RESPONSE OF EMPIRICALLY MANAGED SITES TO WINTER STORMS. CASE STUDY: LA MANCHA, VERACRUZ, MEXICO

Valeria Chávez[1], Edgar Mendoza[1], Erika Ramírez[1] and Rodolfo Silva[1]

The coastal lagoon of La Mancha, Veracruz, Mexico is significantly affected by winter storms, meteorological events known as *Nortes*. Because of the influence of the wind on beach sediment transport and therefore on the dynamics of the inlet, four topographic surveys were made, three during winter storms (November 2013, November 2014 and February 2015) and one more in the dry season (May 2014). Physicochemical parameters at the mouth were registered during November 2014. The circulation patterns of the lagoon were obtained using the numerical model H2D. The beach morphology field data shows that the beach is resilient to the effects of winter storms, as long as sediment availability is not interrupted. The circulation patterns of the lagoon indicate that winds and waves induce the opening and closing of the inlet. The governing force in the lagoon patterns is the tidal oscillations, as corroborated by the physical parameters measured. However, these natural cycles are interrupted by the actions of the local fishermen, who empirically manage the lagoon opening the inlet once or twice a year. We found that the environmental resilience of the estuarine-lagoon system is susceptible to the change in the frequency of the opening of the mouth, so the anthropogenic interference threats the dynamics of the natural system.

Keywords: wetlands; coastal lagoon; beach morphology

INTRODUCTION

The multiple roles and services of coastal and marine wetland ecosystems and their value to humanity have been analysed and documented with special interest in recent years (Cervantes, 2007; Hernández *et al*. 2006; Twilley, 1995). Wetlands have been identified as elements of ecological importance because they provide a habitat for a considerable diversity of organisms and species, and act as a filter for sediments and pollutants. On the other hand, they are recognised as coastal protection elements because they are natural shock absorbers when there is flooding and contribute to the reduction of beach erosion. Moreover, many economic, recreational and cultural activities take place in wetlands, providing social and economic benefits to the communities that surround them.

Nowadays, there is greater awareness of the necessity to conserve wetlands and maintain the ecological functions and services that they provide (Cervantes, 2007). A strategy for Integrated Coastal Zone Management (ICZM) in La Mancha requires analysis of the system connectivity via ecohydrological relationships, which are the interactions between ecosystems, as evidenced through biological, physical, chemical and sedimentary processes and regulated by hydrological processes at different spatial and temporal scales (Seller and Causey, 2005).

The time series of the evolution of natural processes can help evaluate the resilience of the system to disturbances of different timescales. These studies use field work, numerical and/or physical modelling to understand the system's ecological and physical dynamics (Alonso-Pérez *et al*., 2003; Houser *et al*., 2015; Lawson *et al*., 2007; Martins *et al*., 2001; Rivera-Guzmán *et al*., 2014). This paper focuses on the evaluation of the short-term vulnerability of a coastal lagoon, in terms of the erosion or accretion of the beach, the dynamics of the mouth of the lagoon and the hydrodynamics associated with the circulation patterns of the lagoon during winter storms, and the effects of anthropogenic interference in the system.

STUDY AREA

The wetland of La Mancha is located in the central zone of the Gulf of Mexico, in the state of Veracruz, Mexico (Figure 1). La Mancha offers a wide variety of ecosystem services; it is a shelter for animal species and provides food for commercial fishing species, from juvenile to adult stages, thus supplying an economic base for the local fishing industry (Barreiro-Güermes and Matus, 1993). To improve their catch in the lagoon, the local fishermen open the inlet (Rivera-Guzmán *et al*., 2014) 2 or 3 times a year, by making a small break in the sand bar that blocks the inlet. The water exchange between the sea and the lagoon gradually widens this access channel. The lagoon also has high levels of pollution from human settlements on the edge of the lagoon, including heavy metals, and from the discharge of agricultural wastewater (Contreras-Espinosa, 2005). On the other hand, it is a site of

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[1] Engineering Institute, UNAM, Ciudad Universitaria, Mexico City, 04510, Mexico

valuable scenic importance for ecotourism and the wetland vegetation is an area of capture and storage of atmospheric carbon.

