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Interaction of alongshore sediment transport and habitat conditions at Laguna La Mancha, Veracruz, Mexico

Norbert P. Psuty · M. Luisa Martínez · Jorge López-Portillo · Tanya M. Silveira · José G. García-Franco · Natalia A. Rodríguez

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Abstract The habitats of La Mancha Lagoon, located midway along the coast of Veracruz, Mexico, are responding to the change of sediment supply reaching its primary inlet at the Gulf of Mexico. Until several decades ago, an abundant alongshore supply of sediment created a periodic opening and closing of the La Mancha inlet. The hydrologic regime of the lagoon consisted of raised water level and lower salinity during the closures, whereas the open inlet favored lower water level, higher salinity, and sediment accumulation in the flood tidal delta. Currently, diminished alongshore sediment supply has affected the inlet morphology and the discharge regime. Associated with the reduced sediment supply, the inlet is open longer in its periodic cycle, the water level variation is reduced, the salinity contrasts are reduced, and the rate of sedimentation in the flood-tide delta is increased. This combination of alterations to the inlet area is changing the flooding regime and affecting the conditions in a very well-developed mangrove habitat at the lagoon margins as well as conditions within the aqueous portions of the lagoon. Management options produce a conflict between supporting the direction of change or preserving the existing habitats.

Keywords Sediment transport · Inlets · Lagoons · Headland-bypassing · Mangrove habitat · Seedling · Mexico

N. P. Psuty (✉) · T. M. Silveira
Institute of Marine and Coastal Sciences,
Rutgers—The State University of New Jersey,
Sandy Hook, NJ 07732, USA
e-mail: psuty@marine.rutgers.edu

M. L. Martínez · J. López-Portillo · J. G. García-Franco · N. A. Rodríguez
Instituto de Ecologia,
A.C. km 2.5 Antigua Carretera a Coatepec,
Xalapa, Veracruz 91070, Mexico

Introduction

The east coast of Mexico along the Gulf of Mexico is a very dynamic region with a variety of coastal geomorphologies and habitats responding to the localized inputs of sediment and their episodic mobilization under seasonal weather conditions. The central portion of the coastal state of Veracruz is generally oriented north–south, but the coast incorporates a number of headlands created by the Trans-Mexican Volcanic Belt producing offsets in the coastal trend, creating a series of lagoonal embayments, and segmenting the alongshore transport system (Fig. 1). Alongshore sediment transport is primarily from north to south and it is variable because of localized fluvial inputs, lithological barriers, and landforms of sediment accumulation and sequestration. As the alongshore sediment supply waxes and wanes in the coastal compartments, the geomorphological responses in the form of beach features and coastal dunes interact to alter some aspects of the coastal lagoonal habitats and their associated hydrologic regimes. Specifically, the sand barrier at the mouth of the La Mancha lagoon has apparently recently evolved from a condition of relative permanence and stability to a condition characterized as longer durations of being open and much more mobility. Changes in the geomorphological dynamics at the inlet are subsequently affecting elements of the environmental systems within and adjacent to the aquatic and mangrove units of the La Mancha lagoon (Fig. 2). In particular, timing of the prior hydrological regime was important in affecting seedling survival in the mangrove habitats. The vector of the new hydrological regime may signal a change in recruitment opportunity and give insight to conditions of habitat evolution. Whereas the driving variable of sediment supply appears to be a recurring and episodic natural phenomenon, management

