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Ecosystem Functioning: The Basis For Sustainable Management Of Términos Lagoon, Campeche, Mexico

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ECOSYSTEM FUNCTIONING, THE BASIS FOR SUSTAINABLE MANAGEMENT OF TERMINOS LAGOON, CAMPECHE MEXICO

Alejandro Yáñez-Arancibia and John W. Day

Outline

ABSTRACT

For a more comprehensive understanding of the ecosystem functioning coupling physical and biological processes, which is a key concern in the ecosystem-based management approach, we consider four main aspects as important for understanding the functional structure of the Terminos Lagoon ecosystem: (**1**) Historical ecological patterns and the river-basin context, (**2**) Environmental pulsing, physical and chemical seasonality, and metabolism, (**3**) The functional dynamics and ecosystem profile of system, and (**4**) Water budget of Terminos Lagoon. Hydrology and water budget in this tropical coastal ecosystem are important for a number of reasons: (**1**) For estimating the flushing time, or residence time, of mixed estuarine waters in the Lagoon, (**2**) For estimating the nutrients exported to the adjacent Gulf, (**3**) To estimate the metabolism, i.e. production/consumption rates of the system, and to understand the seasonality of aquatic primary productivity patterns, (**4**) To estimate both retention (in the Lagoon) and dispersion/exportation of pollutants (onto the adjacent Ocean) based on the hydrodynamics of the Lagoon. Major values for the water budget and residence time calculations are as follows. The system has a water surface area of 1700 km^2 with a mean depth of 3.5 m. We divided the lagoon into two main sub-systems: the western riverine-influenced 1/3 of the lagoon (567 km^2) and the eastern marine-influenced 2/3 of the lagoon (1134 km^2). Wetland surface, including marshes and mangrove swamps, is 1300 km^2 with a mean water depth 0.2 m. Mean annual river discharge 516 m^3 sec^{-1}, ground water discharge is estimated as 4 x 10^6 m^3 yr^{-1}, average precipitation is 1805 mm yr^{-1}, and average evaporation is 1512 mm yr^{-1}. The mean tidal range is 0.43 m and the volume of tidal prism is 991 x 10^6 m^3. The average salinity ranges from 36 in the adjacent ocean, 35 in Puerto Real inlet, 22 in the mid lagoon, and 0 to 4 into the fluvial-lagoon systems. The system has three ecological periods in a year: nortes (October to February), dry (March to May), and rainy (June to September). This environmental forcing results in a strong seasonality for most physical parameters in the lagoon, i.e., 492 m^3 sec^{-1} of freshwater inflow and a residence time of 1 month during rainy season in the 1/3 Western area, to 4 m^3 sec^{-1} of net freshwater inflow and a residence time of almost 7 months during the dry season in the Eastern 2/3 of the lagoon. We conclude that ecosystem functioning of this pulsing tropical lagoon-estuarine system is the basis for its sustainable management, where coupling physical-biological processes and socio-economic activities should be done in a manner that preserves the subsidies and energetic behavior.

Key words: Tropical lagoon-estuarine system, ecosystem profile, hydrology, water budget, residence time, ecosystem functioning, coastal management, Terminos Lagoon, Gulf of Mexico

1. Introduction

1.1 Ecosystem functioning historical background

Terminos Lagoon is one of the key ecosystems for tropical estuarine and coastal ecology, and over the last 35 years, this ecosystem in the southern Gulf of Mexico, has been the focus of national and international attention because of its ecological and economic importance and the actual and potential impact of human activities. Human activities include urban development into sensitive areas, agricultural activities in the low-land seasonal wetlands, oil and gas activities, over fishing, dredging, deforestation of both freshwater wetland forests and mangroves, shortage of freshwater, and others.

Terminos Lagoon is a critical estuarine ecosystem and extremely important for comprehensive ecosystem-based management studies because of at least ten critical reasons:

(**1**) High natural primary productivity (Day et al. 1982, 1986, 1988, 1996) and high secondary production (Pauly et al. 1999),

(**2**) High ecological diversity, in terms of biological species, functional groups of population assemblages, and habitats (Yanez-Arancibia and Day 1982, 1988; Rojas-Galaviz et al. 1992; Pauly and Yanez-Arancibia 1994; Sanchez-Gil and Yanez-Arancibia 1997; Yanez-Arancibia et al. 1999),

(**3**) Valuable fish, oyster, shellfish, and wildlife resources including the most important fishery area in the southern Gulf of Mexico (Deegan et al. 1986; Yanez-Arancibia and Day 1988, Yanez-Arancibia and Aguirre-Leon 1988; Yanez-Arancibia et al. 1991, 1992; Lara-Dominguez et al. 1993; Reyes et al. 1993;

Pauly and Yanez-Arancibia 1994; Sanchez-Gil and Yanez-Arancibia 1997; Vidal and Pauly 2004),

(**4**) Functional relationships with Campeche Sound through the functioning of estuarine inlets, and the coupling among primary productivity, habitats, and fish community ecology and dynamics (Yanez-Arancibia et al. 1980, 1985a, 1988, 1991, 1993a, 2004; Day and Yanez-Arancibia 1988; Yanez-Arancibia and Day 1982, 1988; Soberon-Chavez et al. 1988; Sanchez-Gil and Yanez-Arancibia 1997),

(**5**) Environmental seasonality and hydro-biological conditions (Yanez-Arancibia and Day 1982, 1988; Yanez-Arancibia et al. 1983; Yanez-Arancibia and Sanchez-Gil 1983; Vera-Herrera et al. 1988; Herrera-Silveira et al. 2002),

(**6**) Temporal changes in the environmental behavior of the system (Yanez-Arancibia and Day 1982), and the current hydrodynamic quantitative status (Herrera-Silveira et al. 2002).

(**7**) Current and proposed oil and gas activities and petrochemical industries (PEMEX-PEP 2004),

(**8**) The inclusion of a large part of the Terminos Lagoon ecosystem in the Mexican National System of Natural Protected Areas as the *Area de Proteccion de Flora y Fauna Silvestre y Acuatica* (Yanez-Arancibia et al. 1993b; DOF1994; CONANP 2004).

(**9**) The extremely complex social, economic, and ecological systems, and a complex set of federal and state regulations, makes the functioning of the established management program very complicated (SEMARNAT-INE 1997; Yanez-Arancibia et al. 1999; Currie-Alder 2004).

(10) There is insufficient attention to the idea of the functional structure of The Terminos Lagoon ecosystem as a basis for sustainable management of the region. Both ecosystems and resources of the coastal ocean system should be managed to reflect the relationships among all ecosystem components, including humans and nonhuman species and the environment in which they live.

Applying this principle will require defining relevant geographic management areas based on the ecosystem approach, rather than political subdivisions (Yanez-Arancibia and Day 2004a, 2004b; Day and Yanez-Arancibia 2005; Compass 2005, Boesch 2005).

1.2 Historical ecological patterns and the river-basin context

Because of its tropical location, Terminos Lagoon has moderate seasonal pulses of temperature and light but strong seasonal pulses of precipitation, both river and ground water discharge, and the impacts of cool season frontal storms (the nortes). The area also has strong near-permanent physical gradients and a high diversity of estuarine habitats. For most of the year, prevailing easterly trade winds cause a net seawater inflow into the eastern inlet (Puerto Real) and a net outflow of estuarine mixed waters from the western inlet (El Carmen). This creates high salinity and clear water conditions in the eastern end of the lagoon. There are two quite distinct wind systems (Yanez-Arancibia and Day 1982). During 'nortes', mainly from October to February, winds are from the northwest with speeds often higher than 8 m sec^{-1}. The nortes occur about six days per months during this season. For most of the rest of the year, there is a sea breeze system that is affected by the trades, with winds predominantly from the east-southeast, with velocities between 4 to 6 m sec^{-1}. There are essentially no winds from the southwest. The major river discharge is into the southwestern part of the lagoon from July until November, creating turbid, nutrient-rich, low salinity water.

There are three ‘seasons’ in this region. From June to September, is the rainy season with almost daily afternoon and evening convectional showers associated with the intertropical convergence zone. From October to March is the period of ‘nortes’ or winter frontal storms; these storms are generally strongest and associated with rains during November, December and January. February to May is the dry season when the intertropical convergence zone is south of the equator. Because Terminos Lagoon is located in the outer tropics, there is only one summer rainy season.

Annual precipitation ranges between 1650 to 1850 mm yr^{-1}. The southwestern part of the lagoon receives more than 50% of the freshwater input, primarily from the Palizada River, a distributary of the Usumacinta River. Total average river discharge into the lagoon is estimated at 6×10^9 m^3 yr^{-1} (Phleger and Ayala-Castanares 1971). The Usumacinta-Grijalva River system is the second largest in Mexico, with an annual mean discharge of a little less than 4000 m^3s^{-1}.

Most biological processes including assemblages of, plankton, benthic and fish populations are strongly influenced by these gradients. Because of the clear marine waters, extensive sea grass beds occur in the northeastern end of the lagoon. Sea grasses have colonized much of the flood tide delta in Puerto Real Inlet and mangroves are also spreading in the area. Sea grasses are also abundant in the inner littoral of El Carmen Island. In contrast, extensive oyster reefs occur in the western part of the lagoon near the river mouths (**Figure 1**). A medium salinity plankton system occurs in the water column of the middle lagoon. Phytoplankton production, nutrient concentrations, chlorophyll levels, and mangrove litter fall are higher in the riverine-influence southwestern part of the lagoon as well as in areas associated with mangroves. Nekton larvae and juveniles generally enter the lagoon through the eastern inlet, reflecting prevailing currents. Peak river discharge is in October, when the highest primary productivity in the mid lagoon and entry of juveniles occurs. The lowest river discharge is in May (**Figure 2**).

It is generally accepted that an important key to wetland function and structure is the hydroperiod of a pulsing water flow regime (Conner and Day 1976, Odum et al. 1995, Mitsch and Gosselink 2000). Organisms not only adapt to the pulse but may also utilize the water-flow energy to enhance productivity as was shown by Odum et al. (1995). Tidal wetlands, especially the contrasting saline and freshwater marshes as in Terminos Lagoon, provide excellent sites for the study of the interaction of physical and biological components in a diverse biological, ecological and physical interactions matrix ecosystem (Yanez-Arancibia et al. 1999).

The Terminos Lagoon region is part of the larger Usumacinta/Grijalva delta system. The Usumacinta River of Mexico and Guatemala is the largest river in Mesoamerica and one of the most significant shared water resources in the Western Hemisphere (Bestermeyer and Alonso 2000; Yanez-Arancibia and Day 2004*b*). The delta comprises the main river, the Usumacinta, and a major tributary, the Grijalva River. The watershed drains one of the largest areas of contiguous tropical forest in the region, including about 178000 ha in Campeche, 724500 ha in Tabasco, 2175700 ha in Chiapas and 4241300 ha in Guatemala. About 36% of the land has been altered due to pipelines and other petroleum industry related activities. The delta prairies are an assemblage of the Mescalapa, Grijalva, and Usumacinta Rivers, and together they constitute a large delta with more than 20000 km2 (Yanez-Arancibia and Day 2004*b*). The Grijalva is 640 km long and the Usumacinta is 1100 km long. The combined discharge is 3000 to 4400 m^3 sec^{-1}, or 118000 x 10^6 m^3 yr^{-1}. Recently the Comision Nacional del Agua (CNA, Mexico) reported a combined discharge of 4402 m^3 sec^{-1} (Day et al. 2003; Yanez-Arancibia and Day 2004*b*). **Figure 2** shows the highest discharge occurs from September to November when high discharge from all tributaries reaches the delta. Discharge is lowest in April-May. The mean annual peak discharge is in October registered in Boca del Cerro (integrated in the Usumacinta discharge, **Figure 2**) with 9581551 m^3/month (Day et al. 2003; Yanez-Arancibia and Day 2004*b*).

Figure 2 presents four decades annual river discharge from 1950 to 1990. There is an apparent increase of river discharge during the last half century. All peaks occur in October, one month later that the highest rainfall month which is September in the southern Mexico and northern Guatemala as well, and the lowest discharge is in April-May. It is evident that the discharge pattern during 1953, 1955, 1957 and 1961, contrasts with a higher discharge in 1968, 1970, 1980 and 1982; and finally we can see a higher freshwater discharge in 1983 and 1990 probably because of the El Nino Southern Oscillation from 1982-83 and 1989-90. The highest river discharge of the Usumacinta/Grijalva rivers from 1950 to the present was in October 1999 (estimated combined discharge of 7000 m^3 sec^{-1}), because one of the most severe El Nino events of the century occurred in 1998-99 (NOAA's Coastal Service Center, U.S. Department of Commerce).

An understanding of ecosystem functioning should form the basis for sustainable management of Terminos Lagoon. Physical-biological interactions in Terminos Lagoon are a key concern because of: (**1**) the tropical location, (**2**) estuary-shelf interactions, (**3**) the estuarine habitat gradient, (**4**) the functional seasonal pulsing, and (**5**) the coupling of physical and biological processes. Preserving ecological functioning is '*the key'* for preserving natural productivity, biodiversity, water quality, and fisheries in a sustainable ecosystem-based management of the region.

2. Environmental pulsing, physical chemical and seasonality, and metabolism

Terminos Lagoon has been an important center for tropical coastal ecosystem studies since the 1960's with intensive work from the 1970's until the

1990's. The conceptual focus of much of this work had to do with the connection between the lagoon and Campeche Sound, the factors sustaining the high fishery catch in the region, and patterns of primary production. There was a realization that the fishery resources in Campeche Sound and the lagoon were strongly dependent on the supply of nutrients, organic matter, energy, and the movement of pre-adults of fish and shrimp from the lagoon-estuarine system to the sea (Yanez-Arancibia et al. 1980; Yanez-Arancibia and Day 1982; Deegan et al. 1986).

There is a high diversity, multi-stock fishery resource in Campeche Sound. 75% of dominant species are estuarine-dependent or estuarine-related in the juvenile and pre-adult stages (Yanez-Arancibia et al. 1980, 1985*a*; Yanez-Arancibia and Sanchez-Gil 1986; Sanchez-Gil and Yanez-Arancibia 1997). Because of the environmental dynamics and circulation patterns of Terminos Lagoon, it is evident that there is a strong connection between the lowland tidal wetlands and the adjacent ocean.

From 1978 to 1982, intensive studies were carried out on the environmental behavior of Terminos Lagoon and Campeche Sound ecological systems with relationship to fishery resources (Yanez-Arancibia and Day 1982; Yanez-Arancibia et al. 1983; Yanez-Arancibia and Sanchez-Gil 1983), focusing on the physical and biological connections between the estuary and the shelf. Because of the prevailing east to west net flow through the lagoon, Puerto Real Inlet on the east strongly contrasts with Carmen Inlet on the west (**Figure 3**). Puerto Real is more saline (30 to 37 psu), warmer (24 to 28 ^{o}C), clearer (>60% transparency), and with higher calcium carbonate concentrations (60 to 90% $CaCO_3$), than Carmen Inlet (15 to 25 psu, 22 to 27 ^{o}C, 40% transparency, 10 to 30% $CaCO_3$, respectively). But both inlets are also different from Estero Pargo which is a tidal channel system intermediate between the two (26 to 39 psu, temperatures of 23 to 32 ^{o}C and transparency in the water column higher than 80%). These parameters are highly correlated with the distribution of sediments, the presence of seagrass beds, and the distribution of mangroves, as well as with the net water flow from Puerto Real to the lagoon and Estero Pargo to Boca Chica.

There are several characteristic seasonal pulses in the central basin of Terminos Lagoon (**Figure 4**). There is a strong seasonality of salinity and temperature. In the central basin, salinity ranges from about 12 psu in November when the highest river discharge and the beginning of the 'nortes' season occurs, to 30 psu in June at the end of the dry season. Water temperature ranges between 19-21 ^{o}C in January-February during the 'nortes' season, to 28-30 ^{o}C in June at the end of the dry season. There is also a high intensity of solar radiation and high water transparency at the end of the dry season. The highest transparencies occur in May-June (~ 50%) during the period of lowest freshwater inflow. If the winds are calm during this period, transparency can exceed 70%. Transparency is highly variable, however, and can change quickly depending on such factors as winds, the tidal cycle, and river discharge. For example, Jensen et al. (1989) reported that the variability of suspended solids was as great as the average (e.g., 64 $\pm$ 66 ppm at the surface and 89 $\pm$ 82 on the bottom).

Recently, Herrera-Silveira et al. (2002) carried out an analysis of the environmental quality of Terminos Lagoon utilizing hydrological and biological indicators and developing an up-to-date hydrodynamic model. They carried out measurements at 22 sites, sampled water temperature and salinity (**Figure 5A**), oxygen, chlorophyll-*a* and suspended particulate material (**Figure 5B**), NO_3 + NO2-N (**Figure 5C**), NH_4-N, and PO_4 –P (**Figure 5D**) each two months for a year. We compared data from the study of Herrera-Silveira et al. (2002) to earlier data from the 1980s to determine any changes over a 20 year period.

The results of Herrera-Silveria et al. (2002) are generally similar to earlier results for the 1980s for Terminos Lagoon. The highest temperatures were about 30 ^{o}C and occurred in the beginning of the rainy season, mainly in the central basin and the southern part of the lagoon. The lowest temperatures (23 ^oC) occurred during the 'nortes' period adjacent to Puerto Real inlet. Surface salinities were highest (34 psu) during the 'nortes' period, while the highest bottom salinities occurred in the inner littoral of Carmen Island and Puerto Real inlet during the rainy period. Oxygen in surface waters was highest (7.5 mg l^{-1}) during the transition between the rainy and nortes seasons, particularly in the southern part of the lagoon adjacent to the inlets of the fluvial-lagoon systems. At the end of the 'nortes' period and during the dry season when temperatures increase, surface oxygen can drop to less than 2 mg l^{-1}. Bottom oxygen ranged between 6.8 mg l^{-1} 3.6 mg l^{-1} during the rainy season in the southern part of the lagoon. The highest chlorophyll-*a* levels (14 mg m^3) occurred during the rainy season, both in the southern part of the lagoon and the inner littoral of El Carmen Island. These areas are characterized by seasgrass beds (*Thalassia testudinum*), macroalgae, and drainage from mangroves. All of these factors lead to higher phytoplankton production (Day et al. 1982, 1986, 1988; Yanez-Arancibia and Day1982, 1988; Rojas Galaviz et al. 1992). The lowest chlorophyll-*a* (1 mg m^3) was at the end of 'nortes' period in the central basin of the lagoon. This comes after a period of major flushing of the lagoon from October to January (Yanez-Arancibia and Day 1982, 1988; Yanez-Arancibia et al. 1985*a*, 1988, 1993; Soberon-Chavez et al. 1988). Suspended particulate material was highest ??**(0.04 *m*g l^{-1})** during the dry period in the south western part of the lagoon, and the lowest values occurred at the end of the rainy season in areas not influenced by the river inlets. In general, SPM is highest during nortes because of high wind resuspension but it is difficult to comprehensively sample the lagoon during these events.

