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Ecological and social basis for the development of a sand barrier breaching model in Laguna de Rocha, Uruguay

Daniel Conde*, Sebastián Solari, Daniel de Álava, Lorena Rodríguez-Gallego, Natalia Verrastro, Christian Chreties, Ximena Lagos, Gustavo Piñeiro, Luis Teixeira, Leonardo Seijo, Javier Vitancurt, Hector Caymaris, Daniel Panario

Facultad de Ciencias, Universidad de la República, Iguá 4225, 11400, Montevideo, Uruguay

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ABSTRACT

Sand barrier complex dynamics play a key role in defining coastal lagoon structure and functioning. Artificial manipulation of these dynamics for biased reasons (e.g., controlling floods, improving fisheries) aggravates conflicts between stakeholders and introduces potential threats to their conservation. This is the case at Laguna de Rocha, Uruguay, a protected area with international recognition, where the sand barrier opening has been the focus of a long-term conflict. A cooperative effort of scientists, authorities, and local stakeholders produced a breaching protocol, aimed to reduce conflicts while preserving the natural hydrodynamics of the system and its associated ecological processes. Historical information and present perceptions about the sand barrier breach were collected, and geomorphological and hydrological studies were carried out. Reconstruction of the historical management of the breaching practice showed that the artificial opening started in the 1950s and that the original procedure, performed by fishermen and cattle ranchers, was gradually left under to managers to, and it is presently performed with heavy machinery. Since the 1980s, inappropriate opening practices may have produced negative effects on the physical and biological structure of the lagoon. Geomorphological studies revealed the sand barrier as a highly vulnerable component of the lagoon and suggested that new opening sites could eventually develop over the long term, given the predictions of climate change and sea level rise. The hydrological approach provided an understanding of the processes driving the opening mechanism and the extent of the flooding of private and public lands. These results outlined the basis for the protocol, to support managers in deciding when to perform the opening, based on a reduced set of indicators (water depth, sand barrier berm elevation, and rainfall forecasts). Reaching a consensus was mainly based upon the existence, for more than 15 years, of a participatory advisory group discussing local environmental problems. The new sand barrier breaching protocol is a significant improvement over the previous situation, and can be generalized for application in similar contexts.

1. Introduction

Along the coasts of the globe, estuaries and lagoons support relevant environmental services such as water quality maintenance and flood control (Cañedo-Argüelles et al., 2012; Duck and da Silva, 2012; Esteves et al., 2008; Isacch, 2008). Coastal lagoons commonly have large salinity and hydrodynamic fluctuations, driven by an intermittent connection with the ocean through their sand barriers. Notably, this process shapes the structure and functioning of these ecosystems and their fundamental ecological features (Smakhtin, 2004). Coastal lagoons are threatened by a diversity of natural and anthropic factors, e.g., eutrophication, floodplain urbanization, extreme climatic events, and hydrological modifications (Esteves et al., 2008).

Worldwide, the artificial opening (i.e. breaching) of barriers fronting coastal lagoons is a common practice (Chavez et al., 2017; Gale et al., 2007; Pollard, 1994) aimed at a variety of purposes, e.g., avoiding/reducing floods, improving fisheries, eliminating algal blooms, or recovering water quality (Palma-Silva et al., 2000; Thomas et al., 2005), sometimes with unforeseen and irreversible negative consequences (see e.g. Ochoa et al., 2012). Studies have recommended caution concerning this practice based upon proven effects on processes and components like salinity, light field, plankton, macrophytes, or fish communities (Bertotti Crippa et al., 2013; Conde et al., 2000; Duarte et al., 2002; dos Santos et al., 2006; Reese et al., 2008; Saad et al., 2002;

* Corresponding author.
E-mail addresses: vladddcc@gmail.com, vlad@fcien.edu.uy (D. Conde).

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Santangelo et al., 2007; Schallenberg et al., 2010; Suzuki et al., 2002; Young and Potter, 2002), but also on currently unclear or veiled potential effects (e.g., location, procedure, frequency, or duration of the breaching). Despite the alleged consequences, artificially opening coastal lagoons is a widespread tradition, often validated by cultural practices and local governments.

Among a wide range of management typologies, integrated coastal zone management (ICZM) has been widely recognized as a powerful environmental governance approach for addressing complex issues in the coastal space. ICZM focuses on the governance structure, the best available scientific information and the participation of local stakeholders as key components of a successful ecosystem-based management (EBM) (McKenna et al., 2008). Nowadays, EBM is recognized as a superior strategy to cope with the complexity of environmental challenges, and its main guiding principles can be applied at national, regional, and local levels (Borgström et al., 2015). Participation of stakeholders in the decision-making process at a local scale has been described as essential for successful and sustainable coastal management (Berkes, 2009; Christie et al., 2005). Particularly in protected areas, this would help to avoid dominant interests from prevailing over less-influential stakeholders (Gönenç and Wolflin, 2004) and to incorporate a larger diversity of perceptions in management plans, thus leading to legitimized decisions and reduced conflicts (Larson and Edsall, 2010; Shackeroff et al., 2011).

In Uruguay, Laguna de Rocha has been widely recognized due to its natural and cultural values (e.g., Ramsar site, MaB Biosphere Reserve, National System of Protected Areas-SNAP) (Rodríguez-Gallego et al., 2013). Its sand barrier, largely the most fragile component of the lagoon, influences the provision of most ecosystem services, and thus plays a key role in preserving the balance of the social-ecological system (Lozoya et al., 2015). Breaching of its sand barrier has been a common practice for several decades (Conde et al., 2015), and is used to reduce flooding in farming areas and in small urban settlements along the floodplain, and also to appease the misperception of upstream Rocha city residents, who believe that a closed sand barrier retards water drainage during city flooding. Breaching is also executed to favor fisheries inside the lagoon, which depend on the influx of larvae of species of commercial value from the adjacent sea.

