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Impact of Inlet Management on the Resilience of a Coastal Lagoon: La Mancha, Veracruz, Mexico

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ABSTRACT

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The importance of conserving wetlands for their functions and services, has shown the need for adequate management practices, which take into consideration the vulnerability and resilience of these ecosystems. The lagoon of La Mancha, Veracruz, Mexico, is a Ramsar site, which in practice is empirically managed by local fishermen. To assess the vulnerability of this ecosystem, the erosion/accretion of the beach, inlet dynamics, the hydrodynamics of circulation patterns in the lagoon during winter storms, and the effects of anthropogenic activities were studied. Four topographic surveys were performed between 2013 and 2015. Complementarily, physicochemical parameters in the lagoon and at the inlet were registered in November 2014.The 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 were obtained using a 2D non linear shallow water numerical model; the results indicate that the winds and waves can induce the opening and closing of the inlet. The governing force in the lagoon hydrodynamics is the tidal oscillation, as corroborated by the physicochemical parameters measured. The natural cycles of the system are altered by the local fishermen, who once or twice a year open the inlet of the lagoon. It was found that the environmental resilience of the estuarine-lagoon system is quite sensitive to the number of times and the season when the inlet is opened and that the anthropogenic interference is increasing the vulnerability of the ecosystem of La Mancha.

ADDITIONAL INDEX WORDS: *Coastal lagoon, beach morphology, circulation patterns, water physicochemical properties*.

INTRODUCTION

Wetlands are areas where water is the primary element controlling the environment and thus the plant and animal life. The United Nations Environment Programme´s World Conservation Monitoring Centre (UNEP-WCMC) estimates that wetlands cover approximately 570 million hectares of the world´s surface and 1.7% of this area is in Mexico; 5% of the national territory (CONAGUA, 2012; 2014). As regards coastal wetlands, 16.8% of the Mexican coast has this type of ecosystem and it is estimated that 35% of these wetlands has suffered some sort of damage, modification or reduction in area (Cervantes, 2007).

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-Trejo *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 (Berlanga-Robles, Ruiz-Luna, and De la Lanza-Espinp, 2008). The anthropogenic activities that take place in these ecosystems, the water crisis and the effects of climate change, have led to numerous actions worldwide aimed at improving practices of Integrated Coastal Zone Management (ICZM). ICZM requires solid information databases of natural, social and economic processes as source indicators to develop exploitation policies. 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; Armaroli *et al*., 2013; Houser *et al*., 2015; Lawson, Wiberg, and McGlathery, 2007; Martins *et al*., 2001; Rivera-Guzmán *et al*., 2014; Taramelli *et al*., 2015). This paper focuses on the evaluation of the short-term vulnerability of a coastal lagoon, assessing the impact of coastline evolution, the dynamics at the inlet of the lagoon, the hydrodynamics induced by winter storms and the effects of anthropogenic interventions on the ecosystem. To generate accurate and appropriate technical information for the hydrodynamic characterization used to assess vulnerability, field

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data and numerical modelled results were obtained for the study area of La Mancha, in the state of Veracruz, Mexico.

STUDY AREA

The wetland of La Mancha is located in the central zone of the Gulf of Mexico, in the state of Veracruz, Mexico. Its ecological importance is recognized through the Ramsar designation as a Wetland of International Importance, February, 2004 (Ramsar, 2013). La Mancha is also considered a priority conservation site of mangroves by the Mexican Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO, 2008).

The area is a cumulative plain formed by lacustrine, fluvial and biogenic sediments, sometimes inter-layered with marine deposits. In the land cover Arenosols, Histosols, Gleysols, Solonchak and Fluvisols can be found, all distinctive of the humid tropical zones. The vegetation consists of mangrove forest, rainforest, tropical grassland marsh, secondary vegetation, fruit trees, crops and cultivated pastures for livestock activities (Hernandez-Trejo *et al*., 2006). The climate type is Aw2, typically hot sub-humid (high humidity within Aw climates) with a summer rainfall regime (Vidal-Zepeda, 2005).

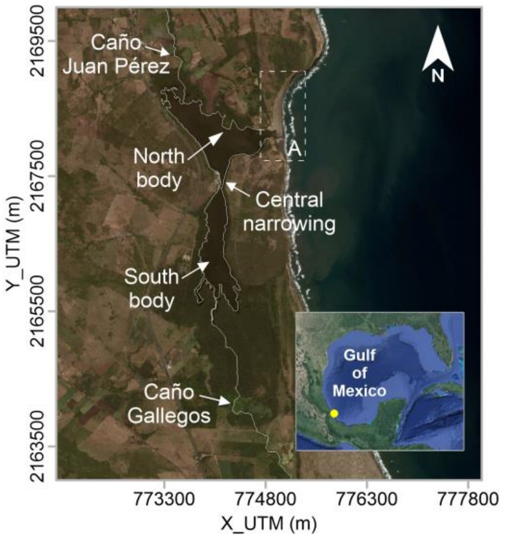

Figure 1. La Mancha, Veracruz, Mexico: Location (image modified from Digital Globe, June 2012).