Herrera-Silveira et al. (2002) provide the first comprehensive survey of nutrients in over 20 years. Both NO_3 and NO_2 were highest (34 *u*M and 1.8 *u*M, respectively) in the rainy season and lowest in the dry season (<2 *u*M and 0.02 *u*M, respectively). The highest values tended to occur in the southern part of the lagoon near the river mouths. NH_4 was highest (12 *u*M) at the beginning of the rainy season in the inner littoral of El Carmen Island and in some of the areas with strong freshwater influence in the southern and southwestern part of the lagoon. The lowest NH_4 (1 *u*M) occurred during the dry period, and similar to the average concentration for the Lagoon of about 2 *u*M. PO_4-P was highest (> 0.9 *u*M) during the 'nortes' period, and lowest (0.01 *u*M) early in the rainy season.

The hydrological results of Herrera-Silveira et al. (2002) are similar to earlier reports with the exception of nutrient concentrations. All reports show that salinity is higher in the eastern part of the lagoon during the dry season. Phleger and Ayala-Castanares (1971) reported 25 to 36.5 psu in the northeastern lagoon near Puerto Real inlet, and from 0 to 28 psu in the southern and western parts during 1964-1966. Salinity was 26 to 39 psu in Puerto Real inlet during 1976-1977 (Bravo Nunez and Yanez-Arancibia 1979). Salinities as high as 40 psu occur in semi-isolated small bodies of water during the dry season (Vargas et al. 1981; Day et al. 1982, 1986, 1996) particularly in the inner littoral of El Carmen Island. In 1972 the average salinity in the lagoon was 33 psu in the dry season and 26 psu in the rainy season (Carvajal 1973). In 1974, the values were 33.5 and 21.9 psu, respectively (Botello and Mandelli 1975).

Nutrient chemistry of the lagoon is determined by circulation, river flow, and biogeochemical processes. This is reflected in the results of Botello and Mandelli (1975), who measured a number of chemical parameters at 27 sampling sites in May (end of dry season) and November (high rainfall and river discharge), 1974. Mean salinity during May and November was 33.5 and 21.9 psu, respectively. PO_4 and $NO_2 + NO_3$ were 2.6 x and 2.2 x higher, respectively, in November; however NH_4 was 3.8 x higher in May. Dissolved oxygen was 147% saturation in November and 99% in May. The higher PO_4 and $NO_2 + NO_3$ occurred during the period of high riverine input. This leads to higher gross and net aquatic primary productivity and thus to higher oxygen levels, as was later shown by Day et al. (1982, 1987, 1988, 1996). Higher NH_4 during May is perhaps due to benthic regeneration combined with lower flushing, more reduced conditions, and biological activity. Plots of nutrient concentration *versus* salinity during the rainy season indicate that the lagoon was a net sink for PO_4 and to a lesser extent for $NO_2 + NO_3$, as was shown by Yanez-Arancibia and Day (1982) based on the data base of Botello and Mandelli (1975). For $NO_2 + NO_3$, all stations with values above 10 *u*M were near the river inlets reflecting river input, or in *Thalassia* seagrass beds; which reflects high community metabolism (perhaps nitrification) and low flushing (Yanez-Arancibia and Day 1982).

Nutrient dynamics have been studied by Day et al (1982) at a lagoon-wide scale; and in *Thalassia testudinum* grass beds of the inner littoral of Carmen Island (Stevenson et al. 1988, Hopkinson et al. 1988, Kemp et al. (1988). Some nutrient data are also available in the Fluvial-lagoon systems (Vera-Herrera et al. 1988). Rates of NH_4 regeneration in sediments of *Thalassia testudinum* were ten times higher in surface sediments (0 to 2 cm) than at depth (18 to 20 cm). Turnover-time for ammonium pools in the surface sediments were about 1 day. Both anaerobic decomposition and denitrification are important biogeochemical processes in Terminos Lagoon seagrass beds and rates of ammonium regeneration were sufficient to supply >70% of the nitrogen required for seagrass growth in this system (Kemp et al. 1988). Nitrogen fixation rates measured in intact cores showed low rates ranging from 0.8 *u*mol N m^2 d^{-1} in February ('nortes') to 50 *u*mol N m^2 d^{-1} in August (rainy). These rates may underestimate actual rates due to low gas diffusion rates in sediments (Stevenson et al. 1988). Separate fixation rates by leaf, root, rhizome, and sediment components in small serum bottles suggest that N fixation provides 10 to 40% of nitrogen demand of the seagrasses. Roots and rhizomes exhibited variable rates up to 30 *n*mol N m^2 d^{-1}; or greater than 100% of demand (Stevenson et al. (1988). The highest fixation rates occurred just prior to increased *Thalassia* production in February (Rojas-Galaviz et al. 1992). Measurements of stocks of organic and inorganic nitrogen in sediment, water and the biota indicates that biotic stocks of 13320 *m*mol m^2 dominated abiotic stocks of 19 *m*mol m^2 of nitrogen in the *Thalassia* system, with less than 0.2% of the nitrogen being in the inorganic form

(Hopkinson et al. 1988). A large percentage of the total organic nitrogen pool (94%) is contained in dead material (746 versus 12610 *m*mol m2, live in dead material, respectively, **Figure 6**). Approximately 75% of the inorganic nitrogen and 97% of the organic nitrogen is in the sediments, as opposed to the water column (Hopkinson et al. 1988, **Figure 6, Table 1**). Inorganic nitrogen uptake requirements are 7.5, 2.5, and 4.0 *m*mol m^2 d^{-1} for phytoplankton, epiphytes and *Thalassia*, respectively, and the nitrogen turnover times ranged from less than 1 day for inorganic nitrogen in the water column to over 3000 days for sedimentary organic nitrogen (Hopkinson et al. 1988).

From this information, we can conclude that: (**a**) N inputs from N-fixation, allochthonous sources, leaching from seagrass leaves and/or nutrient exchange across the sediment-water interface may be important in meeting uptake requirements of epiphytic and planktonic primary producers, and (**b**) in a nitrogen budget for Terminos Lagoon, nitrogen fixation during one period (i.e., 'nortes') appears to be of little quantitative significance to the whole lagoon system, but seasonally it may be extremely important at the scale of the seagrass beds as a local nitrogen input.

A comparison of earlier nitrogen data with that of Herrera-Silveira et al. (2002) indicates that nitrogen concentrations have increased (5x). This suggests that there has been a shift in nutrient limitation. Botello and Mandelli (1975) concluded that nitrogen was limiting in Terminos Lagoon as has been concluded by others for most estuarine systems (Postma 1969; Mee 1978, Day et al. 1989). This change is a reflection of land-use-changes in the basin. In the coastal plain of Campeche and Tabasco, seasonally flooded wetlands have been converted to agriculture and land clearing and agriculture have spread in the upper basin of the Usumacinta river. Similar changes have been reported for the Mississippi Basin (Mitsch et al. 2001).

Salinity and river discharge seem to be correlated to phosphorus and the oxidized forms of inorganic nitrogen during the rainy season. During the dry season, high ammonium levels reflect more local conditions such as turbulence, sediment type, and biological activity. There is a decrease in both nitrogen and phosphorus with increasing salinity, but this is especially pronounced for nitrogen. These mixing diagrams **(Figures 3 to 6)** suggest that Terminos Lagoon is a net sink for both nitrogen and phosphorus. Supersaturation of oxygen during the rainy season indicates net aquatic primary productivity (Day et al. 1982, 1988).

The variation of average salinity and water transparency compared with the coefficient of variation for each sampling station shows an association of stations that varies according to the three climatic seasons**. Figure 7** summarizes the annual balance from a two-year monthly sampling. The graph reflects a geographical similarity that suggests that there are groups of ecologically similar sampling stations. These include the inner littoral of El Carmen Island and adjacent areas (Group 1), the Central Basin (Group II), the fluvial-lagoon system and areas of immediate river influence (Group III, III_2), and El Carmen Inlet (Group IV). Puerto Real Inlet shows a different behavior.

These results provide a simple model of lagoon functioning. Habitats persist throughout the year but their boundaries change due to the physical control of the seasonal parameters. Salinity and transparency do not depend on biological activity, but salinity is important in controlling biodiversity, distribution of organisms, and abundance of different biotic groups. Transparency affects the productivity of primary producers in the water column (phytoplankton, attached microalgae, macroalgae, and seagrasses). Salinity and transparency exhibit strong seasonal patterns due to such factors as river discharge, precipitation, winds, and climatic conditions (**Figure 4**). The seasonality of salinity and temperature is more predictable and regular than that of transparency because winds strong enough to resuspend bottom sediments occur during most of the year (i.e., ‘nortes’ and the sea breeze system).

The two-year monthly data set of Yanez-Arancibia et al. (1983), and the one-year data set (Herrera-Silveira et al. 2002) provide a long-term, comprehensive understanding of the seasonality of physical chemical parameters and of ecosystem functioning as historically described by Gierloff-Emden (1977), Mancilla and Vargas (1980), Graham et al. (1981), Kjerfve et al. (1988), Jensen et al. (1989), and David and Kerfve (1993).

3. The functional dynamics and ecosystem profile of Terminos Lagoon

When Yanez-Arancibia and Day (1982) used the ecosystem approach to describe the structure and functioning of Terminos Lagoon, they described a high correlation between physical and biological processes of the ecosystem and emphasized the need for further study: (**1**) the identification and quantification of ecological connections between Terminos Lagoon and coastal fisheries in Campeche Sound, (**2**) the implementation of an ecological-hydrological model of the lagoon, (**3**) changes that may occur because of human activities, and (**4**) the development of a series of conceptual models for the analysis of ecological and economic connections in Terminos Lagoon region. In a sense, this article constitutes a review of what happened during the last twenty years.

Figure 8 shows the mean annual gradient of decreasing salinity from the northeast to southwest. This gradient is also related to water transparency with clearer water in the northeast. Both parameters are directly related to the circulation pattern where the highest salinity and transparency occur in habitats of highest and persistent marine influence, such as Puerto Real Inlet and El Carmen island inner littoral. The Fluvial-lagoon systems control have the lowest salinity and transparency, and are areas of elevated sedimentation.

Combining the results of salinity, transparency, suspended sediments, wind patterns, and the net circulation, a number of characteristics can be now distinguished: (a) there is a net inflow of water through Puerto Real inlet for approximately 15 hr d^{-1}, and a net export for a similar period through Carmen Inlet (Graham et al. 1981), (b) the net flow of water from Puerto Real to the central basin and along the inner littoral of Carmen Island, to Carmen Inlet, (c) total suspended sediments (Jensen et al. 1989), are highly correlated with the salinity and transparency gradients (Yanez-Arancibia et al. 1983), and the circulation pattern (Kjerfve et al. 1988), (d) Puerto Real Inlet has an average suspended solids level of *ca*. 46 ppm, Estero Pargo Inlet *ca*. 50 ppm and Carmen Inlet *ca*. 85 ppm (Jensen et al. 1989, **Figure 9**).

Five habitats (ecological subsystems) can be defined which reflect interactions between physical conditions and the structure of biotic communities (**Figure 10, Table 2**). Table 2 and Figure 10 show the model of Terminos Lagoon habitats as a consequence of the environmental behavior. Because of the tropical location, there are no strong seasonal pulses of temperature and solar radiation. However, because of a strong seasonality of precipitation, river discharge, persistent currents and winds, and climate (e.g., dry, rain, and ‘nortes’ seasons), there are strong semi-permanent physical-geologic-chemical gradients in salinity, water transparency, and sediment type. These physical processes determine the presence and persistence of five major ecological habitats (or subsystems). These are Groups I to IV plus Puerto Real Inlet. Statistical analysis of the most important environmental parameters and the results of the computer model of Yanez-Arancibia et al. (1985*a*), and Soberon-Chavez et al. (1988) quantitatively describes these habitats (**Figure 10**). Most of the biological processes of the lagoon are strongly influenced by these gradients and they are summarized in **Table 2**.

Models are useful tools for analysis, integration, synthesis and subsequent ecological prediction of a coastal ecological system such as the Terminos

Lagoon and Campeche Sound integrated regional ecosystem (**Figure 11, Figure 12, Figure 13, Figure 14).** The circulation pattern of Puerto Real inlet is characterized by a net inflow of water without a stratified water column (**Figure 11**). This is a result of the prevailing trade winds and strong littoral currents from northeast to southwest, a well mixed coastal water column, and the strong tidal current coming from the sea into the lagoon with velocities between 50 to 60 cm sec^{-1}. This produces on average a net flow from east to west for about 15 hours per day that has led to the development of the large flood tide delta in Puerto Real Inlet. The prevailing easterly trade winds push lagoon water in a westerly direction through the lagoon towards El Carmen Inlet. The circulation pattern of El Carmen inlet is quite different (**Figure 12**). There is generally a stratified water column with estuarine waters flowing out at the surface with velocities between 25 to over 80 cm sec^{-1} for about 15 hours per day, and inflowing sea water on the bottom with velocities generally less than 60 cm sec^{-1}. This net outward flow has led to the development of an extensive ebb tide delta on the continental shelf. The contrasting conditions at Puerto Real and Carmen inlets (**Figures 11** and **12**) is key to understanding the (**1**) water balance, (**2**) circulation pattern, (**3**) habitat characteristics, (4) patterns of primary productivity, and (**5**) the behavior of fish and shrimp population assemblages in the Terminos Lagoon-Campeche Sound regional ecosystem. Particularly important is the environmental gradient of physical, chemical, and biological parameters in the inner littoral of Carmen Island from Puerto Real inlet, to Estero Pargo, to Carmen Inlet (**Figure13**).

Puerto Real Inlet and El Carmen Inlet are contrasting environments because of gradients in environmental dynamics and prevailing forcing functions. Each of the inlets is a characteristic subsystem of Terminos Lagoon (**Figure 10**). Biological productivity is strongly correlated with the gradients that exist in the lagoon as indicated in **Figure 13** (Day et al. 1982, 1987, 1988, 1996; Yanez-Arancibia et al. 1982, 1988, 1991, 1993; Yanez-Arancibia and Lara-Dominguez 1983).

The productivity of fish resources in the area of ecological interactions comprising Campeche Sound-Terminos Lagoon depends on the dynamics of physical variables in this coastal zone that act by modifying the ecosystem and conditioning the dynamics of the biotic communities. Shifts in direction and intensity of the ecological interactions between sheltered waters and the continental shelf produce changes in the diversity, distribution, abundance and persistence of the resources. **Figure 14** is a conceptual model that shows the different flows of biomass between these habitats. The highly connected food web is a significant characteristic of Terminos Lagoon. **Table 3** indicates the average biomass from the model of Soberon-Chavez et al. (1988) of each of the components in each of the habitats (or subsystems) considered.

In general, phytoplankton biomass is highest during the rainy season and highest river discharge period from September to January, and in subsytems I, III, and IV, the littoral zones of Terminos Lagoon, and lowest on the shelf of Campeche Sound in Subsystem (A) typically with clear waters. Seagrasses have the highest biomass in subsystems I and III, the littoral systems in the northeastern and southeastern parts of the lagoon. Subsystem I is the typical *Thalassia testudinum* habitat in the lagoon with high salinity and transparency. Biomass is highest at the end of dry season. Average biomass is less in subsystem III where there is higher turbidity and peak biomass is highest during the rainy season. Organic detritus is highest in the southern littoral part of the lagoon in areas affected by river discharge and drainage from extensive mangroves and fresh water wetlands. Detritus values are higher in El Carmen Inlet and Zone A on the shelf at the end of 'nortes' period indicating the fertilizing effect of the lagoon and river input. Average nekton biomass is highest in the two littoral habitats with seagrasses (I and III) and less in the central basin and low salinity habitats (II and IV). Nekton biomass is higher in the area of the shelf affected by the estuarine plume (Zone A) than in the clearer, high salinity part of the shelf (Zone B). It is evident that both detritus and biomass flows follow the circulation pattern from Zone B, to the lagoon, and then towards El Carmen Inlet to the sea (Zone A). The highly connected trophic web has important sources of organic matter from both pelagic (via phytoplankton) and demersal (via detritus from seagrasses and mangroves) food webs (**Figure 14**). Terminos Lagoon exports through El Carmen Inlet to the continental shelf (Zone A) a flow of 6594 tons per year higher than the flow entering through Puerto Real Inlet. The model simulations indicate that there is a nekton export from the lagoon to Campeche Sound monthly of 60 tons during the dry season, 80 tons during the rainy season, and 200 tons during the 'nortes' period, following the timing of peak aquatic primary productivity and organic detritus concentration. The opposite is true for importation biomass flow and nekton juvenile immigration from the sea to the lagoon, which enter Terminos Lagoon with a high species diversity in February (the end of the 'nortes' and the beginning of the dry season) (Yanez-Arancibia et al. 1980, 1988, 1993).

Yanez-Arancibia et al. (1980, 1985a, 1988, 1993,1999) pointed out that within the biogeophysical framework of the wetlands, the open waters of the lagoon, and the continental shelf, the living resources maintain a complex biological organization that utilizes all of these environments. Functionally, fish resources are related to ecological interactions in the coastal zone and changes in fish resources in space and time are a reflection of the natural variability of physical and biological processes.