Since the nineties, artificial control of the sand barrier of Laguna de Rocha has been under debate by stakeholders, who have been basically aligned in two groups: one favoring the breaching (i.e., land owners, local authorities, cattle ranchers, some neighbors, and some fishermen) while the other group has been more concerned about both the validated and unknown ecological effects (i.e., conservationists, researchers, and some fishermen, as well as DINAMA-National Environmental Authority). Some artificial openings have been reported to have positive effects on fisheries (Fabiano and Santana, 2006), while others had ecological consequences, e.g., on aquatic plants (Rodríguez-Gallego et al., 2015). Also, there is a long-term detrimental effect of the clogging of discharging channels with sediments, which in turn reduces the clearance of water and excess nutrients. The specific locations at which to excavate the channel on the sand barrier and the appropriate water level at the moment of the breaching have been constantly under discussion. Predictions of increasing risks driven by climate change and climate variability (Nagy, 2012) generate more uncertainty and challenges, given the potential expansion of urbanization closer to the sand barrier area.

In late 2011, the authorities that administrate the Protected Area of Laguna de Rocha (i.e., DINAMA and Rocha Provincial Government-IDR) requested the authors of this article to develop a breaching protocol for Laguna de Rocha, which included: i) the development of the technical studies, both natural and social, needed for the protocol, and ii) working with stakeholders to reach a consensus about the technical details of the protocol. From 2011 to 2014 we carried our all technical studies for the protocol, and worked with stakeholders and authorities on the protocol details, looking for consensus at the CAE (Advisory Local Committee, SNAP), an advisory board where all stakeholders and authorities are represented. We worked frequently in workshops with CAE members, as well as by means of other kind of interactions (capacity building activities, individual meetings, interviews, etc.), to show the technical aspects of the protocol development, and to receive opinions for later adjustments. This iteration was done several times until the end of the process, and the final protocol was finished and presented to the authorities and stakeholders in 2015. It was formally approved by the Ministry of the Environment in 2016, as part of the Management Plan of the Protected Area.

The objective of the present article is to show the artificial sand barrier breaching protocol developed for Laguna de Rocha, focusing on the scientific studies conducted to allow its completion. Existing conflicts and social demands that drove the problem are first addressed, then the geomorphological processes taking place at the sand barrier are shown and finally the hydrodynamics forcing the lagoon opening and the flooding process are analyzed. Lastly, how all the information was used to assemble the protocol is presented.

2. Material and methods

2.1. Study area

Laguna de Rocha is a shallow lagoon (average depth: 0.6 m) located on the Atlantic coast of Uruguay (34° 35′ S - 54° 17′ W; Fig. 1), with a surface area of 72 km^2 and a watershed of 1214 km^2. Although only a few hundred inhabitants live close to the lagoon, the system supports one of the most important inland fisheries of the coast of Uruguay (Fabiano and Santana, 2006), and there has been rapid development of tourism. The provincial capital (Rocha city; 26.000 inhabitants) is located in its watershed, on the margins of the main tributary.

Laguna de Rocha is classified as an ICOLL (Intermittently Closed/Open Lakes and Lagoons), i.e., the connection between the sea and the lagoon is not always open, as the entrance closes regularly, completely separating the fluvial and the marine environments (McSweeney et al., 2017). As pointed out by Bond et al. (2013), ICOLL inlets have historically received less attention than those of permanently open lagoons or barrier islands. ICOLL are characteristic of micro-tidal zones dominated by waves, where the tidal range is not enough to keep the inlet open and fluvial discharge is not enough to replace the effects of the tide, either because the fluvial regime is intermittent or because once the lagoon discharges it requires time to refill (see McSweeney et al., 2017, and references therein, for a detailed discussion regarding this particular type of inlet). Factors affecting opening and closing of the sand barrier include external (i.e., sea level and waves) and internal (lagoon water level) forcing agents, as well as the berm height at the barrier, the latter being a key factor in defining the opening and closing of ICOLL (Baldock et al., 2008; McSweeney et al., 2017).

The northern area of the lagoon is dominated by freshwater discharge, while the southern area is largely influenced by the marine intrusion that takes place after the periodic sand barrier opening, producing a steep salinity gradient inside the lagoon, as well as steep gradients in most limnological variables and processes (Bonilla et al., 2005; Piccini et al., 2006; Rodríguez-Gallego et al., 2010, 2015). A phosphorus-driven eutrophication process has been reported to be taking place in the lagoon, triggered by land use intensification in the last several decades (Rodríguez-Gallego et al., 2015, 2017), with manifest consequences like episodes of macrophyte proliferation and cyanobacteria blooms.

Records indicate that sand barrier openings have occurred at levels between approximately 1.1 and 2.0 m above the Official Zero (OZ; an official reference datum defined as the average water level in the Port of Montevideo), producing sharp declines in the water level in the system. The concentration time of the basin is approximately 14 h, basically implying that the lagoon collects the basin runoff generated after a rainfall episode in less than a day. Historically, cattle ranchers have

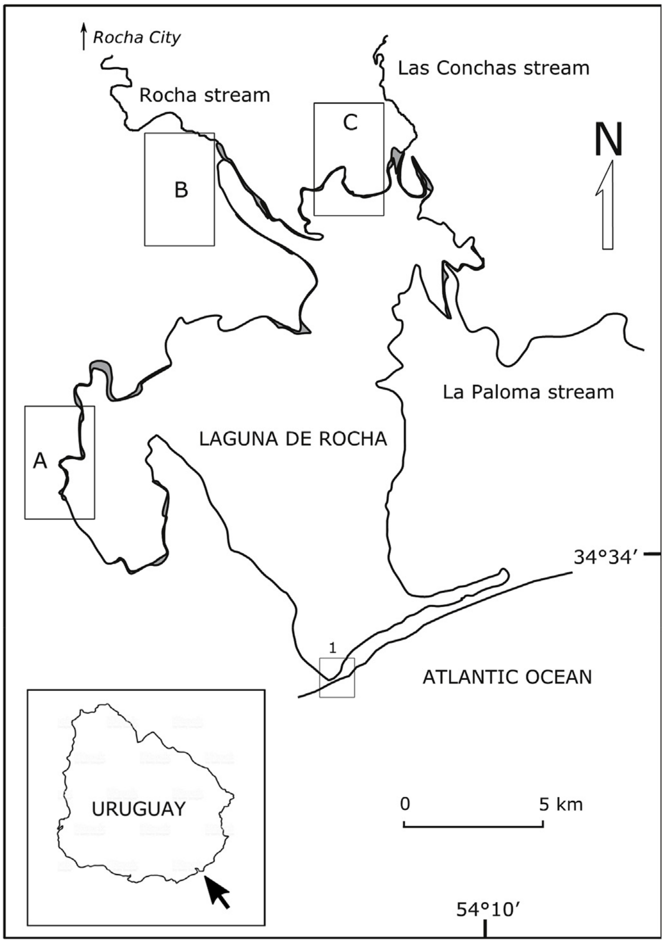

Fig. 1. Location of Laguna de Rocha on the Atlantic coast of Uruguay (the black arrow on the bottom right side of Uruguay shows where the lagoon is located). The provincial capital, Rocha City, is located approx. 5 km North of the map, on the margins of Rocha stream. Zone 1: current opening site of the sand barrier; zones A, B, C are the three places referred to in Table 2, where the flooding extent was specifically studied. Modified from Conde et al. (2015).

requested that authorities reduce the lagoon water level, even before the onset of flooding.