La Mancha is affected by winter storms, meteorological events locally known as Nortes, which may cause wind speeds to rise (up to 110 km/h) and temperatures to drop (between 2 and 15°C in 24 hours). From the results of the hybrid model WAM-HURAC (Ruiz *et al*., 2009), at coordinates 19.75° N and 96.00° W, the months with winter storms were identified from November to March.

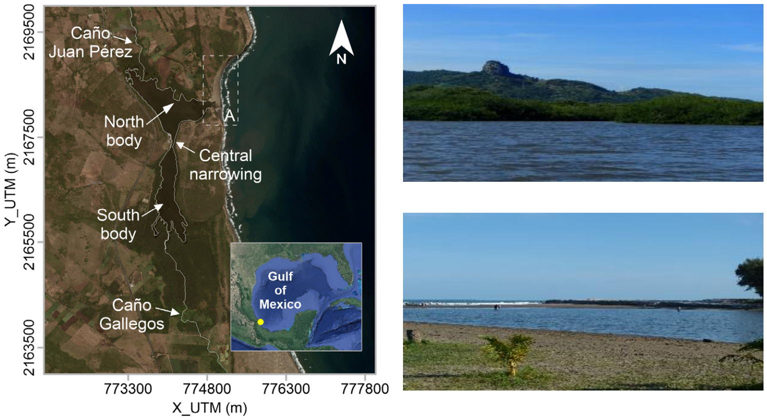

Figure 1. La Mancha, Veracruz, Mexico: Location of the study site, left (image modified from Digital Globe, June 2012); lagoon and mouth, right.

Hydrodynamics and Morphology

The hydrological variability of La Mancha depends on the balance of seawater and the contributions of fluvial, pluvial and groundwater discharges. As the interface between the sea and the lagoon, the inlet governs the hydrodynamic and water quality changes in the water body. When the inlet of the lagoon is sealed, the water level rises and salinity falls, while the opening of the inlet brings a lowering of the water level, higher salinity and sediment accumulation in the tidal delta (Psuty *et al*., 2009). The salinity conditions range between oligohaline and polyhaline. The La Mancha system has undergone severe changes in its morphology and hydrodynamics, as seen by the gradual silting trend of the lagoon that generates changes in water cycles (Matus *et al*., 1994) and the change in the natural cycle of opening and closing of the inlet.

The morphology of the lagoon is characterized by a central narrowing that separates the north and south bodies (see Figure 1). Two north-south oriented sand dunes and a mangrove forest surround the lagoon, whose interaction with the water body is vital to the functioning of the system. The beach (see box A of Figure 1) is the main source of sediment to the lagoon. It is limited at the North by a string of mobile dunes, and at the South by the inlet of the lagoon and a rocky promontory.

FIELD DATA

In order to assess the morphological evolution of the beach and the inlet of the lagoon, four topographic surveys were carried out, three in winter storm seasons (November 2013, November 2014 and February 2015) and one in the dry season (May 2014).

The topographic data was recorded using a LEICA DGPS system. From this data, a representative cross-section of the inlet (MCS) and four beach profiles were defined (see Figure 2) to analyze their time evolution. Figure 3 shows the MCS obtained from each of the surveys conducted. In November 2013 (MCS-N13), the lagoon inlet was closed, thus a sand bar 96 m wide was found. In May 2014 (MCS-M14) the inlet was found partially open and two channels, 30 and 20 m wide, connected the sea to the lagoon; these channels were separated by 30 m of dry sand. In November 2014 (MCS-N14), a single 70 m wide channel was found, located further south than the channels of May 2014. In February 2015 (MCS-F15), the inlet was closed again; although a small portion of the corresponding MCS is below the MSL, there was no connection between the lagoon and the sea.