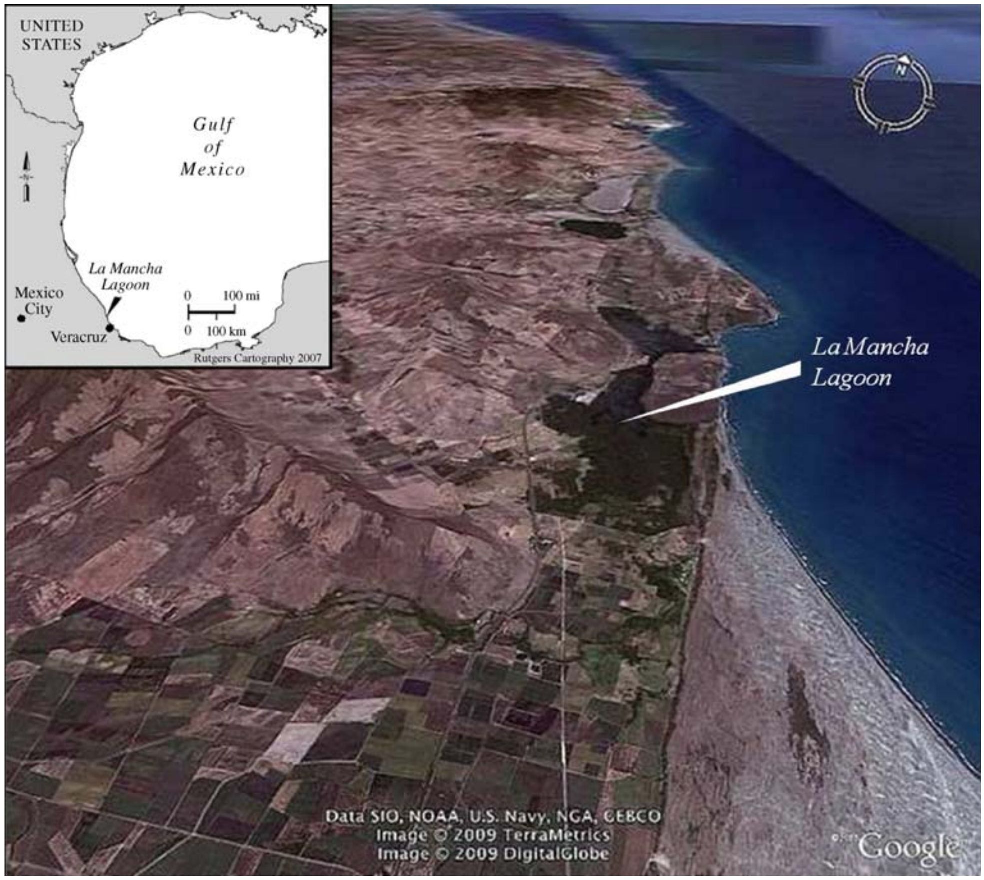


Fig. 1 Segmented shoreline created by volcanic axis projecting into the Gulf of Mexico. Coastal dune fields aligned along a north–south orientation are migrating inland across the NW–SE trending shoreline segments. La Mancha Lagoon is at the confluence of the fluvial plain and the volcanic belt. Image courtesy of Google Earth, Inc

options are not easily programmed to respond to the temporal variability. This paper documents the dimensions of geomorphological and habitat change related to variations in local sediment supply and identifies the range of issues associated with the resulting management concerns.

General setting

The geomorphology of the central portion of coastal Veracruz consists of Holocene fluvial and marine sediments draped around volcanic promontories to create alluviated embayments fronted by a variety of coastal dune forms (Fig. 1). The tides are relatively minor in this portion of the Gulf of Mexico; the diurnal mean tidal range is about 0.6–0.7 m at the port of Veracruz, about 30 Km south of the study site.

Winter storm surges often exceed 1.5 m in the southern Gulf of Mexico as high-pressure systems in North America cause strong cold winds from the north (nortes) (Gómez-Ramirez and Reséndiz-Espinosa 2002). These seasonal northerly winds generate the most energetic waves of the year and create a net north to south drift in the littoral transport system. The norte winds also generate considerable eolian transport in the same direction, producing sizeable coastal dunes and dune fields that often incorporate a transgressive orientation associated with the north-to-south wind vectors (Fig. 1). Hurricanes are another factor in raising water levels and generating storm waves that affect the coastal region in Veracruz. Although hurricane winds are very strong, they are normally of short duration and do not produce a consistent direction of sediment transport. There is a marked rainy season that extends from June to November. This is a period of frequent convectional rainfall, amounting to 1,260 mm per year at the coast and increasing inland.

The La Mancha lagoon consists of two sizeable water bodies that together occupy a coastal topographical niche in the Trans-Mexican Volcanic Belt. They lie downdrift of a volcanic headland and inland of an isolated volcanic remnant (Fig. 1). Further, the La Mancha lagoon complex is at the northern (updrift) margin of a sizeable fluvial deltaic plain that supplies considerable sand to the downdrift coastal transport system. As a result of its shielded and distal situation, the geomorphological evolution of this lagoon site has been marked by minimal sediment input from either the fluvial source or from the alongshore marine source. The lagoon has a single inlet at the northeastern end that, historically, has had an annual periodicity of opening and closing. However, the recent geomorphological evolu-

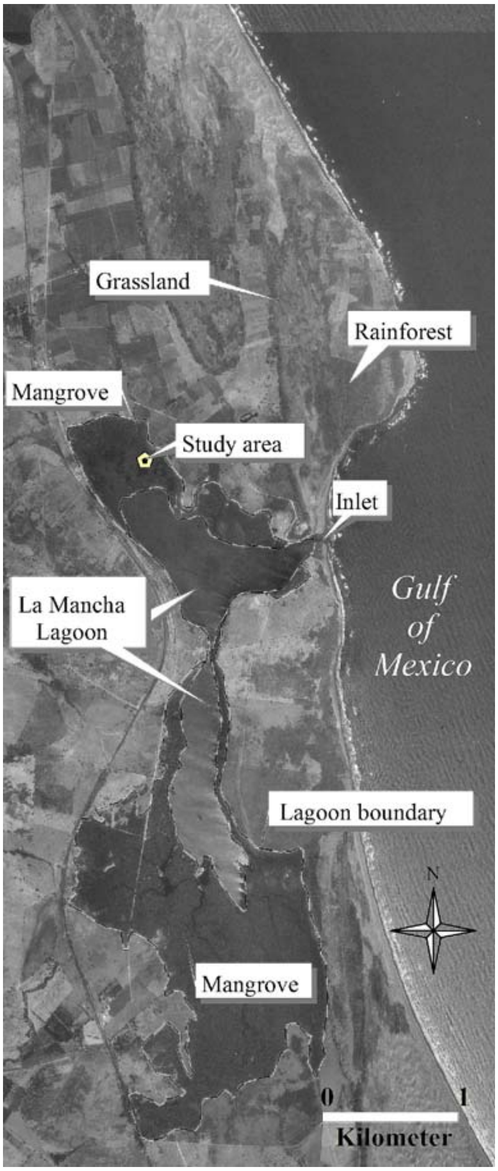


Fig. 2 Topographical associations of the headland and distribution of mangrove and aquatic system in the lagoon. Much of the land use is agricultural with some areas of evolving rain forest and grassland. Study area for mangrove seedling survival is identified. Aerial photo: March 2006