In 2011, the Advisory Local Committee, CAE was formally established, and is composed of local and national authorities, landowners, ranchers, and fishermen. However, it is worthy to note that these stakeholders had been actively cooperating for almost 20 years before the establishment of the protected area, concerning critical environmental topics of the lagoon, showing a remarkable disposition towards building agreements about the artificial opening of the lagoon.

2.2. Perceptions regarding the sand barrier management

Initially, a historical and documentary review was performed of the available material related to the management of the sand barrier. Twenty-six stakeholders, including most CAE members, were consulted in semi-structured and structured interviews (Taylor and Bogdan, 2000), and field observations and open interviews with selected stakeholders were also implemented.

A historical timeline starting in 1920 was developed to describe modifications in sand barrier management. A content analysis of the interviews was performed (Andreu, 2000; Urra et al., 2013). The perceptions of stakeholders concerning the potential social-ecological effects of the artificial opening were also addressed in the interviews. Identification of the main institutional stakeholders associated with the process and an analysis of the current formal mechanism of the breaching decision-making were carried out. Based on the results of the interviews, a diagram was produced by modifying the original output from the software Atlas.ti v8®. Different types of social networking between stakeholders, regarding their affinity for the sand barrier opening as well as their level of influence on the decision-making, were identified.

2.3. Geomorphological analysis of the sand barrier

In order to understand the present physical condition and the recent evolution of the sand barrier of the lagoon, a geomorphological study was carried out, which included photointerpretation, detection of changes over time, and several sediment analyses. Also, the study merged expert expertise with knowledge of local fishermen on the recent past conditions of the area. Digital image processing included georeferencing and orthogonalizing a temporal set of images to detect sand barrier changes from 1943 to 2011. Satellite imagery included sensors CBERS-2B-HRC (2007–2010), QuickBird (2004, 2007, 2008, 2009), and WorldView I (2009–2011) and II (2010–2011). Historical aerial photographs from the Military Geographical Service of Uruguay (1943, 1967) and the Uruguayan Air Force (1986) were also used.

A set of 10 subsurface samples from the interdunal soils along the sand barrier were taken using opaque tubes and hammers to analyze the luminescent response (Thermoluminescence and Infrared Optically Stimulated Luminescence, TL and IR, respectively) (Wintle and Huntley, 1982), conducted with an 801E Multiple Sample Irradiator, Daybreak Nuclear Systems™ 1100 (^{90}Sr source; 1 Gy = 22.4 s). TL fundamentally affects quartz, whereas IR affects quartz and feldspars but also represents a source of uncertainty because of the “anomalous fading” effect (Molodkov et al., 2007), so both results were analyzed together. The organic fraction from one of the samples was dated with the standard ^{14}C technique (sample URU-0581). The sediment fraction between 65 and 90 μm was analyzed for a provenance study, with a petrographic microscope at 300×, and chemically treated with HF, HCl, and H_2O_2 to remove feldspars, carbonates, and organic matter, respectively.

An evolutionary model of the sand barrier was developed by means of a combination of sedimentary analyses, particularly the analysis of the cross-cutting relationships of the clastic and bioclastic sedimentary sequence located near sea level, below the buried interdunal soils.

2.4. Hydrological analysis of the lagoon

In order to characterize the hydrodynamics of the lagoon and to define an empirical cumulative distribution function of the lagoon level, the available daily water level from 1956 to 2005 (data from the Ministry of Public Works, MTOP) was analyzed. To describe the potentially flooded private land surrounding the lagoon, an existing detailed altimetric survey (differential GPS; Leica Geosystem and Leica Geo Office 8.3) from three selected zones was used (see locations in Fig. 1), from where a digital elevation model was developed. Potentially flooded areas were defined for several water levels in the lagoon, discerning between public domain and private land, according to the legal definition of the public boundary of the lagoon, and a bathymetric survey performed in 2012 (SonarMite MILSpec equipped with a Leica SR20 GPS). The flooded private land area was calculated by subtracting the public area from the total flooded area and calculating the ratio to the total flooded area for each water level. The average duration of flooding in each surveyed area was defined by integrating the flooded areas with the empirical cumulative distribution function of the water level in the lagoon. The concentration time of the basin was calculated based on the formulation of Ramser–Kirpich (Chow et al., 1994).

2.5. Short-term dynamics of the sand barrier breaching process

It was stated above that Laguna de Rocha is an ICOLL, and that its inlet opens every year, either naturally or artificially, often more than once per year. The frequency of this dynamic prevents the creation of dunes and the development of vegetation in the stretch of the barrier where the opening occurs. In the last several decades, the openings have occurred in approximately the same area, and therefore study of the short-term opening dynamics focuses on this area. Analysis of the inlet opening dynamics was based on the joint analysis of sea levels and waves, lagoon water levels, and berm height at the opening area.

2.5.1. Available information

The topography of the sand barrier and the bathymetry of the lagoon and the nearshore area close to the inlet were surveyed during this project, between 2012 and 2013. Additionally, bathymetry of a wider area is available in the nautical charts; however, it should be noted that nearshore bathymetry in the nautical charts is of low spatial resolution and is not up to date (data was collected in 1937, and hence, the low reliability).

Wave information at intermediate depths is available from a high-resolution local wave reanalysis for the period 1979–2010, with a 3-h frequency (Alonso et al., 2015). Sea level information is available from measurements in La Paloma harbor, located 10 km eastward from the inlet, for the period 1912–2011 (with frequency varying from daily data at the beginning of the period to one data point every 15 min at the end of the period). Lagoon water level data is available for the period 1956–2011 and was measured close to the inlet (frequency varying from data every 12 h at the beginning of the period to every 30 min at the end of the period; see locations of the measurement stations in Fig. B1 in Appendix B).