For the four beach profiles defined in Figure 2, the estimated volume per meter above the MSL of the dry beach can be found in Table 1. From November 2013 to May 2014, the sand volume in the dry beach decreases because the inlet of the lagoon was open in May. This occurs in profiles 1 to 3, but in profile 4, the volume is 10 times larger in May than in November due to the placement of dredged material from the lagoon in this area prior to the May survey. It was also reported that the inlet was artificially opened in April 2014. In November 2014, the beach profiles are similar to those observed in 2013, showing that the extra sediment (dredged) was again deposited in the north part of the beach by aeolian transport, suggesting that this would be later returned to the lagoon, and implying that the dredging work was not efficient. In February 2015, at the end of the winter storm season, higher volumes were found, proving that aeolian sediment transport is dominant in this beach.

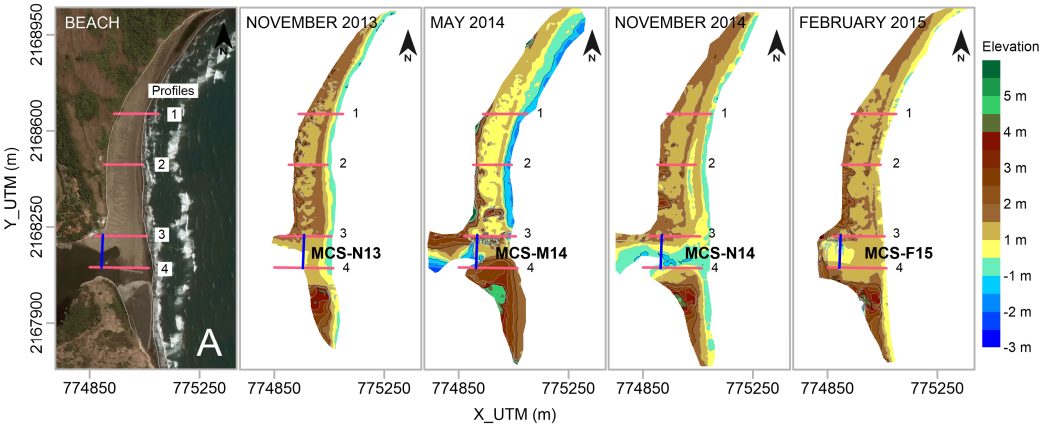

Figure 2. Development of the beach (see box A on Figure 1), showing the locations of the beach profiles monitored.

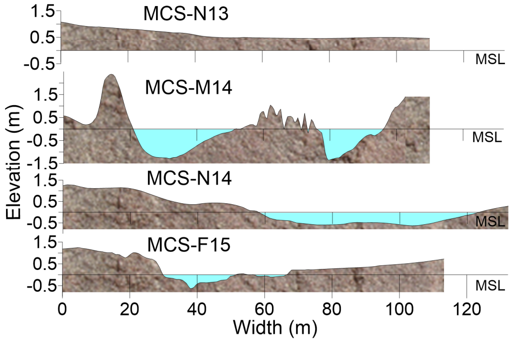

Figure 3. Time evolution of the cross-section of the inlet.

Table 1. Volume per meter above the MSL.

Profile	November 2013	May 2014	November 2014	February 2015
	Volume per meter (m^3/m)			
1	101.6	78.5	128.0	110.1
2	118.0	43.7	113.9	126.2
3	185.5	136.5	170.7	178.4
4	35.7	339.9	38.1	163.1

Physicochemical Parameters

The influence of high-velocity winds on the beach sediment transport as well as in the hydrodynamics of the inlet is the main factor determining the distribution of salinity and density in the lagoon. During the third survey of the study area (November 2014) water salinity, temperature and density were measured superficially at four locations on the MCS (see Figure 4). The sampling took place at each location every 30 minutes from 8:30 to 18:00 on November 6th, 2014.

The time-series of the recorded parameters are plotted in Figure 5. Although the tidal variation during the sampling was only about 0.2 m, the tide seems to govern the water exchange and quality on the MCS. At low tide, the density and salinity for the four sampled points are low, which may be attributed to the ebb current of the estuary-lagoon system. During flood tide, temperature, salinity and density increase but fluctuate around a mean value higher than that of low tide.