The La Mancha lagoon is a shallow, brackish coastal lagoon of 132 ha (Figure 1), with a mean depth of <3 m. 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 water exchange occurs through ebb and flood currents, and is determined by the winter storms, the pluvial and fluvial discharges, as well as the occasional action of local fishermen in opening the inlet of the lagoon. 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, 1994) and the change in the natural cycle of opening and closing of the inlet.

According to the Mexican Secretaría de Marina (SEMAR), in this area the tide is diurnal, with a tidal range of 0.458 m, determined with measured data from 1999 to 2013.

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. The beach is composed of fine sand of biogenic and terrigenous, little-humified materials, plant debris, shellfish and contributions from the stream and dunes, with high permeability. Dune vegetation can also be found.

Climate Seasons

Figure 2 shows a summary of the monthly weather statistics for La Mancha. Figure 2a presents the monthly mean rainfall, obtained from historical records (1981-2008) of the climatological station La Mancha (9° 35' 46"N 96° 23' 01" W) of the Mexican Servicio Meteorológico Nacional (SMN). The shaded area indicates the average for the entire record, thus the months with mean value above this average were considered the rainy season (*i.e.* from June to October).

The study area is significantly 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-Martínez *et al*., 2009), at coordinates 19.75° N and 96.00° W, the months with winter storms were identified.

Figure 2b shows the monthly mean for hours of winds of North and Northeast directions and speeds of over 50 km/h (equivalent to a strong breeze on the Beaufort scale). From this figure, it can be seen that the winter storm season is from November to March. In turn, Figure 2c shows the monthly mean for hours of tropical cyclones, obtained from the HURAC module of the model; the season being from August to October. The remaining months, April and May, correspond to the dry season. Analysis of data from 1955 to 1990 for three SMN stations close to La Mancha by Matus (1994) found the same three seasons, although he included March in the dry season.

Functions and Values

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

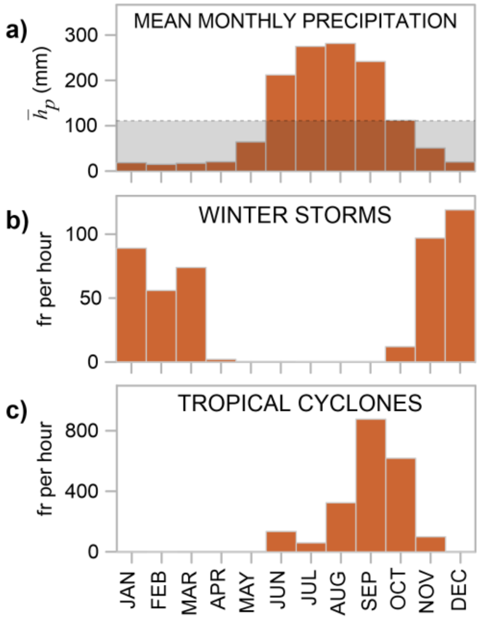

Figure 2. Monthly weather statistics, 1948 – 2010.

La Mancha has been the subject of several studies focused on determining its ecological and biological characteristics. Matus (1994) studied the sedimentology of the lagoon. The distribution of vegetation in the wetland was reviewed by Hernández-Trejo (2009). Contreras-Espinosa (2005) characterized the volume and chemical composition of the water flowing through the inlet of the lagoon. The hydrological regime in the lagoon caused by changes in the morphological cycle of inlet and the potential consequences of management actions in the lagoon was analized by Psuty *et al*. (2009). Such studies have been carried out using field measurements of low accuracy and in a qualitative and descriptive manner, rather than quantitative characterization, which are essential for predicting scenarios and enabling informed decision-making and management.

FIELD DATA

Beach and Inlet Morphology

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. These points were interpolated in a 1 m grid using the Kriging method; the contour maps obtained (Figure 3) were used to estimate the area of the dry beach (Table 1). From November 2013 to February 2015, the dry beach area was found to increase (0.12 km^2 to 0.17 km^2), representing a growth of 41%. From the topographic data, a representative cross-section of the inlet (MCS) and four beach profiles were defined (see Figure 3) to analyze their time evolution. Figure 4 shows the MCS obtained from each of the surveys conducted. The MSC is highly dynamic and significant changes in its morphology are observed over the period of measurement. 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.

The evolution of the beach profiles (defined in Figure 3) is shown in Figure 5 and the estimated volume per meter above the MSL of each dry beach can be found in Table 2. 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.

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.

The maximum and minimum elevations in the MSC were 2.5 and -1.3 m above the MSL, respectively, and both were measured in MCS-N14. Figure 7 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 Figure 7 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.

