S13), where water conditions were characterized by low salinity (Fig. 2a) and high concentrations of nutrients such as: SRSi (Fig. 2g), nitrite (Fig. 2d), ammonium (Fig. 2e), nitrate (Fig. 2c) and Chl-*a* (Fig. 2h), all of which were related to direct groundwater discharges in the form of springs (SGD) which are widely distributed throughout this zone (Troccoli et al., 2004; Aranda-Cirerol et al., 2006). In addition, geomorphologic characteristics of this zone, namely the "sinkholes ring" area, most likely favor freshwater discharges to the sea (Perry et al., 1995). Results of the calculation of the dilution factor supported a conclusion that underground freshwater discharges in Dzilam had a large influence on conditions (no detailed results included for the analyses presented here).

Finally, hydrochemical zone IV included a group of stations located at the eastern portion of the study region, from station S17 to S20 (Rio Lagartos to El Cuyo). It was characterized by high salinity and relatively low concentrations of nitrates and Chl-*a* (Fig. 2c, 2h). However, SRP median values were higher (Fig. 2f) relative to the other zones. Water quality characteristics indicated a seasonal influence of Caribbean waters and the Cabo Catoche upwelling (Merino, 1997).

The specific results for water quality parameter analyses are detailed in Table 8.

3.2. Water quality indices (CI and TRIX)

Values for the Canadian index of water quality for aquatic life ranged from fair to poor in terms of the condition of the coastal marine system of Yucatan (values from 34 to 100; Fig. 3). Results of the TRIX index application (Table 1) indicated that the overall condition of the coastal study system was mesotrophic, which meant that conditions ranged from fair to good (Fig. 4). Generally, the worst water quality conditions (in trophic terms) were found at sites with the greatest influence from anthropogenic activities (S5, S7, S8 and S9 HZ II), while the best water conditions were located at sites where the terrestrial system was included in protected areas (S1–S3, S11–S13 zones HZI and HZIII). During this study, hurricane effects were also involved, it was observed that hurricanes cause reductions in water quality by increasing runoff from inland to the sea, indicating the degree of connection between the coastal wetlands and the sea, as well as reducing transparency and increasing nutrient and sediment concentrations in coastal waters. Hurricanes have shown short-term impacts in salinity and transparency reduction, while in the medium term nutrient inputs increase by runoff and remineralization (Steward et al., 2006).

The level of water quality for aquatic life (CI) found at the HZI was classified as fair (71–75) (Fig. 3), and overall not threatened. According to TRIX, this area showed a good trophic condition (mesotrophic), characterized by moderately productive waters (Table 1; Fig. 4). It was also characterized by natural nutrients inputs from the Celestun coastal lagoon (S1), as well as runoff from the mangrove fringe area (S3 and S4) and a high water residence time (Monreal-Gomez and Salas-de-Leon, 1990; Monreal-Gomez et al., 2004). These findings indicate that the water quality estimated through these indices should be considered normal for this zone, and this information could be useful to establish reference data or starting point for future monitoring programs. The choice of proper reference sites and the collection of historical data to define reference conditions have been focal points in previous initiatives such as the EEC and USA Water Framework Directives (Mangialajo et al., 2007; Muxika et al., 2007), and should be implemented by Mexican directives.

The HZII showed a fair condition according Canadian index, as its values ranged from 49 to 71 (Fig. 3). The area included within this zone is frequently threatened, making it show deviations from natural or desirable water quality values. Based on the TRIX index, the condition of this zone can be considered a transition from good to fair (meso-eutrophic) (Fig. 4), which corresponds to moderate and highly productive waters. The Chuburna-Progreso-Chicxulub area (S6, S7 and S8, mostly HZ II) water condition was related to domestic wastewater inputs from septic tanks which do not receive any pre-treatment, in addition to the coastal current pattern which has been modified and now favors an increase in the water residence time (Medina-Chan, 2004). The poor water quality found at the Sisal location (S5) is a consequence of the wastewater discharges from a shrimp farm, while the water condition at the Chabihau area (S9), is a result of the artificial connection between swamps with high nutrient content and the marine coastal area. Coastal lagoons and swamps are natural sources of nutrients to the coastal zone, however, their inputs occur seasonally through pulses related to natural climatic events such as hurricanes and storms (Newton and Mudge, 2005; Hagy et al., 2006). Thus, the physical modification of the water flux (i.e., artificial connection between these systems) could favor the eutrophication of sea water in this area.

The water quality condition at hydrochemical zones III and IV ranged from poor to good (35–90), with most of the data values between 69 and 98 and median around 72 (Fig. 3); this suggests the water health status is occasionally threatened. The trophic status of these zones ranged from fair (meso-oligotrophic) in HZIII, to good (mesotrophic) in HZIV (Fig. 4). The condition for the HZIII zone was associated with the greatest levels of SGD (Aranda-Cirerol et al., 2006), while results found for HZIV were influenced by Caribbean waters, as well as by a seasonal enrichment process that is attributed to the Cabo Catoche upwelling (Merino, 1997).

3.3. Water quality assessment using regional reference values of indicator variables

The reference values which result from the application of modified criteria of USEPA are shown in Table 4. Fig. 5 shows the contribution of water quality variables and indices to the overall assessment of conditions in Yucatan coastal waters. Specifically, about 52% of the entire area sampled can be classified as in good condition, 38% in fair condition, and 10% in poor condition. HZII showed symptoms of water quality deterioration and primary symptoms of eutrophication, while HZIV had the best conservation status for the entire study region, with most of its metric values indicating a good condition (Fig. 5). The spatial heterogeneity in water quality variables and index values throughout the Yucatan coast is likely to be associated with the relative contribution of local and regional forcing functions such as wastewater discharges, altered water residence times (e.g., HZII), submerged groundwater discharges and the influence of Caribbean waters (e.g., HZIII and IV, respectively).