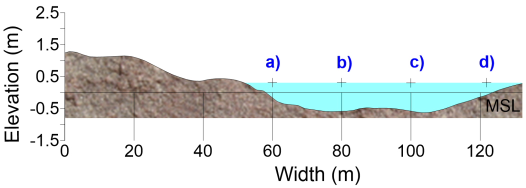

Figure 4. MCS and profiles sampled in November 6th, 2014.

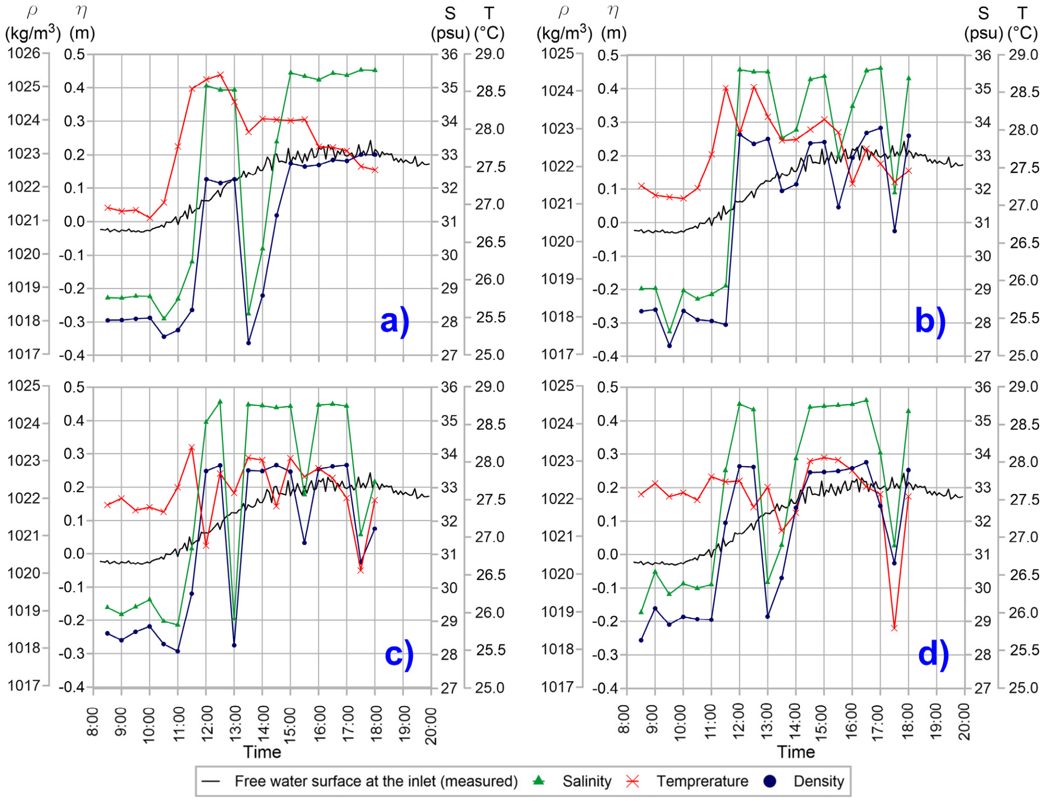

Figure 5. Physicochemical parameters at the sampled profiles of the MCS (November 6th, 2014).

Caño Gallegos Discharge

Two streams bring freshwater into the lagoon: Caño Juan Pérez in the North, and Caño Gallegos in the South (see Figure 1), with Caño Gallegos having the larger discharge. For this reason, the Caño Gallegos flow was monitored using the velocity-area method at four points on its course: 1) close to the Cardel-Nautla road (MEX 180), 2) downstream from some natural springs, 3) upstream from the discharge to the freshwater wetland, south of the mangrove and 4) at the mangrove. The location of these points is shown in Figure 6. The average water velocity was measured using a current meter taking samples at 1 Hz and reporting the average value for 50 measurements. Table 2 shows the flows measured every three months from August 2014 to May 2015 at the four points. The minimum flow occurs at point 1, except in February, when the minimum was recorded at point 4. This change is due to the reduction in circulation all around the lagoon when the inlet is closed. In this period, there is also an increase in the water level of the Caño Gallegos stream and the lagoon, which floods the surrounding mangrove. It can be observed in Table 2 that the discharge of Caño Gallegos increases from gauging point 1 to 3, and decreases at point 4, except during the rainy season (August 2014). This may be attributed to the increasing pluvial and fluvial contributions of the season.