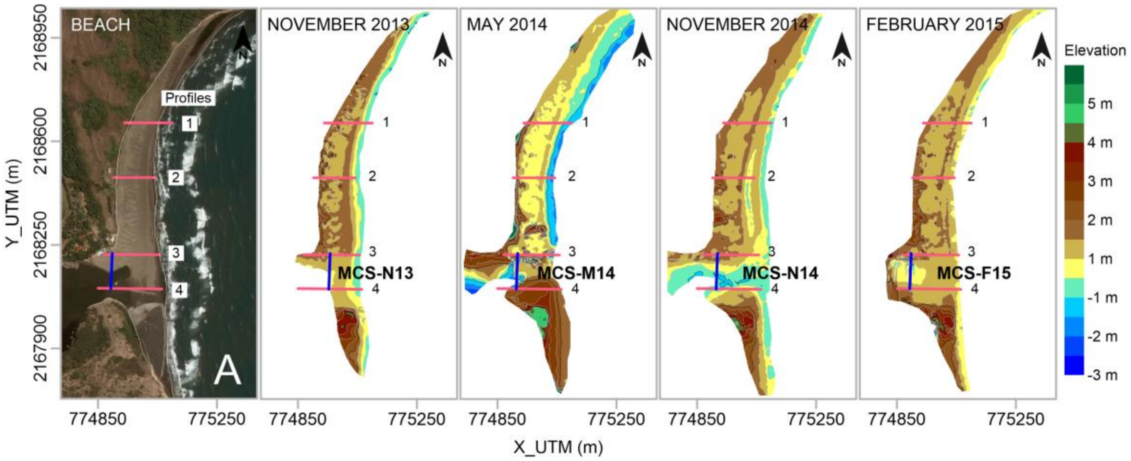

Figure 3. Development of the beach (see box A on Figure 1), showing the locations of the beach profiles monitored.

Table 1. *Superficial area of La Mancha dry beach.*

	November 2013	May 2014	November 2014	February 2015
Area (km^2)	0.1208	0.1517	0.1681	0.1705

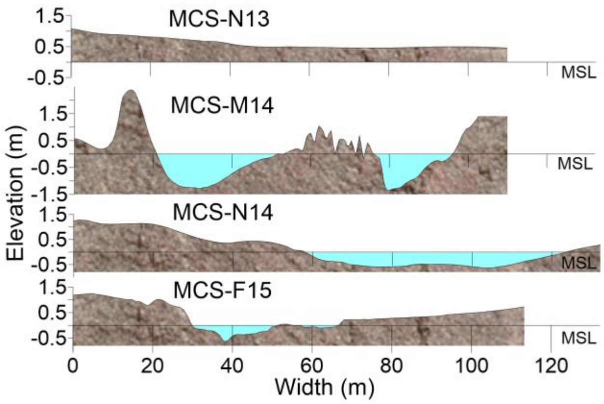

Figure 4. Time evolution of the cross-section of the inlet.

Physicochemical Parameters at the Inlet and in the Lagoon

Winter storms, as mentioned before, are a determining factor in the morphology of the system. The wind rose for the 2014-2015 winter storm season is presented in Figure 8. It can be seen that the wind direction is predominantly from North and North-Northwest, with velocities of up to 13 m/s. 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. The water exchange between the lagoon and the adjacent sea is limited by the morphology of the inlet, and the interaction of salt and brackish water produces pressure gradients which influence the gravitational circulation. On the other hand, the local wind is also responsible for the wind stress that acts on the surface of the lagoon producing frictional circulation (Miller, Pietrafesa, and Smith, 1990).

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 9). The sampling took place at each location every 30 minutes from 8:30 to 18:00 on November 6th, 2014. The free water surface level at the inlet was also recorded during the survey (Figure 10).

The time-series of the recorded parameters are plotted in Figure 11. 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.

As seen in Figure 11, sampling points (b) and (c) have more fluctuations, perhaps because they are close to the centre of the MCS, where the current mixing is more efficient. Regarding temperature, the minimum value is 25.7°C at 17:30 in (d), the maximum is 28.7°C at 12:30 at (a) and the average temperature for the entire record is 27.5°C. The lowest salinity value is 27.7 PSU in (b) at 9:30 (low tide) and the highest salinity (35.6 PSU) occurs at 16:30 (high tide) at (c). The density range in the inlet is from 1017.3 kg/m^3 to 1023.0 kg/m^3, with an average of 1020.7 kg /m^3.