In addition, aerial and satellite images of the inlet area are available, as is a historical record of periods of open and closed barriers, including some records of the opening dates. It is worth noting that after filtering the barrier opening records (retaining only those in which the date was clearly indicated and whether the opening was natural or artificial), the set was reduced to 11 dates of natural openings and 12 dates of artificial openings. These figures were further reduced to 9 and 5, respectively, when the availability of wave, sea level, and lagoon water level on the corresponding dates were considered.

2.5.2. Calculation of derived variables

Waves were propagated to the surf zone by means of linear theory and Snell's law (Dean and Dalrymple, 2002), assuming straight and parallel isobaths and considering the breaking criterion of Thorton and Guza (1983) for irregular waves. While this approach is a major simplification of wave propagation, it is justified because (i) there is no bathymetric information that is both reliable and of adequate resolution to implement a numerical wave propagation model, (ii) available information shows that isobaths in the area might be regarded as rectilinear and parallel, and (iii) waves are not the main forcing agent in the breaching of the barrier, as discussed later.

Once the significant wave height and wave direction at the breaking point were determined, the long-shore sediment transport for each sea state was estimated using the CERC formula (US Army Corps of Engineers, 2002):

$$Q_l = \frac{K}{(\rho_s - \rho)g(1-n)}(EC_G)_b \sin(\alpha_b)\cos(\alpha_b) \tag{1}$$

where Q_l is the long-shore sediment transport rate in $m^3\ s^{-1}$, K is a calibration coefficient whose recommended value when working with significant wave height is 0.39, ρ_s and ρ are sediment density and water density respectively, n is the sediment porosity, E is the wave energy, C_G is the group celerity of the waves and α is the angle between the wave propagation direction and the beach normal. The subscript $_b$ refers to wave conditions at breaking.

Takeda and Sunamura proposed the following expression to estimate beach berm elevation based on field work (Horikawa, 1988):

$$Z_{bm} = \eta + 0{,}125\overline{H_B}^{5/8}(g\bar{T}^2)^{3/8}\ si\ 3{,}5 < \frac{\overline{H_B}^2}{g\bar{T}^2 d} < 10. \tag{2}$$

where Z_{bm} is berm elevation relative to sea level, η is sea level, $\overline{H_B}$ is daily average significant wave height at breaking, $\bar{T}$ is daily average wave period, g is gravity acceleration, and d is sediment size of the beach.

Maximum berm height that could be built by wave action for every sea condition was estimated by means of equation (2), using sea level and wave data for the period 1980–2010. This approach neglects the temporal evolution of the berm growth as well as erosion events. Based on waves and sea level data and using equation (2), a "berm height climate" was estimated for the barrier.

In an ICOLL, the opening process is mainly produced by the interior water level exceeding barrier height (Haines and Thom, 2007), something that is validated by local experience in the case of Laguna de Rocha. The effect of wave storms on the beach profile was modeled by means of a 2DV morphological model (Gonzalez et al., 2007). Barrier profiles were constructed by combining an equilibrium beach profile with the measured berm profiles in the inlet opening zone. Berm profiles were vertically translated in order to reach elevations corresponding to quantiles of 10, 50, and 90% of the "berm elevation climate" described above, and also to an elevation representing a recent closure event (i.e., few centimeters over mean sea level), totaling four profiles. Each profile was subjected to a triangular-shaped wave storm assumed to be representative of severe conditions: storm duration 72 h, maximum significant wave height 4.5 m (approx. 1 yr return period) and constant +1.08 m sea level (approx. 1 yr return period). For the definition of the storm, it was taken into account that for extreme conditions, wave height and sea level could be regarded as independent. Therefore, the modeled storm is expected to have a return period greater than 1 year.

Although in the last decade more sophisticated models have been developed to evaluate the breaching of a sand barrier by wave action (e.g., X-Beach), given the relative relevance of the maritime processes with respect to fluvial processes in the dynamics of barrier breaching in Laguna de Rocha, and given the level of detail of the available information, it is assumed that the use of the 2DV model proposed by Gonzalez et al. (2007) is adequate for the purposes of this work.

2.6. Artificial breaching protocol

To outline the artificial opening protocol, all available information was considered to be potential input to the decision tree. A panel of experts from natural and social disciplines and rangers were asked to define the critical variables to be included in the decision tree, as well as the boundary values between the different phases of the flooding process. The decision tree was assembled based on questions, answers, and decisions, linking the transitions between phases through the changes in the critical variables that build up the system. Critical variables that composed the protocol were kept at minimum, but it is considered that they include, directly or indirectly, all of the different dimensions of the problem.

3. Results and discussion

3.1. Sand barrier management and perceptions of stakeholders

Based on information provided by local stakeholders and administrators, the history of the management of the sand barrier was reconstructed. The sandbar manipulation started in 1950s (1956 or before) (Table 1); however, no specific proof of the starting date was found, as there is no formal MTOP record of the artificial openings before the 1960s. At the onset of the artificial breaching practice, the procedure was performed cooperatively, mainly by local cattle ranchers and fishermen, with rare institutional involvement. Elder stakeholders

Table 1
Temporal evolution of sand barrier artificial management in Laguna de Rocha, according to published information and opinions of stakeholders.

Period	Decision-taking model	Main characteristics
1940–1960	Bottom-up	● Prevalence of natural opening. ● Low frequency intervention. ● Artificial openings performed manually. ● Prevalence of local ecological knowledge. ● Collaboration between ranchers and fishermen. ● Onset of institutionalization of the breaching mechanism
1960–2011	Top-down	● First formal records of opening dates. ● Intensification of the frequency of artificial openings. ● Use of heavy machinery. ● Decision-taking centered on national authorities, with participation of local institutions (DINARA, PROBIDES). ● Scarce or no communication with fishermen community. ● Multiple opening sites without technical criteria.
2011–2015	Collaborative	● First agreement on opening criteria, in the Advisory Local Committee (CAE). ● Decision-taking led by Protected Area Direction, in communication with local authorities and fishermen. ● Development of a protocol for artificial opening and approval by national authorities.

believe that artificial openings until the 1960s had relatively low environmental effects (e.g., on fish captures), because they were executed accompanying, in space and time, the natural process and without heavy machinery.