3.3.1. ASSETS eutrophication assessment

The results of the ASSETS application shows that the influencing factors for Progreso are high meaning that human related activities contribute significantly to the nutrient load to this system. This compares to a moderate level of influencing factors for Dzilam which indicates that there are oceanic processes that may partially influence the Dzilam system but that human related inputs are still important. The overall condition of Progreso is high but conditions are moderate for Dzilam since in the first one primary and secondary symptoms of eutrophication have been detected. In Progreso

Table 8
Statistical description of hydrology parameters and indices.

Station	Statistics	k (m^{-1})	T (°C)	Salinity	DO	Chl-*a*	NO_3	NO_3	NH_4	SRP	SRSi	CI	TRIX
1	Mediana	1.77	28.69	36.77	6.3	5.39	1.54	0.09	0.98	0.22	7.7	72.5	4.43
	SE	0.22	0.78	0.22	0.37	0.59	0.37	0.08	0.83	0.05	1.33	3.46	0.17
	Mín	0.43	22.4	35.09	2.5	0.74	0.22	0.03	0.1	0.03	2	42	3.47
	Máx	3.66	31.06	38	7.79	9.35	5.59	0.89	10.04	0.68	17.5	90.2	6.02
2	Mediana	1.25	28.76	36.53	6.16	4.62	0.92	0.12	0.54	0.16	10.15	71.4	4.54
	SE	0.2	0.75	0.47	0.48	1.23	0.25	0.08	1.01	0.03	1.08	3.39	0.17
	Mín	0.23	22.2	30.2	3.9	0.4	0.05	0.03	0.1	0.03	1.5	42.9	2.87
	Máx	2.77	31.1	37.88	10.56	17.36	3.07	0.87	15.4	0.37	13.85	90.8	5.33
3	Mediana	1.25	28.76	36.56	6.45	3.48	1.28	0.18	0.31	0.27	6.9	71.9	4.13
	SE	0.18	0.8	0.25	0.38	0.51	0.2	0.06	0.62	0.08	1.15	3.83	0.16
	Mín	0.19	21.8	33.66	4.1	0.37	0.05	0.03	0.1	0.03	2.5	42.9	3.22
	Máx	2.49	30.8	37.44	8.57	8.2	2.98	0.71	8.76	0.97	15.9	100	5.22
4	Mediana	1.37	28.67	36.18	6.1	5.72	1.96	0.18	0.77	0.27	10.05	71.7	4.36
	SE	0.14	0.78	0.22	0.47	0.75	0.22	0.07	0.25	0.05	1.58	4.24	0.19
	Mín	0.52	22	35.17	3.05	0.32	0.67	0.08	0.1	0.03	2	52.9	3.28
	Máx	2.41	31.27	37.93	8.78	9.97	3.69	0.88	2.94	0.7	22.35	100	5.52
5	Mediana	1.33	28.6	36.4	5.6	2.78	2.99	0.25	0.1	0.11	13	71.7	4.61
	SE	0.18	0.8	0.24	0.53	0.66	0.34	0.07	0.61	0.12	1.36	2.54	0.26
	Mín	0.37	21.8	35.36	1.61	0.05	1.02	0.1	0.1	0.03	3	53.3	2.43
	Máx	2.68	31.03	38.32	9.58	8.31	5.68	0.96	8.19	1.8	17.8	89.9	5.78
6	Mediana	0.68	28.45	36.81	6.2	4.07	1.29	0.18	0.36	0.2	7	65.8	4.39
	SE	0.24	0.81	0.18	0.57	1.1	0.19	0.07	0.72	0.05	0.87	2.78	0.13
	Mín	0.11	21.6	35.58	2.08	1.85	0.19	0.03	0.1	0.03	1.8	49.4	3.63
	Máx	3.51	30.96	37.95	9.4	17.75	2.89	0.87	10.04	0.55	13.95	89.3	5.2
7	Mediana	1.64	28.56	36.93	7.37	5.75	0.96	0.7	5.61	0.42	5.75	49.4	5.17
	SE	0.31	0.72	0.45	0.62	0.78	0.77	0.11	1.37	0.07	2.1	1.35	0.14
	Mín	0.35	21.6	31.06	1.18	1.32	0.05	0.03	0.1	0.03	1.4	34.6	4.11
	Máx	4.71	30.71	38.65	8.9	10.05	11.61	1.33	15.4	0.84	24.1	52.8	6.02
8	Mediana	0.9	28.13	36.41	4	3.65	1.04	0.25	0.1	0.11	10	72.3	4.58
	SE	0.13	0.82	0.28	0.69	1.36	0.25	0.11	0.3	0.06	1.21	3.61	0.17
	Mín	0.33	21.8	34.99	1.26	1.56	0.56	0.03	0.1	0.03	2	53.2	3.26
	Máx	2.37	31.16	38.24	8.27	18.19	3.6	1.17	3.69	0.65	18.8	100	5.56
9	Mediana	1.06	27.96	36.24	4.48	2.77	1.97	0.41	0.1	0.18	9.7	77.1	4.47
	SE	0.16	0.84	0.26	0.59	1.56	0.31	0.12	0.22	0.04	2.03	3.49	0.24
	Mín	0.16	21.4	34.66	1.23	0.46	0.14	0.03	0.1	0.03	2.7	52.8	2.41
	Máx	2.56	31.29	37.99	7.29	24.7	4.18	1.43	2.58	0.53	27.1	100	5.69
10	Mediana	1.12	27.67	35.8	4.5	1.84	1.21	0.41	1.29	0.27	15.35	81.5	4.48
	SE	0.22	0.82	0.4	0.53	0.65	0.35	0.1	0.59	0.04	1.48	4.77	0.24
	Mín	0.56	21.8	32.78	1.25	0.46	0.15	0.03	0.1	0.03	5.1	45	2.7
	Máx	3.04	31.71	37.48	7.7	10.05	4.08	1.1	6.24	0.43	24.05	100	5.47
11	Mediana	0.86	30.79	35.71	4.12	2.07	1	0.1	0.1	0.14	15.8	100	3.57
	SE	0.1	0.35	0.27	0.33	0.37	0.08	0.04	0.3	0.02	0.58	1.19	0.13
	Mín	0.48	27.89	32.8	1.99	0.46	0.49	0.03	0.1	0.03	13.6	90.9	2.7
	Máx	1.75	32.7	37.19	6.36	5.83	1.49	0.68	3.15	0.29	20.9	100	4.48
12	Mediana	1.37	29.51	36.3	4.78	4.65	0.96	0.14	4.16	0.22	9.4	70.2	4.86
	SE	0.2	0.94	0.68	0.57	0.62	0.38	0.11	0.96	0.04	3.07	2.67	0.15
	Mín	0.2	21.5	30.36	2.04	1.56	0.09	0.02	0.1	0.03	2.55	53.1	3.53
	Máx	3.07	32.12	38.12	8.3	11.23	5.25	1.12	10.82	0.5	35.9	90.2	5.3
13	Mediana	1.27	29.08	36.52	6.11	7.75	1.85	0.18	2.06	0.28	9.3	69.4	5.09
	SE	0.25	0.87	0.87	0.49	1.71	0.33	0.1	1.09	0.04	2.8	3.24	0.21
	Mín	0.55	21.7	26.57	2.5	1.58	0.32	0.03	0.1	0.03	2.95	34.6	3.31
	Máx	3.98	31.46	38.65	8.04	21.17	4.14	1.04	13.74	0.48	34.8	84.7	5.86
14	Mediana	1.67	28.92	36.58	5	2.86	1	0.23	2.21	0.18	10.2	71.6	4.27
	SE	0.31	1.05	0.73	0.49	0.57	0.13	0.08	0.83	0.03	2.87	3.52	0.16
	Mín	0.56	21.4	29.96	2.8	1.11	0.05	0.03	0.1	0.03	2.8	52.8	3
	Máx	4.21	33.9	39.7	8.4	9.23	1.63	0.95	12.62	0.42	40.8	100	5.11
15	Mediana	1.19	28.86	36.6	5	1.9	0.81	0.11	1.34	0.23	9.8	72.7	4.43
	SE	0.18	1.01	0.68	0.64	0.88	0.19	0.07	1.07	0.04	2.66	2.53	0.13
	Máx	2.56	34.33	40	8.4	13.45	2.67	0.77	11.85	0.65	33.45	89.9	5.25
	Mín	0.13	21.6	30.89	1.62	0.79	0.05	0.03	0.1	0.03	1.4	59.3	3.62
16	Mediana	0.74	28.75	37.3	5.6	2.45	0.82	0.16	1.44	0.36	8.4	72.3	4.17
	SE	0.1	1.11	0.56	0.45	0.86	0.16	0.08	1.39	0.04	1.72	2.89	0.15
	Mín	0.05	21.3	31.34	2.27	1.14	0.05	0.03	0.1	0.03	1.2	51.1	3.42
	Máx	1.47	34.36	37.55	8.06	11.13	2.34	0.9	17.31	0.54	25.07	89.4	5.17
17	Mediana	1.16	28.27	36.93	5.2	2.64	0.81	0.32	2.11	0.41	6.35	65.3	4.41
	SE	0.29	1.05	0.18	0.52	0.76	0.21	0.07	1.01	0.07	1.46	3.21	0.13
	Mín	0.1	20.8	35.34	1.4	0.57	0.05	0.03	0.1	0.03	1.4	50.6	3.76
	Máx	4.71	33.06	37.3	7.5	10.81	2.35	0.7	11.77	0.84	20.15	90.9	5.44