Table 2. *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

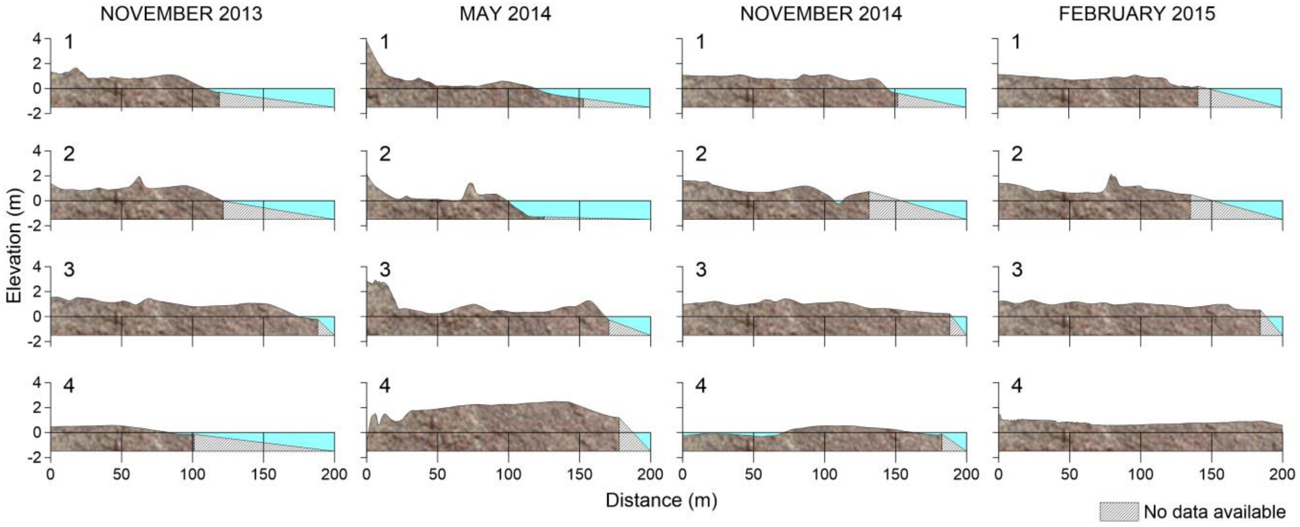

Figure 5. Development of the beach profiles (locations shown in Figure 3).

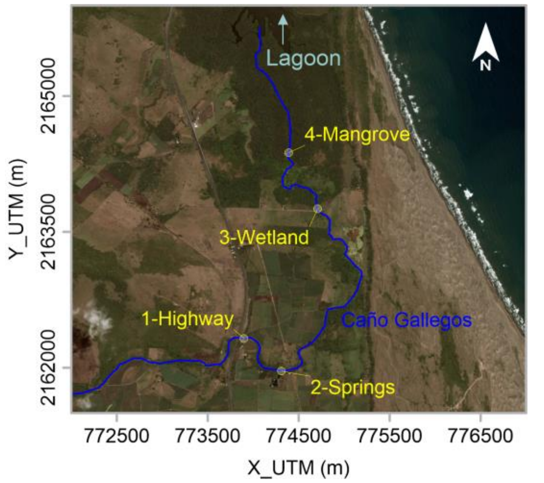

Figure 6. Caño Gallegos stream gauging locations (image modified from Digital Globe, June 2012).

Together with the monitoring of the inlet, a spatial sampling of superficial values of temperature, salinity and pH was performed. The equipment used was a multiparameter probe and each sampling point was georeferenced with DGPS (1 Hz sampling rate). Figure 12 shows the interpolated spatial distribution of the data recorded. The superficial temperature of the lagoon ranges between 28°C and 30°C, decreasing in the south body near Caño Gallegos and in the north body near Caño Juan Perez (see Figure 1), this could be due to convection, forced by the continuous input of the freshwater that usually produces a temperature decrease. Following Cowardin (1978). oligohaline conditions were identified close to Caño Gallegos; east of this area, where the lagoon is shallower, a euhaline condition was found. This is confirmed by the higher temperatures recorded east of Caño Gallegos. Polyhaline values are observed in the rest of the south body, increasing towards the north and reaching euhaline again in the inlet of the lagoon.

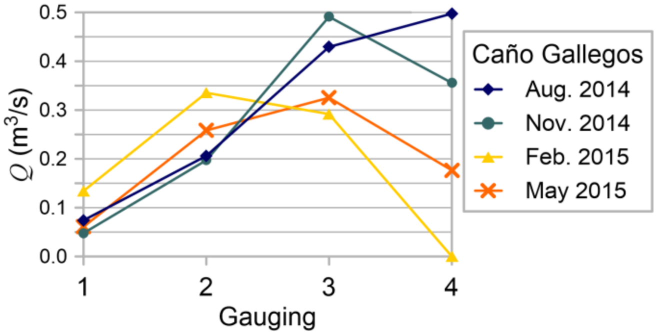

Figure 7. Caño Gallegos stream flow measurements.

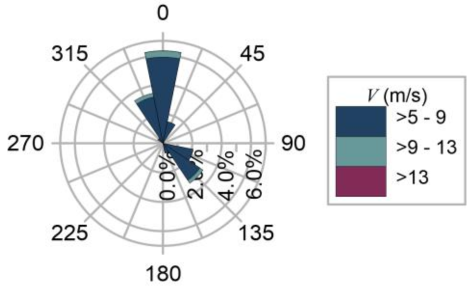

Figure 8. Wind rose for winter storms 2014-2015.

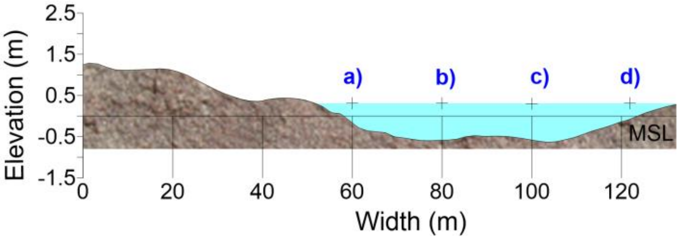

Figure 9. MCS and profiles sampled in November 6th, 2014.