After 1950, the sand barrier occupation process was characterized by consolidation of the fishing communities, housing, and touristic development. Starting in the 1980s, progressive involvement of governmental institutions concerning the sand barrier management (i.e., IDR, DINARA-National Authority on Aquatic Resources, PROBIDES-Eastern Wetlands Conservation Program, and later DINAMA) considerably reduced the active participation of fishermen in the process. On a broad scale, during the second half of the last century, the original bottom-up character of the sand barrier operation changed into a top-down practice (Zagonari, 2008), which in turn led to a higher frequency of artificial openings. Although IDR and DINAMA attained most of the control in the decision-making process in the 2000s, no technical monitoring or evaluation of the potential ecological consequences was implemented beyond casual monitoring of research projects during fieldwork.

Finally, in 2011 (before this study was performed) a rudimentary procedure for the artificial opening was cooperatively developed and agreed upon by fishermen, ranchers, and authorities (during CAE meetings). It consisted of an empirically defined virtual perimeter around the lagoon, made up of four “flooding marks” in the floodplain (at approx. 1.6 m OZ, as later determined in this study). The perimeter represented the limit between non-flooding and flooding conditions, according to the pragmatic judgment of stakeholders, which allowed activation of the sand barrier opening, once the water level reached all marks. Until this agreement was implemented, influential local stakeholders (namely cattle ranchers) kept most of the non-formal control for the opening decision, by pressing on the authorities.

Many of the changes in the biophysical components over the last three decades in Laguna de Rocha were perceived by most stakeholders as undesirable and direct consequences of the artificial openings (Fig. 2). Major concerns of stakeholders were related to the use of heavy machinery (as well as an erratic location) for the excavation of the discharging channel, which led to changes in fisheries captures, water quality impoverishment, reduced depth of the discharging channels, embankment of the sand barrier inner area, and a decreased floodplain area and flooding period. These effects were perceived by local people as a coincidence with the intensification of the artificial openings after the 1960s.

During interviews, stakeholders indicated that the two major reasons to authorize the artificial opening were the reduction of flooding events in urban and sub-urban areas and in livestock ranching areas, and the improvement in the shrimp harvest if the lagoon is closed during springtime. Several stakeholders expressed a preference for the lagoon and the sand barrier to behave naturally, based on the necessity of restoring a system that has been negatively affected in the long term. Mainly among fishermen, there is a prevailing idea that a ban on artificial opening, even partial, would facilitate the restoration of natural processes and understanding of how the system works without intervention. Arbitrariness was perceived among stakeholders as a major problematic factor in sand barrier management until 2011 (Fig. 2).

The analysis of the relationships between stakeholders, and their affinities and influences concerning the artificial opening, showed that, at the time of the analysis (2014), the Director of the protected area had strong connections with most of the stakeholders, but particularly with those with less affinity for the artificial opening (Fig. 3). This was perceived as a significant contribution to preserving positive links and fluid communication between stakeholders. Conversely, IDR often took a leadership role for the artificial breaching based on its legal competences and maintained strong relationships with stakeholders with higher affinities for the sand barrier opening. The other administrative institution (DINAMA) partially balanced the whole set of relationships, showing lower affinity for the opening and the highest incidence in the decision-making. Other stakeholders exhibited a large diversity of opinions regarding the opening, but in all cases had minimal influence in the governance of the problem.

3.2. Sand barrier geomorphology

In the geomorphological study, the sedimentary sequence of the sand barrier that closes Laguna de Rocha (see Table A1 in Appendix A), corresponded to late-Holocene alluvium and sandy deposits which coincided with previous descriptions (Preciozzi et al., 1985). The complete mineral description is highly consistent with a modern origin without evidence of weathering or pedogenesis. The satellite image sequence analysis showed that during the last decade there has been an extensive development of internal banks and a progressive filling of the channels in the southern part of Laguna de Rocha (Fig. 4), partially transforming this fragile component of the system into a delta-type configuration. This obstruction decreases the transport of sediments to the coastal zone because of reduced water column depth and water flow. Images showed a connection between internal bank evolution and a coastline regression of approx. 80 m in the opening area from 1966 to 2011. This suggests an increase in the marine energy relative to the internal hydraulic energy of the lagoon. The artificial opening of the sand barrier for more than three decades, far from the optimal natural conditions, could have caused these changes. Comparable regressions have been reported (Panario and Gutiérrez, 2005) in other estuaries of the Uruguayan coast, and it is likely that the lagoon might develop into a coastal wetland type of ecosystem, as reported elsewhere (Carter and Woodroffe, 1997).