Fish are an important component of the estuary-inlet-shelf system (**Figure 14**). In Terminos Lagoon, the ecological role of fish includes the following aspects: (**1**) energy transformation from primary sources, (**2**) active transfer of this energy through the trophic web, (**3**) energy exchange between neighboring systems through migration, (**4**) a form of energy storage within the ecosystem, and (**5**) acting as energy regulation agents (Yanez-Arancibia et al. 1985*a*). An ecological role of the estuary-inlet-shelf system is to provide fish with food, and areas for spawning, growth, and/or protection. The inlet systems also act as important avenues for migration as indicated by community ecological parameters, population assemblages, and ichthyotrophic categories (Yanez-Arancibia et al. 1985a).

The analysis of fish-habitat affinities based on three statistical methods (**Figure 15**) showed a high level of significance in the estuary-inlet-shelf system, and fish communities reflect the typical characteristics of each habitat. Thus, 7 subsystems were identified, i.e., 5 in Terminos Lagoon: groups I, II, III, Carmen Inlet (C) and Puerto Real Inlet (P); while in Campeche Sound Zones A and B were identified. In every case, the analysis revealed the same ecological subsystem grouping pattern (**Figure 15**) showing a fish population gradient.

It is important to point out that Puerto Real area acts as a bridge for ecological connections and interactions between Campeche Sound and Terminos Lagoon. Fish populations are directly associated with the environmental dynamics that prevail in each one of the subsystems in Terminos Lagoon and Campeche Sound indicating a strong connection between the estuary and the sea, and an ecological coupling of fish resources highly dependent on the functional structure of the estuary-inlet-shelf system (Yanez-Arancibia et al 1985a, **Figure 14**, **Figure 15**).

The diverse biological, ecological and physical interactions that occur within this tropical estuary and the adjacent ocean produce a highly dynamic and variable mosaic of habitats in a matrix of interactions (Yanez-Arancibia et al. 1985*a*, 1991, 1999). From an ecological standpoint, the term biodiversity can have several meaning when applied to Terminos Lagoon (Day and Yanez-Arancibia 1982). It can mean that there is a high diversity of species (e.g., Yanez-Arancibia et al. 1993*b*), a high diversity of functional groups, both for estuarine primary producers and consumers (Day et al. 1982, 1986, 1988, 1996; Rojas-Galaviz et al. 1992; Sanchez-Gil and Yanez-Arancibia 1997; Yanez-Arancibia et al. 1999), a high diversity of environmental factors and forcing functions (e.g., Yanez-Arancibia and Day 1982, Soberon-Chavez et al. 1988;

Yanez-Arancibia et al. 1999), habitats (Yanez-Arancibia and Day 1988) and connections in the food web (Soberon-Chavez et al. 1988), and a high diversity of couplings, both internally and with neighboring systems (Yanez-Arancibia et al. 1985*a*, 2004; Day and Yanez-Arancibia 1988; Soberon-Chavez et al. 1988).

Terminos Lagoon has a number of important functional groups, both of primary and secondary producers (or consumers). A *functional group* is a conspicuous assemblage of biota with similar biological behavior and ecological strategies. The diversity of functional groups of primary producers can be high in estuarine ecosystems (Rojas-Galaviz et al. 1992), normally modulated by salinity gradients, turbidity, sediments, nutrients, and tidal range. **Figure 16** shows the clear seasonality of the pulses of abundance and productivity of different primary producers functional groups. Primary production is generally high during the entire year, but each functional group has a different seasonal pattern in relation to the environmental parameters specific to each gradient. The main productivity peak of mangroves occurs during the rainy season and is related to freshwater input (nutrients and lowered salinity). For submerged grasses the highest biomass and productivity generally occurs during the dry season when water transparency is highest, while the lowest biomass values occurs during the rainy and 'nortes' season. Both marine and freshwater grasses start their productivity pulse at the end of the 'nortes'. Maximal productivity of freshwater macrophytes occurs in February and slowly declines during the dry and rainy seasons, while peak seagrass and productivity occur during the dry season (March-May). Phytoplankton productivity and biomass in the mid-lagoon has a seasonal pattern opposite that of the aquatic macrophytes. Planktonic primary productivity and chlorophyll-*a* levels increase through the rainy season, reaching a peak during the beginning of the 'nortes' season from September until December. Aquatic productivity in mangrove bordered tidal channels is highest during the dry season.

The results from **Figure 16** show that high year-round production in Terminos Lagoon is maintained by sequential pulses by different primary producers. This seasonal programming is one of the functional processes sustaining high estuarine production and supporting significant biomass of fish resources. Fish assemblages, or *functional groups,* are very important in maintaining the structure and functioning, and productivity of consumers in Terminos Lagoon (Pauly and Yanez-Arancibia 1994). At least three groups of fishes occurs in the lagoon-estuarine system (**Figure 17**): (**1**) Resident species, those which spend their entire life cycle within the system, (**2**) Seasonal migrants, those which enter the lagoon during a more or less well-defined season (from either the marine of the freshwater side (and leave during a different season, (**3**) Occasional visitors, those which enter and leave the system without a clear pattern within and among years. To these, two other groups may be added: (**4**) Marine, estuarine-related species, those which spend their entire life cycle on the inner sea shelf under the estuarine plume influence, and (**5**) Fresh water, estuarine-related species, those which spend their entire life cycle in the fluvial-deltaic riverine zone, associated with the upper zone of the estuarine system

In terms of a functional characterization, Terminos Lagoon can be divided into three regions. (**1**) *A tidal river zone*. This is a fluvial-deltaic zone characterized by fresh water to very low salinity, but subjected to tidal rise and fall of water level. (**2**) *A mixing zone*. This is characterized by water mass mixing and the existence of strong gradient of physical, chemical and biotic features, and reaching from the tidal river zone to the seaward location of the ebb-tidal delta. (**3**) *A near shore turbid zone*. This is in the near-shore ocean, between the mixing zone and the seaward edge of the estuarine plume at full ebb tide. This global characterization was described by Yanez-Arancibia and Day (1982) and Yanez-Arancibia et al. (1983), and twenty years later, it was reanalyzed by Herrera-Silveira et al. (2002). This subdivision of Terminos Lagoon recognizes and includes near shore marine components that are estuarine in character, and implicitly considers the seven main habitats in the system as a whole (Yanez-

Arancibia and Day 1982; Yanez-Arancibia et al. 1983, 1999; Yanez-Arancibia and Sanchez-Gil 1983).

The semi-permanent gradients from the freshwater tidal wetlands to the estuarine plume on the inner shelf leads to the identification of the habitats identified and summarized in **Figure 10**, **Figure 18**, **Table 2**. *The fluvial-deltaic systems* in the southern littoral zone of Terminos Lagoon have very low salinity, high turbidity, high nutrient concentrations, silty-clay sediments, *Crassotrea virginica* reefs, demersal fishes, riverine mangrove forests with fringing *Rhizophora mangle* and *Avicenia germinans* basin forests, and in some areas of clear waters typical sumerged fresh water vegetation. *The central basin*, which is the transition zone between marine conditions and the river-influenced zone, is characterized by mesohaline salinity, medium water transparency, silty-clay to sandy sediments, small pelagic fishes, and a typical estuarine phytoplankton production system including some benthic macroalgae. *The inner littoral zone of El Carmen Island*, is dominated by *Thalassia testudinum* and fringing mangrove habitat with near marine salinity, high water transparency, sandy sediments and a high diversity of both benthic and nektonic consumers, mainly demersal fishes. There are fringing mangroves with all three mangrove species and basin mangroves dominated by *Avicenia germinans*. *Puerto Real Inlet*, where there is a net flow of Gulf waters into the lagoon, is characterized by calcium carbonate sediments, clear waters and extensive seagrass beds. *Carmen Inlet*, the estuarine connection with the shelf, has a net transport from the lagoon to the ocean, producing an extensive estuarine plume of medium salinity on the shelf. There are silty-clay sediments and highly turbid waters without submerged vegetation.

In Campeche Sound adjacent to Terminos Lagoon (**Figure 18**), there is a *terrigenous subsystem (Zone A)* strongly influenced by estuarine waters with medium water transparency, no benthic vegetation and with a high content of organic matter in the silty-clay-sandy sediments; and a *calcareous subsystem*

(Zone B) with clear water of full salinity, calcium carbonate sand sediments with seagrass beds and macroalgae. **Table 2** summarize the main ecological characteristics of these subsystems (habitats).

Within the physical framework provided by the wetlands, the lagoon-estuarine environment, and the continental shelf, living resources and environmental parameters maintain a complex biological organization in Terminos Lagoon (**Figures 19** and **20**). These figures propose the ecosystem approach as the basis for the environnebtal management of habitats and resources (Day and Yanez-Arancibia 1988). The primary criterium is the interpretative analysis of the habitats (= subsystems), since they represent the functional structural unit for the holistic integration of the whole ecosystem. The ecological interdependence between Terminos Lagoon and Campeche Sound, and the degree of linkages at the habitat level, modulate evident physical, chemical, and biological gradients, which should be examined for monitoring primary productivity, fisheries resources, petroleum and coastal plain agriculture issues, as well as their environmental impacts for the rational and sustainable management.

The most conspicuous factors (or *forcing functions*) affecting fishery production are: (**1**) physical-chemical conditions in the water column, i.e., transparency, salinity, nutrients, oxygen and temperature, (**2**) bathymetry and sediment type, (**3**) meteorology and climate, (**4**) river discharge, (**5**) tidal range, (**6**) the area of coastal vegetation, i.e., marshes, swamps, lagoons and seagrasses, and (**7**) the interactions between the estuary and the sea (Yanez-Arancibia et al. 1980, 1985*a*, 1999; Yanez-Arancibia and Sanchez-Gil 1986). For ecosystem-based management of Terminos Lagoon and Campeche Sound, these are key concerns.

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4. Water Budget of Terminos Lagoon

In **Figure 21**, we illustrate in a diagrammatic model, the environmental parameters controlling the water and salt balance and illustrating physical variables involved in the functioning of Terminos Lagoon. Our methodological strategy is supported in analyzing the ecosystem functioning in both spatial and seasonal scales. Spatially, the Lagoon was divided in two subsystems. Seasonally, we analyzed the Lagoon behavior during the nortes (October to February), dry (March to May) and rainy (June to November) seasons. The two main subsystems are the western 1/3 and the eastern 2/3 of the lagoon as shown in **Figure 21**. The lagoon has a surface area of about 1700 km^2, therefore the western 1/3 is 567 km^2 and the eastern 2/3 is 1134 km^2. The diagram shows the variable conditions for a steady-state under the influence of tidal forcing, but modulated by the estuarine circulation with a salinity gradient from 36 in the adjacent ocean to 35 in Puerto Real inlet to 0 in the Fluvial-lagoon systems. The circulation pattern of Terminos Lagoon is highly dependent on the direction of the littoral currents, prevailing wind patterns, the hydrodynamics of the two estuarine inlets, tidal forcing, and river discharge (Yanez-Arancibia & Day 1982, Kerfve et al. 1988).

The water budget is important for estimating five important aspects of lagoon functioning: (**1**) the flushing time, or residence time, of mixed estuarine waters into the Lagoon, (**2**) nutrient budgets and the amount of nutrient exported to the adjacent ocean in each tidal cycle and seasonally, (**3**) lagoon metabolism, i.e., production and consumption rates of the Lagoon, and to understand the seasonality of aquatic primary productivity patterns, (**4**) retention (in the Lagoon) and dispersion/exportation of pollutants (to Campeche Sound) based on the hydrodynamics of Lagoon, and (**5**) for a more comprehensive understanding of ecosystem functioning, and coupling of physical and biological processes which is a key concern in the ecosystem-based management approach.

Table 4 indicate the general values for some environmental parameters required for the water budget calculations.

The tidal prism or water exchanged during a tidal cycle (**Vtp**) is calculated as the difference of maximum water volume (**V_1**) at high tide, and the minimum water volume (**V_2**) at low tide.

Maximum Water Volume (**Vmx**) = Volume of water in the open waters of the lagoon at high tide (**Vp**) **+** Volume of water in wetlands (**Vw**),

[Vmx = Vp + Vw]

Vmx = 1700 x 10^6 m^2 area x 3.5 m depth **+** 1300 x 10^6 m^2 area x 0.2 m depth
Vmx = 5950 x 10^6 m^3 **+** 260 x 10^6 m^3
Vmx = 6210 x 10^6 m^3

Volume of the tidal prism in lagoon waters (**Vtp**) at high tide = 1700 km^2 x 0.43 m depth (**Vht**) **+** Volume water in wetlands (**Vw**),

[Vtp = Vht + Vw]

Vtp = 1700 x 10^6 m^2 area x 0.43 m depth **+** 1300 x 10^6 m^2 area x 0.2 m depth
Vtp = 731 x 10^6 m^3 **+** 260 x 10^6 m^3
Vtp = 991 x 10^6 m^3

This **Vtp** is the estimated volume of estuarine waters exported from Terminos Lagoon to Campeche Sound during each tidal cycle. This is a maximum estimate since some of the water in the wetlands will not be completely drained due to friction caused by wetland plants.

The Minimum water volume (**Vmin**) is calculated as maximum water volume (**Vmx**) **-** the Volume of the tidal prism in the lagoon (**Vtp**):

$$[Vmin = Vmax - Vtp]$$

Vmin = 6210×10^6 m^3 **-** 991×10^6 m^3
Vmin = $5219\ 10^6$ m^3

Water and Salt balance (**Wb**)**.** The salt and water balance is modulated by inputs from river discharge (**R**), ground water inflow (**G**), precipitation (**P**), and tidal input (T_1); and losses due to evaporation (**E**), tidal export (T_2), and filtration through Carmen Island as ground water flow between the lagoon and the sea (F_1 and F_2)

$$R + G + P + T_1 + F_1 = E + T_2 + F_2$$

We assumed that $F_1 = F_2$ and that the same volume of water comes in during flood tide as is exported during ebb ($T_1 = T_2$). Thus the equation simplifies to:

$$[R + G + P = E]$$
$$[Wb = R + G + P - E]$$

Wb = 12.7×10^9 m^3 yr^{-1} **+** 4×10^6 m^3 yr^{-1} **+** 4.5×10^9 m^3 yr^{-1} **-** 1512 mm yr^{-1}
Wb = 21.2×10^9 m^3 yr^{-1} **-** 120 m^3 sec^{-1}
Wb = 21.2×10^9 m^3 yr^{-1} **-** 3.8×10^9 m^3 yr^{-1}
Wb = 17.4×10^9 m^3 yr^{-1}

This water budget represents an estimation of the amount of water available to the lagoon in an average year. Of course some complications are evident, such as: the seasonal variations in fresh water input to Lagoon (i.e., a range from 9.1 during dry season to 16.3 x 10^9 m^3 yr^{-1} during rainy season) , the lagoon seasonal circulation pattern (i.e., from southeast to northwest during dry and rainy seasons, and from north northwest during winter storms period), and the spatial variation in salinity (i.e., from 36 in the adjacent ocean, to 35 in Puerto Real, to 0 psu into the fluvial lagoon systems) with a permanent gradient during the dry season, a semi permanent gradient during rainy season, and a mixed gradient (or no gradient) during nortes season.

The western 1/3 of the lagoon receives about 70% (or more) of river discharge. The eastern 2/3 of the lagoon receive 30% (or less) of river discharge. This is the main reason that the salinity ranges from 35 psu in Puerto Real to 0 psu in the fluvial-lagoon systems, mainly in the inner lagoons associated with the Palizada delta, and that lagoon surface area is divided in two main subsystems (**Figure 21).**

Precipitation is another important concern (**Table 5 and 6**). Based on seasonal precipitation patterns, the western 1/3 of the lagoon receives average inputs of 27 (during nortes season), 12 (dry) and 45 (rainy) m^3 sec^{-1}. The eastern 2/3 of the lagoon receives average inputs of 53 (nortes), 24 (dry) and 91 (rainy) m^3 sec^{-1}. For the year, the total input is 80 (nortes), 36 (dry) and 136 (rainy) m^3 sec^{-1}.

The estimated evaporation in Terminos Lagoon in the western 1/3 of the lagoon is 18 (nortes), 35 (dry) and 33 (rainy) m^3 sec^{-1}; and in the eastern 2/3, 35 (nortes), 70 (dry) and 66 (rainy) m^3 sec^{-1}. This yields a total evaporation of 53 (nortes), 105 (dry) and 99 (rainy) m^3 sec^{-1} (**Table 5 and 6**).

Net freshwater inflow varies dramatically by season. During the dry season, in the eastern 2/3 of the lagoon, there is a dramatic reduction in freshwater from input to the lagoon because the dramatic decrease of river discharge, the east to west circulation pattern, and strong evaporation. In the western 1/3 of the lagoon, there is a net freshwater input of 462 (nortes), 227 (dry) and 492 (rainy) m^3 sec^{-1}. In the eastern 2/3 the values are 158 (nortes), 4 (dry) and 200 (rainy) m^3 sec^{-1} (**Table 5 and 6**).

To estimate residence time, we need to assume that Terminos Lagoon is well mixed (which is not always true) and that it is in steady-state (which is generally not true). But, if we accept that the residence time is the amount of time that it takes to replace 63% of the volume of water in the Lagoon (Oczkowski 2004), we have:

$$[\mathbf{N_t = N_o\ e^{-kt}}]$$

Where $\mathbf{N_o}$ is the initial concentration, $\mathbf{N_t}$ is the concentration at time **t**, **k** is the flushing rate, and **t** is time. At steady-state $\mathbf{N_t}$ = $\mathbf{N_o}$ and **k** = **1/t**, so $\mathbf{e^{-kt}}$ = 0.37, and 1 – 0.37 = 0.63 or 63%.

