

Chapter 9

Physical and Morphological Changes to Wetlands Induced by Coastal Structures

Germán Daniel Rivillas-Ospina, Gabriel Ruiz-Martinez, Rodolfo Silva, Edgar Mendoza, Carlos Pacheco, Guillermo Acuña, Juan Rueda, Angélica Felix, Jesús Pérez, and Carlos Pinilla

Abstract This document is focused on the establishment of a methodology to assess erosive processes in a coastal wetland. Particularly, it analyses the spit that separates the lagoon from the sea, elaborating a diagnostic process that helps to characterize the effect of the coastal infrastructure in morphological changes in a short and medium-term. Elements such as the morphology, the wave climate, the hydrodynamic and the evolution monitoring of coastline are key elements to understand whether a coastal wetland is on equilibrium or in the contrary, its state of vulnerability is such that in the slightest change in physics conditions will produce negative effects by the system instability.

G.D. Rivillas-Ospina (✉) • C. Pacheco • G. Acuña • J. Rueda
Departamento de Ingeniería Civil y Ambiental. PIANC-COLOMBIA, Universidad del Norte,
1569, Km 5 Via Puerto Colombia, Puerto Colombia, Colombia
e-mail: grivillas@uninorte.edu.co; cbustosa@uninorte.edu.co; gjacuna@uninorte.edu.co;
jgrueda@uninorte.edu.co

G. Ruiz-Martinez
Departamento de Recursos del Mar, Centro de Investigación y de Estudios Avanzados del
Instituto Politécnico Nacional, 97310, Ant. Carretera a Progreso Km 6, Cordemex,
Mérida, Yucatán, México
e-mail: gruizm@cinvestav.mx

R. Silva • E. Mendoza • A. Felix
Coordinación de Hidráulica, Instituto de Ingeniería, Universidad Nacional Autónoma de
México, Ciudad Universitaria, 04510 Ciudad de México, México
e-mail: rsilvac@iingen.unam.mx; emendozab@iingen.unam.mx; afelixd@iingen.unam.mx

J. Pérez
Departamento de Ingeniería Civil, Universidad EAFIT,
Carrera 49 # 7 sur -50, Medellín, Antioquía, Colombia
e-mail: jperez@eafit.edu.co

C. Pinilla
Departamento de Física, Universidad del Norte,
1569, Km 5 Vía Puerto Colombia, Puerto Colombia, Colombia
e-mail: ccpinilla@uninorte.edu.co

Generally, it describes the procedure performed to properly understand the relation between modifications of coastal processes and the response of a coastal environment. It uses numerical and theoretical models to assess the behavior of the waterfront, considering the historical changes that have occurred to ultimately predict variations of the spit as consequence of the establishment of new civil works. Finally, it concludes with this method of analysis that the evaluated study case will be affected by the works of action to be developed for facilitating the navigability conditions of a new port currently under construction in the city of Barranquilla, Colombia.

Keywords Ciénaga de Mallorquín • Coastal wetland • Coastal erosion • Morphological changes • Port • SANDY® • Wave climate

9.1 Introduction

A coastal lagoon is a body of water that is separated from the ocean by a coastal bar, barrier island or any coastal formation, as a coastal spit. It is nurtured by fresh water from the continental part; and seawater from the marine border (Kjerfve 1986). The coastal lagoons can be connected to other bodies of water through natural channels, or in some cases through artificially built channels.

Wetlands are areas located underwater during different seasons; have hydrophilic vegetation; and are regulated by hydrologic regime and by influence of marine zone, in particular by the tide rise. Within the classification of coastal wetlands it can be found: (a) swamp; (b) estuary; (c) coastal lagoons; and (d) mire. They have an important role in the hydrologic equilibrium and the regulation of the planet climate. They are diverse systems that harbour a large number of ecosystems (Buenfil 2009).

According to the Ramsar Convention (1999), a coastal wetland contains the extensions of marshlands, swamp and mire; surfaces covered by water in natural or artificial regimen, with permanent or transitory flow, stagnant or with continuous flow; freshwater, saltwater. Besides, it includes maritime extensions where the minimum tide level (low tide) that do not exceed 6 m of depth.

From the hydrological perspective, coastal wetlands can be classified into:

Marines. Coastal wetlands and lagoons, including coral reefs.

Estuarines. deltas, tidal marsh, and mangroves.

Lacustrine. Wetlands associated to large continentals.

Riverine: Wetlands adjacent to rivers and streams.

Palustrine: Swamp and Lagoon.

According to Mitsch and Gosselink (1993), the identification of coastal wetlands is regulated by three criteria: (a) it must be a covered water surface; (b) it has

hydrophilic, marshy, saturated or flooded lands; and (c) it has hydrophilic vegetation that are plants that live in flooded zones.

The most important physical processes that involve in coastal wetlands are the currents tidal and the sediment transport (Brunn 1994). Furthermore, there the variations of phreatic level associated with the contributions of river and maritime waters, the residues discharges and even, the wind action.

In relation to landforms, the bars of coastal wetlands can be continuous or discontinuous given the oscillation of the astronomical tide. In some situations by the action of the meteorological tide and processes of short scale that modify the hydraulic behaviour of the body of water such as the salinity intrusion.

Analysing these water bodies, in terms of the mass balance equation, it is possible to identify contributions that influence in the hydraulic of wetlands, such the flow deviations by hydraulic works and the precipitation. The marine border not only provides a transitory flow of seawater due to the tide; so it has a saline layer that notably affects in the wetland hydrodynamics. The outputs are system losses as product of the evaporation; the tide ebb current; and in lesser extent, the opening of artificial mouths in bars and edges that surround the body of water.

Coastal processes have a major role in the dynamics of a coastal wetland, influencing not only in the variation of the water level or in the hydrodynamics behaviour as mentioned in the previous paragraph, it also can change the physic-chemical features of a wetland. Changes in salinity levels are giving by the tidal rise flow through a lagoon mouth that generates discontinuity in the coastline. Dimensions of this natural channel regulate the amount of flow entering, determining the flow velocity that dominates the mouth behaviour and the stability. According to studies made by Brunn and Gerritsen (1961), flows can reach in this tide channels up to 1 m/s.

Despite its importance from the physical and environmental perspective, these systems are under strong anthropogenic impacts. The most common degradation activities are: (a) deforestation; (b) urbanization; (c) water contamination; and (d) restriction of water flows.

In virtue of the aforementioned, this work is focused on the definition of a methodological approach that allows assessing the affections that negatively impact in the coastal bars stability of wetlands. Particularly, the works of coastal infrastructure can generate an imbalance that entails to the wetland disappearance in long-term. The effects of the defence and shelter works such as breakwaters or jetties perpendicularly arranged to the coastline are characterized by the methodology of proposed analysis.

Synthetically, the document seeks to address basic concepts but relevant for the coastal geomorphology which allows defining the study zone through the establishment of a littoral cell. Subsequently, it assesses sediments features in order to understand how the material is transported by currents from the source to the end of calculus domain. No diagnostic study that seeks to understand the integral behaviour, can omit the wave climate weather of a littoral zone so the waves, the tidal and the currents, not only model the shape of the bar; but also, they have a fundamental role in the wetland equilibrium. Alongside, the study of maritime weather is carried out a hydro-morphological model that allows observing how currents interact with

sediments. Then, a temporal evolution of the bar is made, analyzing the role that have the structures to modify the sediments sources and the bar configuration that protect the wetland. Finally, it is developed a plant modelling of the bar to represent morphological changes that can generate a maritime work in long-term.

9.2 Geomorphological Aspects of Coastal Wetlands

9.2.1 Mallorquín Lagoon

Geomorphology is the science that focuses its study on the terrestrial and marine relief present on the planet (Ruiz 2009). This science centres its interest in the detailed analysis of beaches configuration, phenomena and processes that regulates its evolution and physical conditions that, from present to the future, condition the behaviour of a coastal environment (Table 9.1).

The coastal zone is a dynamic environment from many perspectives. From the geomorphology, it is possible to observe different variations made in a wide range of temporal and spatial scales (Del Río and Gracia 2009). Changes that occurred in a wetland spit are described by advances and relapses of coastline that seasonally vary when the beach profile is on dynamic equilibrium. However, the erosive process appears like a modification of natural state of this evolutionary process which has an anthropic and natural origin (Van Rijn 1993).

Conceptually, the word coastline is used to define the boundary that exists between the land and the surface of a body of water, independently of a temporal defined scale; and it assumes that the coastal zone is the land and water area that borders the coastline, extending to a point where it covers all coastal processes that

Table 9.1 Phenomena and process interaction in geomorphology process

Transport	River
	Erosion
	Wetlands
	Storms
Wave climate	Temperature
	Precipitation
	Evapotranspiration
	Heat flows
	Wind
Level variations	Climate change
	Subsidence phenomena
	Eustatic
Anthropogenic impacts	Coastal infrastructure
Coastal process	Currents
	Water waves
	Tides

are involved in the marine dynamic. Beaches of these environments, like those associated to wetlands, can be characterized as emerged or submerged thanks to geological processes, as the subsidence or raising, that cause that the medium level migrates above or below to the average of the historic sea level.

The shoreline of coastal lagoon is under the classification of barrier island formed by a coastal bar whose geometric configuration in plan and profile is function of wave features that arrives to its coastal zone. Generally, these barrier systems are integrated to a body of water with salty features or estuarines when they have communication with any river source. These systems, that are known as wetlands or coastal lagoons save a large biodiversity and have a fundamental role as weather regulators. From the marine environment perspective, these natural elements have a beach profile of thin width, an alignment that allows the dissipation of wave energy and also, permits the sediment transport along the littoral.

Currently, one of the most common problems in littoral zones of coastal wetlands is the coastal erosion caused by anthropic or natural impacts. For the analysis, it is used morphologic temporal domains that vary in function of the shore affectations. Therefore, it defines three stages known as short, medium and long-term. In the long-term (years-thousand of years), the erosion process is manifested in a special domain of regional context and it is associated with events derived from the sea level rise and geological changes (Cooper and Pilkey 2004; Javrejeva et al. 2012). In intermediate scales (years, decades), usually the erosive phenomena is influenced by an unbalance in sediment transport rates as product of the inappropriate establishment of coastal structures or interventions in the upper part of the basin, as the reservoirs to the energy generation or flood abatement (Komar 1998; Cooper and Pilkey 2004). In the short-term, it is related with waves with a high content of energy, wave trains that directly influence in the beach where all their energy is dissipated, and any coastal process resulting in the loss of material from the beach.

The resilience of coastal bar that protects a wetland is assessed from its regulatory capacity with external forces, or from a mechanical perspective, when it is capable to maintain a mass balance in sedimentary terms. On this subject, it can mention the positive or negative regulation to characterize processes through which the beach assures a proper functioning (Ruiz 2009). The positive behaviour occurs in a waterfront that remains invariable in spatial and temporal terms; regardless of the solicitations exposed. The negative scenario is reflected when exists a temporal variation of sediments so the system adapts to the forcings of maritime weather without losing control.

The interpretation of that resilience is what defines the concept of equilibrium in a bar or in a coastline given that it can be affirmed with certainty that a beach has equilibrium when the quantity of gained or loosed material remains unchanged in time, and mechanically represents a conservative phenomenon. It is a concept that allows to assess the variability of beach shape in a temporal threshold and it is used as support to predict changes that will happen in the bar for variations in conditions that govern the coastal dynamic. Therefore, the static equilibrium is the state in which the bar is allocated when not appreciably variance in time. The slightest change in the configuration during a period of short and medium-term implies a transference to the domain of dynamic equilibrium.

There is another behaviour related to seasonal variations during a time interval in the spit. The coastline of the bar changes its morphological aspect until reaching the equilibrium (static or dynamic), but this is a regular state which is infinite, given the incidence and effect of meteo-marine conditions. According to Woodroffe (2003), a spit that has these features can be classified as metastable.

According to Ruiz (2006), the geometric configuration of coastline is a physical representation which shows the sediments response to process that act on it. In consequence, the spatial domain of a coastline can be analyzed from two approaches; for one hand, assessing the variation in plan and for the other one, with the transversal section of a beach.

The development of plan analysis must be performed by dividing the spit bar or the beach that separates the wetland in differential spatial increments within a coastal cell (Fig. 9.1) that by physical factors presents some morphological features of that particular environment. The idea of carrying out this analysis is to find any erosion sign or sediments accumulation throughout time.

Analyzing the wave climate, it can be observed that the main modeller of marine environment in terms of erosion is the waves generated by the wind. There are other secondary variables with a bold influence in erosion phenomena as: (a) weathering of rocky environments; (b) the tidal range; and (c) the configuration of beach.

By virtue of described processes, the most significant morphological features or frequently more observed in coasts and that are associated with the topic of coast erosion are cliffs, coastal terraces, natural archs, caves, bays or coves and the abrasion platform (Thornbury 1954).

In relation to the material deposition on the coast, this process owes its existence to the sustained action and medium intensity of waves that carry the material towards the beach. Most of coasts in the world are composed by sand and in some cases, by gravel; but sediment sources are originated from the material transported by rivers that can generate deltas that sustain extensive beaches. Another scenario consists in beaches defined by cliffs that are affected by erosion and also support the coastal zone. Based on these sediments, there are different coastal shapes such as beaches, bar, spit, tombolo and submerged bars.