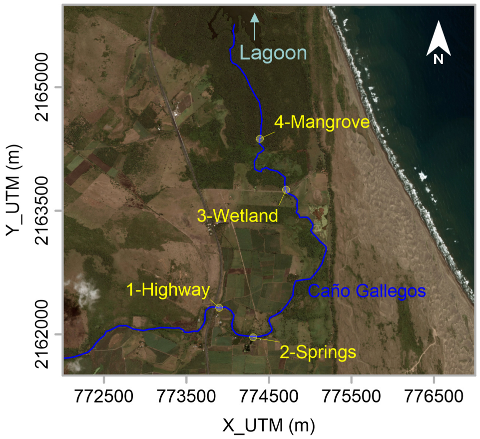

Figure 6. Caño Gallegos stream gauging locations (image modified from Digital Globe, June 2012).

Table 2. Caño Gallegos stream flow measurements.

Gauging	August 2014	November 2014	February 2015	May 2015
	Q (m^3/s)			
1	0.074	0.048	0.134	0.061
2	0.206	0.197	0.335	0.258
3	0.429	0.491	0.292	0.325
4	0.497	0.356	0.000	0.176

NUMERICAL MODELLING

The circulation patterns of the lagoon were computed using the H2D model (GIOC, 2001). Two weeks were modelled, from October 26 to November 11, 2014. The tide levels were obtained for the nearby port of Veracruz, from the Pronóstico de Marea MAR V1.0 2011 programme, developed by the Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE). The numerical domain was a 6 km long square as shown in Figure 13. The grid was created using field bathymetry and topography data (obtained during the surveys), and the digital elevation model of 5 m horizontal resolution from INEGI (Mexican Instituto Nacional de Estadística y Geografía) (2014). The domain was discretized in a regular grid with cell dimensions of 10 m (Figure 7).

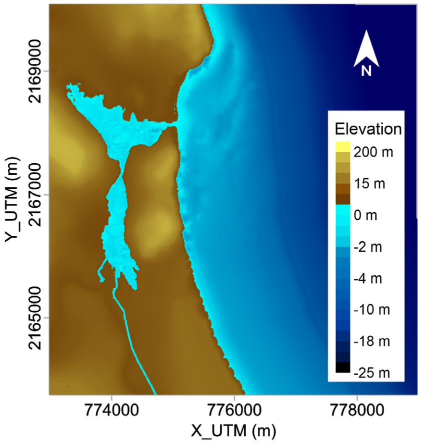

Figure 7. Numerical modelling domain.

RESULTS

The spatial variation of the results was analyzed for four moments selected from the tidal signal, i.e. ebb, low tide, flood and high tide, in the transition from neap to spring tides. These points are presented on the tide forecast in Figure 8.

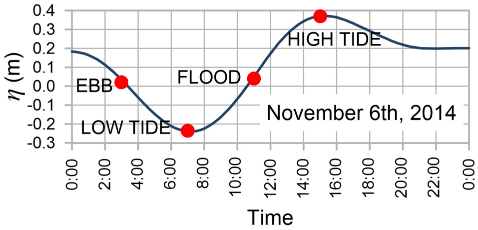

Figure 8. Ebb, low, flood and high tide levels.