Input-Output is equal to net freshwater inflow (water budget) to the Lagoon (direct precipitation, plus river discharge, plus ground water inflow, minus evaporation). So the volume of freshwater in the lagoon,

$$\mathbf{[Vfw = 1 - (S_L / S_{off}) + Vmax]}$$

Where **Vfw** = volume of freshwater in the Lagoon, $\mathbf{S_L}$ = salinity in the Lagoon, $\mathbf{S_{off}}$ = salinity in the adjacent ocean, **Vmx** = maximum volume, and

$$\mathbf{[Rtw = Vfw / Fwi]}$$

Where **Rtw** = residence time of water in Terminos Lagoon, **Vfw** = volume of freshwater in the Lagoon, and **Fwi** = freshwater inflow to the Lagoon. From the average values in **Table 1**,

Vfw = 1 – (22 / 36) x 6210 x 10^6 m^3

Because the mean annual discharge of the Palizada River pattern discharge is 394 m^3 sec^{-1}, we can calculate the mean discharge from the Palizada River (**Rp**) during the nortes season based on seasonal flow of the Usumacinta river. The mean annual discharge for the Usumacinta (**Ru**) = 2153 m^3 sec^{-1}, and the mean annual discharge for the Palizada (**Rp**) = 394 m^3 sec^{-1}. The mean nortes discharge for the Usumacinta (**Ru**) = [1167 January + 1333 February + 4500 October + 3333 November + 2000 December / 5 months] = 2467 m^3 sec^{-1}. Thus, the norte discharge of the Palizada is:

2467 m^3 sec^{-1} / 2153 m^3 sec^{-1} = 1.15
1.15 x 394 m^3 sec^{-1} = 453 m^3 sec^{-1}
Rp = 453 m^3 sec^{-1}

As a result of applying this method, we obtained the seasonal discharge of rivers draining into Terminos Lagoon. These rivers have strong seasonal variations, with discharge during the dry season less than 1/3 of the rainy and nortes seasons. This is an important implication for the circulation and salinity distribution of the Lagoon. **Table 5** shows our calculations for the seasonality of river discharge into the lagoon.

In this system, precipitation (**P**) falling onto the surface of the Lagoon may contribute significant amounts of freshwater to this system, particularly during the rainy season.

[Pm x Md = Pd]

Where **Pm** = monthly precipitation in millimeters, **Md** = numbers of days in month, and **Pd** = precipitation in millimeters per day.

Precipitation (**P**) mm day^{-1} was averaged by season to obtain mean seasonal precipitation (mm day^{-1}) which was converted to (m sec^{-1}).

Seasonal precipitation (m sec^{-1}) x area of the Lagoon surface of interest (m^2) = mean seasonal volume of water falling onto the region per unit time (m^3 sec^{-1}).

As an example, the following calculation was used to determine the volume of rain per unit time falling on the western 1/3 of the lagoon during the nortes season: Area of the western 1/3 of the lagoon = 567 Km^2 and the eastern 2/3 = 1134 km^2.

January 82.8 mm/31 days = 2.67 mm day^{-1}.
[2.67 January + 1.31 February + 7.72 October + 4.75 November + 3.70 December] / 5 months = 4.03 mm day^{-1}.
4.03 mm day^{-1} / [(1000 mm / 1 m) x (1 day / 24 hours) + (1 hour / 60 minutes) + (1 minute / 60 sec)] = 4.67 x 10^{-8} m sec^{-1},

4.67 x 10^{-8} m sec^{-1} x 567 km^2 (in m^2) = 26.48 m^3 sec^{-1}

Because of the large surface water area and shallow depth of the lagoon, evaporation is a crucial parameter to consider. We used the seasonal estimation of evaporation in Terminos Lagoon calculated by Oczkowiski (2004) based on a surface of 2500 km^2. She estimated 26 m^3 sec^{-1} for the western 1/3 of the area, based on a surface of 8.33 x 10^8 m^2 and a total annual evaporation of 1512 mm yr^{-1}. The evaporation data from our calculations were based on a surface of 5.67 x 10^8 m^2 for the western 1/3, and 11.34 x 10^8 m^2 for the eastern 2/3. The seasonal water budget and the net freshwater inflow are indicated in **Table 6**.

Seasonal trends in evaporation are significantly different in Terminos Lagoon. As shown in **Table 6**, it appears that evaporation rates are similar during the dry and rainy season and particularly low during the nortes season. While these variations were not specifically measured for the lagoon, but estimated from Oczkowiski (2004), it makes sense that during the turbulent, cooler nortes season, the water column would be well mixed and less stratified, keeping the surface-most water from excessive heating and thus lessen the rate of evaporation.

There is considerable ambiguity in the definition of residence time (S. Nixon and B. Kjerfve, personal communications). Those who work on rivers and freshwater wetlands tend to think of residence time like the flushing of a container, e.g. the amount of time it takes to replace all of the “old water” in a system with “new water”. This line of thought suggests that water decays linearly with time. However, this is not the case for estuaries where there is ebb and flow of water and mixing of freshwater and saltwater. Thus water replacement time in a system like Terminos Lagoon does not behave linearly but decays exponentially. Thus, the “flushing” of “old water” from a system can be calculated by the equations described above,

$$[\mathbf{N_t = N_o\, e^{-kt}}],$$

$$\mathbf{[Vfw = 1 - (S_L / S_{off}) + Vmax],}$$

and $\mathbf{[Rtw = Vfw / Fwi]}$

The difference in the decay structure of the linear and exponential plots has important implications for ecosystem management, as to how pollutant, nutrients, or the rate of aquatic primary productivity behaves in the system. While the rate of loss stays the same in an exponential decay, the concentration drops off sharply right away and then, over time, decreases much more slowly. If the residence time is known, and something unwanted were introduced to the system, it would be easy to determine how long it would take until the concentration of the unwanted component was reduced to a “safe level’, simply by using the exponential relationship.

By constructing the water budget we have already taken the first step in determining the residence time of Terminos Lagoon. But, in addition to knowing the net volume of water per unit time flowing into the Lagoon, the volume of freshwater present in the Lagoon must be determined.

In order to do this, both the salinity of the water inside of the lagoon and the salinity of the water on the adjacent ocean has to be determined. Recall that all of the calculations have been made on both a seasonal and spatial basis. Four papers describe multiple salinity measurements within the Lagoon over the period of a year (Day et al. 1982, Yáñez-Arancibia & Day 1982, Yáñez-Arancibia et al. 1983, Herrera-Silveira et al. 2002). Representative sampling stations from those papers were selected that seemed to best represent the western 1/3 and eastern 2/3 parts of the Lagoon. Based on those papers we have the offshore salinity, the lagoon salinity, and salinity values were read from the published graphs and entered into an excel spreadsheet. Mean salinity for nortes, dry and rainy seasons, and for the western 1/3 and eastern 2/3 of the water area of the lagoon were calculated. For our residence time calculations, we used the following average salinity values; in the western 1/3, nortes (20 psu), dry (25), and rainy (15); in the eastern 2/3 of the area, nortes (25), dry (30), and rainy (20).

By dividing each seasonal/spatial salinity value for the lagoon by the offshore salinity the proportion of ocean water in the Lagoon was determined. Thus, the proportion of ocean water and freshwater in the Lagoon was quantified. After multiplying the proportion of freshwater in the lagoon by the volume of the lagoon (area x depth), we were able to get an estimate for the volume of freshwater in Terminos Lagoon (**Table 7**).

Example calculation used to determine the volume of freshwater in the western 1/3 of Terminos Lagoon during the nortes season:

Area of western 1/3 of Terminos Lagoon 5.67×10^8 m^2

Mean depth 3.5 m

Mean offshore salinity 36 psu

Mean salinity during nortes period for this area 20 psu

20 psu / 36 psu = 0.55 and 1 –0.55 = 0.45 or 45% of this area of the Lagoon is freshwater.

0.45 x [(5.67 x 10^8 m^2) x 3.5 m] = 0.89 x 10^9 m^3 of freshwater in the western 1/3 of Terminos Lagoon.

Example calculation of the residence time in the western 1/3 of the Lagoon during the nortes season:

Volume of freshwater in Terminos Lagoon western 1/3: 0.89 x 10^9 m^3

Net inflow of freshwater into the western 1/3: 462 m^3 sec^{-1}

Residence Time = (0.89 x 10^9 m^3) / [462 m^3 sec^{-1} x (60 sec / 1 minute) x (60 minutes / 1 hour) x (24 hours / 1 day)] = **22 days**.

Example calculation used to determine the volume of freshwater in the eastern 2/3 of Terminos Lagoon during the nortes season:

Area of Eastern 2/3 of Terminos Lagoon: 11.34 x 10^8 m^2

Mean depth 3.5 m

Mean offshore salinity 36 psu

Mean salinity during nortes period for this area 25 psu

25 psu / 36 psu = 0.69 and 1 –0.69 = 0.31 or 31% of this area of the Lagoon is freshwater.

0.31 x [(11.34 x 10^8 m^2) x 3.5 m] = 1.23 x 10^9 m^3 of freshwater in the eastern 2/3 of Terminos Lagoon.

Example calculation of the residence time in the eastern 2/3 of the lagoon during the nortes season:

Volume of freshwater in Terminos Lagoon eastern 2/3: 1.23 x 10^9 m^3
Net inflow of freshwater into the eastern 2/3 during nortes: 158 m^3 sec^{-1}

Residence time = (1.23 x 10^9 m^3) / [158 m^3 sec^{-1} x (60 sec / 1 minute) x (60 minutes / 1 hour) x (24 hours / 1 day)] = **90 days**.

Table 7 presents the results of the residence time calculations. The residence times for the entire lagoon were long, but residence time for the western 1/3 of the area was considerably less than residence times calculated by Oczkowski (2004) which for the western 1/3 of the lagoon, were 73, 146, and 49 days for nortes, dry and rainy periods, respectively. The differences between our calculations and those of Oczkowski were likely due to differences in the values used for the different areas of the lagoon, the average salinity values used, and the net water inflow. Our salinity average for seasonal periods as well as for geographical area (i.e. western vs. eastern) are based on field data several years of observations (Day et al. 1982, Yáñez-Arancibia & Day 1982, 1988, Yáñez-Arancibia et al. 1983, Herrera-Silveira et al. 2002). We used a different value for the surface area of the lagoon (1700 km^2) rather than the value of 2500 km^2 used by Oczkowski (2004). This latter value includes the wetlands surrounding the lagoon. For these reasons, we believe that our calculations are more accurate.

There are several published values for residence time of Terminos Lagoon, as well as papers describing the residence time concept and calculations in the Lagoon (Kerfve et al 1988, 1989, Jensen et al. 1989). David & Kjerfve (1998) calculated residence times on the order of 10 days, much shorter than the residence time values in **Table 7.** The differences in these values are due to a variation in methodology. When calculating the residence time, David & Kjerfve (1998) included an extra term for tidal inflow (also referred to as the tidal prism) in their “net inflow” or water balance calculation. They also divided the net inflow by the total volume of the lagoon to get residence time. Further, they did not include evaporation from the lagoon surface as one of their parameters. One of the problems with this kind of a calculation, and thus the reason that we made the decisions that we did, is that much of the shelf water introduced into the Lagoon over a tidal cycle sloshes in and out around the entrances of the lagoon. Much of this water does not become part of the overall lagoon hydrodynamic system as a considerable portion of the water entering on the flood tide leaves on the ebb through the same inlet. Thus we felt that to include the tidal prism in these calculations (and thus use the volume of all of the water in the lagoon, not just the volume of freshwater) would be a less accurate way of estimating residence time at this scale.

It became quite clear at the end of the water budget analysis and the residence time calculation, that there is considerable seasonal and spatial variability in the lagoon. The net freshwater inflow to the lagoon varies dramatically by season. In fact, during the dry season, in the eastern 2/3 of the lagoon, evaporation is about equal to precipitation and discharge (**Table 6**) suggesting a long residence time for this period as was described by Yanez-Arancibia & Day (1982, 1988) and Yanez-Arancibia et al. (1983), Jensen et al. (1989), and reflected in the silty/clay isolated sediments zone described in the literature in the eastern 2/3 of the lagoon. Any decreases in freshwater inflow will increase the residence time. The theoretical value for the dry period in the eastern 2/3 (i.e., *ca*. 5 years) is an extreme indicator that in the southern end of this region has a distinct behavior with the lowest values of water transport (Kjerfve 1988, Jensen et al. 1998), a high rate of silty/clay sediments (Yanez-Arancibia et al. 1983), the highest salinity values during dry season and a distinct habitat for juvenile fish (Yanez-Arancibia & Day 1982). Probably the residence time in this area is not 5 years during the dry season, because the hydrodynamic behavior of the Lagoon, but it could have a value of about 1.5 years as was calculated by Yanez-Arancibia & Day (1982).

On the other hand, it is clear from **Table 7** that the Western 1/3 area has a much shorter residence time. This area receives 70% of the total freshwater discharge to the lagoon and discharges estuarine mixed waters to the adjacent Gulf through El Carmen Inlet, often with a velocity > 80 cm sec^{-1}. The calculated residence time for this area is about one month. This reflects the net eastward flow through the lagoon, the strongly tidal Carmen inlet, and the high fresh water input.

5. Management implications

5.1 Identifying Indicators and a monitoring protocol

Indicators for measuring the effects of changes in freshwater, both in quantity and quality, on biological and ecological characteristics and functioning of the lagoon, should reflect the factors that affect these changes. These include climate change, normal environmental variability (i.e., normal year to year variation in rainfall), and human activities (i.e., urban development, agricultural activities in the coastal plain freshwater wetlands, oil and gas activities, over-fishing, dredging and filling in freshwater wetlands and mangrove swamps, deforestation in the watershed, and freshwater diversions).

We suggest eleven parameters as potential indicators for a robust monitoring program to document the impacts of changes in freshwater input: (**1**) soil and water salinity, (**2**) turbidity and water transparency, (**3**) soil accretion and elevation change, (**4**) mean chlorophyll-*a*, (**5**) nutrient concentrations, (**6**) oxygen concentration, (**7**) coliform bacteria, (**8**) change in seagrass biomass and distribution **,** (**9**) mangrove litterfall, (**10**) mangrove stem growth, and (**11**) river discharge. If all of these parameters cannot be measured, a subset can be chosen.

Figure 22 shows the location of suggested sampling sites appropriate for a monitoring program. The locations of these sites are based on the functional dynamics of Terminos Lagoon and the habitats or subsystems defined in **Table 2** and **Figure 10**. These sampling sites cover the two Inlets, the Inner littoral of Carmen Island, the Central Basin, and the Fluvial-lagoon system inlets to the lagoon.

Site 1 = Puerto Real Inlet
Site 2 = Inner Littoral Carmen Island (Isla Pajaros)
Site 3 = Estero Pargo Inlet
Site 4 = Carmen Inlet
Site 5 = Central Basin (western)
Site 6 = Central Basin (mid western)
Site 7 = Central Basin (mid eastern)
Site 8 = Central basin (eastern)
Site 9 = Fluvial-lagoon (Candelaria river inlet)
Site 10 = Fluvial-lagoon (Chumpan river inlet)
Site 11 = Fluvial-lagoon (Palizada river inlet)
Site 12 = Fluvial-lagoon (Atasta inlet)

For monitoring the water column (Sites 1 to 12), we recommend consideration of the following parameters and frequencies of sampling:

1. Continuous measurement of water level with tide gauges at one location in the lagoon. Measurements of climate data such as temperature, rainfall, and cloud cover. For monthly measurements, water column depth, time, tidal state, and current speed and direction should be measured in addition to temperature, pH, and conductivity.

2. Salinity, surface and bottom, monthly.

3. Water transparency, Sechi depth, and suspended particulate material, monthly.

4. Chlorophyll-*a* surface concentration, monthly.

5. Nutrient concentrations at the surface, monthly.

6. Oxygen concentration at surface and bottom, monthly.

7. Coliform bacteria at the surface and in *Crassotrea virginica* reefs. Monthly, particularly at Sites 4 and 9 to 12.

8. Depending on the instrument used, temperature, pH, conductivity, and other parameters can be obtained.

For sites 1, 2 and 3 in Thalassia testudinum beds, we recommend the following parameters and frequencies of sampling :

1. Seagrass biomass, monthly, or seasonally as described in the next point.

2. Distribution of seagrasses can be monitored using aerial photographs, three time per year, in February (end of 'nortes' season), May (end of dry season), and October (the highest river discharge at the end of the rainy season).

For sites for mangrove sampling in Estero Pargo, Boca Chica, and Atasta, in Rhizophora mangle and Avicenia germinans habitats, we recommend the following parameters and frequencies of sampling :

1. Mangrove litterfall, monthly.

2. Mangrove stem growth, yearly.

3. Soil accretion, yearly.

4. Sediment elevation, yearly.

5. Soil salinity, monthly.

6. Water column depth inside mangrove swamps using either a continuous water level gauge, or monthly during litterfall collection. This can be correlated with the water level taken at other locations with a water level gauge.

Expected use of data :

The monitoring data set can be used for interpreting the impacts of changes in freshwater input on the following functional attributes of Terminos Lagoon.

A). Changes in productivity of Terminos lagoon over time. Fresh water input can affect productivity in a number of ways. River discharge provides freshwater which reduces salinity, nutrients which stimulate productivity, and suspended sediments that reduce light penetration in the water column. Day et al. (1996) showed that mangrove productivity was related to soil salinity, temperature, and rainfall. Therefore, measurements of mangrove litterfall and stem growth and soil salinity can be correlated with mean lagoon salinity, climate data, and river discharge to determine the impact on mangrove productivity. Long-term productivity sites currently exist at several sites in Terminos Lagoon including Estero Pargo, Atasta, and Boca Chica. The degree of flooding also affects mangrove productivity. Because sea level rise is projected to accelerate, the surface elevation of mangrove soils must increase vertically if mangroves are to survive. Measurements of soil accretion and elevation change provide accretionary data that can be compared to sea level changes over time. Soil accretion can be measured with marker horizons and elevation change can be measured with a sedimentation elevation table - SET (see Cahoon et al. 1995). Accretion and SET sites currently exist in Terminos at Estero Pargo, Boca Chica, and Atasta.

Changes in the quantity and quality of freshwater input can affect the productivity of phytoplankton and seagrasses in terms of nutrient concentration and water column turbidity. Measurements of seagrass biomass and aerial extent and chlorophyll are indicators of productivity. Correlation of these data with nutrients, water column transparency, river discharge, and other factors can help understand the impact of changes in freshwater input.