Currently, the coastal bar of Mallorquín Lagoon has 3.5 km of length and an average width of 96.7 m of variable section. The recent lagoon mouth that connects the sea has a length of 88.41 m and is located at the east of the groin, at a distance of 1.4 km. The littoral coast is confined between Madalena River discharge (close to the coastal groin) and León stream (to the west), which intermittently flows into the sea and commonly finalizes its flow in the Mallorquín wetland (Fig. 9.1).

In the littoral bar of the coastal lagoon can be found three types of sedimentary environments: (a) beach environment; (b) narrow and open lagoon environmental ambient; and (c) restricted and protected lagoon environment. With regard to the first feature, it can observe that the beach environment is affected by a swell perpendicularly arriving at the coast and waves diffracted by the coastal structure. Besides, it can observe a coastal spit 2 km away from the coastline which is adhered to the

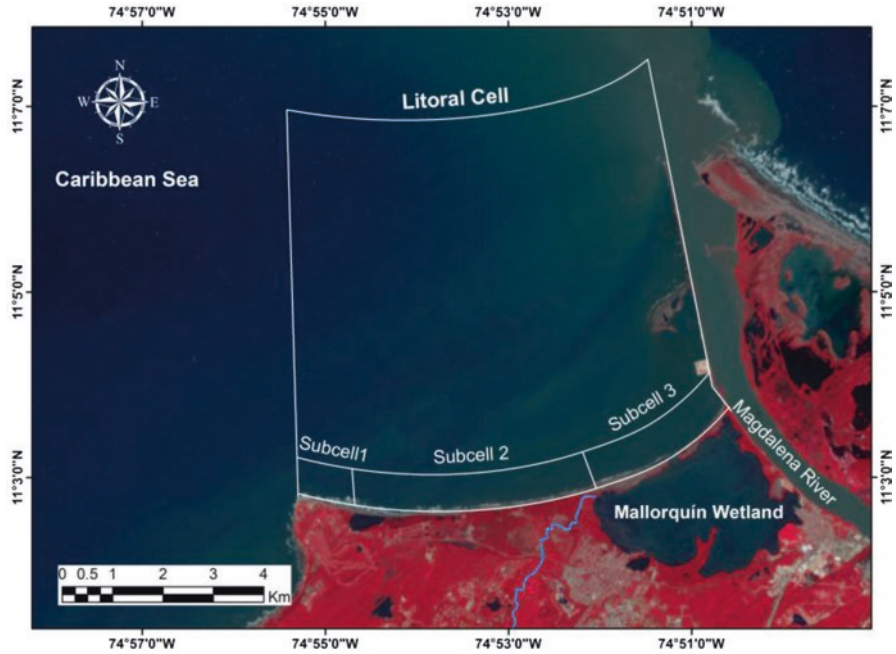


Fig. 9.1 Littoral cell of the Mallorquín Lagoon based on Landsat imaging 2015

coastal protection work (Fig. 9.2). The coastal spit behaviour is very dynamic, increasing its size during the dry season and inversely, it loses materials during the winter season when the waves has a high energetic content.

Analyzing the shoreline lagoon, it can be observed that it is part of a strip of sediments that flows parallel to the coast from river mouth (“Bocas de Ceniza”). The waves overcomes the coastal protection and sediment is transported by the diffraction to the coastal spit and subsequently, to the beach. Therefore, the morphological configuration of the bar is function of diffracted and refracted waves that travel in a submarine platform relatively low.

The characterization of the wetland morphological configuration is based on a classification that considers the processes and phenomena of marine environment, through the establishment of differential increases or littoral cells. This methodology allows identifying the relations among physical variables, forcings and natural restoration mechanisms of the system. The level of detail of this multilevel approach depends on the focus, the project or the processes scale that require to be assessed.

There are three approaches or methods of analysis to understand the relation between the natural variables of marine environment: White-box testing, Grey-Box testing and Black-box testing.

White-box Testing. It is located at an intermediate level between the three types of approaches, since through this, it is possible to develop an analysis on how exter-

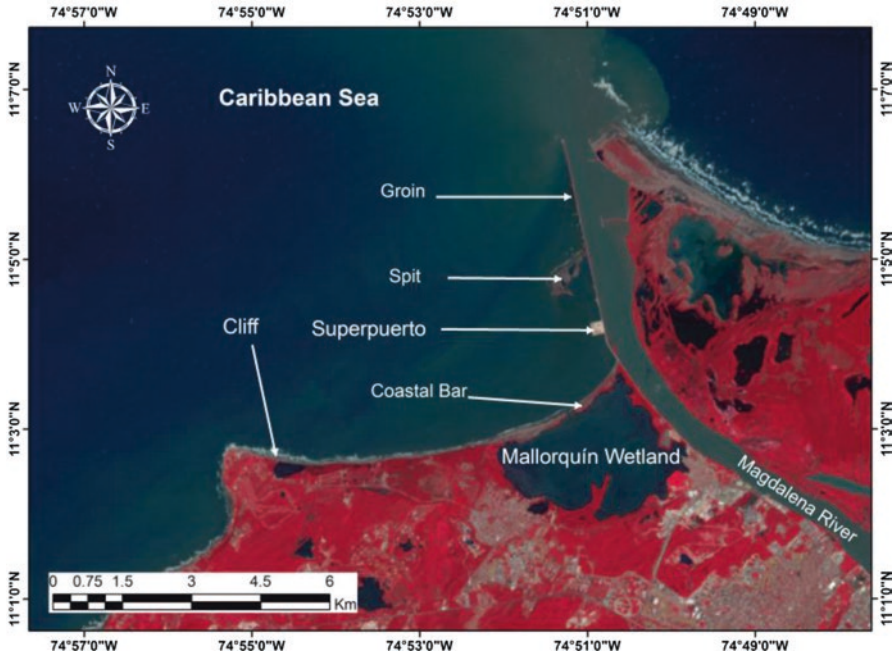


Fig. 9.2 Morphological features of the Mallorquín Lagoon based on Landsat imaging 2015

nal agents (natural element), phenomena (forcings), and processes (effect) correlate qualitatively within the natural environment.

Black-box Testing. It is the most generalist approach since it only allows making a description of more relevant elements of the system from a physical perspective.

Grey-box Testing. This analysis is the most detailed of all because within the qualitative description, it allows to identify the elements contained not only in general but in every littoral cell or subsystem and so establishing physical relations between the natural variables.

In virtue of the aforementioned, we have selected the gray-box testing for the analysis of the Mallorquín lagoon, where it allows to identify not only of in a general manner but also the elements contained within subsystems (subcells) or littoral cells that compose it, with the purpose to understand the relations between natural variables and physical processes that are part of the wetland dynamic. The process identified elements such as cliffs, shallow, rivers, bars, coastal arrows, tidal mouths, infrastructure works, alignment changes, presence of sand dunes, among others.

The model developed for the lagoon description considered among other aspects, those with higher relevance from the physics perspective in the identification of change tensors in the wetland: (a) geographical coordinates of boundary conditions that delimitate the littoral cell; (b) physics dimensions of the beach (plant-profile); (c) the characteristic material of the coast; (d) the configuration of the beach on plant.

The most important morphological features identified in the stage of characterization, correspond to coastal spits; the Magdalena River Delta; the submarine canyon; the sources of sediments (Magdalena River and small continental streams); coastal dunes; and coastal infrastructure. The selection of these morphological attributes is related to the fact that they correspond to those physical entities that more influence in the shape of beach and their evolution in time. Therefore, the borders of littoral cell were defined to considering in the left extreme of Bocas de Ceniza Groin; and the other side, the cells ends in the cliffs located at “Punta Roca”. It has a subsystem (subcells) that ends in the intersection zone with the León Stream when it opens the lagoon mouth.

Another aspect to consider, in detail, in the morphological analysis is to determine the marine structures built by men, identifying the affection grade that this intervention has had on the current shape of the beach. To give more physical sense to the study, results of morphological analysis are used to give a diagnosis that allows understating the causes and effects that led to the configuration of the coastline and, in general, of the littoral cell.

The bar of Mallorquín Lagoon is contained in a littoral cell confined between two physical borders: (a) Bocas de Ceniza Groin (Breakwater); and (b) Punta Roca (Cliff located at the west of the wetland). It is not observed along the coastline any type of physical, natural or artificial element that can influence in the morphological configuration of the whole cell or in the shape of beach. The most relevant feature from the geomorphologic perspective is related to the formation of a coastal spit in proximities of the groin to maintain the navigability activities (Bocas de Ceniza Groin). The beach presents a parabolic profile where the sand is the predominant material. Just in the western region of the littoral cell, it is identified rocky elements (cliffs or abrasion platforms) in the beach as shown in Fig. 9.2.

The beach has a variable section in plant throughout its length, with a mean width of 121 m. Additionally, it describes a defined discontinuity by a lagoon mouth that connects the wetland with the sea. This mouth has a dynamism associated with the wave climate variability and the oceanographic processes (currents, waves and tides). This is closed during the most part of the year, holds a width of 24.78 m approximately, but commonly it generates a channel at the end of the year (November, December) by with the influence of North Winds, Cold Fronts and extreme hydro-meteorological phenomena. Its position has varied in time to the present, and it is not expected to change physical conditions that have endured during last decades.

9.2.1.1 Impacts and Diagnosis

Perhaps, the event that triggered main changes in morphological level was the construction of the coastal structure as shown in Fig. 9.3. In ancient times, the system was composed of a cove and a set of bars generated by sediments from the Magdalena River. Subsequently, in the 1930s began the construction of a navigability channel in the Magdalena River, the Port Terminal and the works of shelter of the external

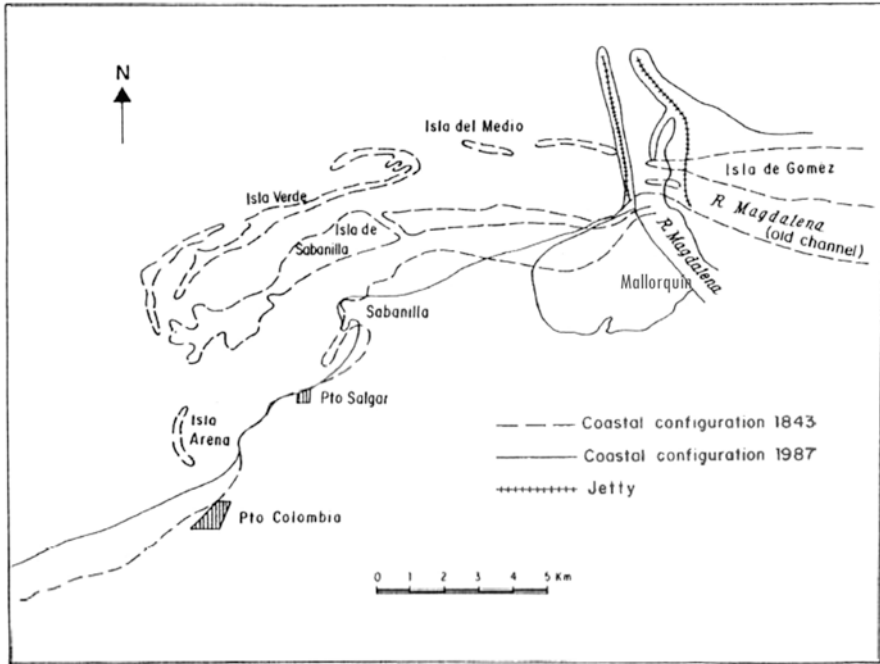


Fig. 9.3 Historic coastline modifications (Source: Martínez et al. 1990)

channel. This generated a change in the marine dynamic since before of the construction, the system could be considered, from the morpho-dynamics perspective, as in stable equilibrium.

After the mentioned event, the coastal system presents the natural tendency to adjust to new physical conditions trying to restore its state of equilibrium, but when it is altered, the feeding mechanism does not allow returning to the initial condition. This entails to the new configuration with a coastal bar and body of water in its upper part, with islands and internal lagoons generated during the events of Magdalena River rise. However, the fact of losing the main source of sediment brings associated unexpected effects since the marine environment lost its capacity of self-generation and it is erode continuously; so it can define that until now, the beach of Mallorquín Lagoon presents a metastable equilibrium. This is an indicator of the close relation between the river and the coastal zone near to the estuary, including the lagoon.

The physical parameters, which intervene in the formation of the configuration in plant for the wetland bar, are very different; but it could demonstrate that the longitudinal transport and the washing material in transversal direction are more relevant elements for the configuration of a costal system.

At present, the coastline of all nations that have border with the ocean is subject to erosion and sedimentation. As it was mentioned before, the coastal zone is a dynamic environment where many processes from the environmental, physical and biological perspectives occur. In consequence, any intervention made will produce

a change in the balance that the system has leading to a response from the natural environment in search of new balance between processes and physical conditions. However, it is important to note that the activities developed by the human being in the coast, do not consider relations between meteo-marines processes and the physical variables that involve the beach, so the regulatory and restore process is interrupted.