The maps of the velocity magnitude are presented in Figure 9, for the lagoon as a whole and for three zones in more detail, the inlet, the central narrowing and Caño Gallegos. During ebb, the highest velocities are found south of the central narrowing, decreasing from the northern zone to the maritime area, as the tide affects the sector connected to the sea most. At low tide, the velocities are lower compared to ebb, but they follow the same trend: higher in the south of the lagoon. At this moment, the water keeps moving toward the sea, with the highest magnitudes. Then, the effect of the flood through the inlet causes the water levels to increase in the north of the lagoon; the direction of the velocity in the inlet corroborates the flood. The velocities at Caño Gallegos during flood indicate that the water is flowing into the lagoon, so this effect dominates over the tidal wave. During high tide, in the south, the water levels start to increase, but are smaller than those in the north, which is directly exposed to the tidal wave.

The magnitude of the velocities increases and the tidal wave enters the lagoon, as seen in the velocity directions; this effect is reflected up Caño Gallegos, where the water is entering the stream. In the transition from high tide to ebb, it appears that the narrowing acts as an inflexion point between the increase and decrease in the water levels, between the north and south ater bodies.

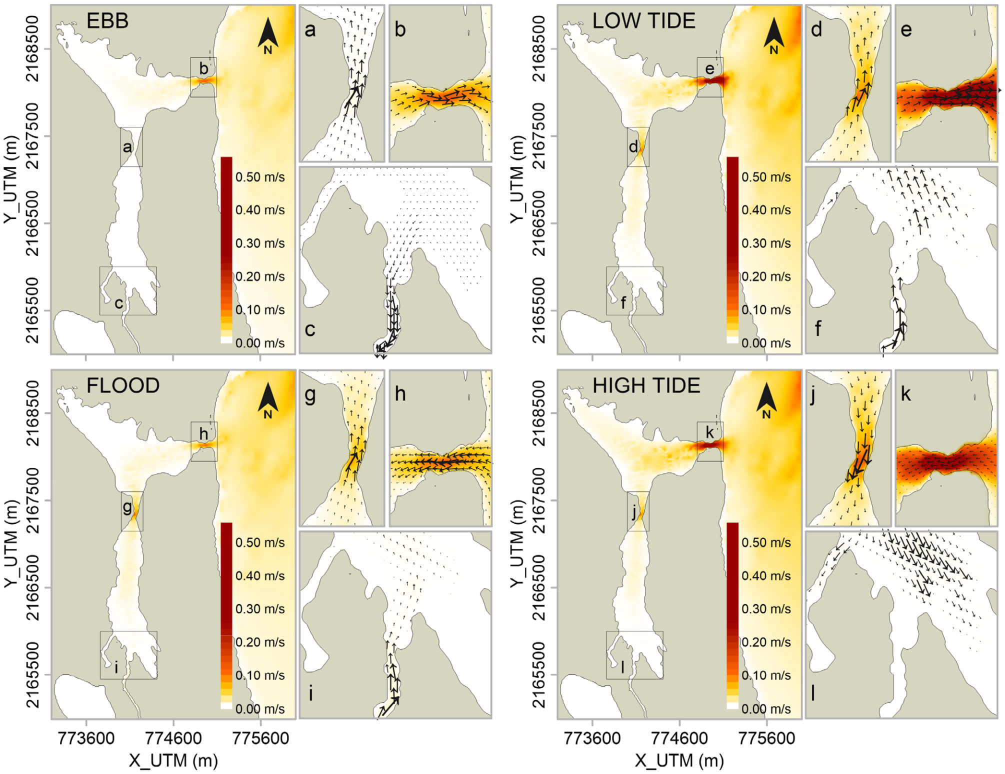

Figure 9. Spatial distribution of the velocity.

DISCUSSION

The morphology of the inlet of the lagoon measured from November 2013 to February 2015 (Figure 3), shows that the sand barrier that closes the inlet is naturally formed by sediment transported by wind, waves and currents. Various authors (Contreras-Espinosa, 2003; García-Gil, 2006; Martínez *et al*., 2012) report that the opening of the inlet depends on inland discharges or on the increase in water levels in the lagoon. Nevertheless, during the monitoring for this study, artificially induced opening was carried out by the local fishermen, influencing the results. This anthropogenic interference is now part of the dynamics of the system, although the inlet is resilient to these induced openings, as sediment transport is sufficient to induce the formation of a sand barrier. In this sense, the artificial opening of the inlet does not affect beach stability.