B). Data on rainfall, evaporation, groundwater input and river discharge can be used to calculate annual water budgets. Over time, this will provide data on interannual variability in the water budget and if there are longer term trends in the elements of the water budget (i.e., drying due to global climate change). The water budget information will also allow calculation of inputs of materials such as nutrients and suspended material.

C). Water quality and ecosystem health. Parameters such as nutrient concentrations, chlorophyll, turbidity, and coliform bacteria can serve as indicators of water quality. Statistical approaches have been used to develop indices of water quality or trophic state indices. Monitoring data could be incorporated into such programs to develop period estimates of lagoon health. These could then be compared with changes in the quality and quantity of fresh water input to determine the impact of these changes on water quality. Not only are absolute nutrient concentrations important, but the ratios of nutrients are important to determine potential limiting nutrients using Redfield stochiometry (see Day et al. 1989 for a general discussion). On average, concentrations of NO_3 increased by a more than a factor of 5 and PO_4 by a factor of about 2 over a 30 year period. However, the average N:P ratio remained the same at about 20 for the entire lagoon. This indicates a fairly balanced nutrient situation, thus the increasing nutrient concentrations should lead to higher productivity. The central basin may have shifted from a condition of nitrogen limitation to one of phosphorus limitation over the past several decades. Mean lagoon chlorophyll-*a* was 3.0 in the 1970's and 5.6 in 2002. This suggests an increase in productivity has occurred. However, since these are only two years of data, it is difficult to determine if this is a real increase in productivity. Careful analysis of the monitoring data will help to answer this question.

D). Sustainability of ecosystem functioning. Taken together, the above information will allow a determination of the sustainability of the functioning of the Terminos lagoon ecosystem. Long term changes in freshwater input to the lagoon can lead to changes in a number of functional attributes of the system. If freshwater input decreases, mangroves can become stressed and less productive. This can lead to less below ground productivity and thus less organic soil formation and the ability to keep up with rising sea level. Freshwater and nutrient input has been related to aquatic primary productivity and fisheries, thus a long-term trend of decreasing freshwater input to overall lower lagoon productivity. Increasing freshwater will enhance ecosystem productivity. For mangroves, this stimulatory effect occurs over a broad range of input. But for phytoplankton and seagrasses, eutrophication can occur at higher levels of nutrient input. Seagrasses are especially susceptible nutrient increase because overgrowth of epiphytes occurs at high nutrient concentrations.

5.2 Management guidelines and recomendations

Sustainable management of Terminos Lagoon should be based on an understanding of the status of the lagoon and how it functions. Monitoring data provide a baseline for assessing the health of the lagoon.

Any approach to restoration and sustainable management of Terminos Lagoon is facilitated by the elaboration of a scientific and management conceptual framework. An important guiding principle is that system functioning should form the basis for a sustainable plan (Day et al. 1997, 2000). In other words, it is important to work with the natural system, applying the principles of ecological engineering whenever possible (Mitsch and Jorgensen 2003). Ecological engineering, defined as “the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch and Jorgensen 2003), involves creating and restoring sustainable ecosystems that have value to both humans and nature. This approach combines basic and applied science for the restoration, design, and construction of aquatic and terrestrial ecosystems. Ecological engineering relies primarily on the energies of nature, with human energy used in design and control of key processes. One of the key principles in ecological engineering is self-design. This is the idea is that we allow the natural system to work with as little control as possible so that long term survival is more probable.

From a practicable perspective, management of the lagoon should involve a number of specific activities. The monitoring plan is designed to provide information on the functioning, sustainable management, and health of the lagoon ecosystem. Specific management activities should include the following.

1. Preservation of wetlands. Because of their value for habitat, nursery areas for fishery species, water quality improvement, regulation of biogeochemical cycles, recharge areas, storm buffers, carbon storage, and other values, it is important to preserve wetlands.

2. Hydrologic restoration in wetlands. Hydrology is a key to wetland functioning. Studies in many areas have shown that disruption of hydrology leads to loss of wetland function and wetland deterioration. For example, the alteration of hydrology has been shown to be a primary cause of wetland loss in the Mississippi delta (Day et al. 2000).

3. Use of buffer strips in agricultural areas. The nutrient data on the lagoon suggest that nutrient levels in the lagoon have increased over the past several decades. A likely source of these nutrients is from agricultural lands that have been cleared during this period. This is especially the case for seasonally flooded freshwater wetlands of the coastal plain. The use of buffer strips has been shown to be an effective management tool for the reduction of nutrient loss from agricultural areas (Mitsch et al. 2001).

4. Use of wetlands for sewage treatment. The use of wetlands offers an economic and ecologically sound approach to assimilation of sewage effluent (Kadlec and Knight 1996, Day et al. 2004). This approach offers a viable solution for the urban area of Cd. del Carmen.

5. River diversions into wetlands. Sea level rise is predicted to increase significantly during the 21st century. This will threaten the wetlands surrounding Terminos Lagoon and the health of the entire lagoon ecosystem. Introduction of river water into wetlands increases their ability to survive sea level rise.

Broader perspectives :

Management should consider activities in the Usumacinta Basin, and anticipate future change, especially global climatic change, and potential increases in the cost and availability of energy. Because the Terminos is at the bottom of the Usumacinta basin and is affected by activities in the basin, restoration and management will be more effective if the drainage basin is considered. Activities in the basin such as changes in freshwater, suspended sediment, and nutrient fluxes affect management of the delta. For examples for the Mississippi basin see Mitsch et al. (2001), Day et al. (2005), Kesel (1989) and Rabalais et al. (1996**)**.

Global climate change and decreasing availability and increasing cost of energy potentially have important implications for delta restoration (Day et al. 2005). Coastal restoration and management efforts will likely have to be more intensive to offset the impacts of climate change including accelerated sea level rise, increased temperature, and changes in precipitation patterns. Climate change predictions include a 1 to 5^{o}C temperature rise and a 30-60 cm sea level rise during the 21st century (IPCC 2001) and potential changes in local freshwater inflow to estuaries. If there is a decrease in local freshwater discharge or rainfall, diversions from the Usumacinta may be important for controlling salinity and for providing sediments and nutrients for restoring and maintaining coastal wetlands.

Restoration and management efforts may need to focus more in coming decades on less energy-intensive, ecologically engineered management techniques that use the energies of nature as much as possible if, as some predict, energy becomes more costly and less available (e.g., Masters et al. 1991, Campbell and Laherrére 1998, Kerr 1998, Bentley 2002, Deffeyes 2001, 2002, Hall et. al. 2003, Heinberg 2003). Energy intensive activities such pumping of dredged sediments for coastal restoration may become much more expensive in the future. Increased cost and reduced availability of energy suggests that those methods of restoration and management that rely on natural energies and use relatively low amounts of fossil energy (i.e., ecologically engineered solutions) are the ones most sustainable in the long term (such as using diversions of river water to maintain wetlands).

Finally we can reinforce the approach given by Day and Yanez-Arancibia (1988): (**1**) protect the structure and basic functioning of Terminos Lagoon/Campeche Sound ecosystem, (**2**) utilize the natural energy inputs and subsidized natural production, (**3**) plan more carefully the urban and industrial development in harmony with natural processes, (**4**) determine the optimal yield of biotic resources such as fish and macroinvertebrates, and 5) permanently monitoring changes in resources and habitats. The Terminos Lagoon/Campeche Sound study provides a useful model for applying the ecosystem-based management approach, useful to other tropical coast as well.

TABLES

Table 1. Plant uptake requirements and abiotic and biotic pools of Nitrogen in Terminos Lagoon *Thalassia testudinum* beds. After Hopkinson et al. (1988).

Pool identification	Plant requirement ($u$mol m^2 d^{-1})	Standing stock ($u$mol m^2)	Turnover Time (d)
Phytoplankton	**7.5**	**2.3**	**0.3**
Thalassia	**4.0**	**705.7**	**176.0**
Epiphytes	**2.5**	**37.5**	**15.0**
Sediments:			
Macro-organics	**-**	**410.4**	**-**
Micro-organics	**-**	**12150.0**	**3100.0**
Ammonium	**-**	**15.1**	**-**
Nitrite-Nitrate	**-**	**0.2**	**3.8**
Water:			
Ammonium	**-**	**4.0**	**-**
Nitrite-Nitrate	**-**	**<1.0**	**<0.5**
Dissolved organics	**-**	**50.0**	**11.4**

Table 2. Main ecological characteristics of Subsystems in Terminos Lagoon and Campeche Sound, southern Gulf of Mexico.

Subsystems in Terminos Lagoon :

Puerto Real Inlet: Salinity psu 29 (rainy) to 37 (dry). Temperature ^oC 23 ('nortes') to 28 (dry to rainy). Transparency 60% (dry). $CaCO_3$ 60 to 90%. Strong sea water influence. Affinity with Central Basin (dry), and strong affinity with Inner Littoral Carmen island ('nortes', dry, and rainy seasons). Macroalgae and *Thalassia testudinum* benthic community. High diversity of fish and macrobenthic community. The emergent flood delta is a typical feature with a fan effect from the sea to the lagoon. The shrimp *Farfantepeneus duorarum* is typical in this subsystem.

***Inner littoral Carmen Island*:** Salinity psu 26 (rainy) to 39 (dry). Temperature ^oC 23 ('nortes') to 32 (dry to rainy). Transparency 80 to 100%. $CaCO_3$ 60 to 80%. Affinity with Puerto Real Inlet ('nortes', dry, and rainy seasons). *Rhizophora mangle*, *Thalassia testudinum* and macroalgae community. High diversity of demersal fishes and macrobenthic community. High chlorophyll-*a* value such as 14 mg m^3 (rainy), and highest value of NH_4 12 uM (rainy).

***Central Basin*:** Salinity psu 12 (rainy) to 30 (dry). Temperature ^oC 20 ('nortes') to 30 (rainy). Transparency 50 to 70%. Muddy with fine sand and clay-silt $CaCO_3$ 30 to 40%. Transition zone, related with Puerto Real (dry) and with the Fluvial-lagoon system ('nortes', rainy). Macroalgae benthic community. Medium diversity of demersal and small pelagic fishes and macrobenthic community. Lowest NO_3 concentration <2 uM (dry), and lowest NO_2 0.02 uM (dry).

***Fluvial-lagoon System* (eastern *versus* western):** The eastern part (III-1) present average salinity psu 19 (rainy) to 23 (dry and 'nortes') with more influence from Puerto Real inlet than the western end.

Temperatures in the range of Central Basin. Transparency 45% (dry). Related with Central Basin during dry season. Silty-clay with fine sand and $CaCO_3$ 20 to 30%. Seagrasses, basin mangrove swamps, and *Crassotrea virginica* reefs. High diversity of demersal fishes and macrobenthic community. The western end (III-2) present strongest riverine influence. Salinity psu 4 (rainy) to 20 (dry), and an average of 20 ('nortes' period). Temperatures in the range of Central Basin. Transparency 29% (dry) to <10% ('nortes'). Related with El Carmen Inlet during dry, rainy and 'nortes' periods. Silty-clay with $CaCO_3$ 10 to 30%. Highest value of suspended particulate material 0.04 mg l-1 (dry). No seagrasses, but riverine mangrove swamps, and *Crassotrea virginica* reefs. Both, III-1 and III-2 subsystems are related with Central Basin during 'nortes' period, and presents medium-low diversity of demersal fishes and macrobenthic community, high chlorophyll-*a* value such as 14 mg m^3 (rainy), highest NO_3 concentration 34 *u*M, and NO_2 1.8 *u*M, and highest value of NH_4 12 *u*M (rainy).

Carmen Inlet**:** Salinity psu 15 (rainy) to 25 (dry). Temperature ^oC 22 ('nortes') to 27 (dry to rainy). Transparency >40% (dry). $CaCo_3$ 10 to 30%. Related with III-2 during dry season and with Inner Littoral Carmen Island and Central Basin during 'nortes' and rainy periods. No seagrasses, but riverine mangrove swamps. The submerged ebb delta is a typical feature with a fan effect from the lagoon to the shelf. The shrimp *Litopeneaus setiferus* is typical in this subsystem.

Subsystems in Campeche Sound :

Zone A**:** Heterogeneous, strong estuarine and riverine influence. Turbid waters. Transparency 7 to 42%. Surface salinity psu 32 to 35, bottom 35 to 37. Surface temperature ^oC 22 to 28, bottom 23 to 27. Silty-clay sediments with $CaCO_3$ 10 to 60% and high organic content >10%. pH 7.6 to 8.3. Dissolved oxygen <4 ml l^{-1}. No macrobenthic vegetation. High diversity of demersal fish community, and typical presence of blue crab *Callinectes* spp, and shrimp *Farfantepeneus aztecus.* Fringe and riverine mangrove swamps in the coastal vegetation. Terrigenous coastal plain associated.

Table 2…continue.

Zone B**:** Homogeneous, typical tropical marine area. No estuarine or riverine influence. Clear waters. Transparency 50 to 90%. Surface and bottom salinity psu 35 to 27. Surface temperature ^oC 26 to 29, bottom 24 to 28. Sandy sediments with $CaCO_3$ 70 to 90% and very low organic content <10%. pH 7.7 to 9.0. Dissolved oxygen >4 ml l^{-1}. Typical macrobenthic vegetation with macroalgae and *Thalassia testudinum* . High diversity of demersal fish community, and typical presence of blue crab *Callinectes* spp, and shrimp *Litopeneus duorarum.* Scrub mangrove swamps in the coastal vegetation. Calcium carbonate coastal plain associated.

A natural border, open and with variable limits, can be found between Zones A and B, where values of environmental parameters overlap. *Litopeneus setiferus* is the typical shrimp in between both zones. High diversity of fish community in the inner sea shelf exist.

Source of information: Yanez-Arancibia and Day (1982, 1988), Day et al. (1982, 1987, 1988, 1996), Yanez-Arancibia et al. (1983), Yanez-Arancibia and Sanchez-Gil (1983), Kjerfve (1986), Kjerfve et al. (1988), Jensen et al. (1989), Herrera-Silveira et al. (2002).

Table 3. **Average biomass (g m^2) for structural components in the Terminos Lagoon ecological model in each one of the subsystems (habitat). After Soberon-Chavez et al. (1988)**

Components / Subsystems	B	I	II	III	IV	A
Phytoplankton	19.26	156.50	133.48	150.71	155.44	30.61
Seagrasses	0.43	28.93	1.95	13.61		
Organic detritus	8.86	48.53	45.05	121.40	123.86	32.16
Zooplankton	0.03	0.33	0.28	0.29	0.34	0.36
Benthos	0.09	0.16	0.07	0.12	0.08	0.15
Nekton	0.85	1.75	0.75	1.22	0.58	1.16

Table 4. Main environmental parameters in Terminos Lagoon required for water budget and residence time calculations. Data were selected from our source of information : INEGI, Comisión Nacional del Agua, SEMARNAT, Instituto Nacional de Ecología, Day et al. (1982, 1988), Yánez-Arancibia and Day (1982, 1988), Yanez-Arancibia et al. (1983) and unpublished data, Kerfve et al. (1986, 1988, 1989), Jensen et al. (1989), and Herrera-Silveira et al. (2002).

- Total system surface area 3000 km^2, including water water surface areas and mangrove swamps and marshes

- Water surface area 1700 km^2, including 100 km^2 with submerged vegetated area

- Western 1/3 water surface area 567 km^2

- Eastern 2/3 water surface area 1134 km^2

- Wetlands surface including marshes and mangrove swamps 1300 km^2

- Mean water depth of the lagoon 3.5 m

- Mean water depth in the wetland area 0.2 m

- Palizada River discharge 480 m^3 sec^{-1} (high average in rainy) to 288 m^3 sec^{-1} (low average in dry); average yearly 394 m^3 sec^{-1}

- Chumpan River discharge 50 m^3 sec^{-1}

- Candelaria & Mamantel combined river discharge 72 m^3 sec^{-1}

- Mean annual total river discharge 516 m^3 sec^{-1}

- Historical range of total river discharge 9.1 to 16.3 x 10^9 m^3 yr^{-1}

- Average River discharge 12.7 x 10^9 m^3 yr^{-1}

- Ground water discharge 4 x 10^6 m^3 yr^{-1}

- Precipitation annual average 4.5 x 10^9 m^3 yr^{-1} [1805 mm yr^{-1}]. Equivalent to 143 m^3 sec^{-1}

- Evaporation average 1512 mm yr^{-1}. Equivalent to 120 m^3 sec^{-1}

- Potential Evapotranspiration 1586 mm

- Actual Evapotranspiration 1471 mm

- Average salinity in the adjacent ocean off Puerto Real 36 psu

- Average salinity entering through Puerto Real 35 psu

- Average salinity in Terminos Lagoon 22 psu
- Average range salinity into the fluvial-lagoon systems 0 to 4 psu
- Average salinity entering Campeche Sound through El Carmen Inlet 22 psu
- Average daily water surplus 293 mm
- Tidal range average 0.43 m (range 0.3 to 0.7 m)
- Freeze free period 365 days

Table 5. Seasonality of river discharge into Terminos Lagoon

	Palizada River (m^3 sec^{-1}) *Western 1/3*	Chumpan + Candelaria + Mamantel Rivers (m^3 sec^{-1}) *Eastern 2/3*
Mean annual	394	122
Nortes	453	140
Dry	250	50
Rainy	490	175

Table 6. Seasonal water budget in Terminos Lagoon for separate subsystems (m^3 sec^{-1})

Area and Climate season	Discharge (+)	Precipitation (-)	Evaporation (=)	Net freshwater Inflow
Western 1/3 :				
Nortes	453	27	18	462
Dry	250	12	35	227
Rainy	480	45	33	492
Eastern 2/3 :				
Nortes	140	53	35	158
Dry	50	24	70	4
Rainy	175	91	66	200

Table 7. Volume of freshwater, net water inflow, and residence time in Terminos Lagoon for both seasonal and spatial scale.