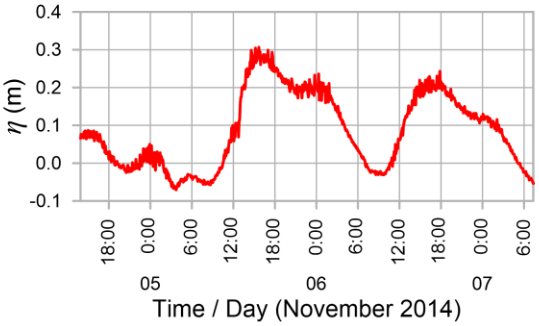

Figure 10. Free water surface measurments at the lagoon inlet, November 2014.

The pH values are inversely proportional to the temperature, which would explain the pH distribution in the lagoon shown in Figure 12. The higher pH values are found in the inlet, because in coastal areas the water tends to be alkaline, ranging from 7.5 to 8.4.

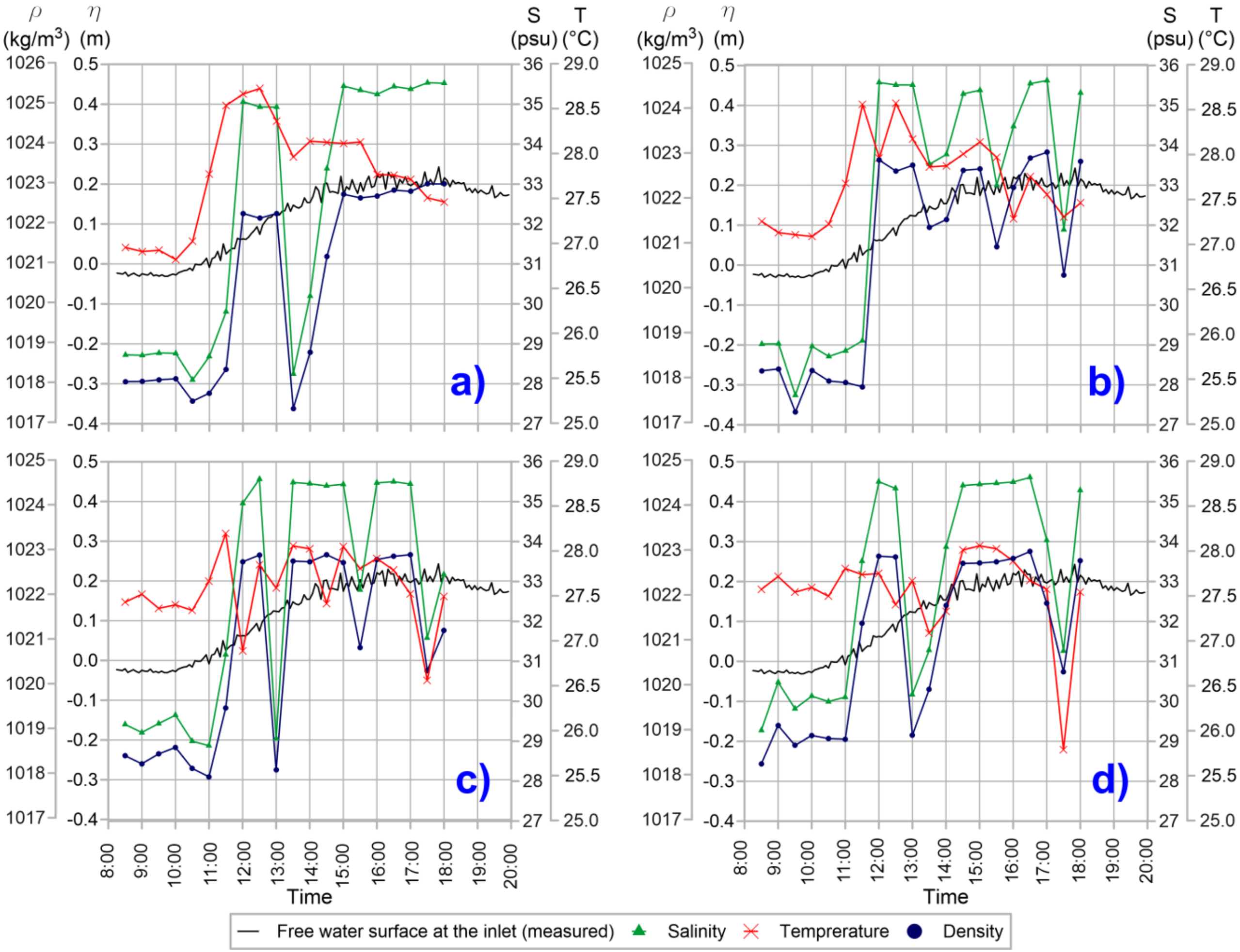

Figure 11. Physicochemical parameters at the sampled profiles of the MCS (November 6th, 2014).