When large infrastructure developments are carried out the morphological response of the coast and the effects derivate from the physical alteration are usually don't taken in account, and many others cannot be predicted a priori by the complexity of involved phenomena. In the studied zone, it was found as principal anthropogenic impact with negatives effects in the equilibrium of system since its establishment, the protection works of the external navigability channel for the Barranquilla Port. This resulted in a disruption of flowing sediment due to its perpendicular disposition to the coastline, with the consequent erosion associated not only in the unprotected area; besides, the sediment that flows as bedload through the principal channel of the river ending in a submarine canyon (Fig. 9.4). Only a small number of sediment reaches to overcome these two obstacles during certain times of the year, in function of the wave direction and the effects of the diffraction of western groin.

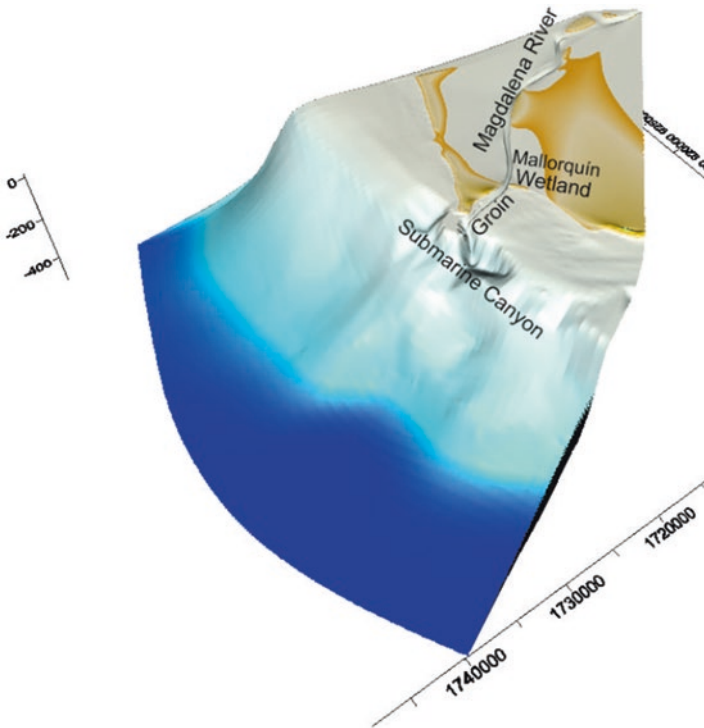


Fig. 9.4 Digital Elevation Model (DEM) of Submarine Canyon at Bocas de Ceniza Mouth

Furthermore, it is important to note as a positive element that the actual coastal dune associated with the Mallorquín coastal wetland remains unchanged. During the field-work, it was evident just one event of anthropic nature. It was observed that fishermen from the adjacent communities to prepare the pass of their vessels from the lagoon to the sea irregularly build craft channels (Fig. 9.5), altering the natural dynamic of the coastline. These accesses are built in two locations: (a) the first one is made by residents of the neighbourhood “La Flores” precisely in the point where the tidal channel opens naturally during storm events; (b) a second channel was built by residents of the neighbourhood “La Cangrejera” in proximities of the León stream inside the wetland, where the coastal bar has a minimum average width of 47 m. These channels affected directly the hydraulic conditions of wetland since allow the access of sediments from the marine border, interrupt the path of sediments through the bar, and the sediment enters in the water body reducing its hydraulic depth.

The analysis performed to date, can be used as monitoring indicators and permit to affirm that the coastal zone related to the Mallorquín Lagoon is a highly vulnerable system because it has lost its capacity of natural self-regeneration, and any change made in this system will have a direct and negative consequence, also hard to measure in short-term.

The nearest anthropogenic impact is due to the construction of the “Superpuerto” (Fig. 9.6). This mega work will produce important changes in dunes and in the sediment transport, that constitutes fundamental variables to maintain the quasi-balance

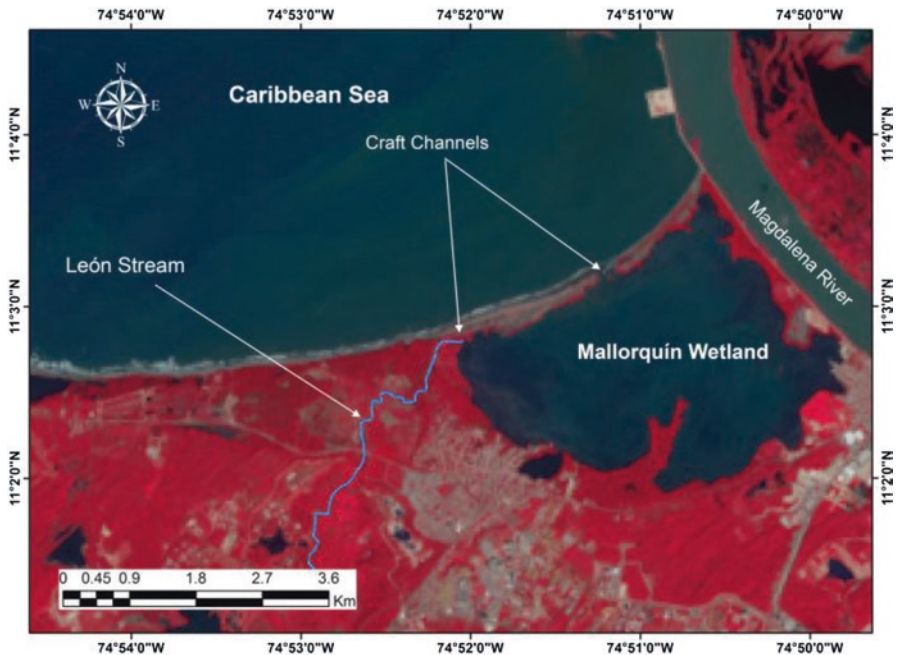


Fig. 9.5 Craft channels to communicate the coastal wetland to the sea

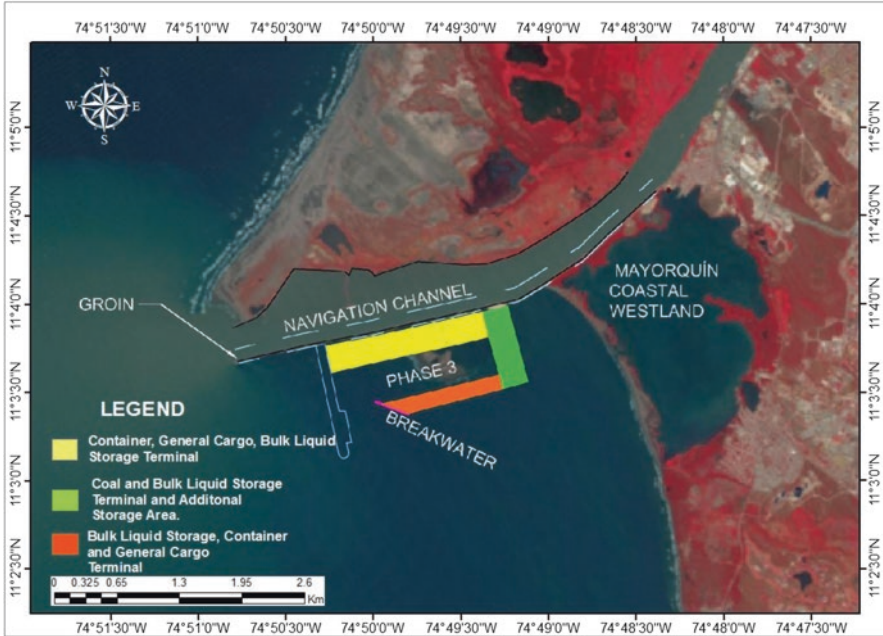


Fig. 9.6 Superpuerto Port

of sediments that has currently the beach but if coastal processes are modified, huge and relevant changes will be observed in the wetland.

Finally, it is recommended as in any other coastal engineering project, the understanding of those variables that allow the comprehension of the problems that coastal wetlands experiment. The recognition of the morphological behaviour will serve as a comparison element during the development of an intervention work, determining with this, the way to understand the capacity of self-regeneration of the bar that protects the wetland, and it will be an indicator of how it can evolve in time since it will be possible to maintain the ecosystemic services of these bodies of water.

9.3 Physical Properties of Sediments

From the engineering perspective, one of the elements that must be considered in the analysis of anthropogenic impacts of the bar of Mallorquín Lagoon with meteor-marine conditions and anthropogenic impacts, are the coastal processes that model the zone.

It is properly the interaction between the processes and physical contour of the coastline what origins the active dynamic of the beach, determining its configuration on-site and in profile. In this regard, we must consider the effect of currents,

astronomical tide (if applicable), and the proximity to the continents, since they relate directly to the sediments transport and in particular, with its main manifestation, the erosion and accretion of the beach phenomena.

9.3.1 Sediment Sampling

Along the littoral of Mallorquín Lagoon we recollected 65 sediment samples in 23 locations, following a transverse and longitudinal path throughout the bar.

The methodological procedure made to each sediment sample considered the following elements (Fig. 9.7):

The sediment transport in a beach is a complex process to asses and comprehend. Firstly, because it is facing a two-phase flow conditions (water-sediment); and on the other hand, during the transport to the beach, the flow can be classified under the turbulent regime, where it is very important the friction between layers of fluids and a fully developed boundary layer is present. For this reason, currently there are a larger number of theoretical and empirical models in order to try to quantify the transport of material and the form how it correlates with the morphology of the seabed. There are mathematical models that approach effectively the real problem, but they require intensive field data to be validates and calibrated.

The above-mentioned aspects make the selection of a sampling site complex but that well evaluated will lead to important and correct conclusions regarding the state of equilibrium of the beach. This physical bases enables to say that several samples must be displayed and characterize different locations of a beach, and therefore, the samples taken have to be consistent with the physics of transport phenomena.

Consequently, samples were extracted from three points in each profile. In the Berm Zone (B); in the Washing Zone (L); and finally, in the submerged zone (S) that correspond to a depth of one meter (1.0) roughly. With the selection of these points, it covers a broad spectrum of phenomena related to the sediment transport in a beach, as the waves and the currents in the submerged beach, and the wind in the dry beach. By sampling site, they were recollected 3 kilos of sand in a straight line from the berm to the submerged area, with spaces between line and line of 50 m.

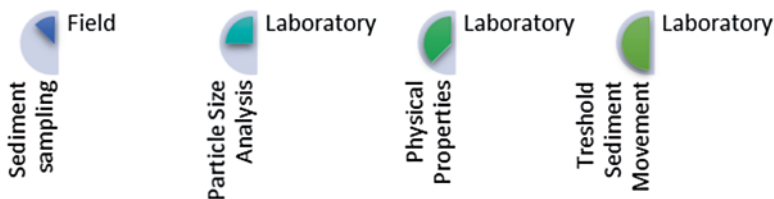


Fig. 9.7 Sediment samples analysis process

9.3.2 *Sample Statistics Distribution*

Analytical methods to quantify the form, the size and the composition of sediments are based on statistical assumptions that have been developed during the years. However, the significant fact is that under the principle of characterization of the grains of material a detailed study of their origin and form can be reached.

A statistical procedure is applied to problems where it is necessary to make the classification of materials (composition and size), to establish mechanism that originated the beach and know the way how the sediments were deposited. The classification is made from the main statistical parameters of the sample and based on it, it can determine whether the material dispersion or deposition was created by the waves and/or the currents, as well as, to define which are the physical factor that intervene in the configuration of the beach. This information is very relevant at the moment to carry out the diagnosis and the analysis of agents that can generate erosion in a littoral system and to value the sediment interaction with physical processes in the coastal zone.

For the representation of the mechanical analysis of sediment, we have adopted logarithmic functions. This gives a lot of practicality and relevance to the study, allowing that the sample properties are expressed in terms of statistical deviations from the normal distribution function. It is possible to express the frequency analysis from statistical and mathematical principles covering the entire distribution of sample sizes, without practical or theoretical limitations, when are applied to the full spectrum of sizes of sediment (Inman 1952). Parameters that depend on the order statistics such as mean, median, standard deviation and asymmetry are applied using different methodologies (moments, quartiles, logarithmic methods graphs, etc.).

An adopted method for the analysis of size distribution of the sediment sample consists in express the statistics through a logarithmic expression that describes the diameter conversion (d) in millimetres to units phi (ϕ), using the equation $\phi = -\log_2 d$ (Krumbein 1936). In reaching this classification, and in the particular case of sediments, measures of the central tendency of the mean and the median of the samples diameter is taken into account, where one of these two variables can acquire a greater importance than the other. In a normal distribution, the mean is the diameter value that represents the centre of gravity of the frequency distribution while the median, from a geometric perspective, is the amount that divides systematically the frequency curve (Inman 1952).

The influence of the median is relevant when it is about avoiding in the analysis affections in the extremes at the moment to adjust the distribution; instabilities that can potentially be originated by dispersions with respect to the mean for samples that have a large number of sizes (Inman 1952). For its algebraic character, the central value of a large quantity of sediments samples can be obtained by means of the analysed group, which reflects the average size that the sediment has in the source where it was founded. Although, it must be remembered that it is more recommended for quantification porpoises the use of the arithmetic mean.