Western 1/3	Volume Freshwater (m^3)	/ Net water Inflow ($m^3\ sec^{-1}$)	= Residence Time (days)
Nortes	0.89×10^9	462	22
Dry	0.62×10^9	227	32
Rainy	1.17×10^9	492	28
Eastern 2/3			
Nortes	1.23×10^9	158	90
Dry	0.67×10^9	4	1938
Rainy	1.78×10^9	200	103

FIGURES

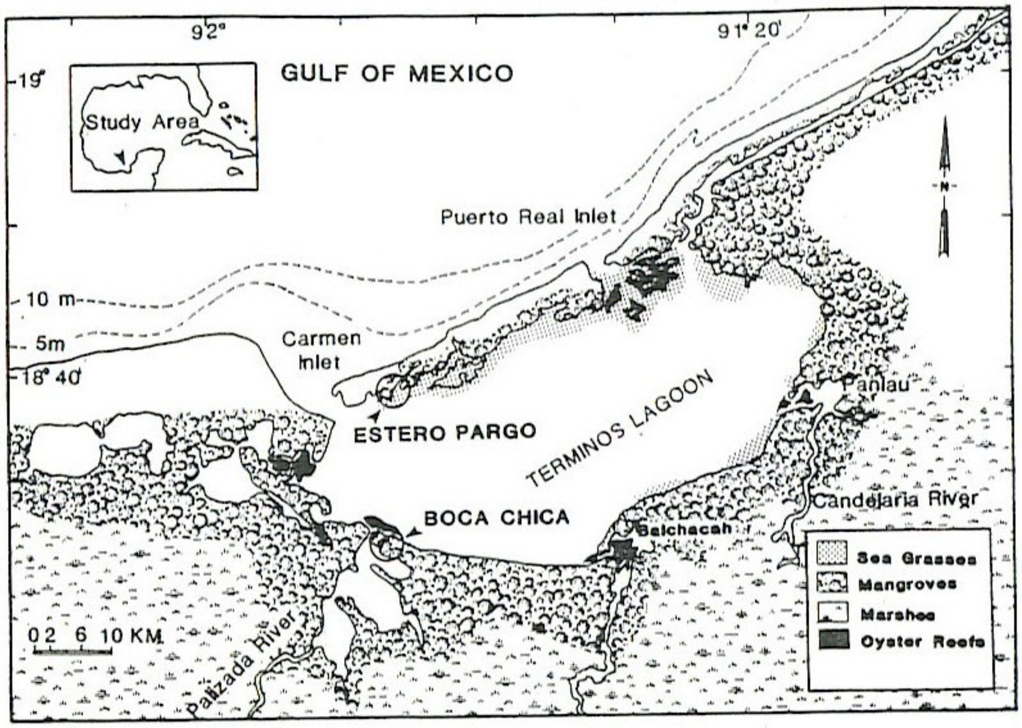


Figure 1. The Terminos Lagoon region in the southern Gulf of Mexico. Geomorphology and global ecosystem characteristics depending on the two inlets connecting the lagoon with Campeche Sound into the shelf. Puerto Real Inlet in the northeast end modulating the flood delta into the lagoon and the marine waters distribution. The Fluvial-deltaic systems and low-land wetlands of the lagoon modulating the freshwater discharge and the estuarine water distribution into the Central Basin. Carmen Inlet in the western part of the lagoon modulating the ebb delta and the estuarine water distribution into the sea shelf. LandSat TM October 1993. The map shows BPR = Puerto Real Inlet, El Carmen Inlet, PG = Punta Gorda, CA = Bajos del Cayo and ESP = Estero Pargo, both in the Inner littoral Carmen Island, Fluvial-lagoon systems are CP = Candelaria-Panlau, CHB = Chumpan-Balchacah, PE = Palizada-del Este, PA = Pom-Atasta.

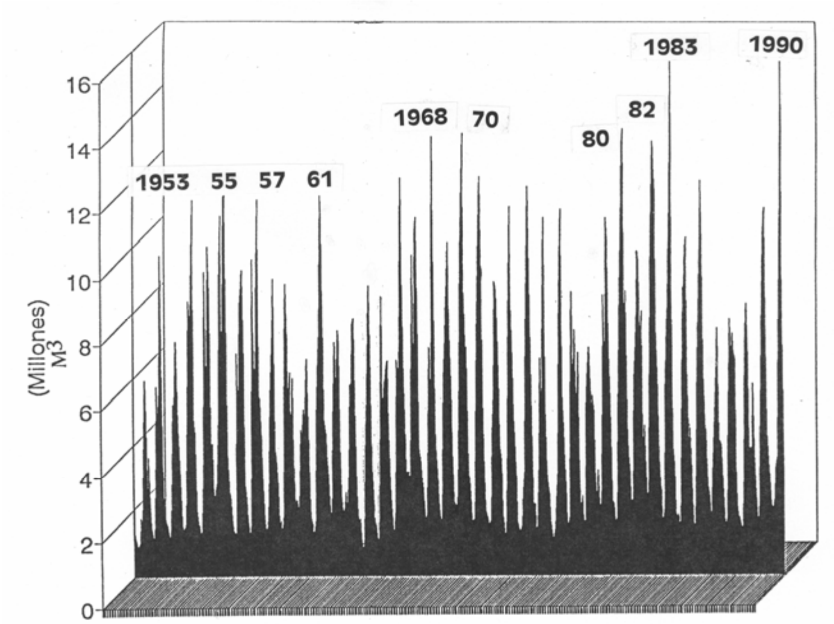


Figure 2. Long-term multi year monthly pulsing of freshwater discharge of Usumacinta River from 1950 to 1990. Integration of hydrometric values for Boca del Cerro, Rio San Pedro and Rio Chacamax, hydrometeorological stations, from Comision Nacional del Agua (CAN, Mexico). During the four decades, major pulsing occurs in October, lowest flood occurs in April-May. Explanation in the text. Redrawn from Yanez-Arancibia et al. 1993*b*.

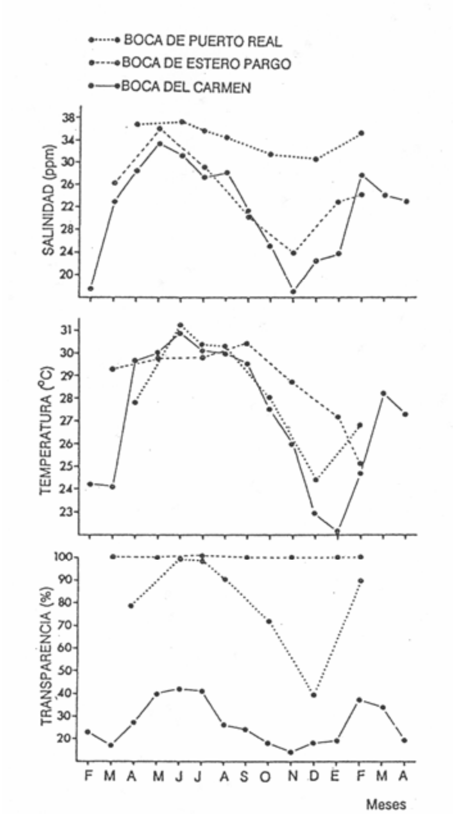


Figure 3. Seasonal variation of salinity, temperature, and water column transparency, in Puerto Real, Estero Pargo, and Carmen inlets. The lowest values are from November to January ('nortes' season) and the highest values are from May to July (end of 'dry' and beginning of the 'rainy' seasons). Redrawn from Yanez-Arancibia et al (1983).

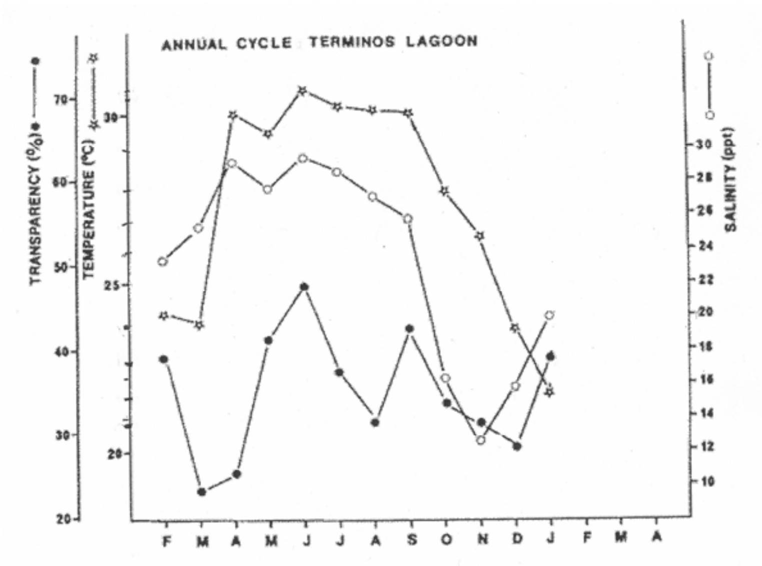
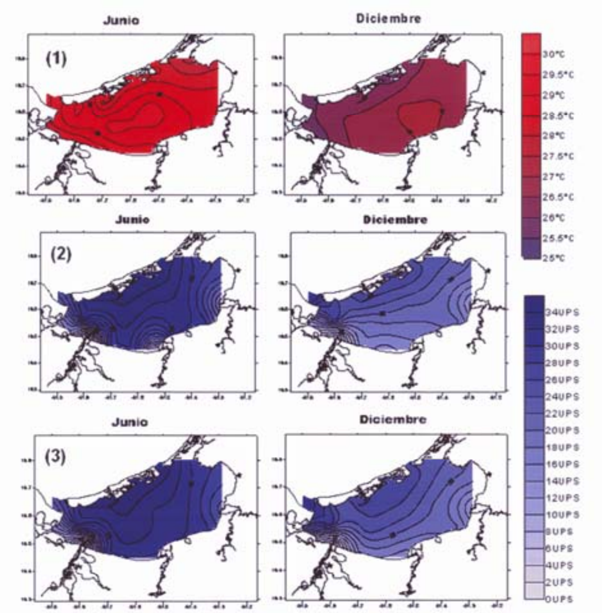
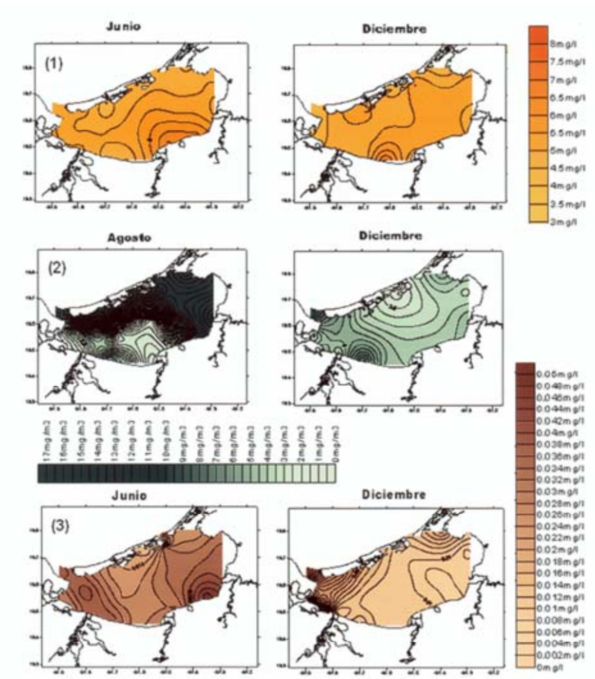


Figure 4. Typical seasonal pattern of average values of transparency, temperature, and salinity, for each sampling station indicated in the map during a two-year cycle in Terminos Lagoon. Redrawn from Yanez-Arancibia et al. (1983).



Seasonal distribution of (1) Surface temperature . (2) Surface salinity.
(3) Bottom salinity. June (rainy) and December ('nortes') period

Figure 5. [A]. Seasonal distribution of (1) temperature, (2) surface salinity, and (3) bottom salinity. Figure and data base from Herrera-Silveira et al. (2002).



Seasonal distribution of (1) Bottom oxygen. (2) Chlorophill-a.
(3) Suspended particulate material. June and August (rainy)
and December ('nortes') period

Figure 5 [B]. Seasonal distribution of (1) bottom oxygen, (2) chlorophyll-*a*, and (3) suspended particulate material. Figure and data base from Herrera-Silveira et al. (2002).

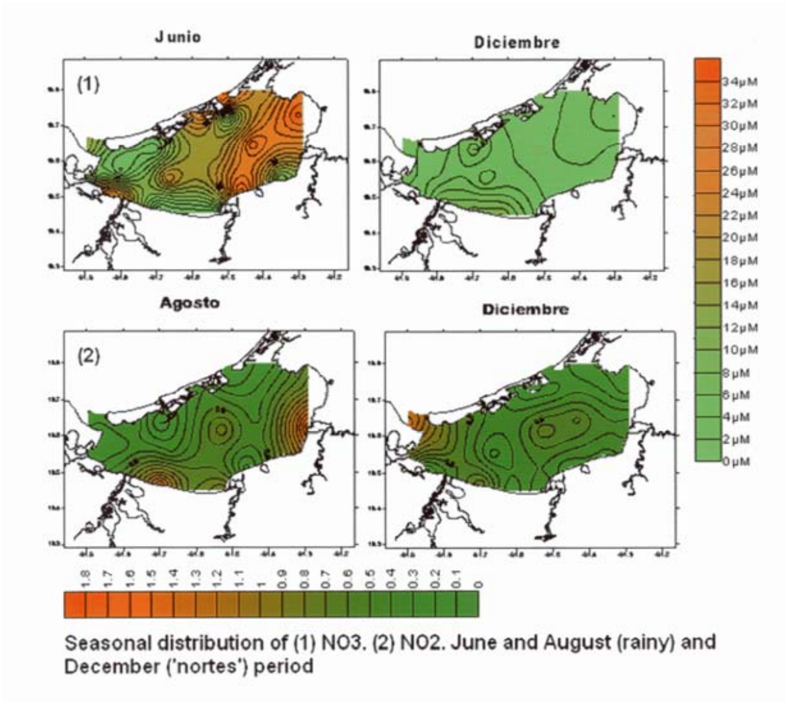


Figure 5 [C]. Seasonal distribution of (1) NO_3, and (2) NO_2. Figure and data base from Herrera-Silveira et al. (2002).

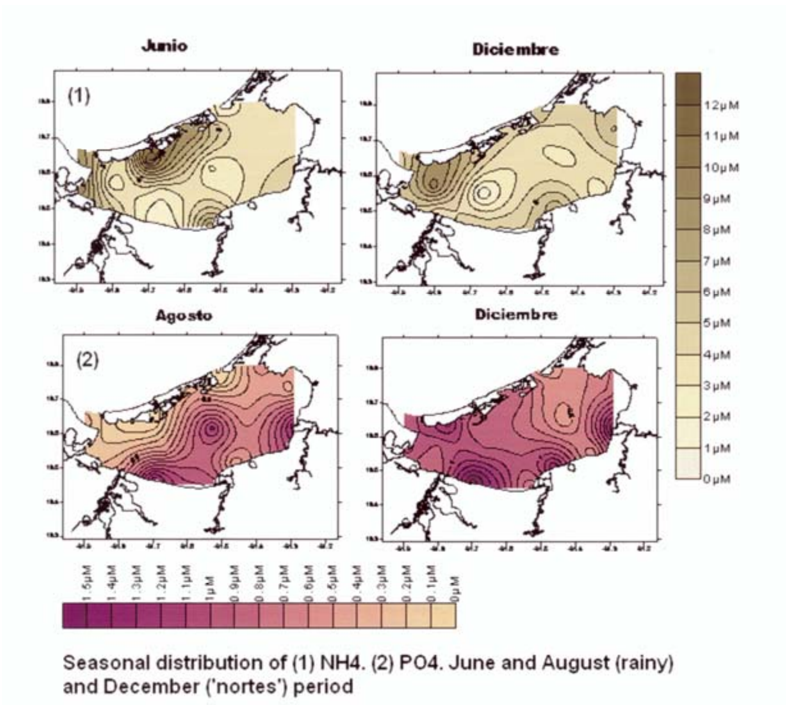


Figure 5 [D]. Seasonal distribution of (1) NH_4, and (2) PO_4. June and August (rainy season), December ('nortes' period). Figure and data base from Herrera-Silveira et al. (2002).

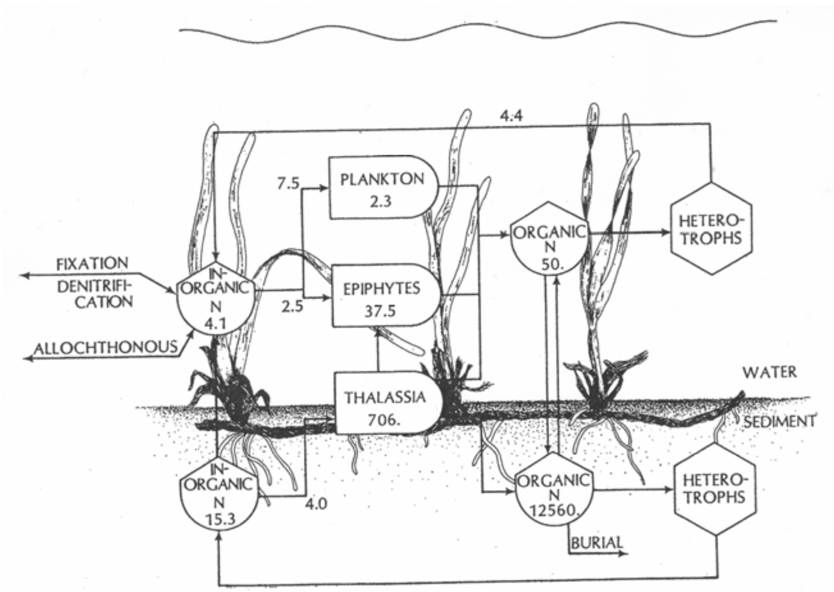


Figure 6. Conceptual model of the Terminos Lagoon *Thalassia testudinum* beds community for Nitrogen cycle. Value calculation in Table 1. After Hopkinson et al. (1988)

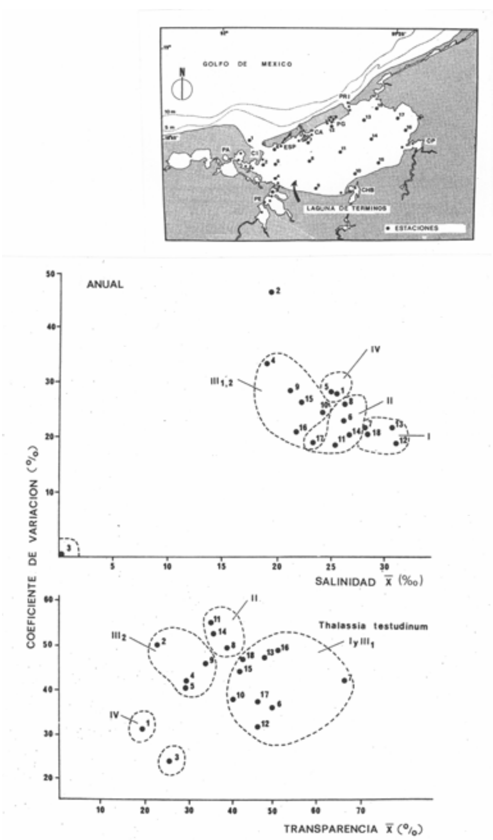


Figure 7. The relationship of average salinity and transparency over 15 months to the coefficient of variations for each sampling station indicated in the map. Assemblages of sampling sites with ecological affinities are shown. Redrawn from Yanez-Arancibia et al. (1983).