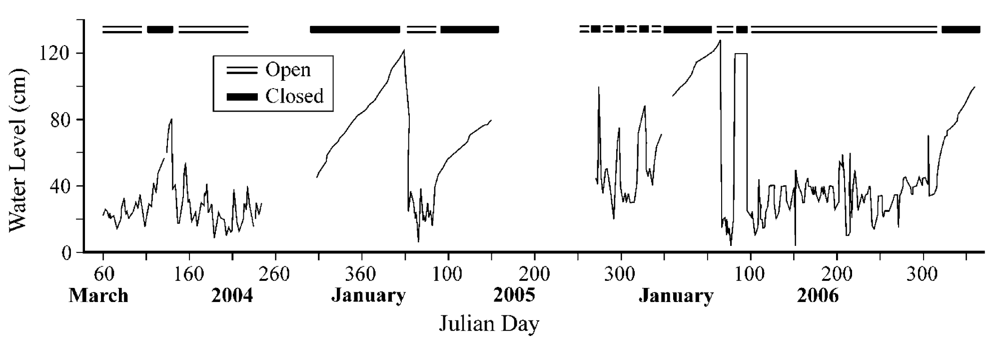
tion has witnessed changes to the paths of sediment supply reaching La Mancha and these changes have produced a suite of impacts to the system.

Hydrological characteristics

The inlet to La Mancha lagoon is located between two volcanic headlands and is spatially restricted to this narrow zone. Its hydrological characteristics interact with the sediment supply available at this limited site. In the past, the inlet was open only for a few months during the latter part of the rainy season. The inlet would be sealed subsequently by a broad sand berm that was episodically elevated during the norte period by higher water levels that transported sediment onto its crest and displaced it slightly inland, similar to a process of berm elevation and inland displacement at Tupilco Inlet in Tabasco, Mexico (Psuty 1967). The high elevation of the storm berm would cause rain water and inland fluvial discharge to collect in the lagoon and elevate the standing water level until rainy season accumulations raised the water levels to eventually breach the sand barrier in the inlet. This hydraulic regime of high water level during the drier norte period and lower water level in the latter part of the rainy season was essentially driven by the availability of sediment at the inlet and the storm surge processes that broadened and elevated the beach berm across the inlet.

Present day conditions show a different hydrological regime from that of the past. Monitoring of the water levels at La Mancha reveals a much longer portion of the year with low water levels (indicative of an open inlet) (Fig. 3). Over the span of the 3 years of lagoon elevation monitoring on-site (2004–2006), although the record is incomplete, the inlet was open about half of the time. Further, the inlet was open for more than the rainy season. Overall, there was considerable variation in the water level of the lagoon throughout the year as the sediment alternatively clogged the opening and was breached by the rising lagoon level. In general, the norte season tended to coincide with higher

Fig. 3 Water level variation in the La Mancha Lagoon, 2004–2006, in relationship to functioning of the inlet



water levels in the lagoon, thereby suggesting that storm surges were contributing to elevation of the berm and aiding in the closure of the inlet. There seems to be a seasonal signature in 2005 and 2006 with prolonged periods of low water level during most of the rainy season and higher water during the winter norte season. There are also short durations of oscillating water levels that are more likely related to rain events than to inlet morphologies.

Geomorphological evolution

Sediment supply

Alongshore transport of sediment to maintain the sediment budget of the beach-dune system is often the product of wave and current processes, but eolian transport processes may be important contributors to alongshore supplies in special situations along embayed coasts. Parts of the west coast of South Africa (Tinley 1985) and southern Brazil (Hesp et al. 2007) have been described as having substantial eolian transport from one embayment to another across intervening headlands. Tinley (1985) has named these areas “headland bypass dune fields” and has noted the importance of these dune fields in the regional and local sediment budget. These headland areas are locations of large dune forms that migrate from one embayment, across the intervening projecting headland, and into the next embayment. In so doing, sediment is transferred downdrift to support beach and dune forms in the next embayment. Swart and Reyneke (1988) and Schoonees and Barwell (1991) have interpreted associations of regional coastal geomorphologies that are related to the pulsations of sand crossing headlands during times of natural mobilization, stabilization, and re-mobilization to support episodes of accretion and erosion. These are examples of the complexity of downdrift sediment transport scenarios in sites of irregular shorelines and with localities of sediment availability. An additional effect to the sediment transport situation occurs when human intervention is applied to alter the pattern of sediment mobility by either attempting to restrict transport or inadvertently accelerating transport. McLachlan et al. (1994) point to downdrift erosion results that have occurred because of dune field stabilization decisions that eventually changed the sediment supply coming into an embayment across a headland. They call attention to the need to fully understand the sediment pathways that exist in a coastal unit and to consider the cascading effects of interruptions anywhere in the sequence of sediment transport.