In physical terms, this procedure allows to verify whether the consideration of percentiles 16 and 84 in the analysis of sediment properties, the volume distribution of the sand sample is symmetrical, whereas if we want to know how is the symmetry behavior and the continuity in the distribution extremes, the analysis must be performed for percentiles 5 and 95 (Inman 1952). It is vital to consider in the analysis other significant points in the cumulative curve of the sediment distribution in terms of ϕ , simplifying with this the original mechanical analysis of sediment, these are:

$$\phi_5, \phi_{16}, \phi_{50}, \phi_{84}, \phi_{95}$$

The theoretical formulations to determine the statistical behavior of the data in Phi units are:

$$\phi = -\log_2 d \quad (9.1)$$

$$d = 2^{-\phi} \quad (9.2)$$

d : diameter of the sediment particle in millimetres.

ϕ : Phi units.

To determine the principal moments or order of the data series associated to the sediment samples, it was used the following formulations:

$$\bar{d} = \frac{\phi_{16} + \phi_{50} + \phi_{86}}{3} \quad (9.3)$$

\bar{d} : Average diameter.

$$s = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \quad (9.4)$$

s : standard deviation.

$$Sesg = \frac{\phi_{16} + \phi_{84} - 2\phi_{16}}{2(\phi_{84} - 2\phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)} \quad (9.5)$$

$Sesg$: Statistical Bias.

The sediment classification based on the statistical parameters suggests a scale ranging from very platykurtic to extremely leptokurtic (Fig. 9.8); from highly biased for the coarser material to very fine bias; and finally, it is given a description of the material sample from very well sorted to very poorly sorted, according to the standard deviation (Fig. 9.9).

By employing the SANDY script (Ruiz et al. 2016) we determined the statistical data, the size distribution and the material classification (Fig. 9.10). It is important to underline that this programme consider for the classification the following rules: (a) American Section of International Association for the Testing Materials (ASTM);

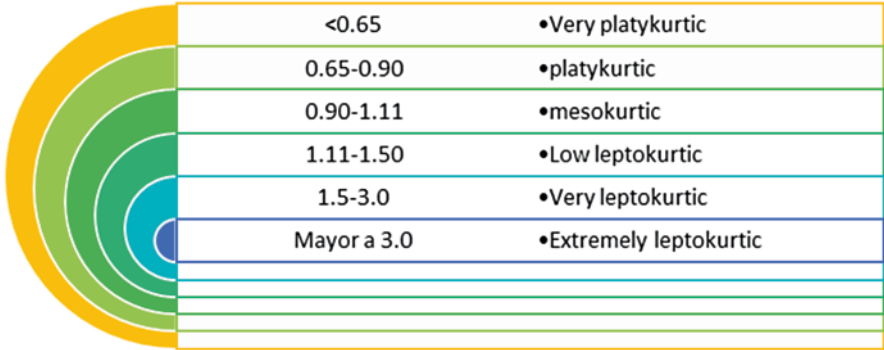


Fig. 9.8 Material classification respect to the kurtosis

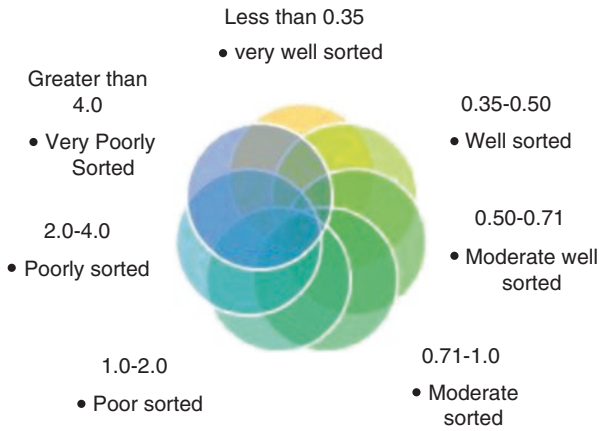
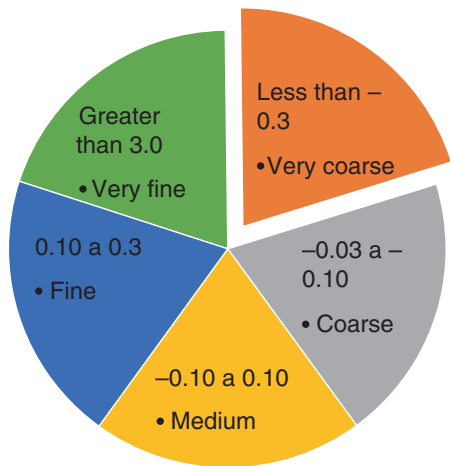


Fig. 9.9 Material classification respect to the standard deviation

Fig. 9.10 Sediment Classification with respect to statistical bias



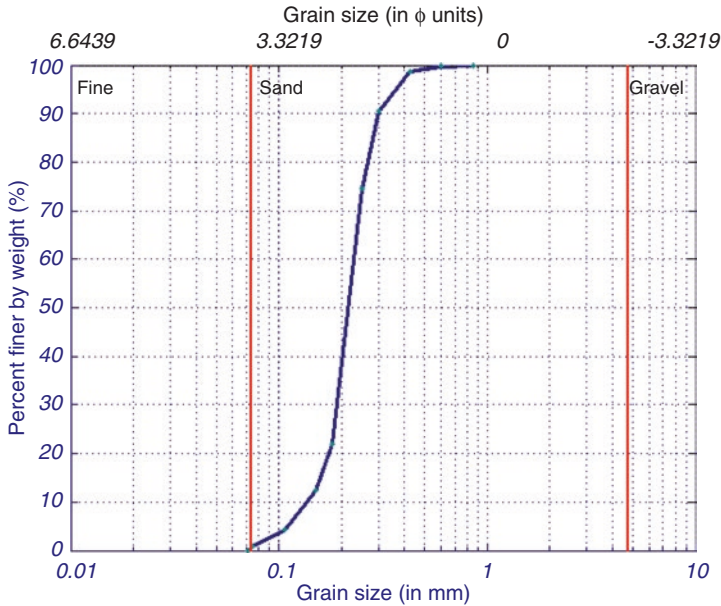


Fig. 9.11 Cumulative mass retained berms zone. Coastal bar Mallorquín Lagoon

(b) Wentworth classification; and (c) The Unified Soil Classification System (SUCS) (Fig. 9.11).

9.4 Wave Climate Analysis

The objective of the wave climate analysis is to provide detailed knowledge, both in deep water and in specific points of the area of interest, the current situation of the wave characteristics, sea level and currents that allow helping to understand the hydrodynamic operation of the study area. Without this knowledge, it is not possible to determine the causes and possible solutions to the problems of coastal erosion of a beach.

In search of characterizing the atmospheric conditions in the area of the Mallorquín coastal lagoon, it was extracted the climate information from the database NCEP North American Regional Reanalysis (NARR). The NARR database starts from January 1st, 1979 until December 31st, 2013 with information every 3 h daily, hourly and monthly of the Central America and the Caribbean hemisphere. The NARR information contains the main physical parameters of the meteo-marines conditions such as the wind, heat flows, solar radiation, and humidity, among others.

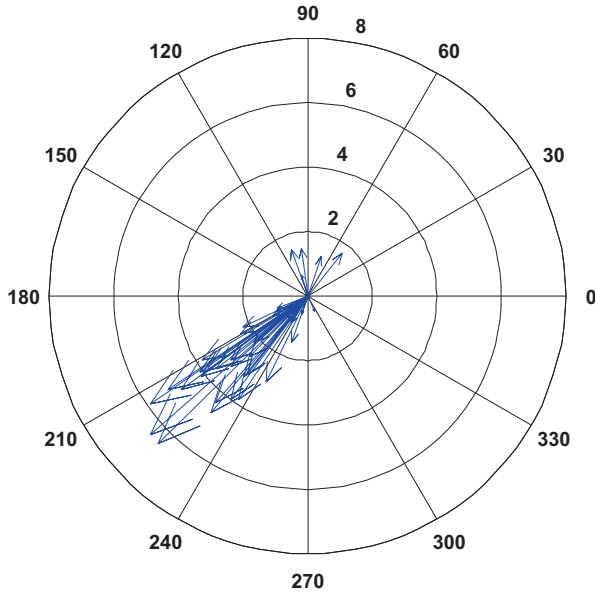


Fig. 9.12 Annual average wind rose (1979–2013) for October month (Source: NCEP North American Regional Wave Reanalysis: NARR)

9.4.1 Wind

Most of the year, the study area presented prevailing north-easterly winds (Fig. 9.12), october were a months with the great magnitude of the wind, with records between 8 m/s and greater variability, registering northwest, north and northeast winds.

9.4.2 Wave Conditions

From the point of view of the coastal engineering, one of the main objectives to advance a restoration project or to make a diagnosis of the condition of a coastal area, must be determined sea states that represent marine conditions, mainly the waves and wind, for both mean regime and during extreme events.

Through the use of mathematical statistics and probability adjustment functions are estimated and classify the sea states, their direction, magnitude and recurrence.

For the study was used the synthetic wave information of virtual buoys near to the zone developed by the company *Buoyweather*. The series of synthetic waves were generated by the reanalysis technique with the WAVEWACTH III model, which have an hourly and temporary resolution and a 30 years period.

9.4.2.1 Virtual Buoy 11.5 °N –74.5 °W

It can develop a mean regimen analysis of waves to analyse the behaviour of the maritime climate in a coastal wetland. For this, it analyses the probability of any storm is overcome in medium time. Besides, it is possible to classify physical variables by a joint probability analysis in order to characterize the phenomena magnitude with its persistence in different season of the year. This allows construction waves and wind roses and frequency histograms.

The potential of bars erosion that protect wetlands can be determined by an analysis of unfavourable weather conditions, known as extreme analysis. This is focused on the events characterization that have the larger energetic amount and that also, generate drastic changes in littoral zones, appearing during each winter season.

These analysis were developed with the data sample of a virtual buoy 11.5 °N, 74.5 °W, it identified an average waves associated to the 50% of exceedance probability, with a significant height of 1.78 m, and an extreme waves (95%) with a significant height of 2.87 m (Fig. 9.13a).

Based on the results of joint probability curve of significant height- peak period (Fig. 9.13b), obtained from the virtual buoy, the higher probability is defined by significant height of 2.1 m and a peak period of 6.9 s. The joint probability between the significant height and the direction (Fig. 9.13c), it has been found a value of 1.8 m and 49° respectively.

From the curve of exceedance probability (Fig. 9.13a), it was defined the threshold to the identification of maximum values in the time series, represented by the straight line on the Fig. 9.14.

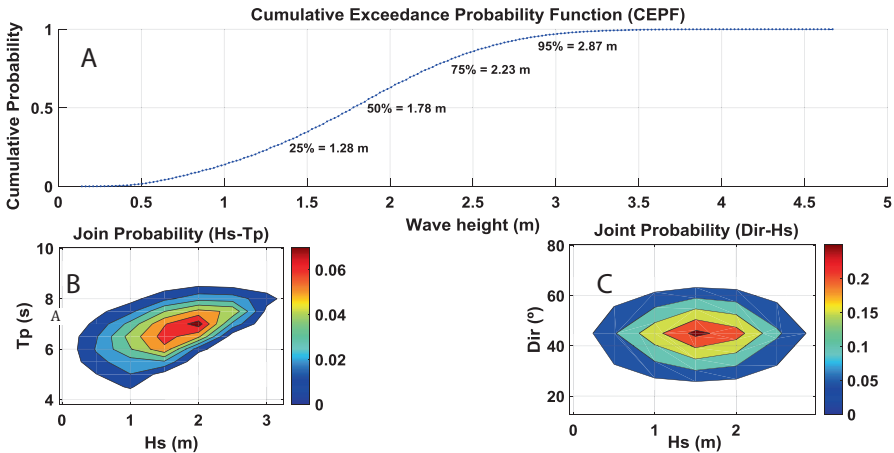


Fig. 9.13 (A) Exceedance probability of wave height; (B) joint probability of significant wave height against peak period; (C) joint probability of significant wave height against wave direction. At virtual buoy 11.5 °N y –74.5°W. Time period: 01-jan-1979 to 31-jan-2014

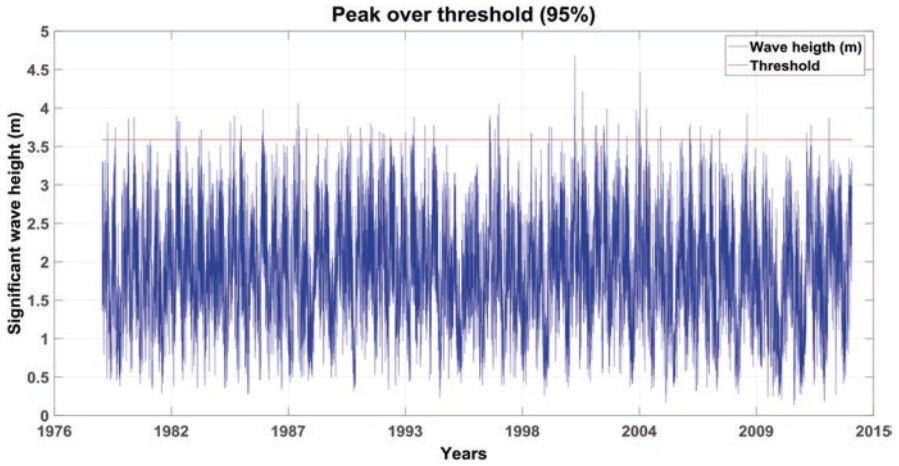


Fig. 9.14 Maximum wave height based on threshold

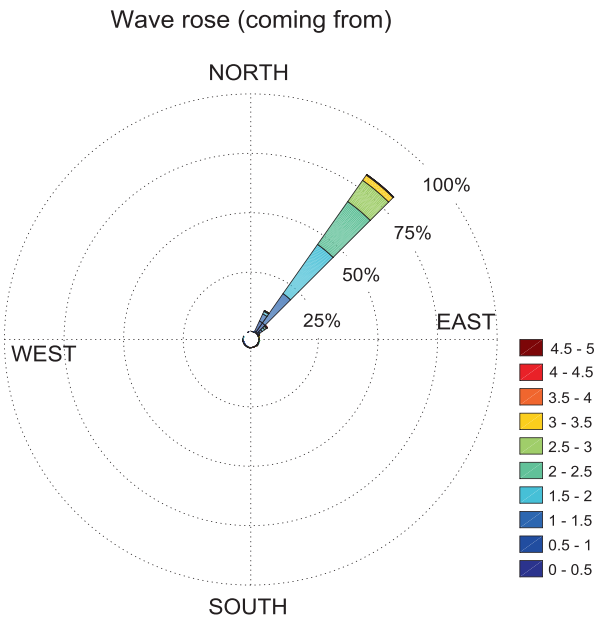


Fig. 9.15 Wave rose in the study zone

The wave rose of synthetic series (Fig. 9.15) indicated that the predominant wave direction was to the southwest, between the 35 and 49°, an average of the significant height value between 1.5 and 2 m, and maximum values of wave between 4.5 and 5 m.