(*continued on next page*)

Table 8 (*continued*)

Station	Statistics	k (m^{-1})	T (°C)	Salinity	DO	Chl-*a*	NO_3	NO_3	NH_4	SRP	SRSi	CI	TRIX
18	Mediana	0.45	28.16	37.09	4.5	1.56	0.82	0.26	1.7	0.32	9.95	78	4.16
	SE	0.15	0.96	0.22	0.45	0.95	0.23	0.06	1	0.04	2.51	2.68	0.19
	Mín	0.03	21	35.02	2.6	0.59	0.05	0.04	0.1	0.03	1.3	60.1	2.91
	Máx	2.07	32.2	37.26	7.9	11.23	2.91	0.75	11.31	0.57	30.2	89.4	5.5
19	Mediana	0.76	28.33	36.8	6.27	1.19	0.89	0.28	2.47	0.29	7.8	68.5	4.24
	SE	0.14	0.93	0.38	0.52	1.79	0.18	0.08	0.95	0.05	1.3	1.94	0.19
	Mín	0.14	20.9	33.52	2.4	0.58	0.18	0.03	0.1	0.03	1.1	56.4	2.92
	Máx	2.26	31.4	37.86	9.42	18.14	2.48	0.87	11.64	0.59	16	81.5	5.78
20	Mediana	0.75	28.16	36.8	6.2	2.3	0.95	0.23	1.55	0.3	13.35	73.3	4.54
	SE	0.22	0.92	0.59	0.61	1.14	0.13	0.07	0.68	0.05	2.06	2.24	0.21
	Mín	0.14	20.4	31.56	1.78	0.79	0.05	0.03	0.1	0.03	0.5	54.9	2.75
	Máx	3.57	31.21	37.8	9.86	17.45	1.64	0.78	7.23	0.7	25.1	81.8	5.39