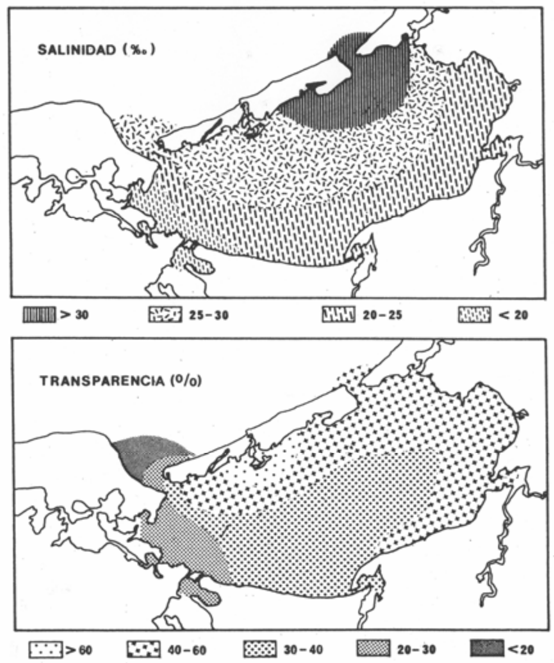


Figure 8. Diagrammatic model of mean salinity and transparency gradient in Terminos Lagoon. Both parameters are independent on the lagoon metabolism and presents a close relationships with the water circulation pattern. Major salinities and transparencies are associated to areas of higher and persistent marine influence related to Puerto Real Inlet. Redrawn from Yanez-Arancibia et al. (1983).

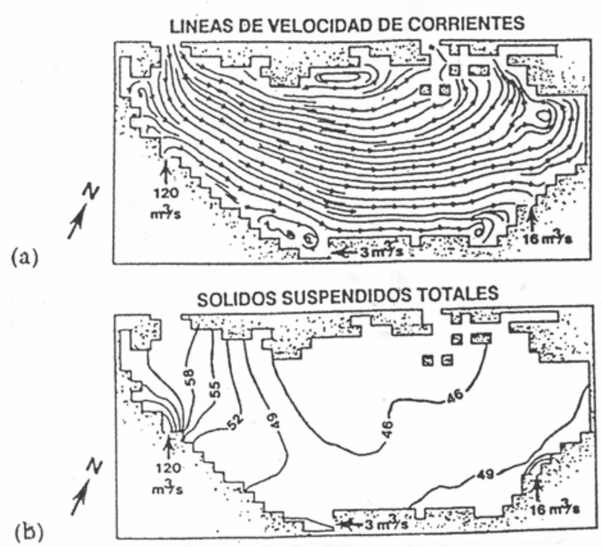


Figure 9. Hydrodynamic-dispersion simulation model of total suspended sediments (ppm) in Terminos Lagoon during 24 April 1987 (dry season, east/southeast winds of 3 m sec^{-1}), 15:52 hours pm GMT, correlated with LandSat TM. After Jensen et al. (1989).

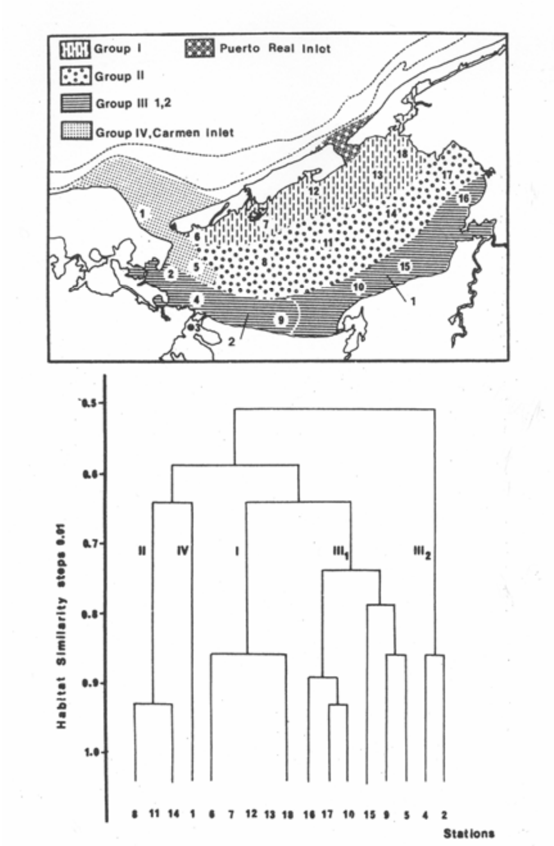


Figure 10. **Maps and dendrogram of the clustering of localities in Terminos Lagoon using the simple matching coefficients index of similarity and the single linkage clustering methods, based on annual environmental characteristics of the ecosystem (Table 2). The dendrogram reflects five (I to IV and Puerto Real inlet) groups of sampling sites which were defined as different habitat. After Yanez-Arancibia and Day (1982).**

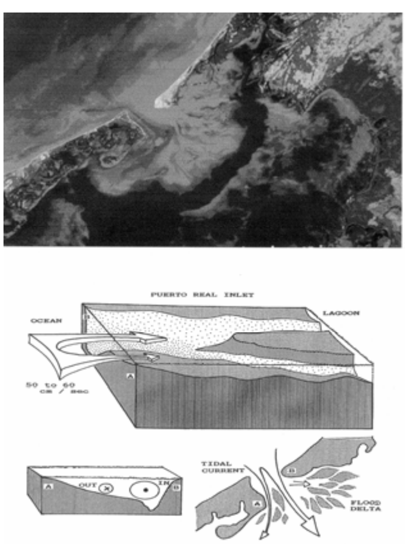


Figure 11. Diagram of circulation pattern in Puerto Real inlet on a transect from A (El Carmen Island) to B (mainland). The model assume no stratification, the water balance is induced by tidal current and modulated by winds. The fan effect on the inner flood delta into the lagoon is shown correlated with LandSat TM.

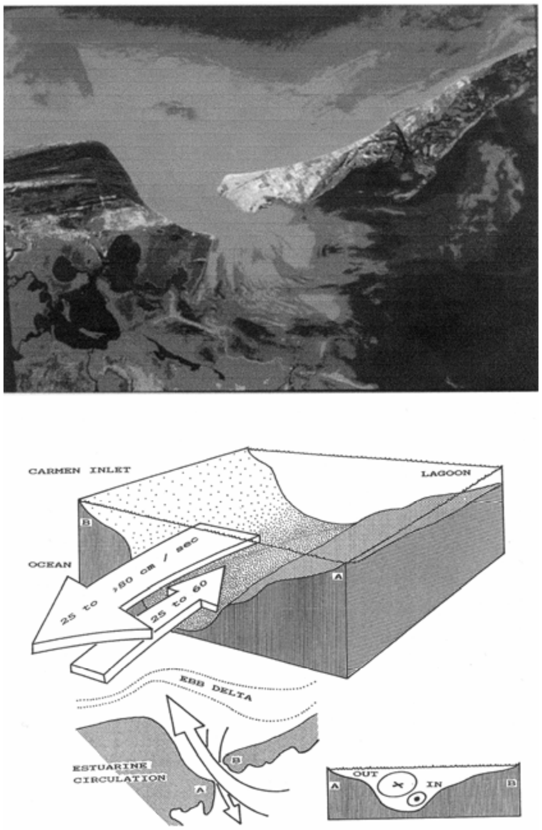


Figure 12. Diagram of circulation pattern in El Carmen inlet on a transect from A (mainland) to B (El Carmen Island). The model assume a two layer flow that is moderately stratified. The water balance is induced by river discharge, lagoon estuarine water discharge, and modulated both by winds from southeast and the littoral current from east to west. The fan effect on the external ebb delta onto the shelf is shown correlated with LandSat TM.

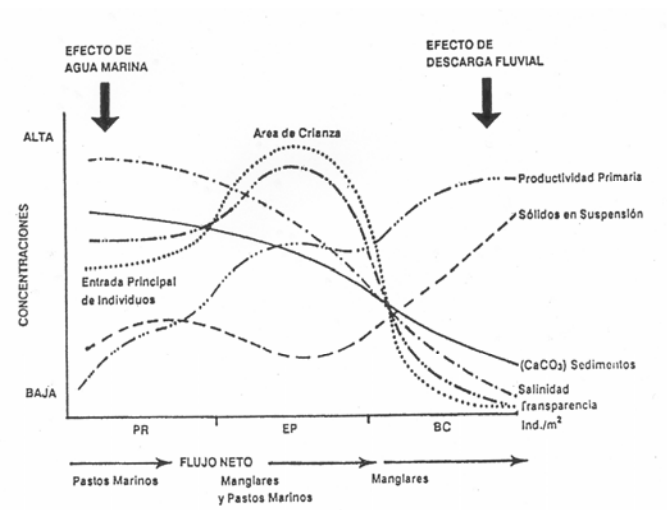


Figure 13. Spatial pattern of different ecological parameters in a transect from Puerto Real Inlet (PR), to Estero Pargo Inlet (EP), to El Carmen Inlet (BC) on the inner littoral of El Carmen Island. The net water transport and direction is shown, from seagrass habitat (PR), to mangrove/seagrass (EP), to no submerged aquatic vegetation (BC).

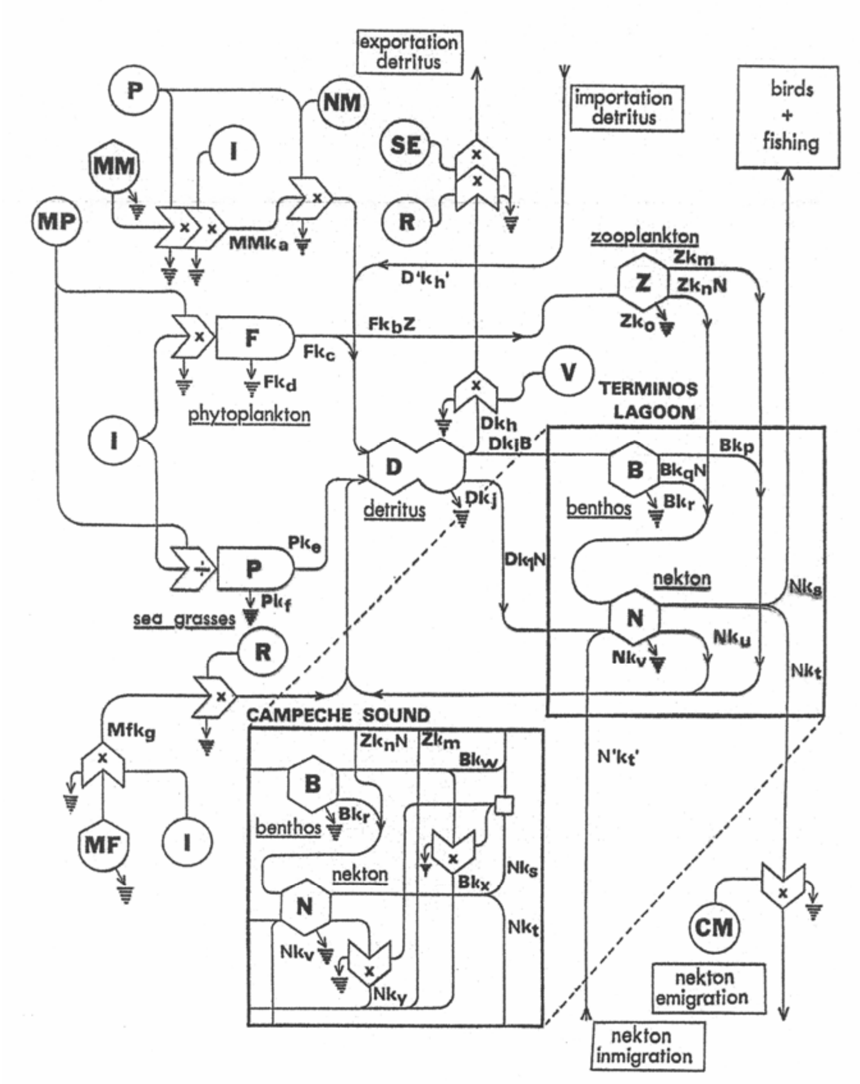


Figure 14. Ecological model integrating the biotic structural components(estuarine producers and consumers) and production mechanisms (forcing functions) in the Terminos Lagoon-Campeche Sound ecosystem. The linkage between the lagoon and the shelf is strong specially via fish and shrimp migrations, and is modulated by the circulation pattern, seasonal climatic conditions, and aquatic (phytoplankton and seagrass) and mangrove (detritus) productivity. MP = production mechanisms, MM and MF = mangrove litterfall, D = organic detritus, NM = sea level, I = light radiation, V = 'nortes' winds, SE = southeast winds, P = pluvial precipitation, R = river discharge, F = phytoplankton, Z = zooplankton, Pk = seagrasses, , B = benthos, N = nekton, CM = fish migration. Arrows indicate flow direction. Small letters and subindex mean biomass flows among subsystem in Terminos Lagoon and Campeche Sound (g m^2 yr^{-1}). Sea Table 3. After Soberon-Chavez et al. (1988).

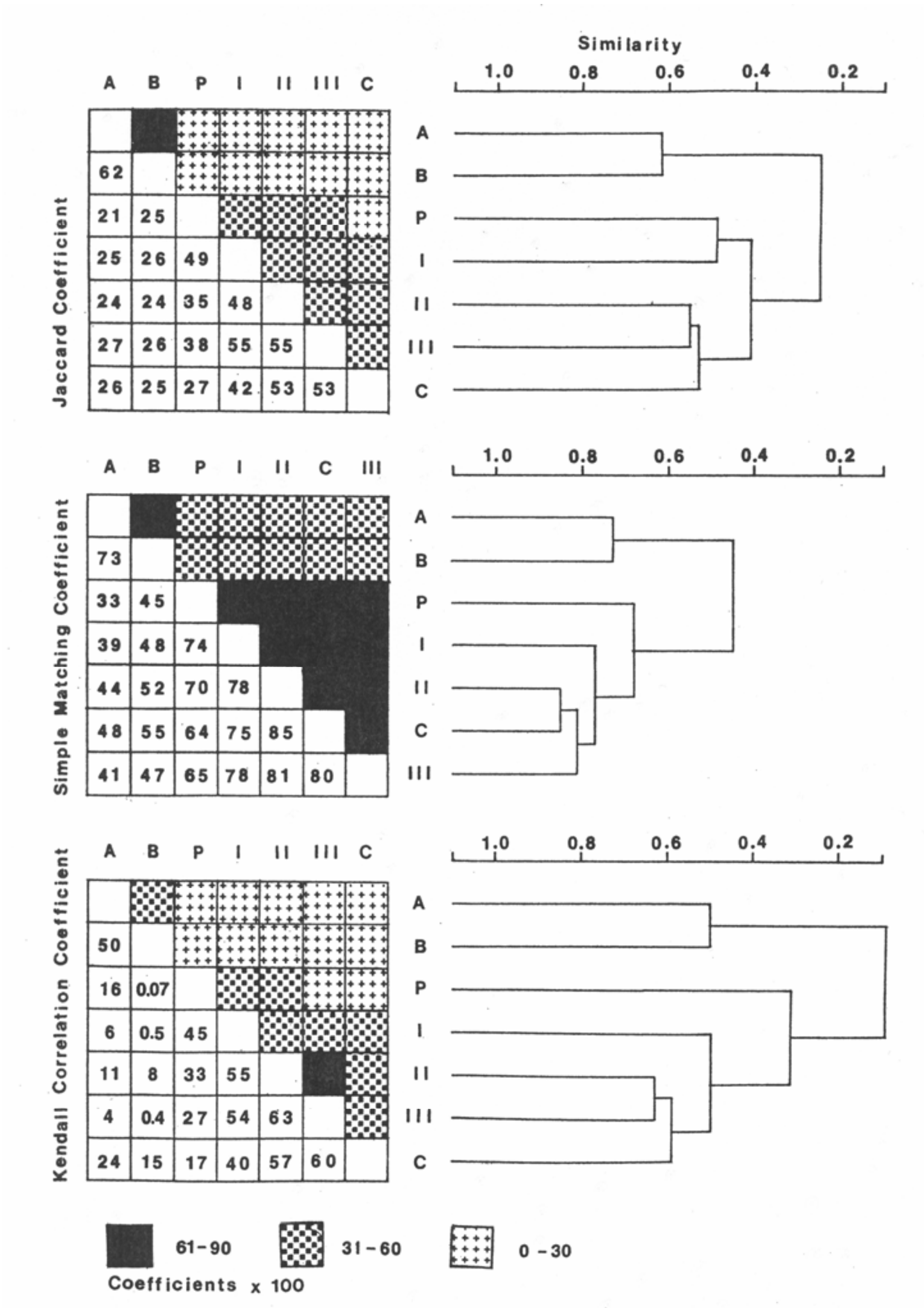


Figure 15. Dendrogram that groups the seven habitat in the estuary-inlet-shelf system: Terminos Lagoon (Subsystem I to III), Carmen Inlet (C), Puerto Real Inlet (P), and Campeche Sound (Zones A and B), Jaccard's coefficients, simple matching and Kendall's correlation with average linkage group methods were used. The dendrograms and trellis diagrams reflects the different grouping of fish in the seven different ecological subsystems (Table 2). Puerto Real Inlet is closely related to subsystem I in Terminos Lagoon and acts as a link between the shelf and the lagoon-estuarine system. The three methods used in the numerical model shows the same pattern of affinity and interrelationship. The values in the trellis diagram are multiplied by 100. This coupling of physical-biological characteristics is maintained by the functional seasonal pulsing of the whole system. After Yanez-Arancibia et al. 1985*a*.