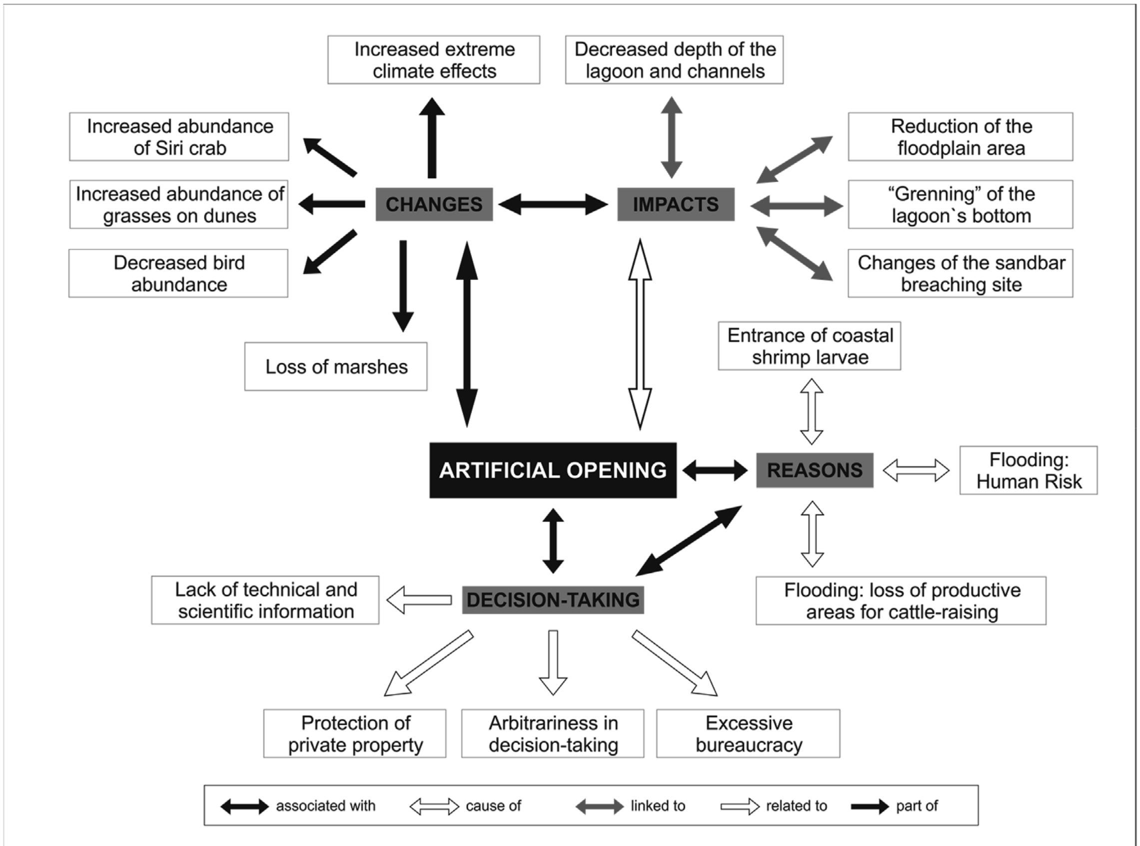

Fig. 2. Diagram depicting opinions of stakeholders on the changes and effects observed in the Laguna de Rocha sand barrier during the last 30 years, the reasons for artificial opening to be allowed, and the diversity of issues that could generate conflict or consensus for the artificial opening decision.

The presence until now of a channel in the interior of the lagoon along the whole sand barrier (Fig. 4) suggests that this area has potential for openings in several low sites, particularly if extreme marine conditions and high water levels in the lagoon occur simultaneously, although this has not been tested yet. Semi-permanent small water bodies and flooded depressions close to the present sea level along the sandbar correlate well with knowledge of local people of marine ingressions by sea waves during high-energy events (overwash) until the end of the 1930s and early 1940s (particularly in the "Barra Vieja" zone). This is further supported by the results of the TL and IR analyses (Fig. 5, upper panel), which indicate the presence of a sequence of young sands and shells (low luminescence) surrounded by older sands (high luminescence) along the whole sandbar. This is assumed to be robust evidence of the subsistence of recently abandoned channels,

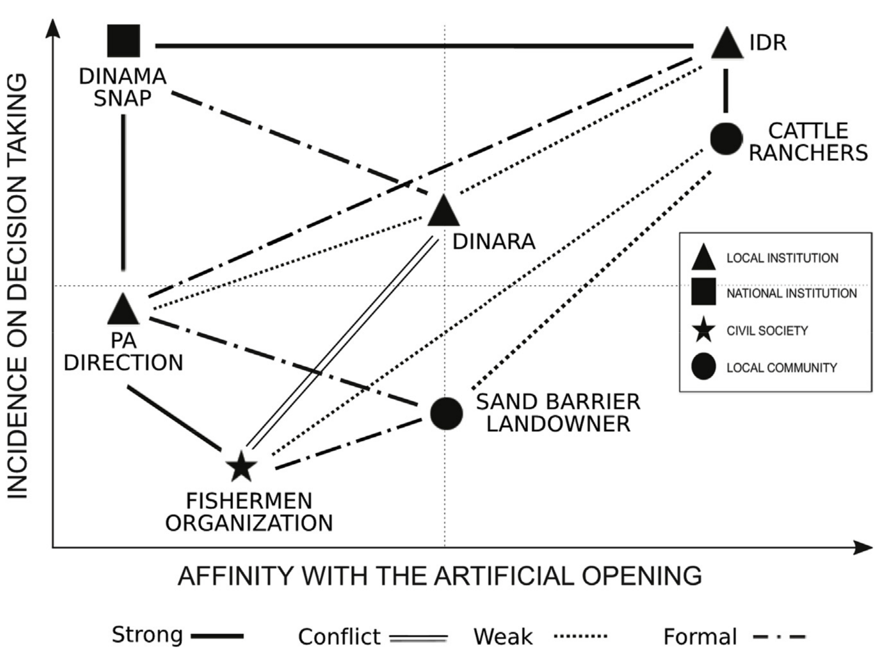

Fig. 3. Laguna de Rocha stakeholders map showing individual influence on the decision-making process (vertical axis), affinity concerning the artificial opening of the sand barrier (horizontal axis), and relationships among stakeholders (lines). No connector between components denotes no evident relationship (DINAMA: National Environmental Authority; SNAP: National System of Protected Areas; PA Direction: Laguna de Rocha protected area Director and rangers; DINARA: National Authority on Aquatic Resources; IDR: Rocha Provincial Government).