The La Mancha lagoon embayment is apparently being affected by the updrift changes in sediment transport across the headland at its northern extent. Similar to the occurrences in South Africa and Brazil, sand has been transported downdrift across the headland by eolian processes to supply sediment to the adjacent beach. But, conditions have been changing in the past several decades. Natural encroachment of vegetation cover has decreased the bare sand area and has reduced the transport of sediment downdrift (Fig. 4). Aerial photography from 2006 demonstrates the very broad extent of parabolic dunal forms that were formerly active in this area and the lack of bare sand at present (Fig. 5). Aerial photography from 1980 to 2006 depicts considerable change in vegetation cover and subsequent stabilization of the dune field (Fig. 5) (Psuty et al., in preparation). During this time, an area of 90 ha that previously was mobile sand dune has changed to agricultural use (2%), grassland (53%), and tropical rainforest in various stages of succession (35%) (Psuty et al., in preparation). Only 10 % of the original mobile dune area continues to function in its earlier condition. As a result, the quantity of sand moving across the headland to the vicinity of the La Mancha inlet has decreased.

The impacts of sediment transport across the headland and the reduction of transport are manifest in the shoreline changes in the receiving area through an analysis of aerial photographs from 1980, 1995, and 2006 (Fig. 6). Each of the photographs is used to trace a shoreline position (wet/dry line (Boak and Turner 2005)) and the edge of vegetation at the upper beach (Fig. 6a–c). The portion of the photograph incorporating the shoreline immediately north of the inlet on each of the photographs was registered to a common base, in this case it was the geo-referenced 2006 aerial photograph. The rms error following registra-

Fig. 4 The partially stabilized dune field located in the headland to the north of La Mancha lagoon is reducing the transport of sediment into the beach zone at the lagoon inlet (June 2005). The view is from the north looking toward the south, immediately updrift of the entrance to La Mancha Lagoon; a small portion of the lagoon is visible in the upper right corner of the photograph

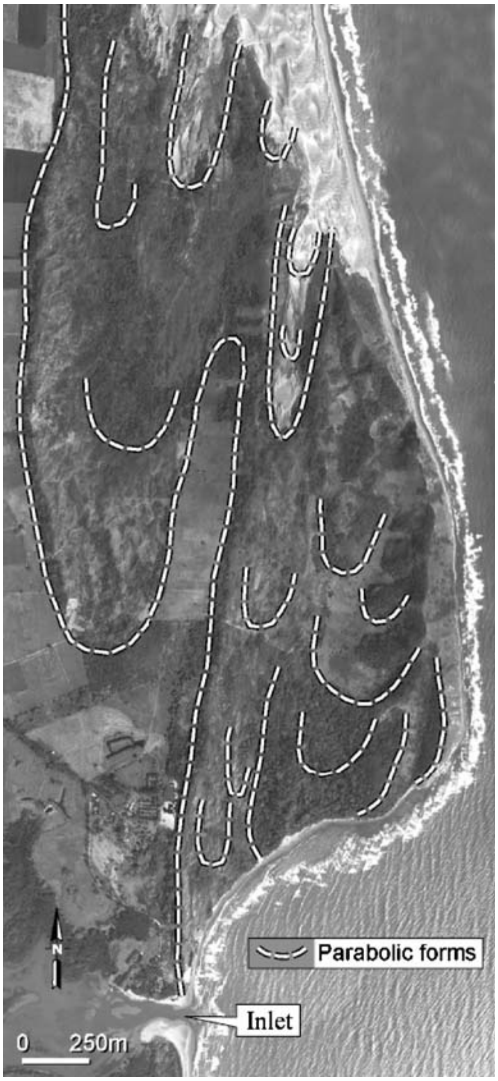


Fig. 5 Two major lobes of former eolian transport across the headland leading to the inlet at La Mancha Lagoon, 2006 aerial photo. A few of the parabolic dune features are identified. Many more are present. The flood tidal delta at the inlet is extending into the lagoon

tion was less than 2 m. Once registered, change analysis was accomplished by applying the Digital Shoreline Analysis System program (DSAS) (Thieler et al. 2005) to the shoreline position and to the vegetation edge position. In this instance, a general shoreline trend line is constructed and transects spaced at about 10 m intervals are extended to intercept the shoreline orthogonal to the shoreline. A distance from the baseline is measured for each year and differences in shoreline and vegetation edge position are calculated and plotted (Fig. 7).

The 1980 aerial photography depicts a large swath of bare sand transgressing the headland to supply the beach immediately north of the inlet to La Mancha (Psuty et al., in preparation). The 1995 aerial photography subsequently presents an increased vegetation cover, but with areas of bare sand remaining. A comparison of the shoreline position between these 2 years (Fig. 7a) reveals an almost consistent seaward displacement of the shoreline as well as the vegetation edge. The maximum displacement of the shoreline was about +52 m, near Transect #36, and it decreases gradually to Transect #82. There is an inland displacement of the shoreline from Transect #83 to #89, of from −1 to −4 m. However, that may be within the range of error of this aerial photo analysis and this dimension of change also applies to an area of the shoreline that is in bedrock rather than in mobile sand. Thus, the several meter variation is probably associated with the inherent error of this approach. The displacement of the vegetation edge is greater than the shoreline displacement because the 1980 edge position was irregular and often not in the coastal foredune position. Some of the seaward displacement of the vegetation in the vicinity of Transects #1–35 is the product of foredune development and stabilization in the beach profile.

The 1995–2006 aerial photographic comparison (Fig. 7b) is also relatively consistent over the sandy area. The zone of Transects 1–44 has an inland displacement greater than 60 m, with a maximum of −84.5 m at Transect #27. Thereafter, the inland displacement decreases gradually to Transect #83. This latter location is in bedrock and is at the same location where there was variance from the general trend in the previous comparison, indicating influence of the local lithology rather than mobile sediment. The vegetation edge displacement is also very consistent throughout the sandy sector, reaching a maximum inland displacement at Transect #34, −81.3 m. The vegetation unit is at the base of scarped foredune in this photography, extending through Transects #1–83.