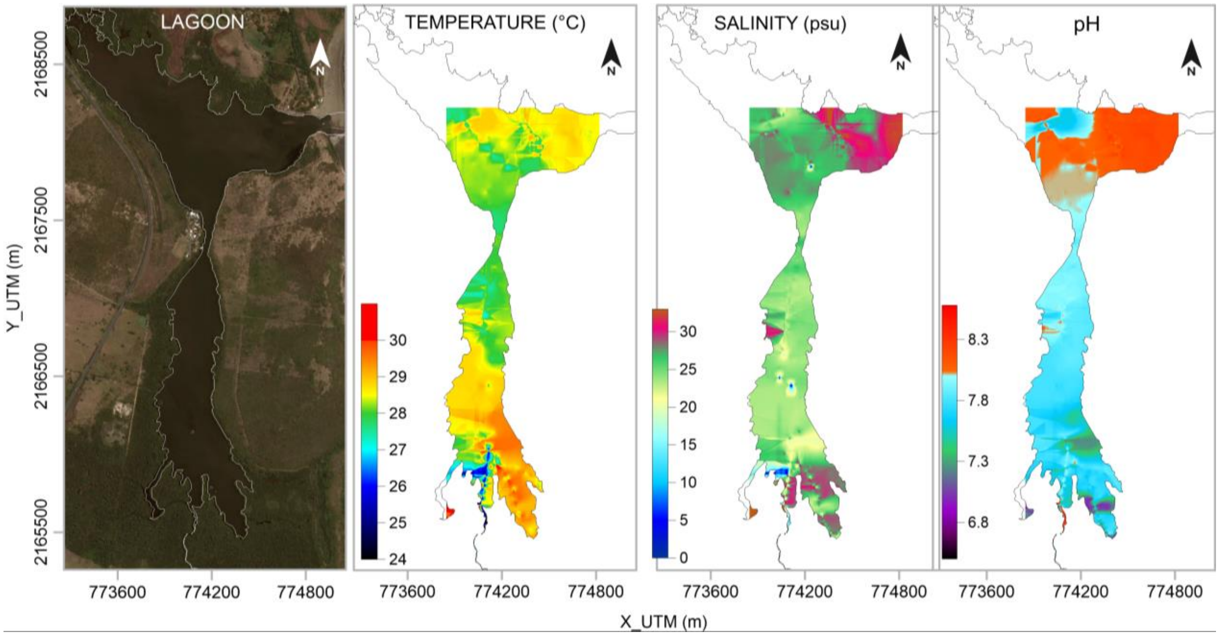

Figure 12. Spatial distribution of superficial physicochemical parameters at La Mancha lagoon: temperature, salinity and pH (November 6th, 2014).

NUMERICAL MODELLING

The circulation patterns of the lagoon were computed using the H2D model (GIOC, 2001), which is a depth averaged non-linear shallow water equations solver. The patterns obtained are the result of the interaction between the tide and the Caño Gallegos stream. 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). Since there is no historical data available for the discharges of the Caño Gallegos, the value used for the simulation was that obtained during the fieldwork (see Figure 7) for gauging point 3 (Wetland). The input of the discharge was located at 774391, 2164376 UTM. 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), which was produced using LIDAR data. The domain was discretized in a regular grid with cell dimensions of 10 m.

Four observation points were selected to monitor the water level as well as the horizontal and vertical components of the depth averaged velocity and the discharge: the northern end of Caño Gallegos (774103, 2165756 UTM), the central narrowing (774173, 2167376 UTM), the inlet (774913, 2168136 UTM) and the northwest end of the lagoon (773453, 2168576 UTM).

Validation

A comparison between the measured water level at the inlet of the lagoon and the results of the numerical model, is shown in Figure 14. For the 36 hours presented, the numerical results represent the changes in water level at the inlet appropriately.

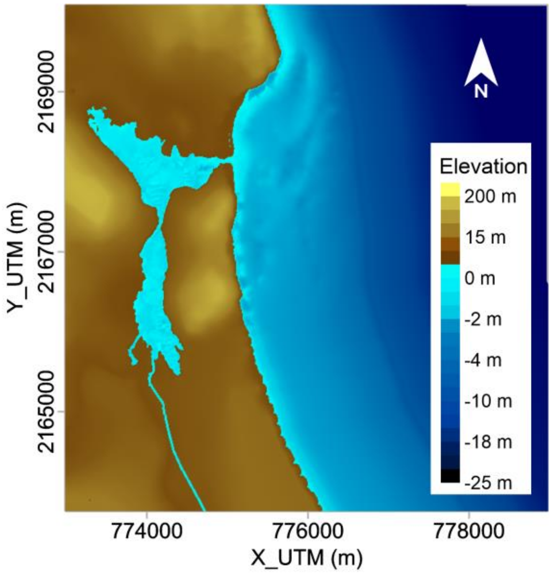

Figure 13. Numerical modelling domain.

RESULTS

The time series for the four observation points are given in Figure 15. At the inlet of the lagoon, no delays or significant distortion of the tide oscillation is observed, compared to the initial forcing series. However, a reduction in amplitude, approximately 40% in spring tides and 20% in neap tides, was found.

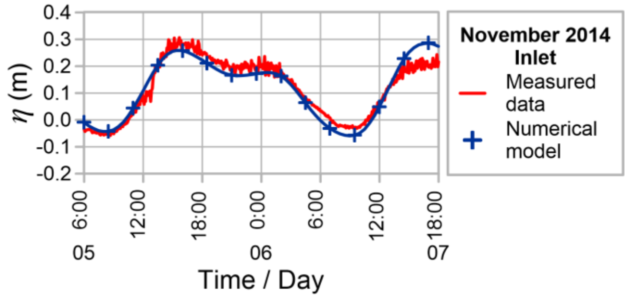

Figure 14. Free water surface: comparison between the measured data and the numerical model results.