The physicochemical parameters measured in November 2014 (winter storms and opened inlet) vary, according to the tidal conditions (see Figure 5). From the circulation patterns of the lagoon, obtained with the numerical model, it was observed that the tide is the controlling factor in the northern part of the lagoon, whereas in the south, the stream discharges modify the circulation.

Sudden changes in the salinity and the depth in the lagoon, induced by the intrusion of salt water when the inlet is open, are the result of the natural cycle of the inlet dynamics, but also of the artificial opening of the inlet and the trend of silting in the lagoon. Estuarine species are adapted to these changes. However high mortality rates in fauna were observed during the surveys made after the lagoon inlet was opened. Also, according to Contreras-Espinosa *et al*. (2005), the opening of the inlet limits the efficient use of nutrients in the lagoon. The artificial inlet opening is carried out by the local people without scientific or management protocols, they seek only to increase species availability in the lagoon to facilitate the catch. In this scenario, water renovation in the estuary cannot be guaranteed and the balance of the ecosystem is endangered.

CONCLUSIONS

La Mancha is a complex system, where continental and marine forcings define its dynamics. The ecological, cultural and economic importance of the system mean that it should be properly understood and evaluated so that management policies can be proposed. La Mancha is subject to significant anthropogenic actions, such as the induced alteration in the inlet dynamics and the effects on environmental conditions by farming, fishing and agricultural activities. These characteristics, along with natural phenomena, like winter storms, beach erosion and accretion, makes La Mancha a vulnerable system. But, the beach stability is determined by the northern dunes, which supply the sediment for the beach. The beach morphology field data, obtained over 15 months, shows that the beach is resilient to the winter storm effects, as long as sediment availability is not interrupted. The environmental resilience of the estuarine-lagoon system is susceptible to the change in frequency of the opening of the inlet, so the anthropogenic interference, without scientific and technical bases threatens the natural dynamics of the system. The periodicity of the inlet openings should be subjected to a well-founded management program that considers the dynamics of the whole system, *i.e.* its environmental, ecologic, economic and social aspects).

REFERENCES

Alonso-Pérez, F., A Ruiz-Luna, J. Turner, A.C. Berlanga-Robles, and G. Mitchelson-Jacob. 2003. Land cover changes and impact of shrimp aquaculture on the landscape in the Ceuta coastal lagoon system, Sinaloa, Mexico. *Ocean and Coastal Management*, 46(6-7), 583-600.

Barreiro-Güemes, M.T. and J.C. Matus. 1993. Diagnóstico ecológico y de uso de recursos de la laguna de La Mancha, Veracruz: Propuesta para su manejo. *V Congreso Latinoamericano de Ciencias del Mar* (La Paz, B.C.S, Mexico), pp.186.

Cervantes, M. 2007. Conceptos fundamentales sobre ecosistemas. In: Sánchez, Ó.; Herzig, M.; Peters, E.; Márquez, R., and Zambrano, L. (eds.), *Perspectivas sobre Conservación de Ecosistemas Acuáticos en México*. Mexico City: SEMARNAT, pp. 37-68.

Contreras-Espinosa, F. 2003. Dinámica Espacio–Temporal de Nutrientes en la Laguna de La Mancha, Veracruz, México. Mexico City: Universidad Autónoma Metropolitana, 66p.

Contreras-Espinosa, F. 2005. Lagunas costeras de Veracruz. In: Moreno-Casasola, P.; Peresbarbosa-Rojas, E., and Travieso-Bello, A.C. (eds.), *Manejo Costero Integral: El Enfoque Municipal*. Xalapa, Veracruz: Instituto de Ecología, A.C., pp. 205–228.