Inlet morphology

There are two main components to the geomorphological features at the inlet: 1) the storm berm, and 2) the flood tidal delta. The storm berm is part of the beach and it is created primarily during the norte storm surge, and at times during the hurricane storm surge. When there is adequate sediment in the beach, the berm becomes elevated and is displaced inland as storm waves and higher water levels cause accumulation high on the profile. But if sediment supply is inadequate and the beach profile is low and sediment-starved, norte waves and high waters may construct a lower and more-easily breached berm. Under very low sediment supply, the norte conditions may breach any existing low berm and allow for longer periods of an open inlet and low water in the lagoon. Thus, reduced sediment supply results in a more poorly-developed storm berm and creates an opportunity for greater occurrence and greater duration of an open inlet into La Mancha lagoon. Also, in association with the lower storm berm and with a

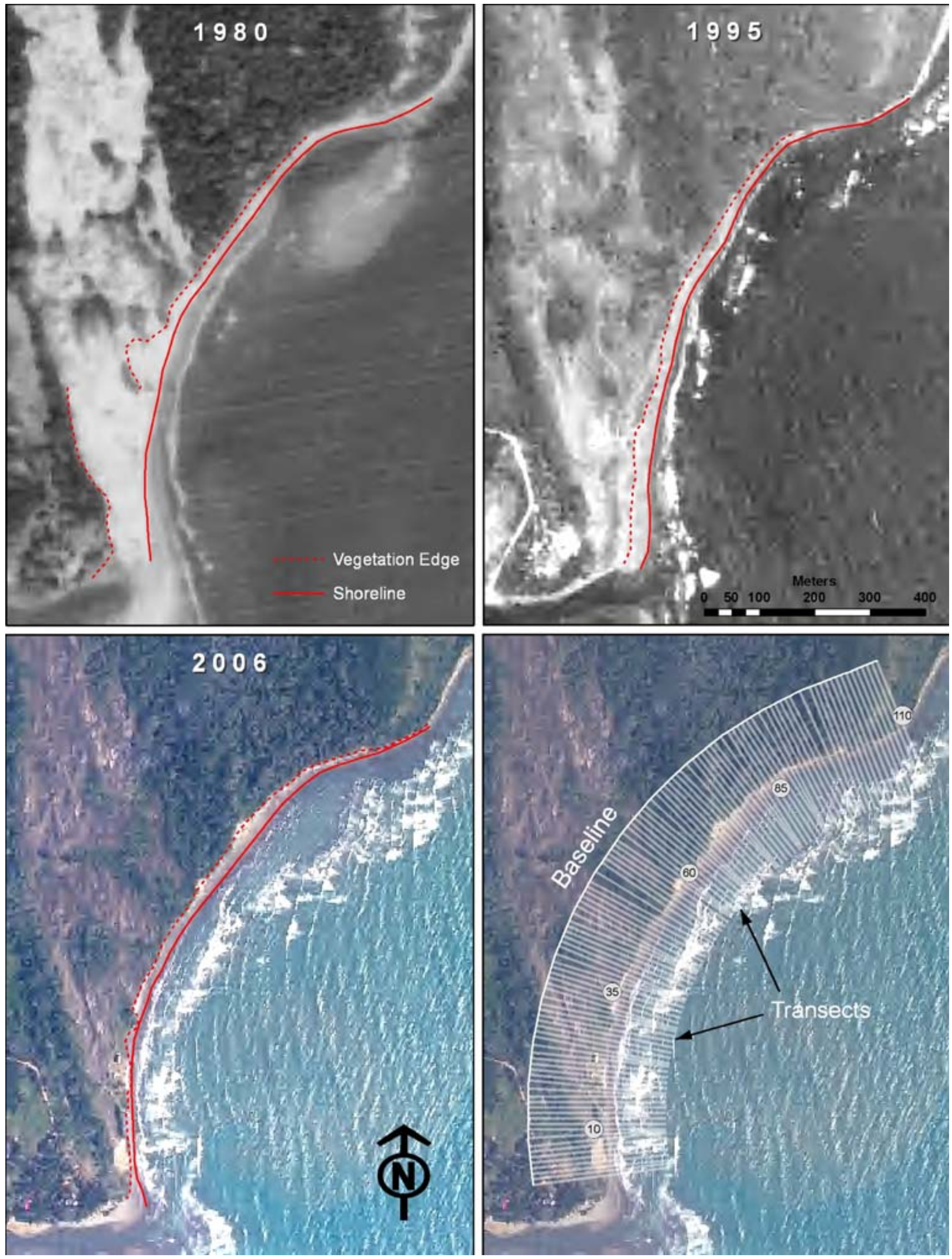


Fig. 6 Aerial photographs with the interpreted position of the shoreline and the seaward edge of vegetation, **a** 1980 lines, **b** 1995 lines, and **c** 2006 lines. Panel **d** incorporates the reference baseline and the 110 transect lines along which distance measurements were made

longer period of the open channel to the inlet, there is a greater duration when tidal exchanges can direct and sequester sediment into the northern section of the lagoon. This is an important change to the subaqueous environmental character near the inlet because the former relationship of the lagoon to sediment supply was at the distal margin of the fluvial plain emanating from the south. The northern end of the lagoon was shielded from sediment coming across the headland and was also inland of a barrier that prevented beach sediments from entering through the inlet. It was the deepest portion of the lagoon. However, with the change in sediment supply at the inlet, the longer duration of an open inlet has been accompanied by an areal expansion of the flood-tide delta formation and the shallowing of the northern portion of the lagoon. The inlet continues to pass through the temporal oscillation of being open and closed. However, the pattern of long periods of high water alternating with short periods of low water and inlet opening is changing. This situation, in turn, is causing changes in salinity gradients, distribution of sediment types, and it is affecting many of the ecological habitats within the lagoon and along its margins.