In the northwest end and at the narrowing of the lagoon, the reduction in tidal amplitude is about 70% during spring tides and 60% during neap tides. The delay of the wave phase is 4 and 2 hours in spring and neap tides, respectively. A distortion of the oscillation was also found, caused by the effect of the bottom friction and the borders. In the case of the Caño Gallegos inlet, the oscillation is less distorted than that observed at other points, indicating a lesser effect of the tide, though there is an increase in amplitude from neap to spring tides.

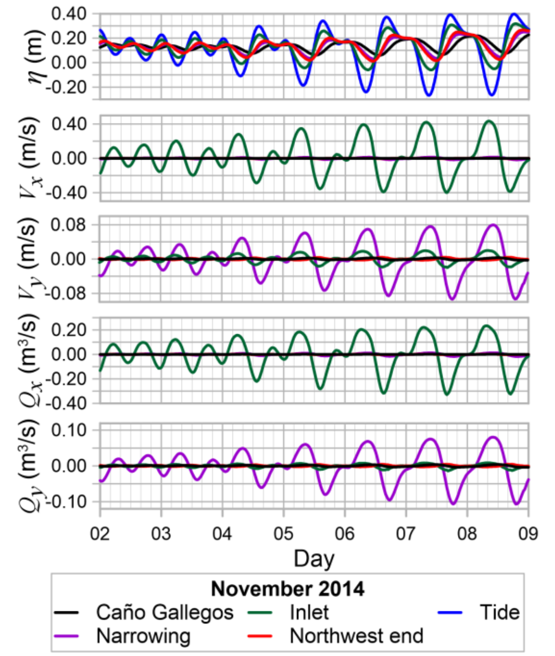

Figure 15. Time-series results for the four locations monitored.

The times series of horizontal and vertical velocity components (Figure 15) show that the highest values of velocity in the X direction occur in the inlet (the X axis coincides with the longitudinal axis of the inlet), being practically zero for the other points, as the wave propagates along the lagoon, with north-south/south-north direction predominating. This is in agreement with the velocities in the Y direction; in this case, the highest values are found at the central narrowing, because of the significant reduction of the cross-section. At the inlet, the ebb and flood velocities have similar values (about 0.40 m/s in spring tides and 0.15 m/s during neap tides), where the opening and closing of the inlet is conditioned by waves and wind.

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 16.

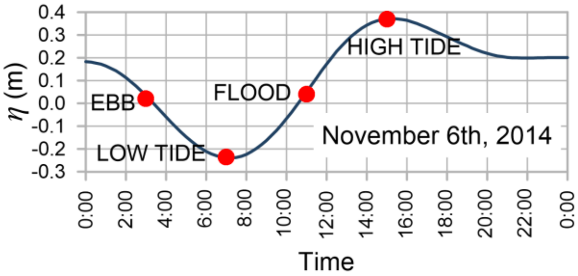

Figure 16. Ebb, low, flood and high tide levels.

In Figure 17, the variations in the water level are shown. The maps of the velocity magnitude are presented in Figure 18, 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.

DISCUSSION

A strategy for 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 land-sea (from

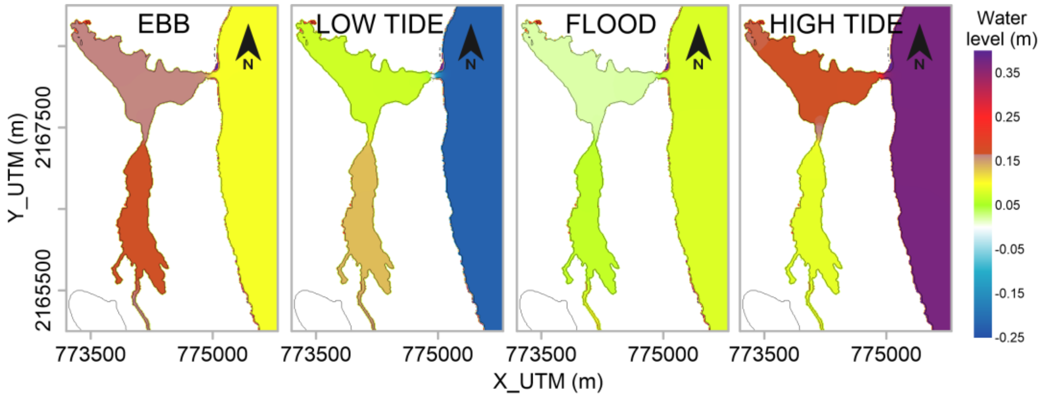

Figure 17. Spatial distribution of the water surface elevation (UTM coordinates).