Based on the probability curve of extreme exceedance, which has been built from the data above the threshold (Fig. 9.16) of 95% (2.87 m), it was found the

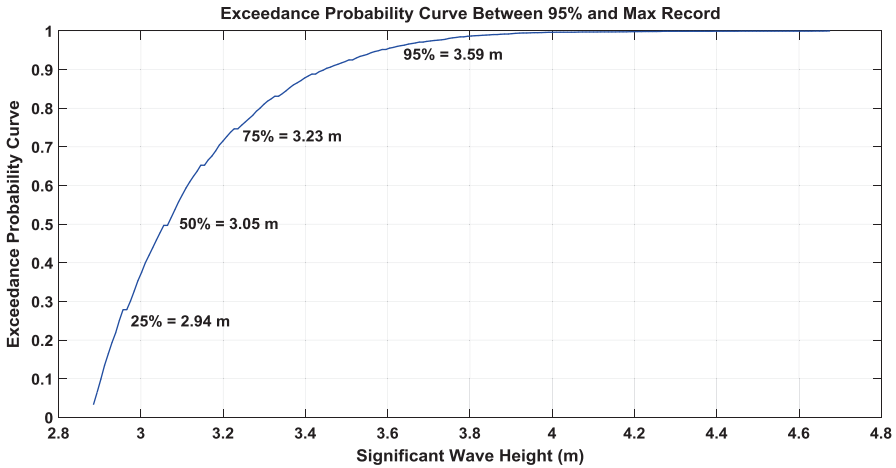


Fig. 9.16 Exceedance probability of wave height at virtual data series 11.5°N and -75°W. Time period 01-jan-1979 a 31-jan-2014

extreme wave more recurrent has presented a height of 3.05 m, and a critical extreme wave, which exceeds the 95%, comprises from the 3.59 m to the maximum height register of 4.68 m.

9.4.3 The Astronomic Tide

The astronomic tide is defines as a group of regular movements of ascendants or descendants sea level with periods of 12 or 24 h that are caused by the gravitational attraction made by the moon and the sun on the Earth, as well as, the effect from other planets. When there are investigations on the beach, or coastal studies are carried out, it is necessary to know the behaviour of the tide wave, especially for predicting its amplitude given that it is a determinist phenomenon. To approach the study of its behaviour consists in considering the astronomic tide as the sum of a finite number of waves, whose amplitude and phase are known; because of they have been associated with planetary movement.

To the study, it is developed a decomposition through the astronomic analysis considering The Earth, The Moon and the Sun movements, in order to determine the relative frequency and importance of each one of components (Cartwright 2001). Taking into account the tide amplitudes, it is possible to identify two types of tide: spring and neap tide.

9.4.3.1 The Harmonic Analysis of Astronomic Tide

The tide description and prediction is realized by the tide harmonic analysis which consists in decomposing the registers of sea level in a finite number of waves whose period and phase has been perfectly established, coinciding with periods of some astronomic movements related to the Earth, the Moon and the Sun, as it was described previously.

The method of harmonic analysis consists in obtaining from an hourly register all data of sea level, the amplitudes and phases of component waves. These parameters are known as harmonic components, due to the assumption where is considered that the responses of seas and oceans to the tidal forces do not change in time (Dronkers and Schonfeld 1959).

The astronomic tide is the sum of constituent waves from the Fourier coefficients

$$y(t_n) = a_o / 2 + \sum_{k=1}^M a_k \cos(\omega_k t_n) + b_k \text{sen}(\omega_k t_n) \quad (9.6)$$

The determination of the tidal regime from the observation point, was made by the equation used for the calculus of the factor “F”, equation which takes the amplitudes of the harmonic constituents.

$$F = \frac{K_1 + O_1}{M_2 + S_2} \quad (9.7)$$

F: phases of harmonics

F = 0.00 a 0.25, represents a semi-diurnal tide.

F = 0.25 a 1.50, represents a mixed tide predominantly semi-diurnal.

F = 1.50 a 3.00, represents a mixed tide predominantly diurnal.

F = Greater than 3.00, corresponds a diurnal tide.

It was conducted the modelling of astronomic tide for a period of 52 years (2008–2032), so for this time series were determined their respective harmonics.

According to determined harmonics, it was obtained a factor F of 1.86, and a value z of 0.27 m, ranking the tidal regimen of the study zone as mixed micromareal tide predominantly diurnal.

9.5 Hydrodynamic in Coastal Wetlands

9.5.1 Model of SWAN

The SWAN model is based on the Action Balance Equation. The model can be used without the effect of the current, reducing the equation in terms of the energy balance equation for calculus of local scale (9.8).

$$\begin{aligned} \frac{\partial N_{(\sigma,\theta;x,y,t)}}{\partial t} &= \frac{\partial c_{g,x} N(\sigma,\theta;x,y,t)}{\partial x} + \frac{\partial c_{g,y} N(\sigma,\theta;x,y,t)}{\partial y} + \frac{\partial c_{g,\theta} N(\sigma,\theta;x,y,t)}{\partial \theta} + \\ \frac{\partial c_{g,\sigma} N(\sigma,\theta;x,y,t)}{\partial \sigma} &= \frac{S_{(\sigma,\theta;x,y,t)}}{\sigma} \end{aligned} \quad (9.8)$$

Where,

$N = E/\omega$, is the density spectrum of action; E = density spectrum of energy; ω = absolute frequency of wave; θ = wave direction; σ = relative frequency; x, y = spatial coordinates in the horizontal; $N(\sigma,\theta)$ = density spectrum of action; $c_{g,x}, c_{g,y}$ = prorogation velocity in the coordinates x, y .

The term $S_{(\sigma,\theta)}$ is the density source of energy and the division $\frac{S_{(\sigma,\theta)}}{\sigma}$ is the density action; these terms represent the effects of the generation during the interaction and dissipation of irregular waves (nonlinear).

9.5.2 The Hydrodynamic Delft3D Model

The numerical model with the computational module “Flow” solves the Navier-Stokes equations, considering the Boussinesq assumption, in which the effect of the density variable is taking into consideration in terms of pressure. The turbulence is considered by the Reynolds efforts and is represented through the k-l y k-ε approximations (Uittenbogaard et al. 1992). The model uses the temporary scheme Alternating Direction Implicit (ADI).

The continuity and momentum equations in the direction of x and y are expressed respectively as: (9.9, 9.10, and 9.11).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (9.9)$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} - fv + \frac{1}{\rho_0} P_x - F_x \frac{\partial}{\partial z} \left(v_v \frac{\partial u}{\partial z} \right) = 0 \quad (9.10)$$

$$\frac{\partial v}{\partial t} + \frac{\partial vu}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial vw}{\partial z} - fu + \frac{1}{\rho_0} P_y - F_y \frac{\partial}{\partial z} \left(v_v \frac{\partial v}{\partial z} \right) = 0 \quad (9.11)$$

The turbulence closure model k- ε is engaged to transport equation, without the interaction of the waves, and it is expresses as (9.12, 9.13)

$$\frac{\partial k}{\partial t} + u \frac{\partial k}{\partial x} + v \frac{\partial k}{\partial y} + w \frac{\partial k}{\partial z} = \frac{\partial}{\partial z} \left[\left(v_{mol} + \frac{v_{3D}}{\sigma_k} \right) \frac{\partial k}{\partial z} \right] + P_k + B_k - \epsilon \quad (9.12)$$

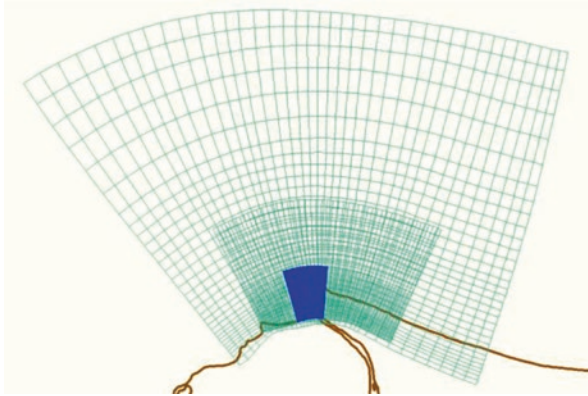


Fig. 9.17 Computed wave grid with Wave module. Nested grid at Mallorquín Lagoon

$$\frac{\partial \varepsilon}{\partial t} + \mathbf{u} \frac{\partial \varepsilon}{\partial x} + v \frac{\partial \varepsilon}{\partial y} + w \frac{\partial \varepsilon}{\partial z} = \frac{\partial}{\partial z} \left[\left(v_{mol} + \frac{v_{3D}}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial z} \right] + P_\varepsilon + B_\varepsilon - \varepsilon_\varepsilon \quad (9.13)$$

Where Prandtl-Schmidt numbers are $\sigma_k = 1$ and $\sigma_\varepsilon = 1.3$, P_k represents the production of turbulent kinetic energy in cutting flows, ε is the dissipation by turbulent energy (m^2/s^3) and it is the kinetic energy (m^2/s^2). The flow of thrust reversal B_k represent the transformation from kinetic to potential energy, and it is associated with the dissipation of energy and the edge flow respectively.

9.5.2.1 Meshes Deneration; Initial and Boundary Conditions

The numerical model Delf3D permits to use structured, flexible and unstructured meshes. For this case, it was used flexible structured meshes for the Flow module, and curvilinear grid for the Wave module considering a general area for the Mallorquin wetland as shown in Fig. 9.17.

Meshes of wave module are rectangular and curvilinear (Fig. 9.17), composed of square and rectangular cells. The largest mesh has cells with a size roughly of 1.8*1.8 km. The intermediate mesh has cells with sizes of 600*600 m, and the smallest mesh, which covers the sector of Bocas de Ceniza has cells of about 90*90 m.

The mesh of Flow module is flexible and is composed of square and rectangular cells with an average size of 30*30 m for the sector of Bocas de Ceniza mouth and for the Mallorquín coastal wetland, and 550*210 m for other sectors.

Bathymetry was constructed from the ETOPO1 database information and the bathymetries developed in the river mouth of the Magdalena River and navigable channel (Fig. 9.18) and cover all the coastal area associated to the Mallorquín lagoon.

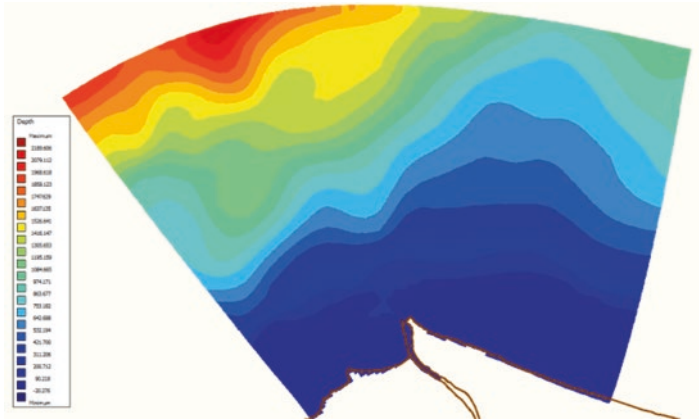


Fig. 9.18 Bathymetry of the study zone

9.5.3 Calibration of the Numerical Model

Calibration of the numerical models ensures that modelling results approaching to ocean-atmospheric conditions present in the study zone. For this project, it was used reference information which allows calibrating the hydrodynamic and wave model. Besides, it was used information of levels variations of the limnometric station of Casa Pilotos (Fig. 9.19) and wave information available of the directional buoy closer to the study area used by the Maritime General Direction (DIMAR), *in spanish*, . For the calibration of the morphodynamic model, a longitudinal transect of these seabed within the access channel of Magdalena River was used.