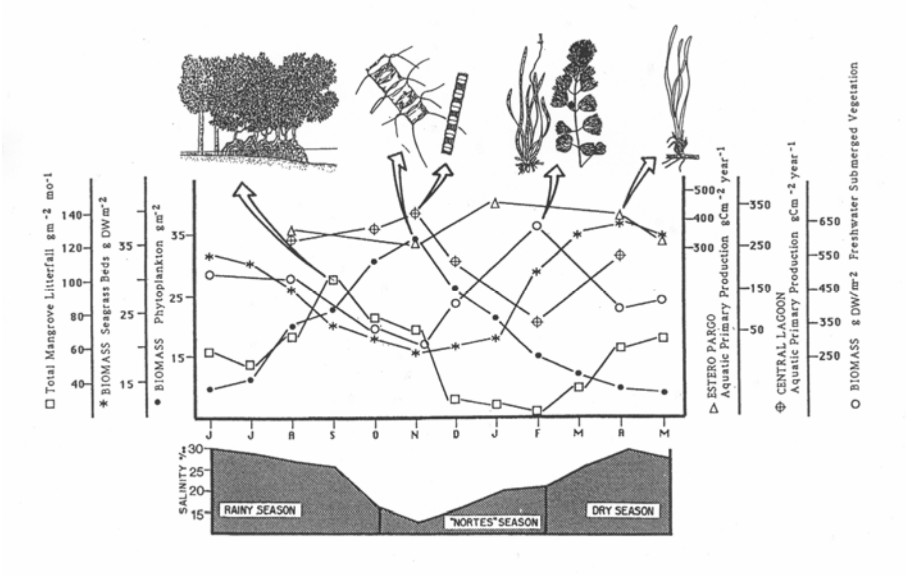


Figure 16. Seasonal patterns of primary production and plant biomass of the different functional groups of primary producers in Terminos Lagoon. The illustration above the graph are common representatives of different primary producers groups (left to right) black *Avicennia germinans* and red *Rhizophora mangle* mangroves; two genera of diatoms *Chaetoceros* and *Skeletonema* important components of estuarine phytoplankton; two species of freshwater submerged aquatic vegetation *Vallisneria americana* and *Cabomba palaeformis*; and the dominat marine seasgrass of the lagoon *Thalassia testudinum*. The decrease of salinity (below) during the rainy and 'nortes' season correspond to the period of high river flow, and high input of river borne organic matter. Redraw from Rojas-Galaviz et al. (1992).

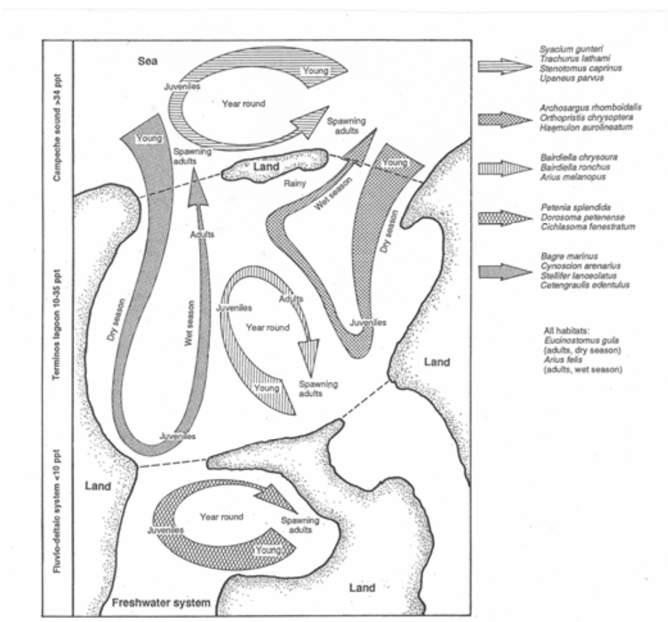


Figure 17. Examples of fishes with characteristic migration pattern within, outside of, and into and out of Terminos Lagoon, indicating: a) sequential habitat utilization, and b) seasonal programming following the productivity timing and utilizing the ecosystem functioning. After Yanez-Arancibia et al. (1988*b*) as redrawn by Pauly and Yanez-Arancibia (1994).

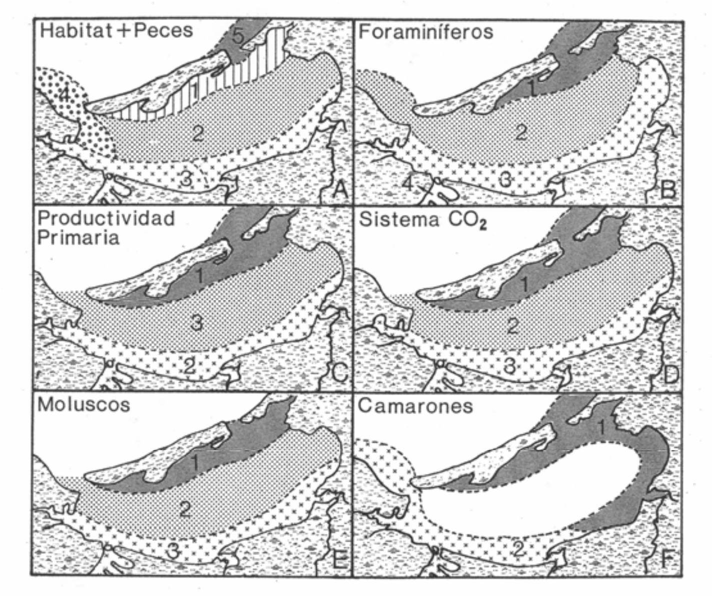


Figure 18. General distribution pattern of ecological parameters and fauna assemblages in Terminos Lagoon, correlated with the defined habitat's pattern in Table 2, Figures 10 and 20. [A] Environmental parameters and fish assemblages, 1. Inner Littoral Carmen Island and *Thalassia testudinum* beds, 2. Mesohaline Central Basin, 3. Fluvial-lagoon systems and oligohaline areas, 4. Carmen Inlet, 5. Puerto Real Inlet. [B] Foraminifera assemblages, 1. Open Gulf, 2. External lagoon, 3. Internal lagoon, 4. Fluvial mixed. [C] Aquatic primary productivity areas, 1. Clear waters, 2. Fluvial-lagoon area, 3. Central Basin. [D] The CO_2 system, 1. Marine zone, 2. Intermediate mixed zone, 3. Estuarine zone. [E] Mollusc assemblages, 1. Marine influence zone, 2. Central Basin, 3. Fluvial-lagoon system with *Crassostrea virginica*. [F] Main distribution of shrimp 1. *Farfantepeneus duorarum*, 2. *Litopeneus setiferus*. After Day and Yanez-Arancibia (1988) from several authors.

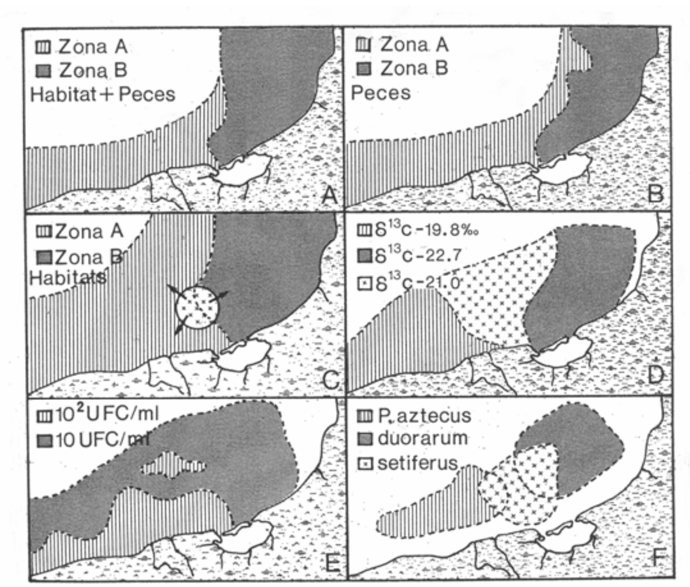


Figure 19. General distribution pattern of ecological parameters and fauna assemblages in Campeche Sound, correlated with the defined habitat's pattern in Table 2, Figures 10 and 20. [A] Environmental parameters and fish assemblages. [B] Demersal fish population assemblages. [C] Environmental parameters and the overlapping area, Zone A the terrigenous sedimentary area estuarine influenced, Zone B the calcium carbonate sedimentary area marine influenced. [D] Isotopic carbon proportion in sediments. [E] Heterotrophic bacteria concentration. [F] Main distribution of shrimp 1. *Farfantepeneus duorarum*, 2. *Litopeneus setiferus*, 3. *Farfantepeneus aztecus*. After Day and Yanez-Arancibia (1988) from several authors

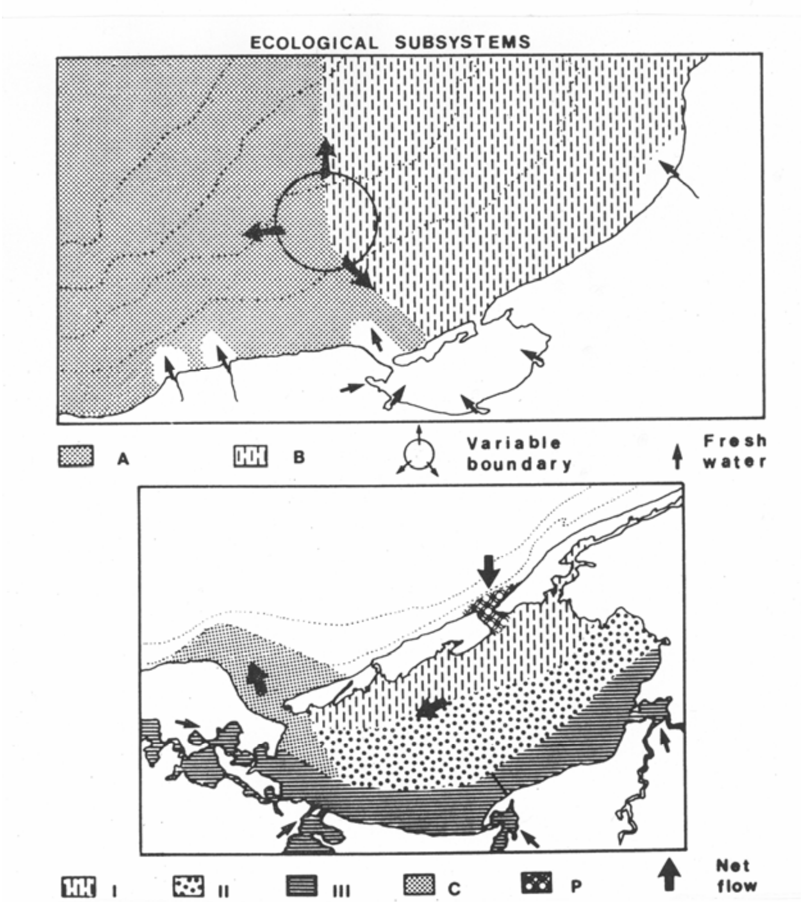


Figure 20. Habitat diversity in the estuarine ecosystem of Terminos Lagoon (below), and the adjacent Campeche Sound (above) showing the different habitats (or ecological subsystems). The inner sea shelf shows Zones A and B, associated with El Carmen and Puerto Real inlets respectively. The lagoon-estuarine system consist of five main habitats related to water circulation, river discharge, salinity, water depth, sediment type, aquatic primary productivity, submerged vegetation, and fish population assemblages. Sea Table 2 .

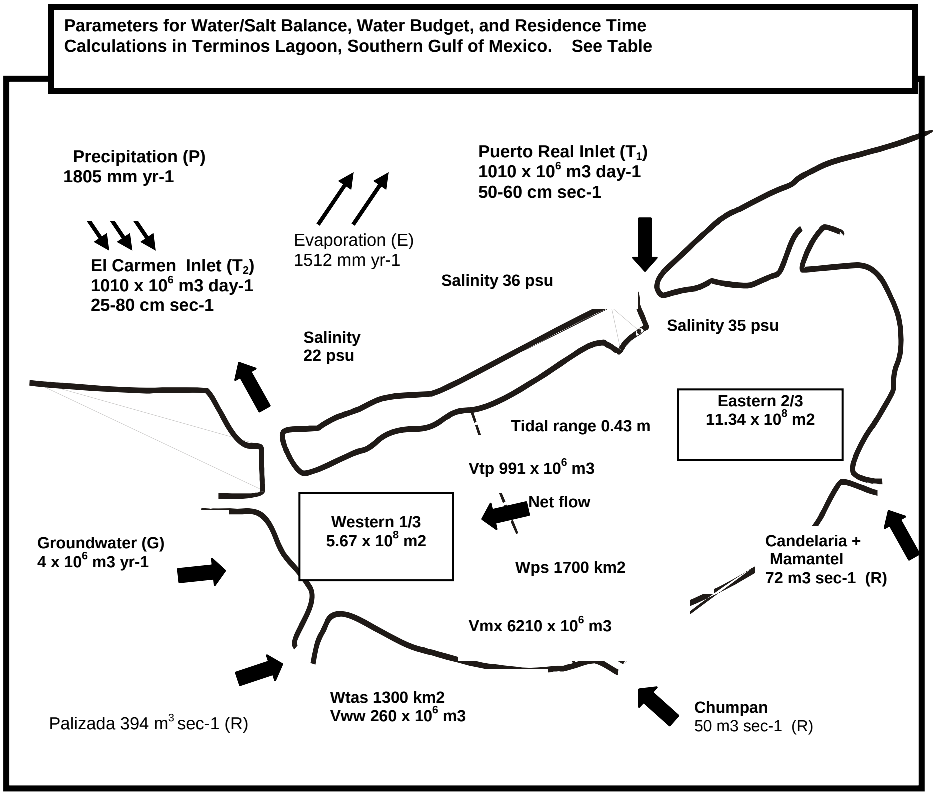


Figure 21. **Diagram showing the environmental parameters controlling the water and salt balance and illustrating physical variables involved in the functioning and water budget calculation of Terminos Lagoon region ecosystem. See Table 4 to 7 and explanation in text.**

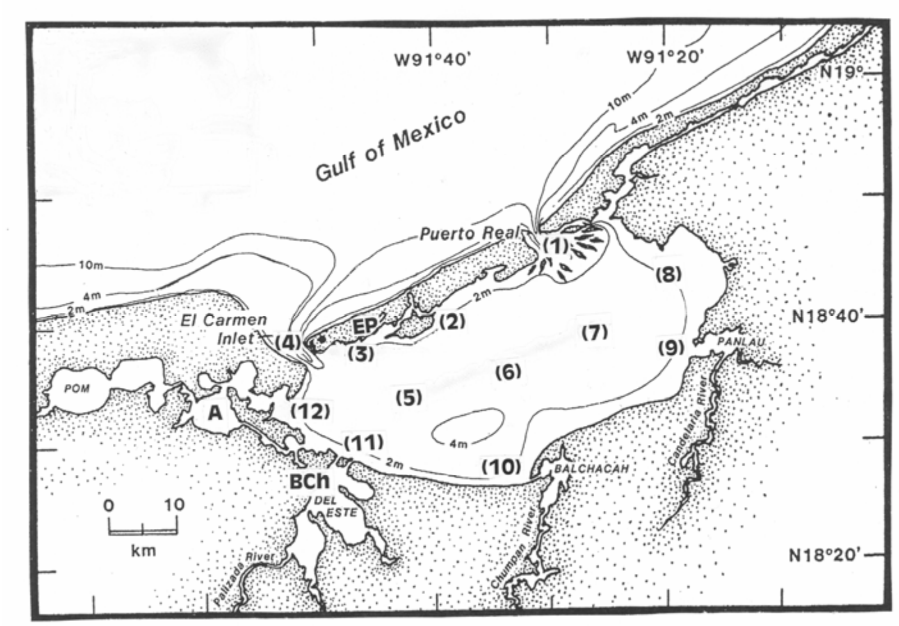


Figure 22. General map of Terminos Lagoon indicating the sample sites suggested, as appropriate for a "monitoring programme", based on: a) the ecosystem functioning, and b) the data base defining the habitat diversity in the region. Sites 1 to 12 are located in the water plate. Sites EP = Estero Pargo, BCh = Boca Chica, and A = Atasta are located in the swamps system. Sites distribution follows the habitats characterization given in Table 2. (1) Puerto Real Inlet, (2) Inner Littoral Carmen Island (Isla Pajaros), (3) Estero Pargo Inlet, (4) Carmen Inlet, (5) Central basin (western), (6) Central Basin (middle west), (7) Central basin (middle east), (8) Central Basin (eastern), (9) Fluvial-lagoon (Candelaria river inlet), (10) Fluvial-lagoon (Chumpan river inlet), (11) Fluvial-lagoon (Palizada river inlet), (12) Fluvial-lagoon (Atasta inlet). With a focus of "hydrological basin" it is also suggested to sample the rivers entering Terminos Lagoon, for instance in the bridges area on the road Escarcega-VillaHermosa.

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Parameters for Water/Salt Balance, Water Budget, and Residence Time Calculations in Terminos Lagoon, Southern Gulf of Mexico.   See Table