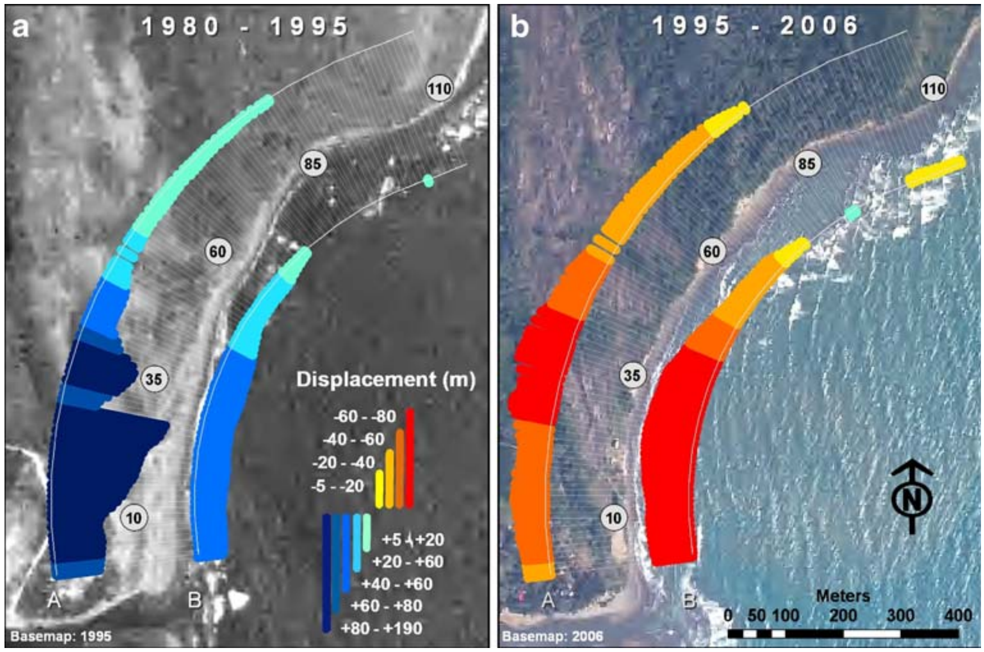


Fig. 7 Measurements of displacement of shoreline and vegetation edge for pairs of photographs: panel **a** 1980–1995; panel **b** 1995–2006. The inland band represents the vegetation edge displacement; the seaward band represents the shoreline displacement. Measurements are made along each transect

Habitats

When the inlet is closed, water level may increase up to 120 cm, or until it overtops the sand bar naturally, discharging the supratidal accumulation through the newly-created inlet. Mean interstitial salinity in the lagoon ranges from 28–38 ‰ during the dry season, which includes the "nortes" period, and from 12–31‰ during the rainy season (Hernández-Trejo 2009). Oysters (*Crassostrea virginica* Gmelin) and a variety of fish species are harvested by the local inhabitants from the lagoon (Ruiz-Guerrero 2000; Hernández-Trejo 2009).

The lagoon is surrounded by a mangrove forest that covers a total surface of 335 ha (Hernández-Trejo 2009) (Fig. 2). This forest is highly heterogeneous with many plant associations, ranging from monospecific stands, to patches with a more diverse composition, which depends on local hydrologic and geomorphological conditions (Hernández-Trejo et al. 2006). With increasing flooding frequency and duration, mangrove forest stands tend to be taller and more diverse. As flooding becomes less regular and lasts for shorter periods of time, mangrove forest stands are shorter and monospecific (Hernández-Trejo et al. 2006). The most abundant plant species are *Avicennia germinans* (L.) Stearn, *Laguncularia racemosa* (L.) Gaertn, *Rhizophora mangle* L., and *Conocarpus erectus* L. *Rhizophora* grows at the edge of the lagoon and covers 10% of the forest, in monospecific stands. Farther inland, *Rhizophora* can also be associated with *Avicennia*, but when this occurs, the latter is most abundant. *Avicennia* and *Laguncularia* are the most abundant species in the mangrove forest, and compose 66% and 22%, respectively, of the forest (Hernández-Trejo 2009). These two species may grow in dense monospecific stands or in association with each other, or with *Batis maritima* and *Conocarpus erectus*.