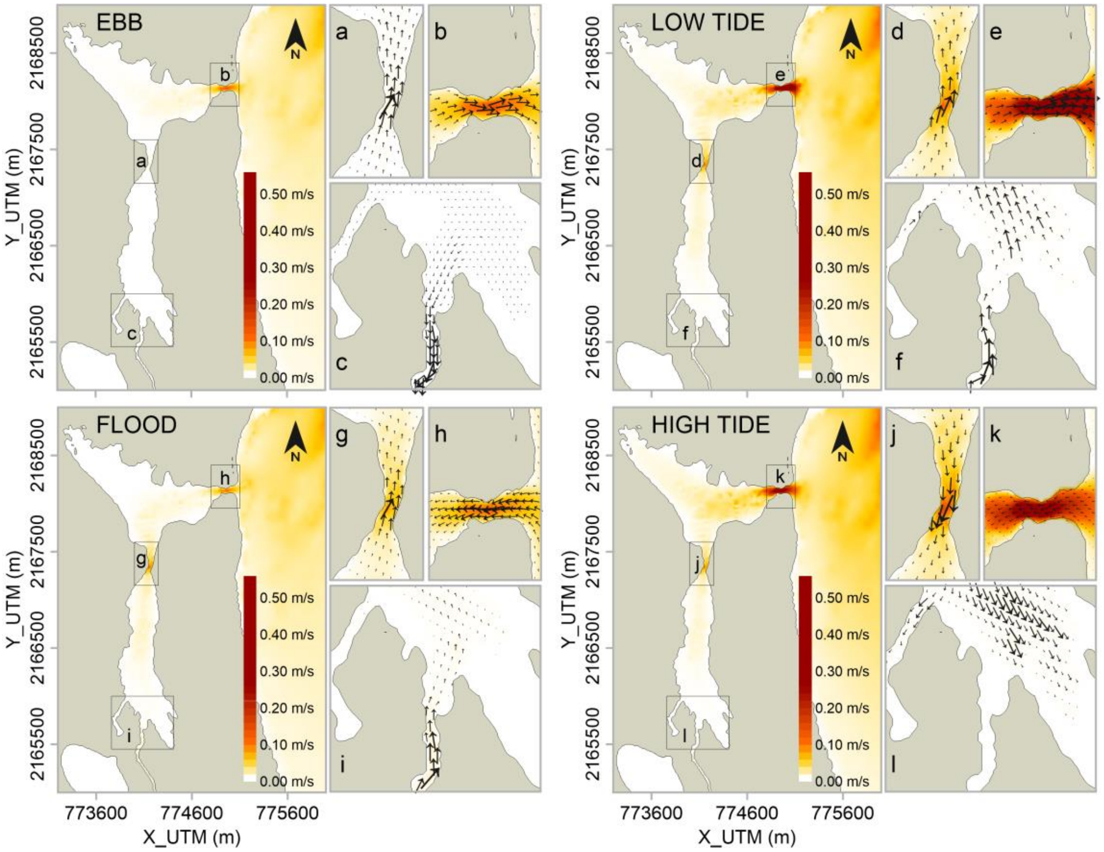

Figure 18. Spatial distribution of the velocity.

hydrological basins) and sea-land (tides and currents) contributions are also key to the system management (Twilley, 1995). A third element to consider is the degree of vulnerability of the system to natural and anthropogenic hazards, to determine the resilience of the system to these perturbations (Dayton *et al.*, 1984). The induced openings of the inlet affect the physicochemical properties of the water and the circulation patterns of the lagoon; these conditions need to be quantified and understood. The resilience of the system to the management of the inlet may be determined in terms of the return time (Montefalcone, Parravicini, and Bianchi, 2011) of the induced openings, which can be monitored with topographic surveys of the beach and the inlet.

The ability of the beach to recover after the morphological changes induced by winter storms (the resilience) was determined from November 2013 to February 2015. In the beach area an accretion of 41% was registered (Table 1). The beach presents embryo dune formations, well graded fine sand and a dissipative profile near the inlet, so the beach can be considered stable. A long-term study by Martínez *et al*. (2012), reports that the beach suffered a reduction of 85 m near the inlet of the lagoon from 1995 to 2006. However, in an annual analysis, these effects are not detected.

The morphology of the inlet of the lagoon measured from November 2013 to February 2015 (Figure 4), 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 9). This was also observed in the recorded superficial data (Figure 8), where the salinity, temperature and pH fall from North (inlet) to South (discharge of Caño Gallegos). From the circulation patterns of the lagoon, obtained with the numerical model, it was observed that the tide oscillation had a delay and a reduction in amplitude as it propagated to the south of the lagoon (Figure 15). The main causes of this are the bottom friction and the boundary effects. Wind and waves are the dominating forcing in the dynamics at the inlet of the lagoon, inducing its opening and closure. On the other hand, 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, Rivera-Guzmán, and Segura-Aguilar (2005), the opening of the inlet limits the efficient use of nutrients in the lagoon. The artifical 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 escenario, water renovation in the estuary cannot be guaranteed and the balance of the ecosystem is endangered. The ecological consequences over longer periods have not been studied.

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 circulation patterns of the lagoon, forced by a tide oscillation and the discharge of Caño Gallegos, indicate that wind and waves induce the opening and the closing of the inlet. The controlling force of the lagoon patterns is the tide, as corroborated by the physicochemical parameters measured in the inlet and the lagoon. However, this natural cycle is interrupted by the action of local fishermen in opening the inlet at certain times. 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).

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