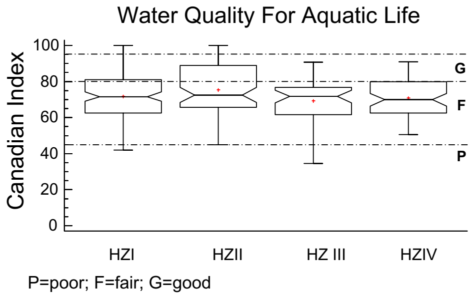

Fig. 3. Canadian index (CI) values for each hydrological zone. For this study G-good combines excellent (95–100), and good (80–94),of original CI; F-fair combines fair (65–79) and marginal (45–64) of original CI and poor P-poor (0–44).

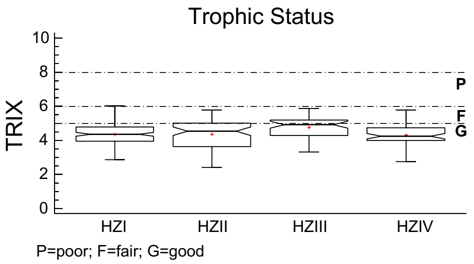

Fig. 4. TRIX index values for each hydrological zone. G-good water quality (combines high and good of original TRIX); F-Fair; P-poor. Good.

filamentous green macroalgae are dominant, the seagrasses coverage has disappear in the first kilometer offshore; there is an interruption of coastal water flux which results in the stem of water with high chlorophyll-*a* and low dissolved oxygen (1.41 mg l^{-1}), also the septic tanks used to collapse and let all the urea content flow trough groundwater to the sea, then HAB occurrences are more persistent and closer to the shore. In the case of Dzlam the moderate condition is due to the groundwater discharges facilitated by sinkholes ring which catch water from cattle ranch and rubbish dump, seagrasses coverage is not a problem, the HAB occurrences are not persistent. For Progreso, there will be changes in the watershed in the future because the increases in population, tourism and gulf courses development, also it is almost a fact that oil extraction begins and it means urban development that will cause much worse conditions than are observed at present. For Dzilam, no change is expected in the condition in the future because part of the land and marine area has been constitute as a natural conservancy zone, also this is a fisherman locality which is far from big cities, then low impact activities as bird watching, and boat trips seems to became complementary activities in the future.

The combined components indicate that Progreso has poor overall rating and that Dzilam is good. While these results show that the relative scores are the same as for the TRIX and Canadian Index results, Progreso is in worse condition than Dzilam, the ASSETS results indicate a worse condition in Progreso than indicated by the Trix and the Canadian Index results (Table 9). The reason for this may be explained by the fact that the Trix and Canadian methods use Chl-*a*, dissolved oxygen and nutrient concentrations while the ASSETS uses additional biological indicators (macroalgae, submerged aquatic vegetation spatial coverage, HAB occurrence) and thus draws from a greater number of the possible impacts than the other two indices do. Additionally, nutrient concentrations are not used in the ASSETS method but are used in the other two methods. The use of concentrations can be misleading since low concentrations may be interpreted as a low impact of eutrophication when in actuality concentrations may be low while algae blooms are excessive. On the other hand, high concentrations can be mistakenly interpreted as high impact of eutrophication in cases where turbidity from suspended sediments may limit algal growth and thus limit the development of low dissolved oxygen and other eutrophication related problems.

3.3.2. Phytoplankton metrics and water condition

Four phytoplankton zones (PZ) were identified based on phytoplankton species composition, richness and abundance, as well as on the richness and abundance of harmful species (HABs). These zones did not overlap completely with those identified for the water quality component; nonetheless, they were spatially distributed in a similar way (Fig. 6). Differences in the distribution of zoning types may be due to a time lag in the phytoplankton community response to hydrochemical conditions, as well as to transportation via currents and tides. Additionally, at each location we observed connectivity between the terrestrial and the coastal marine ecosystems, as well as a salinity continuum from low to high levels (Arhonditsis et al., 2003). Phytoplankton metrics were related to local water quality conditions, indicating their dependence on resource availability and the environmental matrix (Morales-Ojeda, 2007).

Based on phytoplankton metrics, the marine coastal condition for Yucatan may be considered generally good with a tendency to fair values; specifically, 49% of the marine samples had a good condition, 39% had a fair condition, and 12% showed a bad condition which was associated with primary symptoms of eutrophication (e.g., at Sisal [S6], Progreso [S7] and Chicxulub [S8]). Phytoplankton represents a good short-term biological indicator of primary symptoms of eutrophication in areas impacted by anthropogenic activities. Moreover, harmful phytoplankton species richness and abundance can be used to identify specific sites which are at high risk of developing a HAB (Cloern, 2001). Phytoplankton community measures are a primary tool in diagnosing eutrophica-