Hydrodynamic calibration results according to the variations of sea level (Fig. 9.19) demonstrate a large adjustment between measured and modelled data. Despite available in situ information is subject to diverse processes and variations such as the flow, waves and the wind, it was possible to hourly simulate the variations of the sea level during a 4 months period. Based on the characterization of the astro-nomic tide, previously made, it was observed a pattern of mixed semidiurnal tide.

Results of wave calibration (Fig. 9.20), made possible to approximately reproduce the variation of the significant wave height of the study area, evidenced by the comparison between the variation of the significant wave height measured by the buoy, and the results simulated by the model. Based on the above mentioned and the general behaviour of time series, it was possible to adapt the numerical model to represent the conditions of average wave of the study zone.

After calibrating the hydro-morphodynamic model is necessary to identify the representatives modelling scenarios for the analysis of oceanographic conditions of the study zone, for purposes of establish the diagnosis of erosion problems of the coastal zone.

Consequently, the analysis of the hydro-morphodynamic analysis in 2010 was focused on characterized climate seasons of the study zone: Dry (February); Humid (October) (CIOH 2010), and according to the highest and lowest tides of each season, predefined from the Grenoble Model (Le Provost et al. 1994).

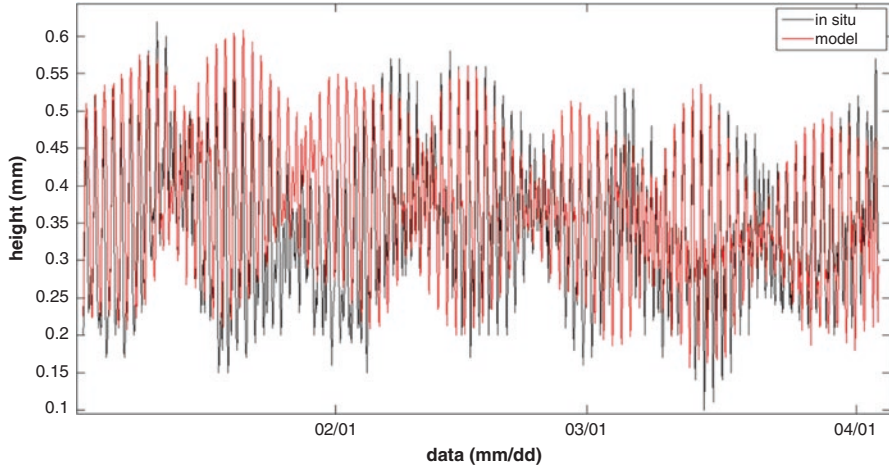


Fig. 9.19 Water levels calibration from Casa Pilotos station

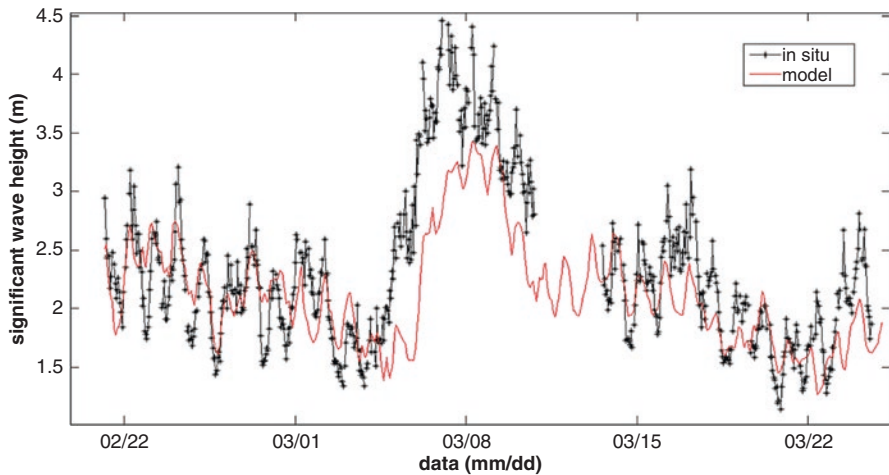


Fig. 9.20 Water waves calibration from DIMAR data buoy

9.5.4 Dry Season: February

9.5.4.1 Coastal Currents

The velocity rate in surface during the phase of high tide describes paths dominated by the river in the estuary zone (Fig. 9.21a). There is a vectors change due to the wave action and the diffraction phenomena that is generated in the edge of the groin, reaching speeds of the order of 1.6 m/s. Subsequently, they flow in the current direction, reducing the speed up to 0.3 m/s and align with bathymetric contours to initiate the movement in a south-westerly direction.

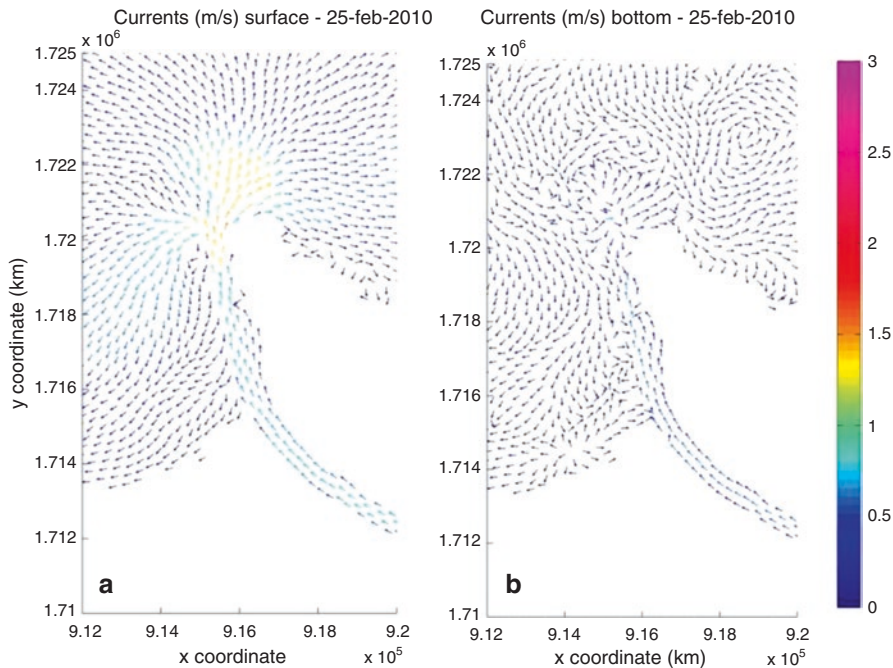


Fig. 9.21 Velocity field during highest astronomical tide during dry season (February, 2010) (a) surface (b) bottom

In the bottom layer as it was expected (Fig. 9.21b), the cascade of turbulence is fully developed; and besides, from the interaction between particles of different paths, arise rotational movements due to the shear stresses effect in the turbulent boundary layer. There, the viscous stresses have a great relevance to change the direction of the velocity fields, enabling the formation of vortices and chaotic movements that create a two-phase flow without a defined trajectories. This can be one of the reasons why the spit is originated next to the Western Groin, where the influence of the depth is so important that supported by the diffraction effect permit the deposition of coarser sediments.

9.5.4.2 Wave Height

In the Mallorquín lagoon arrived wave fronts of 0.8 m maximum and minimum of 0.2 m (Fig. 9.22a). This is because the groin generates a warm area that changes the behavior of wave trains, creating conditions of less intensity in terms of wave energy. The behavior of wave propagation during the dry season of 2010 showed wave heights in front of the access channel with maximum values up to 2 m (Fig. 9.22b).

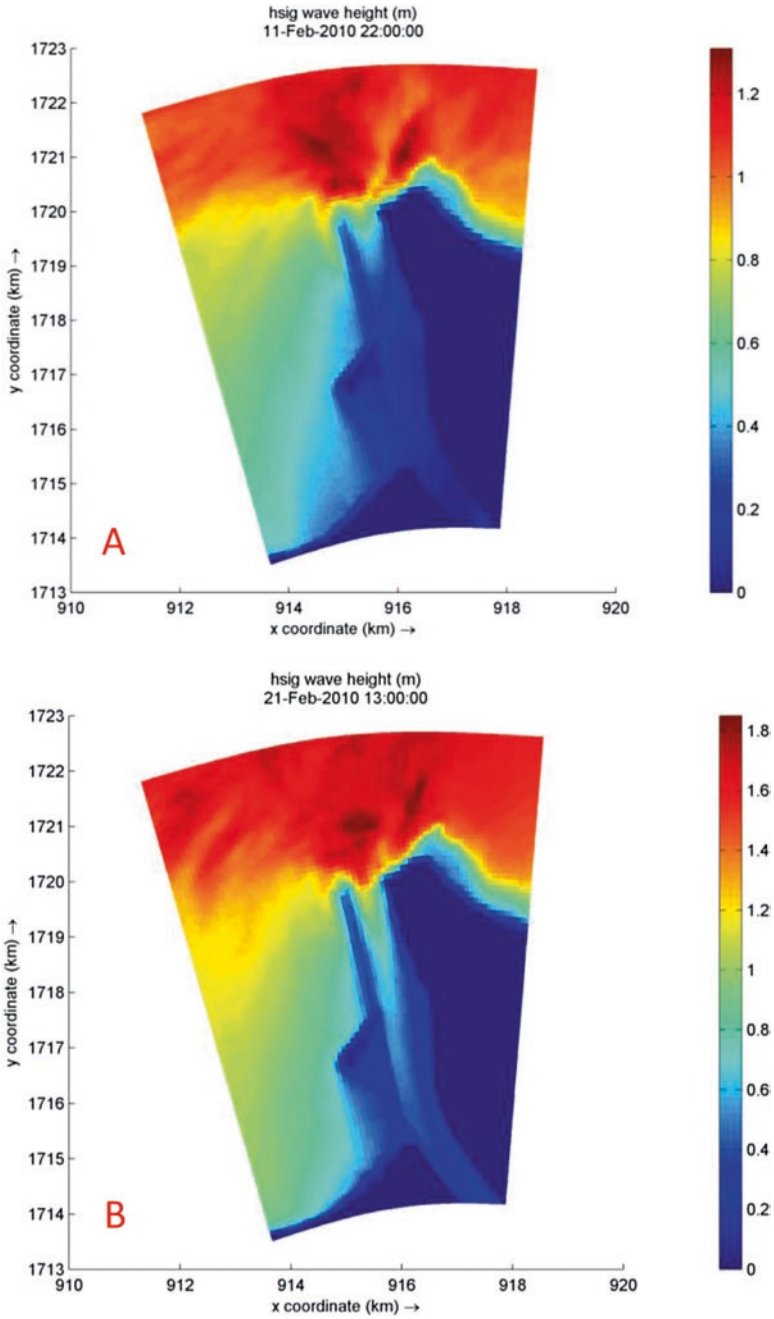


Fig. 9.22 Significant wave height (A) lowest and (B) highest. (February, 2010)

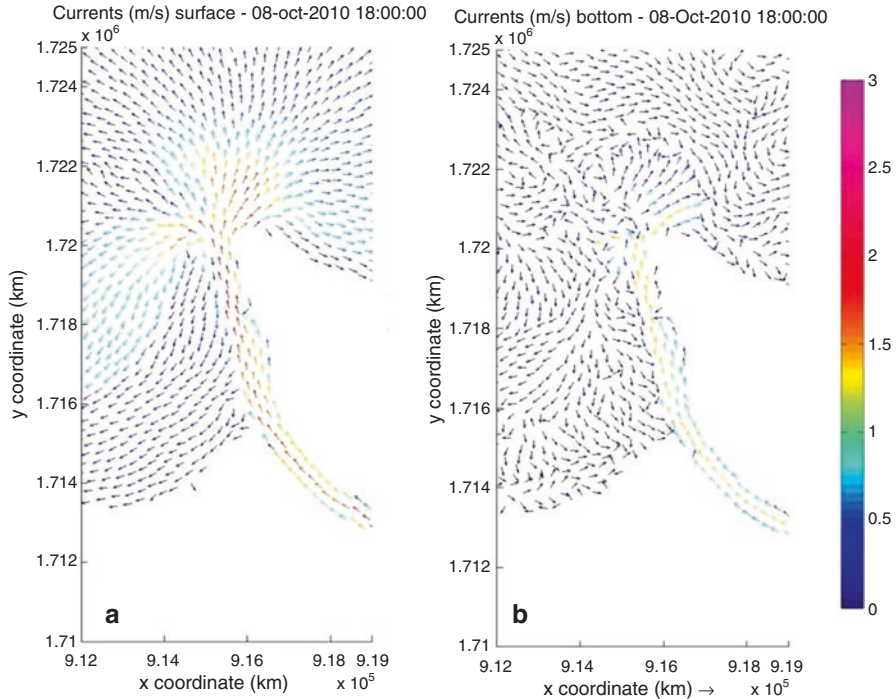


Fig. 9.23 Velocity field during highest astronomical tide during dry season (October 2010) (a) surface (b) bottom

9.5.5 Humid Season: October

9.5.5.1 Currents

The surface current field during the maximum level at the time described intense wet conditions compared to the dry season (Fig. 9.23a). There are flow velocities between 0.13 and 2.33 m/s, and a mean of 1.59 m/s; the maximum velocity values in the estuary surface. Similarly, velocities in the lagoon coastline increase, reaching values of 0.6 m/s.