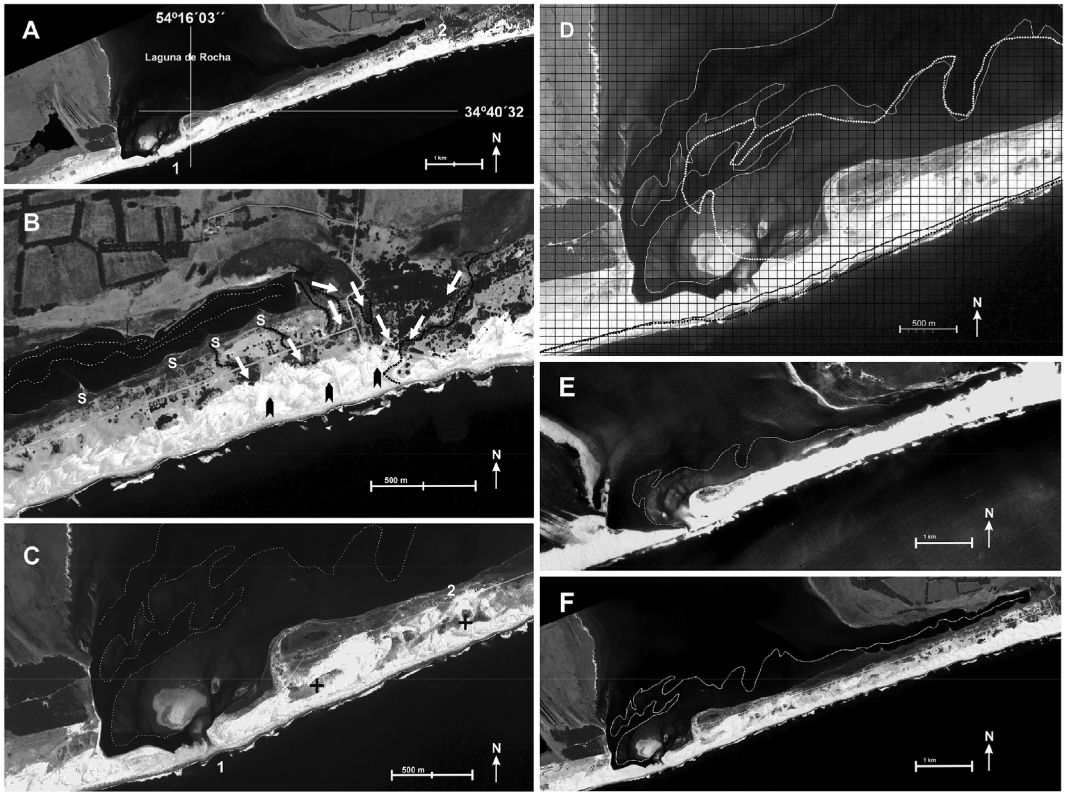

Fig. 4. Geomorphological features of Laguna de Rocha sand barrier system. Dunes with scarce vegetation are shown in whitish tones. (a) Numbers 1 and 2 indicate different opening areas of the lagoon (1, current opening zone; 2, a relict area, "Barra Vieja"); (b) White arrows indicate slopes into streams and creeks (black dotted lines) corresponding to some of the historical opening areas; black arrows indicate remnant areas with evidence of seawater intrusion; S: sand ridges formed by internal waves in the lagoon; (c) Soils with level similar to sea level (+symbols), associated with relict openings. The dotted white line inside the lagoon indicates the limit of the silty-sandy bank (depth less than 1 m) delineating the deeper channels; (d) Movement of sand banks inside the lagoon toward the west between 1966 (dotted line) and 2011 (continuous line). The receding shoreline on the marine side of the sand barrier is also shown (1943, dotted black line; 2011, solid black line). The grid side is 50 m (satellite image WorldView II - 11/15/2011); (e) Detail of the 1943 SGM image; (f) Detail of the 2011 WorldView II image.

which fully matches observations of older fishermen still living in the zone.

The sand barrier evolutionary model (Fig. 5, lower panel) shows simultaneous multi-breaching sites along the sandbar, driven by the combination of sea waves and aeolian transport of sands onshore. This sand, which could build up dunes in combination with NE-directed long-shore drift, also has the potential to close the conspicuous sandbar. The hydraulic pressure of the lagoon water body on the sand barrier is also a significant process concerning its water soil saturation and the consequent elevation of the water table. Sand barrier saturation reduces the dissipative capacity against wave action by reducing substrate permeability, enabling the penetration of sea waves into low-lying areas, especially in depressions between dunes. In this latitude, extreme rainfall events are commonly associated with a subsequent increase in sea level due to storm surges (strong southern winds with extended fetch of approx. 50 km and high wave energy) (Gutierrez et al., 2016), potentially producing a larger effect on the sand barrier structure.

3.3. Lagoon hydrodynamics and flooding areas

The lagoon daily water level variability was analyzed based on the 1956–2005 data series. Lagoon water level exhibited a significant inter- and intra-annual variability that essentially corresponded to the characteristic precipitation pattern in eastern Uruguay combined with the variability of the sand barrier openings. The time series shows how the hydrological functioning of the lagoon involves the superposition of two processes, one seasonal and one daily, the latter being much more variable. The common seasonal progression corresponds to the rise in the lagoon water level towards the end of summer and autumn, while in winter the system exhibits the maximum water levels (Fig. 6, left). In 72% of the 50-year data series, the maximum level occurred in winter, a fact that was also confirmed by applying a hydrological monthly balance (UNESCO, 2006; balance not shown). From the same time series, the empirical cumulative distribution function of the water level was derived (Fig. 6, right), where the 88% non-exceedance probability value indicated the legal public boundary of the lagoon perimeter (i.e., 0.87 m OZ).

In Table 2, the results of the analysis of the magnitude of the flooding areas for three zones of major interest in Laguna de Rocha (named A, western coast; B and C, northern coast; see locations in Fig. 1) are shown. It is concluded that in these areas, the water level that can cause a natural opening (between 1.1 m and 2.0 m) would also flood a much higher proportion of public than private lands. In zone A, for example, one of the most critical areas because of its extreme flatness, an opening at 1.49 m ZO would flood 23% of private lands, but 77% of public lands (these results were also verified for other shoreline sites along the lagoon; not shown here). These results are relevant, given the long-term complaints from cattle ranchers about their lands being flooded when the sand barrier is closed. Here, information that this perception was partially wrong, or the argument overused, to force the artificial opening and favor their cattle-raising activity, has been provided. Moreover, data show that the flooding period commonly lasts only from a few days to a few weeks.

In Laguna de Rocha, cattle forage along the lagoon shore, even though the stripe around the lagoon's margin is public land. This is the result of changes in national legislation that occurred in the 1970s and that introduced the concept of a floodplain. The legislation established that public land around water bodies is defined by the maximum