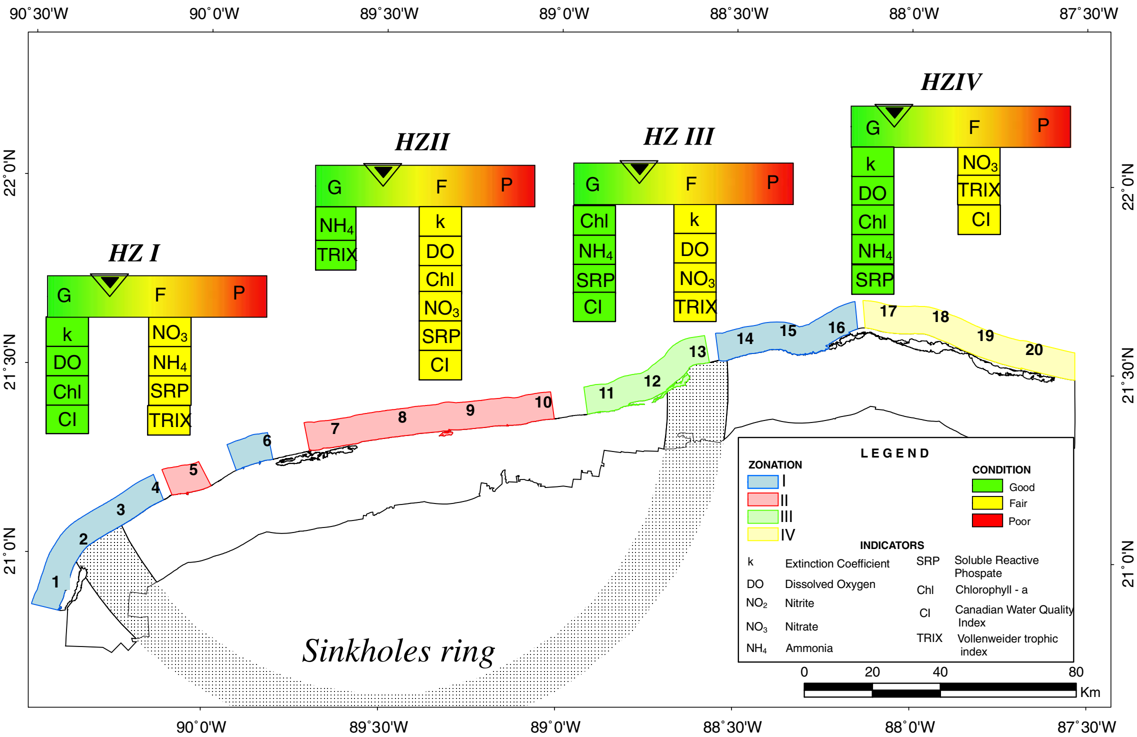

Fig. 5. Overall water quality health status of marine water in Yucatan, Mexico. Coloured arrows over the condition band indicate the global status based on water quality; indicator variables are also represented below the condition band. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 9
Comparisons among the three approaches: TRIX, CANADIAN INDEX and ASSETS.

Sites	Trix		Canadian index		Assets[a]			
	Mean Values	Condition	Mean Values	Condition	Index			Condition
					IF	OEC	FO	
Progreso	5.2	Fair	48	Fair	H	H	WH	Poor
Dzilam	3.6	Good	96.3	Good	M	M	NC	Good

[a] ASSETS IF, influencing factors or pressure; OEC, overall eutrophic condition or state; FO, Future outlook or response; and condition, ASSETS synthesis which is a single rating that is a combination of the three components.

tion, not only because they serve to detect an initial response to nutrient enrichment, but also because they encompass a wide range of taxonomic and functional diversity which is closely linked to marine ecosystem health (Devlin et al., 2007). In this study, 15 harmful phytoplankton species were identified (Table 10), which represented an additional two species compared to results reported by Alvarez-Gongora and Herrera-Silveria (2006). This difference in results may be partial evidence suggesting that coastal marine environmental conditions continue deteriorating.

Based on phytoplankton metrics, zone I (PZI), which included stations S1–S4 (Celestun to Punta Baz), was characterized by a mix of oceanic and coastal phytoplankton species, reflecting a connection zone where water from the coastal lagoon and Celestun wetlands meets Gulf of Mexico waters. The dominant phytoplankton species found in this area are tolerant to salinity and water transparency (Morales-Ojeda, 2007; Alvarez, 2004). In addition, this zone showed a great abundance and number of harmful phytoplankton species; however, HAB events have not been reported for this area (Troccoli-Ghinaglia, 2001; Alvarez-Gongora and Herrera-Silveria, 2006). Despite richness and abundance values for such harmful species, this area showed an overall good or at least fair condition (Fig. 6). The hydrodynamics of this zone suggest a high water residence time and coastal upwelling (Monreal-Gomez et al., 2004) which favors greater phytoplankton richness and abundance resulting in greater Chl-*a* average concentrations (Fig. 2h).

In the case of PZII, which extended from Sisal (E5) to Dzilam (E11), coastal species dominated (e.g. *Prorocentrum minimum*, *Bidulphia tuomeyii*) and cyanophyte species were common (*Merismopedia elegans*, *Merismopedia glauca* and *Merismopedia tenuísima*). Phytoplankton community cell abundance was high, and this zone showed the highest number of HAB species richness registered for this study (Table 11), making it highly susceptible to develop a HAB. This situation is aggravated by the fact that nutrient inputs due to human activities are more persistent and intense than ever within the region (Herrera-Silveira et al., 2004; Aranda-Cirerol et al., 2006). Based on phytoplankton metrics, the overall condition of this area can be considered fair with a tendency to worsen (Fig. 6).