Contreras-Espinosa, F., N.E. Rivera-Guzmán, and R. Segura-Aguilar. 2005. Nutrientes y productividad primaria fitoplanctónica en una laguna costera tropical intermitente (La Mancha, Ver.) del Golfo de México. *Hidrobiológica*, 15(3), 299-310.

García-Gil, G. 2006. El ambiente geomorfológico. In: Moreno-Casasola, P. (ed.), *Entornos Veracruzanos: La Costa de La Mancha*. Xalapa, Veracruz: Instituto de Ecología, A.C., pp. 127-138.

GIOC. 2001. Manual de Referencia Modelo Numérico H2DII. Cantabria: Grupo de Ingeniería Oceanográfica y de Costas, Universidad de Cantabria, 85p.

Hernández-Trejo, H., A. Priego-Santander, J. López-Portillo, and E. Isunza-Vera. 2006. Los paisajes físico-geográficos de los manglares de la laguna de la Mancha, Veracruz, México. *Red de Revistas Científicas de América Latina, el Caribe, España y Portugal*, 31(3), 221-219.

Houser, C., P. Wernette, E. Rentschlar, H. Jones, B. Hammond, and S. Trimble. 2015. Post-storm beach and dune recovery: Implications for barrier island resilience. *Geomorphology,* 234, 54-63.

Instituto Nacional de Estadística y Geografía. 2014. Modelo digital de elevación de alta resolución LiDAR, Tipo terreno con resolución de 5m. http://www.inegi.org.mx/geo/contenidos/datosrelieve/continental/presentacion.aspx

Lawson, S.E., P.L. Wiberg, and K.J. McGlathery. 2007. Wind-driven sediment suspension controls light availability in a shallow coastal lagoon. *Estuaries and Coasts*, 30(1), 102-112.

Martínez, M.L., G. Vázquez, J. López-Portillo, N.P. Psuty, J.G. García-Franco, T.M. Silveira, and N. Rodríguez-Revelo. 2012. Dinámica de un paisaje complejo en la costa de Veracruz. *Investigación Ambiental*, 4(1), 151–160.

Martins, I., M. Â. Pardal, A.I. Lillebø, M.R. Flindt, J.C. and Marques. 2001. Hydrodynamics as a major factor controlling the occurrence of green macroalgal blooms in a eutrophic estuary: A case study on the influence of precipitation and river management. *Estuarine, Coastal and Shelf Science*, 52(2), 2001, 165-177.

Matus, J.C. 1994. Dinámica sedimentológica en secas, lluvias y nortes en la launa de la Mancha, Veracruz, México. *III Congreso de Ciencias del Mar* (La Habana, Cuba), Paper 802, pp. 310.

Psuty, N.P., M.L. Martínez, J. López-Portillo, T.M. Silveira, J.G. García-Franco, and N.A. Rodríguez. 2009. Interaction of alongshore sediment transport and habitat conditions at Laguna La Mancha, Veracruz, Mexico. Journal of Coastal Conservation, 13, 77-87.

Rivera-Guzmán, N.E.; P. Moreno-Casasola, S.E. Ibarra-Obando, V.J. Sosa, and J. Herrera-Silveira. 2014. Long term state of coastal lagoons in Veracruz, Mexico: Effects of land use changes in watersheds on seagrasses habitats. *Ocean and Coastal Management*, 87, 30-39.

Ruiz-Martínez, G., R. Silva-Casarín, D.M. Pérez-Romero, G. Posada-Venegas, and E. Bautista-Godínez. 2009. Modelo híbrido para la caracterización del oleaje. *Ingeniería hidráulica en México*, XXIV(3), 5-22.

Seller, B.D. and B.D. Causey. 2005. Linkages between the Florida Keys National Marine Sanctuary and the South Florida Ecosystem Restoration Initiative. *Ocean and Coastal Management*, 48, 869–900.

Twilley, R.R. 1995. Properties of mangrove ecosystems and their relation to the energy signature of coastal environments. In: Hall, C.A.S. (ed.), *Maximum Power: The Ideas and Applications of H.T.* Odum. Niwot, Colorado: University of Colorado Press, pp. 43-61.