The bottom layer has speeds between 0.02 and 2.21 m/s, with a mean of 1.57 m/s (Fig. 9.23b). The most turbulent flow is not only in the river mouth, but also, along the coastal protection works, and in front of the lagoon, paths follow the same direction with great velocity.

9.5.5.2 Wave Propagation

The behavior of the significant wave height during the humid season (October) 2010, presented records up to 1.69 m in front of the access channel (Fig. 9.24a). In front of the wetland, there is not high values since the protection of the breakwater

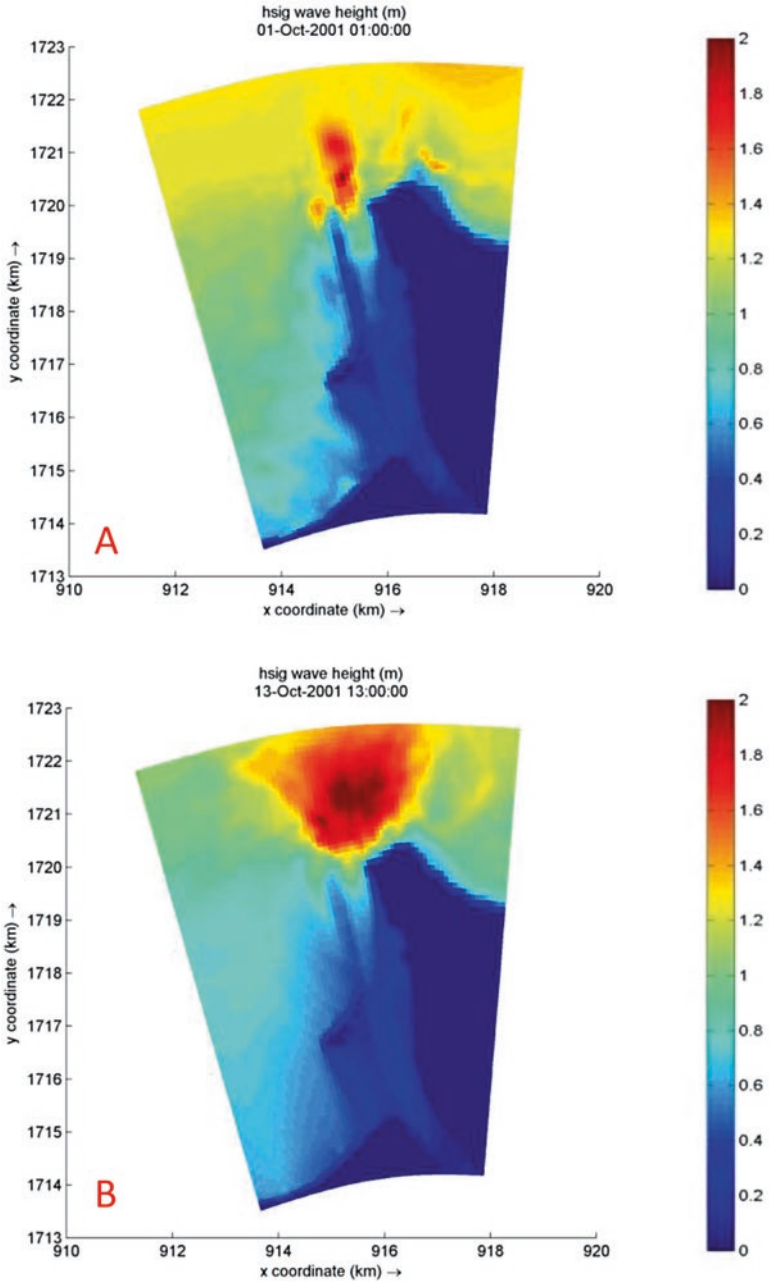


Fig. 9.24 Significant wave height (A) lowest y (B) highest (October 2010)

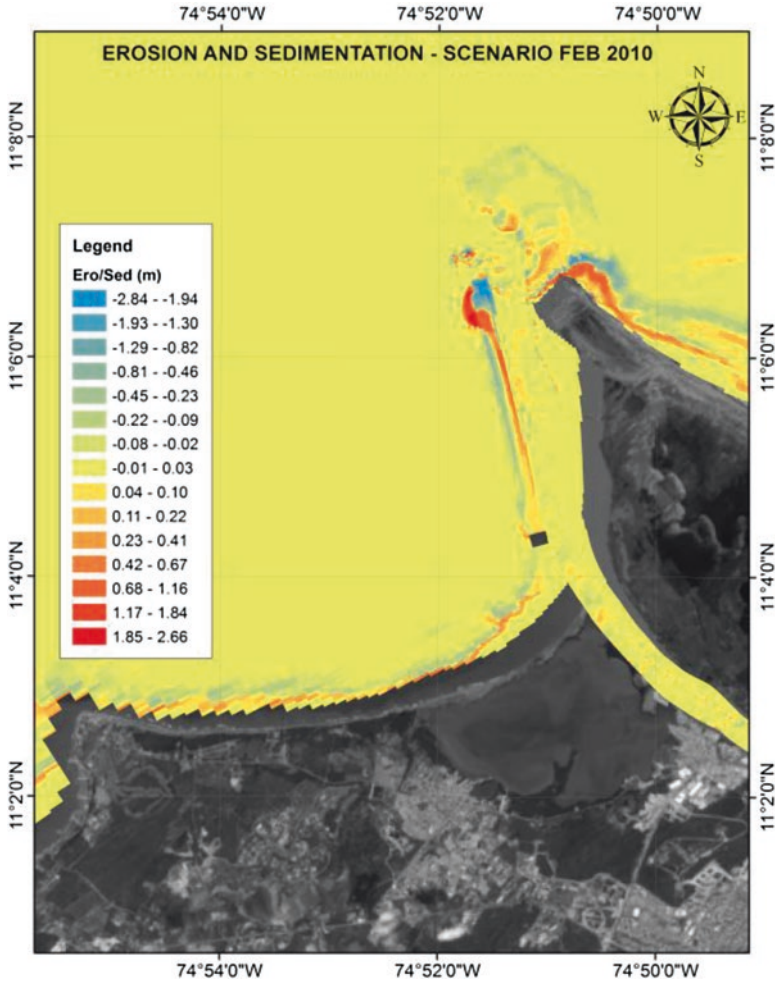


Fig. 9.25 Erosion and accretion of Bocas de Cenizas zone after 30 days of hourly modelling, since October 1st, 2010 to November 01st, 2010

values, the waves during this time changes its direction so that only reach maximum wave heights of 0.6 m and a minimum of up to 0.1 m (Fig. 9.24b).

9.5.6 Hydromorphological Modelling

Results of the erosion (blue color)/accretion (red color) modelling in the bottom (Fig. 9.25) for February on 2010, allow observing that predominates the material accumulation of up to 0.10 m in external borders of both the Eastern and Western Groin. However, at the extreme of the western groin is generates an erosion point

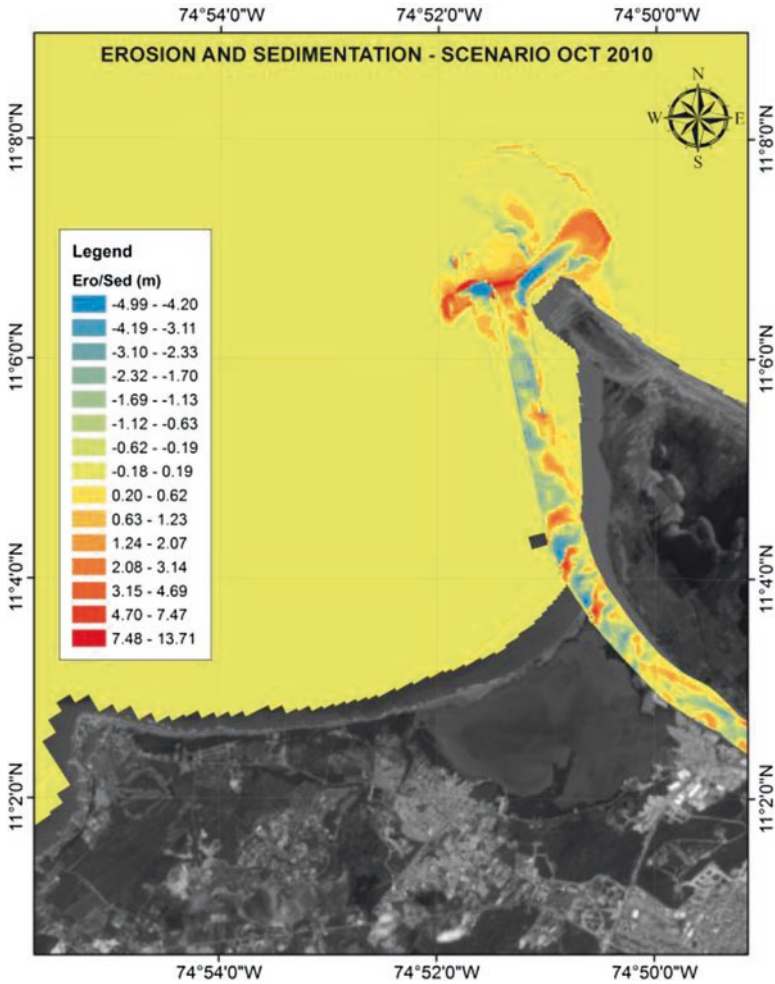


Fig. 9.26 Erosion and accretion of Bocas de Cenizas zone after 30 days of hourly modelling, since October 1st, 2010 to November 01st, 2010

with loss of material of up to -2.84 m. That material is deposited at the same height in the protected border where the generated currents by the diffraction, allow the sediment transport to the Mallorquín Lagoon. Even, it can observe how the first part of the “Superpuerto” works interrupt the sediment transport to the coast. Nevertheless, part of the sediment reaches bordering the construction work and travels in parallel direction to the coastline, supporting in lesser extent to the coastal bar of the Mallorquín Lagoon. It can observe in its proximities, accumulations of sediments from 0.31 to 0.46 m.

Based on results of erosion and accretion during October of 2010 (Fig. 9.26), it is generated deposit zones in the river mouth product of the highest waves that arrive to the zone by the effect of cold fronts and even extreme hydrometeorology phenomena.

There are points with material accumulation up to 14 m, and losses up to 4.9 m towards the sector of the border of the western groin. The strong meteo-marine activity creates a change in the local hydrodynamic helped with the change in the wave direction, which affects the sediment transport to the wetland. For this reason, during this season, the bar diminishes in some sectors its dimension in plant.

9.5.7 Analysis of Evolution in Plant of Mallorquín Lagoon

One of the most important activities for the professionals who study coastal processes are geomorphologic changes that are produced as result of the establishment of coastal infrastructure, or in general, natural changes that suffers a littoral environment of a rigid physical configuration of geological origin.

For the changes analysis that commonly presents a beach, it is necessary to know in detail which is the equilibrium state of the coastal bar Ruiz (2004). This includes not only a typical beach but also a barrier island that protects a wetland of the wave action. For that, since some decades ago, it is implementing theoretical model that allows from the establishment of geometric functions known to determine the final shape of the beach configuration.

The concept of static equilibrium, proposed by Tanner (1958), is defined by a confined coast in a condition of natural or artificial border that allows the generation of a soft beach in harmony with the conditions of maritime climate.

The shape in plant is adjusted to the local wave conditions in order to promote the sediment transport in the beach and for defining a configuration that achieves the proper energy dissipation that guarantees the equilibrium state in the time. Apart from the aforementioned, a water front that presents an unbalance condition, will vary its shape until finds the proper condition to guarantee the sediment transport and deposition process that travels to the beach. In this sense, the diffraction and refraction processes; and in some cases, the reflection take a fundamental role in the shape that will have the beach.

In relation to the beach shape, there are a lot of definitions in the state of the art. Krumbein (1947) denominate them as salient beaches, Silvester et al. (1980) describes them as pocket beaches and Yasso (1965) know them as salient beaches, to name just a few of them.

According to the described above, the static equilibrium represents that condition where the beach neither gains nor losses sediment, only transports and distributes along the coastline as a result of a symmetry between the isobaths, the coastline and wave fronts. This, in physical terms, allows concluding that the breaking wave takes place around the beach profile, thus avoiding excessive erosion. There is not littoral transport in the beach, and in accordance with Leblond (1979) there is a

condition of proportionality between the sediment, the profile and the wave that travel to the coast.

In accordance with Hsu and Evans (1989), a beach has two types of equilibrium condition: static and dynamic. The dynamic equilibrium exists naturally when the beach has a continuous supply of sediment that induces a change in the width of recurring beach. Physically, this represents a coastline that follows a logarithmic profile, with a fixed point on a border where begin a curved section to the end section that is parallel to the coastline. It can underline with precision that the shape of a beach in plant, is a measure of how the currents transport the material.

The types of beaches, such as the found in the Mallorquín Lagoon, have been formed by the morphological evolution resulting from the action of waves and erosion processes over decades, obtaining progressively the shape presented today. This document attempts to reach a level of understanding of how evolved the beach front that protects this coastal wetland and attempt to infer the processes of change and loss of stability that can be achieved by establishing new physical elements in the littoral system.