Results for PZIII (S12–S15) and IV (S16–S20) show overall good condition according to phytoplankton community metrics (Table 5) however, some differences were observed between these two zones. The former was characterized by benthic coastal species (*C. closterium*) and showed the highest phytoplankton community species richness (Table 11); it was also the zone where the inshore Yucatan HAB event started, and is characterized by being influenced by nutrient input pulses from groundwater discharges in the form of springs, as well as the presence of extense seagrass beds abundant in epiphyte cists (Alvarez-Gongora and Herrera-Silveria, 2006). On the other hand, PZIV showed a phytoplankton species composition characteristic of oligotrophic and warm marine waters (e.g. *Cerataulina pelagica*, *Leptocylindrus danicus*, *Guirnardia flacida*, *Pseudonitzschia pungens*, various species of *Rhizosolenia*, and pico phytoplankton organisms). Overall, phytoplankton community species richness and abundances were low (Table 11)

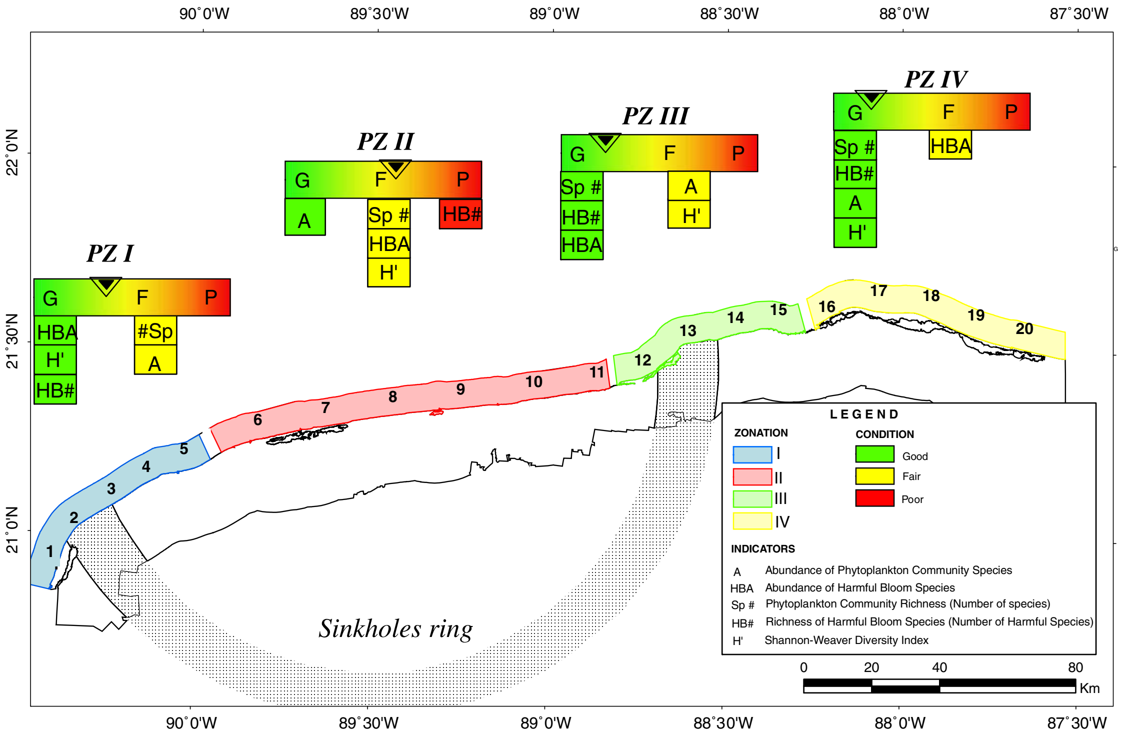

Fig. 6. Overall condition of the phytoplankton community and harmful algal blooms (HAB) for the coastal marine system of Yucatan. Coloured arrows over the condition band indicate the global status based on the phytoplankton; indicator variables are also represented below the condition band. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 10
Harmful phytoplankton species found in the marine coastal system of Yucatan. (NT = non-toxic. T = toxic).

HAB species	
Nitzschia longissima var. *reversa*	(NT)
Cylindrotheca closterium	(NT)
Scrippsiella trochoidea	(NT)
Gonyaulax polygramma	(NT)
Heterocapsa circularisquama	(T)
Dinophysis caudata	(T)
Gambierdiscus toxicus	(T)
Prorocentrum minimum	(T)
Pyrodinium bahamense var. *compressum*	(T)
Pseudonitzschia-delicatissima	(T)
Prorocentrum lima	(T)
Prorocentrum dentatum	(T)
Akashiwo sanguinea	(T)
Prorocenrum mexicanum	(T)
Karenia brevis	(T)

Table 11
Median values for phytoplankton measures per zone.

	Phytoplankton community			HAB's species	
Zone	Richness (no. of species)	Abundance (Cel/ml)	Shannon div. index *H*′ (bit/ind)	Richness (no. of species)	Abundance (Cel/ml)
I	27	524	0.7	3	25
II	20	87	0.8	4	16.4
III	20	55	0.7	3	12.6
IV	10	72	0.6	3	11.7

compared to the other zones. This zone is influenced by oligotrophic waters from the Caribbean current, and is seasonally affected by the Cabo Catoche upwelling (Troccoli et al., 2004), which causes changes in phytoplankton abundance and species composition. The initiation of the *Karenia brevis* toxic HAB along the west coast of Florida has been associated with upwelling events, which may be responsible for the transport of nutrients or algae from deep offshore locations across the Florida shelf to the coast (Lanerolle et al., 2006). In the same way, the Cabo Catoche upwelling could play a similar role in our study system.

3.3.3. Submerged aquatic vegetation (SAV)

The northern coast of Yucatan showed hydrological and physiographic conditions which favor the presence of more than 40 species of algae and seagrasses covering the seafloor (Aguayo, 2003; Herrera-Silveira et al., 2004). A total of four SAV zones were identified for the study system based on species composition, abundance and temporal changes (Fig. 7). Changes in SAV species composition and reductions in cover have been used as a secondary symptom for eutrophication in coastal ecosystems (Cloern, 2001; Bricker et al., 1999; Bricker et al., 2003; Bricker et al., 2007). SAV metrics indicated that the overall condition of the coastal marine system under study was good with a tendency to become fair. Specifically, 50% of the coast area sampled showed to be in good condition, 30% in fair condition and 20% in bad condition. Signs of deterioration were observed at locations such as Celestun (S1), as well as from Sisal (S6) to Telchac (S9). In the case of Celestun, the coastal trawl fishery has severely impacted SAV coverage, while for locations from Sisal to Telchac a series of portuary, urban and tourist development activities (dredging, docks, beach filling, fishing practices, sewage in septic tanks) have altered watershed conditions and impacted water quality, biodiversity and primary producers.