Responses to changing conditions

Water level and salinity fluctuations have a significant effect on the species growing in this ecosystem. For instance, oysters are sometimes at risk of massive mortality because of high water levels and an associated reduction of oxygen. When this situation occurs, the local fishermen may act to open the inlet manually, by using shovels (Hernández-Trejo 2009). Fish species present in the lagoon change depending on whether the inlet is open or closed. For instance, when the inlet is closed, *Citarichthys spilopterus* Günther (bay whiff, flounder), *Centropomus parallelus* Poey (fat snook), *Gerres cinereus* Walbaum (yellow fin mojarra) and *Selene vomer* (L.) Jordan and Evermann (lookdown) are the dominant species. However, when the sand barrier is breached and the inlet is open, *Archosargus probatocephalus* Walbaum (sheepshead), *Anisotremus surinamensis* Bloch (black margate), *Sphyraena barracuda* Walbaum (great barracuda), and *Lutjanus apodus* Anderson (snapper) are found in the lagoon. In addition, there are species that are found in both open and closed inlet conditions: *Ictalurus* sp. (catfish), *Centropomus undecimalis* Bloch (snook), *Bairdiella ronchus* Cuvier (ground croaker) *Diapterus auratus* (irish pompano, white mojarra), and *Eugerres plumier* Cuvier (striped mojarra) (Ruiz-Guerrero 2000). All of these species have an important commercial value because they are a major supply to the local stores and restaurants, especially flounder, fat snook, yellow fin mojarra, and striped mojarra. Importantly, all of them are present when the inlet is closed, and only the striped mojara is also present during open inlet conditions.

The mangrove forest at La Mancha has practically no understory and juveniles are generally absent (Fig. 8), even those from the dominant species, such as *Avicennia*. Seedling germination of *Avicennia* at La Mancha is very high, and seedlings are dispersed by water currents at the end of the rainy season, in September and October. As many as 30 seedlings per square meter have been counted at the study site, meaning that, potentially, almost 60 million *Avicennia* seedlings could be found in the La Mancha mangrove forest. Nevertheless, very few of them survive until the next rainy period. A possible constraint to survival is that seedlings germinate when the sandbar closes the inlet and the water level begins to rise. Lugo (1986), Janzen (1985), Sousa et al. (2007), Krauss et al. (2008), and others have indicated that flooding might play an important role in seedling survival in mangrove forests.

Based on the above potential constraint, we marked a total of 120 *Avicennia* seedlings and monitored their survival at weekly intervals, from September to December 2000. On each occasion we also measured water level. On August 31, the inlet was open and the water level on that date was at 4 cm on our datum. The seedlings were developing their first pair of true leaves. We observed that, as water level increased, seedling survival decreased, following a lineal trend with negative slope (Fig. 9). These results agree with earlier studies that revealed that flooding has an affect on mangrove species (Janzen 1985; Lugo 1986; Sousa et al. 2007; Krauss et al. 2008) and that mangrove seedlings are more sensitive to flooding than adults (Krauss et al. 2008). In addition, Sousa et al. (2007) found that establishment of the seedlings is best in the lower intertidal elevations (or when water level does not increase too much or too rapidly) because floating in the water makes rooting difficult. Once established and rooted in the soil, seedlings need to have achieved sufficient height so that they are not totally submerged in water. Thus, seedling growth rate plays a key role in seedling survival. Under optimal environmental conditions (e.g., adequate light availability) and before seedlings lose their cotyledons, growth rate is very fast (almost 10 cm per month). Afterwards, upon losing the cotyledons, growth rate is much slower and decreases to 1–3 cm per month (Ríos-Figueroa 2007). In this sense, the success of seedling survival depends on their growth rate and the speed at which flooding occurs. We observed that as long as some green tissue was above the water surface, seedlings remained alive (Fig. 10). Death began after total submersion.

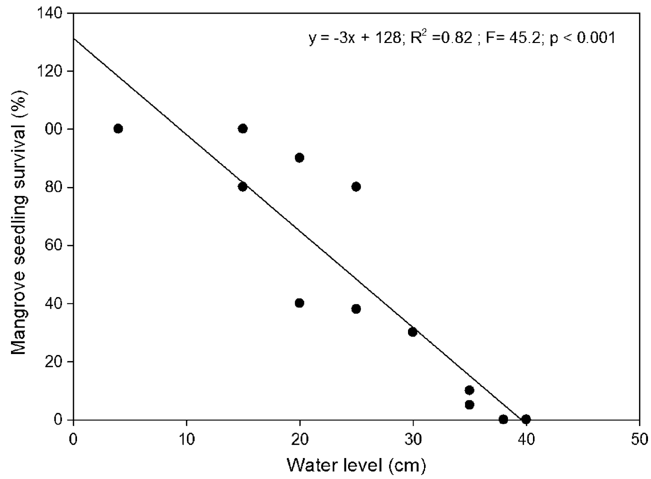


Fig. 9 Seedling survival of *Avicennia germinans* is positively related to lower water level, September–December, 2000. The study site is depicted on Fig. 2

Fig. 8 Seasonal inundation of root zone in *Avicennia germinans* at piezometer station. Water level is 60 cm at this station, inlet is closed, February 21, 2006. Submerged roots are visible in foreground

Fig. 10 New growth at top of *Avicennia germinans* seedlings, relative to water level. Higher water levels would inundate the seedling leaf growth and prevent recruitment; September 8, 2008

What are the possible scenarios given the current changes in the inlet dynamics? From our perspective, it all depends on when the sand bar closes the inlet. If it occurs earlier in the year (as it did in 2004), water level will rise earlier and seedling recruitment will likely be even more limited. If, however, the inlet closes later during the year (as it did in 2006), the chances are that seedlings will have a better opportunity to grow and hence survive subsequent flooding. That is, a delayed flooding may provide “windows of opportunity” for seedling establishment (Eriksson and Fröborg 1996). In addition, Hernández-Trejo et al. (2006) observed that mangrove forest height and diversity increased with an increase of flooding frequency, depth, and duration. Thus, with a decreased flooding regime (open inlet for longer periods of time), it seems very likely that mangrove forest diversity will decrease.