9.5.8 Model of Parabolic Curve

For analysis on plant, a parabolic model developed by Hsu and Evans (1989) was applied, which fits very well to the planimetric shape of a beach. In their model, it is defined a point of diffraction from which wave fronts change direction. This point must be located on land, in a salient, a natural barrier or a coastal structure. Whether the beach is in equilibrium, it should be considered the time that the wave takes to propagate from the point of diffraction to the coastline. Whether, there is also a wide area of breaking waves since the submarine platform is very shallow, it should take

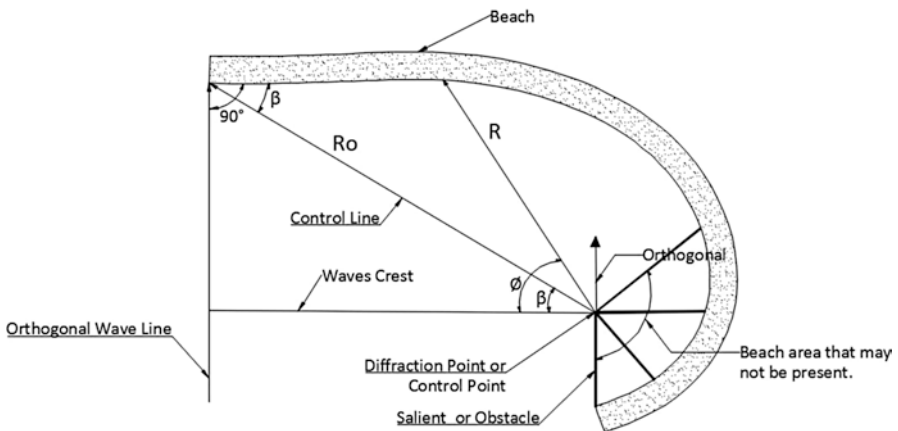


Fig. 9.27 Model of parabolic curve

into account the propagated wave refraction (Fig. 9.27). The general expression describing the parabolic model is:

$$\frac{R}{R_o} = C_o + C_1 \left(\frac{\beta}{\theta} \right) + C_2 \left(\frac{\beta}{\theta} \right)^2 \tag{9.14}$$

$$C_o = 0.0707 - 0.0047\beta + 0.000349\beta^2 - 0.00000875\beta^3 + 0.00000004765\beta^4$$

$$C_1 = 0.9536 - 0.0078\beta + 0.0004879\beta^2 - 0.0000182\beta^3 + 0.0000001281\beta^4$$

$$C_2 = 0.0214 - 0.0078\beta + 0.0003004\beta^2 - 0.00001183\beta^3 + 0.00000009343\beta^4$$

Where C_o , C_1 , C_2 , C_o , C_1 y C_2 are dimensionless coefficients that vary with β . β is the angle between the control line and the tangent point where the coastline becomes straight. This angle, generally, is between the ranges from the 10° to the 80° , because it covers most of obliquities with the waves arrives recurrently to salient beaches R is the radius from the diffraction point to the coastline which has an angle θ with respect to the wave front. R_o that starts in the salient to the point where the coastline becomes straight.

It is important to note that if the modelling line is adjusted to the actual coastline, the physical meaning of this result indicates that the beach is in static equilibrium.

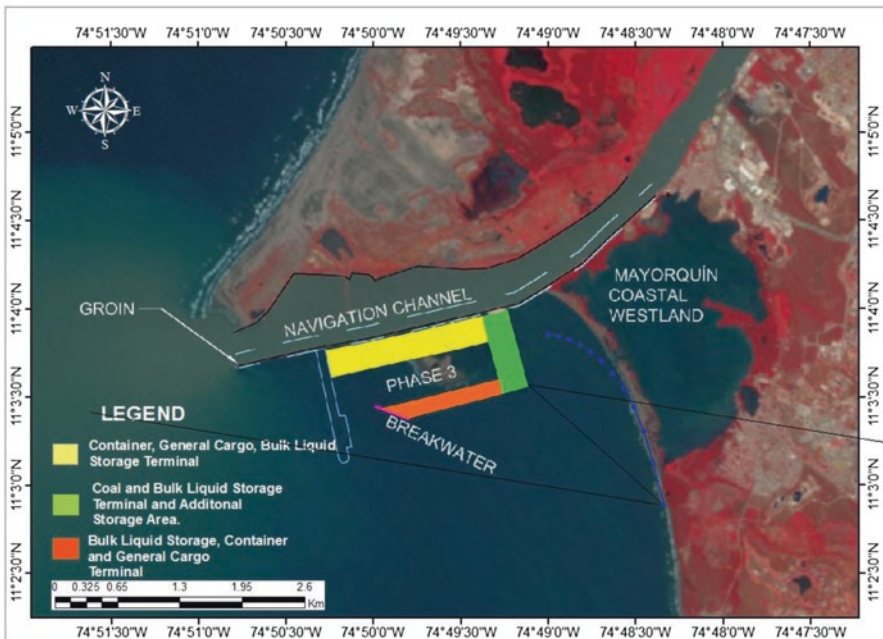


Fig. 9.28 Results of MepBay model. Evolution of the coastal bar due to the Superpuerto works

In case of variations in the model adjustment, there is an indicator that reflects a dynamism on the beach, which can be interpreted as dynamic equilibrium. Therefore, the beach is unstable and can erode quickly at the slightest change in the behaviour of the coastal system.

The modelling of the plant configuration and application of theoretical parabolic model was carried out with the MepBay model as shown in Fig. 9.28, developed by the University Of Santa Catarina Brazil. The importance of using the MepBay lies in the fact that efficiently determines morphological changes in plant and perform a physical interpretation of the equilibrium state of the beach (Raabe et al. 2010).

The modelling results (Fig. 9.28) indicate that with the establishment of the Maritime Terminal “El Superpuerto”, the balance of the beach will be seriously affected. The coastline undergoes significant changes, especially in the shadow area generated by the port. However, this condition of the coastline gain should be analysed carefully, because only it will be presented if the current sediments source remains unchanged of the coastal zone (Fig. 9.28). However, the reality is very different, because for the entry of large ships will be built a navigable channel of 20 m of deep. This indicates that the little sediment currently crosses by the effect of diffraction of the salient in the groin (Tajamar) will end at the bottom of that navigable channel.

9.5.9 Identification of Potential Erosion

The erosion rate of the coastline from many countries has dramatically increased in recent decades. These forces to, the professionals dedicated to the study of coastal processes, carry out a regular monitoring of changes that are seasonally generated on a beach. This is not unrelated to the bars that protect coastal wetlands, even if they have been affected over the years by the establishment of infrastructure for the development of human activities in coastal environments.

A simple and cost-effective way to elaborate a changes diagnosis and the quantification of potential erosion in a coastal bar, it is based on the analysis of satellite images. With images of LANDSAT project and the use of the application of Geographic Information Systems (GIS), it was effected a variability analysis of the spatial and temporal coastline, from 1973 until today. The analysis of the coastline and its changes over time are a powerful tool to determine processes of erosion and accretion in a littoral cell, evaluating differences between space increments of each of the lines drawn.

The methodology consists in drawing for each year and with a seasonal frequently, the polyline representing the coastline for the period measured. In one image, the different polylines overlap to get a map like the one shown in Fig. 9.29.

Then, to determine the potential for erosion suffered by the wetland littoral bar, the Digital Shoreline Analysis System (DSAS) developed model by the US Geological Survey was used (Thieler et al. 2009). Based on selected segments in the model it described the most representative changes on the coastline. For its applica-

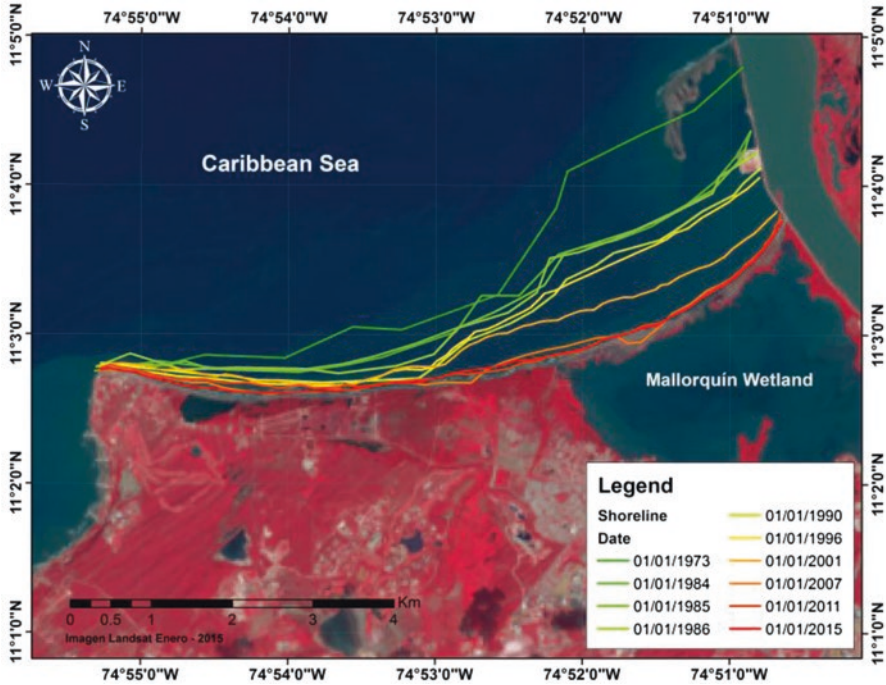


Fig. 9.29 Historic shoreline evolution of Mallorquín Coastal Wetland, Atlántico. From 1973 to 2016

tion, it is requires the establishment of transversal sections spaced uniformly in the sector where will be evaluated the coastal erosion.

After an attributes revision between the generated lines, satellite imagery and polylines, it is develop the model to statistically determine the change rate of the coastline and consequently the erosion potential.

This model calculates the potential erosion using different methods: (a) a linear regression; (b) weighted least squares regression; (c) the change rate on an endpoint; and (d) jack-knife iterative regression techniques

For this study, it was used the No. 1 method because there were a complete data series, representative statistical of the historical variability of the coastline.

As it shown in Fig. 9.30, the most intense changes that have taken this coastal lagoon are in the vicinity of Bocas de Ceniza groin. It can appreciate that historically this location has presented an erosion rate per year of 0.14 m which extends along the entire bar that protects the Mallorquín Lagoon. In the place where finishes the subsystem or sub cell in the discharge of León stream, the rate decreases to 0.11 m/year (Fig. 9.30). The erosion continues to decline until it reaches the border of the cell in the area known as Punta Roca, where have cliffs and an abrasion platform of more than 8 m of height.

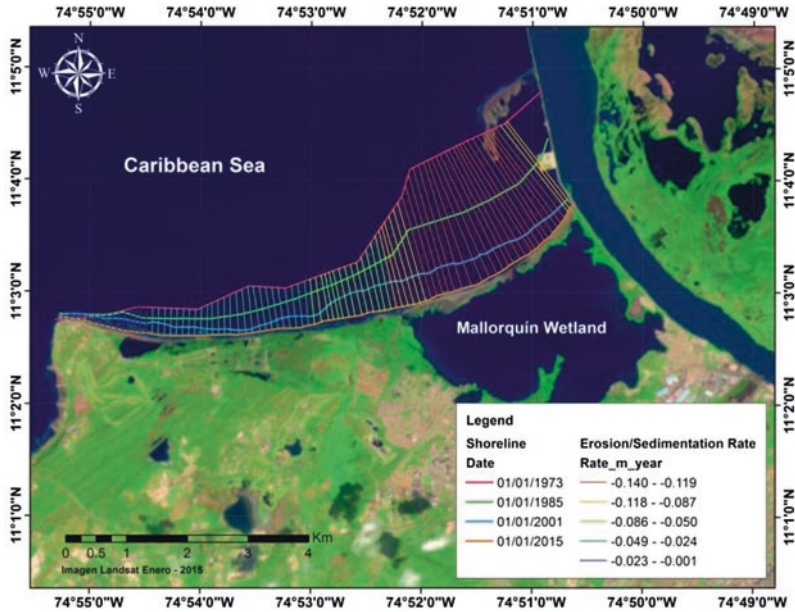


Fig. 9.30 Rates of shoreline change computed using linear regression

9.6 Conclusions

Based on the results obtained, it can be concluded that the associated littoral bar to the coastal wetland “Mallorquín Lagoon” is in dynamic equilibrium. It should be noted that any change in the marine dynamics will produce drastic changes in the behaviour of the wetland, reducing the width of the bar and perhaps its total loss.

From the hydrodynamics perspective, it is clear that the lack of sediment in the system, whose contribution rate varies depending on season weather conditions. There is a gain during the dry season and a reduction of the sedimentary contribution during the humid season by the change in wave direction.

The temporal evolution of the coastline confirms that the wetland has lost its water mirror and has undergone an intense erosion process. The coastline has moved about 2.5 km, with rates recession 0.14 m/year in the most critical area.

For all these reasons, it is recommended to take preventive measures that take into account the way how will be reduced environmental impacts for the loss of sediment that arrives to the bar, since it is expected that the navigable channel of 20 m traps this sediment that comes from the estuary of the Magdalena River. There are two potentially negative effects. A back siltation process of navigable channel and in the port; and a loss of the coastal wetland.

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