Four seagrass species (*Thalassia testudinum*, *Halodule wrightii*, *Syringodium filiforme* and *Halophila decipiens*) and more than 35 algae species were recorded, of which the most common were cal-

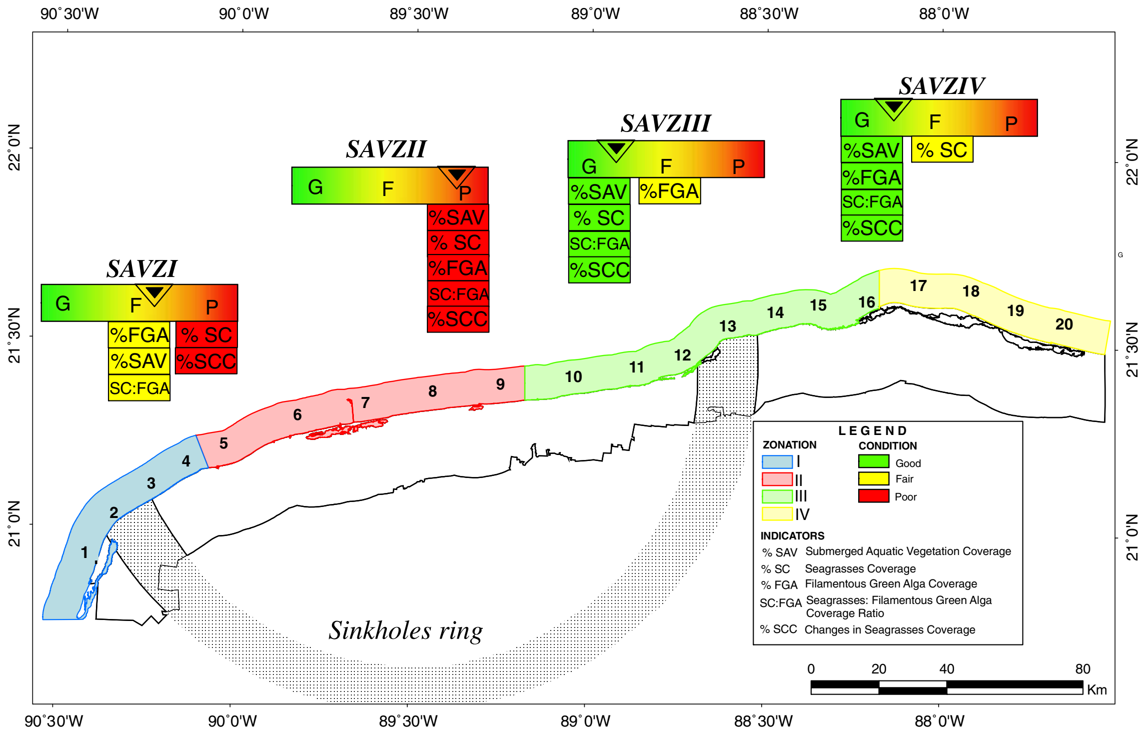

Fig. 7. Overall condition of the coastal marine system of Yucatan based on submerged aquatic vegetation (SAV). Coloured arrows over the condition band indicate the global status based on the SAV; indicator variables are also represented below the condition band. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

careous green algae (*Penicillus capitatus, Caulerpa mexicanum Caulerpa proliferates, Halimeda tuna, Halimeda monile, Halimeda incrassata, Acetabularia crenulata* and *Udotea flabellum*) and other opportunist species (*Hypnea* sp., *Laurencia* sp., *Bostrichia* sp., *Ripocephalus* sp., *Chaetomorpha* sp. and *Enteromorpha* sp.) which have been shown to respond to pollution (Patricio, 2007).

The SAVZI was dominated by small and discrete seagrass patches of *H. wrightii* and *T. testudinum* (the latter to a lesser extent), with a relative cover between 5% and 40%. The lowest cover was recorded in front of the port of Celestun, and this finding was probably more due to trawl fisheries than to low water quality (Fig. 5). A study conducted at the Mediterranean coast showed that repeated passes of trawl gear over seagrass beds caused the mechanical damage on *Posidonia oceanica* meadows by pulling up leaves and rhizomes (Sanchez Jerez and Ramos Espala, 1996). Finally, algae showed relatively low abundance values indicating fair conditions (Fig. 7).

SAVZII has experienced a loss of 80% of its original SAV cover during the last ten years (Aguayo, 2003). Species dominance patterns mostly in areas < 3m deep shifted from the seagrass *T. testudinum* to green filamentous algae (*Chaetomorpha* sp., *Enteromorpha* sp.) and *Caulerpa* sp., indicating human impacts on water quality and sediment characteristics. Field evidence and experimental research indicate that cultural eutrophication is the major cause of seagrass disappearance due to light reduction through stimulation of high-biomass algal overgrowth in the form of epiphytes and macroalgae in shallow coastal areas, and as phytoplankton at deeper coastal waters (Burkholder et al., 2007).

SAVZIII was characterized by the highest SAV cover values (50–100%), with *H. wrightii* dominating in shallow areas (<1.5 m depth), while *T. testudinum* and *S. filiforme* mixed with calcareous green, brown and red algae dominated in deeper regions (1.5–4 m depth). Human impacts in this zone are of low intensity, and conditions of low marine currents which favor sedimentation and nutrient inputs via springs could favor SAV development. For example, in coastal regions with significant groundwater discharges, vigorous growth of some rooted aquatic plants has been observed at reduced interstitial salinities as a consequence of elevated nutrient availability and reduced osmotic stress (Johannes, 1980).