This information is particularly relevant because of the intense destruction (35%) of mangroves on the global scale over the last decades (Valiela et al. 2001). Thus, in order to ensure the continued maintenance of mangrove forests and their diversity over the next several decades in the La Mancha lagoon, management of the environment systems conducive to the early growth of mangrove seedlings will need to attain high priority.

Management alternatives

Driven by the changing environmental conditions and the impacts on the local inhabitants that have an economy related to the commercial species present at this time, local management offices are weighing a series of options regarding a practical response (Table 1). No single option solves all of the issues that are arising because some objectives are favored by the increased changes whereas other objectives are favored by retention of past conditions.

For instance, if no action were taken and the current tendencies were maintained, the inlet mouth would be maintained in an open condition for longer periods of time. Salinity would be higher, thereby affecting the oyster habitat, and ichthyofauna would change to mostly marine species, at the expense of losing important commercial fish.

Table 1 Matrix of considerations for managing the causes and effects of changes at the inlet to La Mancha Lagoon

Option	Benefit	Cost
1. No action	• Maintain existing tendencies • Higher salinities for oysters • In migration of marine fishes	• Increasing coastal erosion • Inlet mouth open for longer periods • More sedimentation in the lagoon • Lower fluctuation of lagoon level • More impact on mangrove
2. Restoration—affect the results	• Maintain historical tendencies • Keep the depth of the lagoon • Reduce environmental impact • Remove sediment placed by human activities • A single action	• Does not solve the problem of coastal erosion • Needs to identify a location to place removed sediment
3. Augment/maintain the transport of sediment—affect the causes	• Reduce erosion and its effects • Strengthen the bar at the mouth of the lagoon • Maintain the water fluctuation in the lagoon • Improve the habitat of the mangrove and its associated flora and fauna	• Decrease the duration of an open inlet • Increase the obstruction • Reduce the salinity in the lagoon • Diminish the migration of marine fishes
4. Dredge on a small scale—affect the results	• Low operational cost • Minimum environmental impact • Permits migration of marine fishes • Better salinity for oyster production	• Annual effort • Needs a location for dredge spoil disposal • Decreases the variation in lagoon water level
5. Construction of engineering structures at the mouth of the lagoon—affect the results	• Long-term effect • Favors the migration of marine fishes • Maintains high salinity • Maintains connection between lagoon and Gulf • Accumulates sediment to the north of the structure	• Very expensive • Eliminates the fluctuation of water level in the lagoon • Increases erosion south of the structure • Increases sedimentation in the lagoon • Decreases the quality of the mangrove habitat • Negative impact on associated mangrove species

Depending on when the inlet opens, mangroves would be affected at different intensities. If flooding were delayed, chances of survival for mangrove species would increase (Table 1). However, with decreased flooding the diversity in mangrove forests might decrease too.

As an alternative to this "no action option", several management choices would have different costs and benefits. For instance, dredging the lagoon at different time periods and with different intensities would artificially maintain historical tendencies (such as depth of the lagoon). However, the benefits would be temporary, maintenance costs would be elevated, and the problem of coastal erosion would not be solved. If engineering structures were built at the mouth of the lagoon, yet another option, the natural dynamics of this ecosystem would be totally modified. This would be a very expensive long-term solution, and with great long-term impacts as well. Certainly, the communication between the Gulf and the lagoon would be maintained, and migration of marine fish would be favored. Nevertheless, most of the commercially important fish would be lost, and probably the lack of water level and salinity fluctuations would have a negative impact on the mangrove community (Table 1).

In brief, some of the management options tend to work with the processes that are driving the changes and other options are more directed toward the products of the changes. Retention of the processes involves a longer-term approach that is lower impact and perhaps less demanding of cost and infrastructure. Modification of the results could be a short-term effort, but it would need to be repeated on some temporal scale to be effective. As important as the desired outcome is the knowledge of the vectors of the evolving conditions and the evaluation of the variety of outcomes within the context of the total system. Therefore, some management decisions fit within the trend of the evolving system, whereas others attempt to interrupt the directions of change, albeit only the short-term scale.

Summary and conclusions

Sediment transport by eolian processes is important to the hydraulic regime of La Mancha lagoon. The availability of sediment supply passing across the headland to the position of the inlet into La Mancha supported the creation of a substantial storm berm across the inlet and that resulted in a high water level in the lagoon for much of the year. Some of the plant communities along the lagoon margin and within the lagoon (*Rhizophora mangle*) were established in association with the high water and lack of sedimentation within the lagoon. Others (*Avicenia germinans* and *Laguncularia racemosa*) were more closely associated with lower water levels in the lagoon. Now, because of the natural stabilization of the headland dunes, a decreased sediment supply at the inlet is responsible for a reduced storm berm and more opportunities for an open inlet. Ancillary changes in the form of greater duration of low water level, increased salinity in the lagoon, and shallowing of the northern portion of the lagoon are driving associated modification of the habitats and applying stresses throughout the system. Management options can be applied to address the causes of the changes or modify the effects of the changes. Neither is a complete solution to the evolving coastal system and its associated habitats.

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Aerial Photography

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