Although SAVZIV was dominated by calcareous green and red algae mixed with low cover levels of *S. filiforme* and *T. testudinum* (5–40%), its overall condition was considered good. Sediments are scarce in this zone, and water currents during the sampling periods were more intense relative to other areas which posed logistic constraints on data recording. In this sense, it has been observed that hydrodynamics are strongly related to sediment characteristics (texture) and depth, which are key variables for seagrass establishment (Peralta et al., 2005).

3.4. Overall coastal condition

The combined water quality, phytoplankton, and SAV metrics indicated that 53% of the sampled coastal marine system of Yucatan is in good condition, 40% in fair condition and 7% in poor condition (Fig. 8). Degradation symptoms are more evident in the central region, from Sisal to Telchac (stations S5–S9), where human activities have diversified and become more intense. For instance, the port terminal at Progreso acts as a physical barrier, affecting the coastal current pattern; in addition, this portion of the coast supports the largest proportion of the coastal population of Yucatan which results in high nutrient inputs from waste waters, via seepages and punctual groundwater discharges to the ocean, as well as shrimp farms in the particular case of the locality of Sisal.

Remaining zones showed an overall good condition. Nonetheless, the coastal urban development and inland activities are having a negative impact and this is evident in terms of the water quality component and SAV at the localities of Celestun (S1–S4) and Dzilam (S10–S15), and this condition is especially critical at

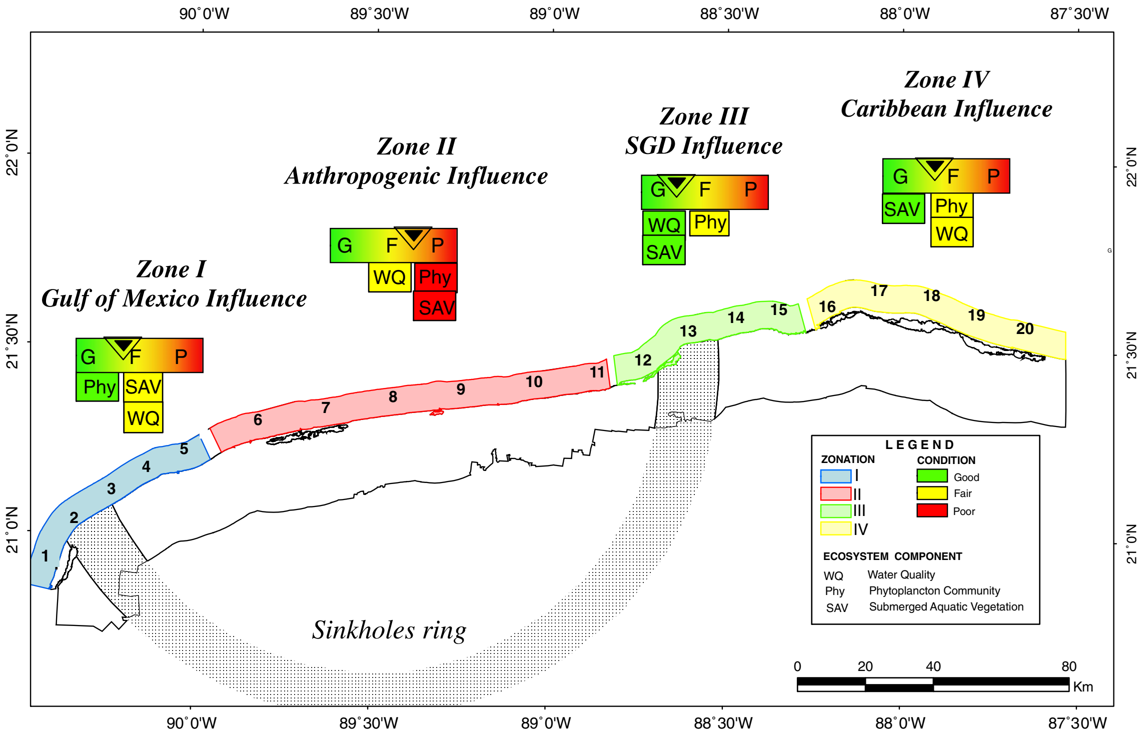

Fig. 8. Overall condition of the coastal marine system of Yucatan based on the three components considered. Coloured arrows over the condition band indicate the global status based on the water quality, phytoplankton and SAV; echa component is also represented below the condition band. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sites with high levels of connectivity between groundwater discharges and the ocean associated to the "sinkhole ring" area.

The diagnosis based on water quality, phytoplankton and SAV conducted in this study has helped to identify differences in the magnitude of values for the measured variables within each zone (i.e., subregional scale), as well as to recognize that each metric responds differently according to site-specific combinations of local and regional conditions. However, the variability observed in the data for each metric used at the finest spatial scale (i.e., within stations) suggests that in order to improve the robustness of future analyses of this type and the efficiency of resulting management strategies, this evaluation should be done at finer spatial scale.

This is the first attempt to establish the ecological condition of a marine coastal ecosystem in Mexico based on three components: water quality, phytoplankton and SAV. The classification criteria used here to define the thresholds for each condition are based on analysis of available data recorded during 5-years of research and monitoring. This adds strength to these results which should be useful as baseline information for future monitoring programs that evaluate whether the condition of each zone improves or worsens after the proposed actions in the marine coastal zoning program are implemented. The classification criteria used to establish the boundary conditions for each variable are based on a deviation from a reference condition; we expect that as more information becomes available, extreme conditions will potentially be revised as well as our confidence in the reference data.

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