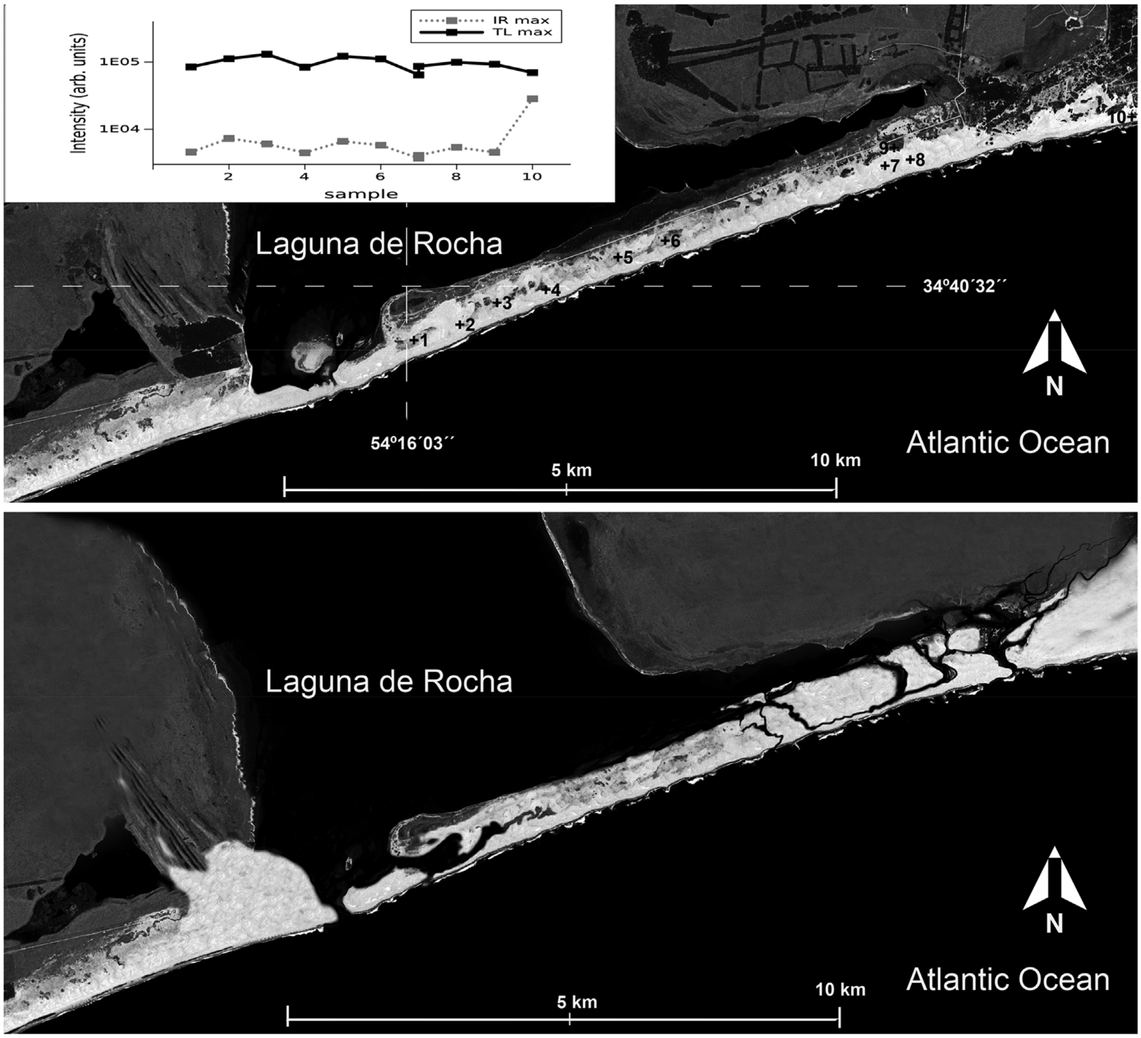

Fig. 5. Comparative images with details of the Laguna de Rocha sand barrier system, based on satellite image WorldView II (11/15/2011). Upper panel: in the upper left corner, a graphic representation of the maximum recorded infrared-stimulated luminescence and thermoluminescence values (IR and TL, respectively) are shown. The vertical axis shows log arbitrary units of TL and IR intensity; the horizontal axis shows the 10 sampling sites from where samples were analyzed along the sandbar, shown on the image with correlative numbers. Lower panel: representation of the proposed evolutionary model of the sand barrier based on sediment analysis, ^{14}C dating, analysis of sand barrier changes from images, bathymetric, and altimetric data, and local ecological knowledge (see text for explanation).

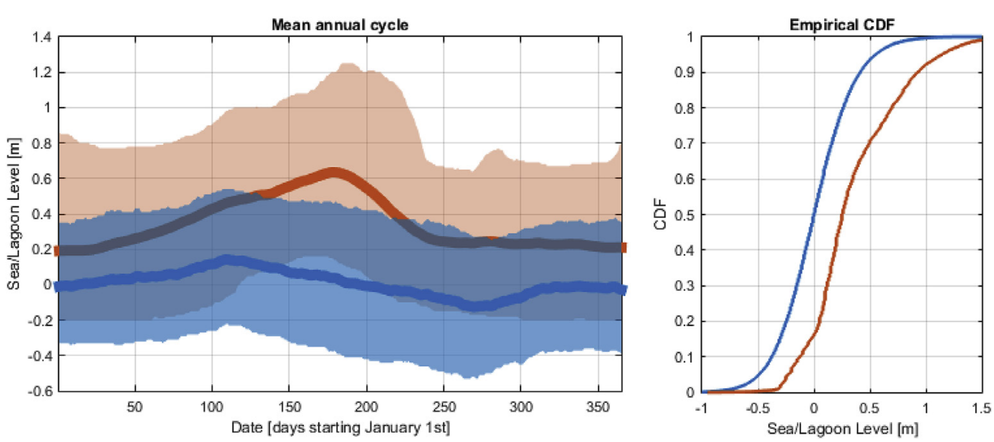

Fig. 6. Analysis of the lagoon water level (red) and sea level gauges at La Paloma harbor (blue). Left: mean annual cycles (mean value and range 10%–90% quantiles). Right: empirical cumulative distribution functions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

flooding level during the last 12 years, thus changing the previous limits imposed on the private land. Despite the legal changes, no institutional arrangement was implemented; consequently, landowners persisted in exploiting the entire floodplain to feed their animals. This practice adds extra complexity to the problem, because landowners start complaining about flooding even when their own lands are still not flooded. However, to achieve an appropriate water level for a natural sand barrier opening to proceed, a minor portion of private lands must be flooded for a relatively short time. Given this conflict, a cautious collaboration among public and private owners is still

Table 2
Private and public flooded areas in three selected zones (A, western coast; B and C, northern coast; see locations in Fig. 1) in Laguna de Rocha, for different lagoon water levels. Discrimination of private or public flooded areas was made according to the legal demarcation of the limits of the lagoon (i.e., 0.87 m OZ).

Water level (m)	Zone A (West)			Zone B (North)			Zone C (North)		
	Flooded area (ha)	Public (%)	Private (%)	Flooded area (ha)	Public (%)	Private (%)	Flooded area (ha)	Public (%)	Private (%)
0.35	14.8	100	0	24.4	100	0	23.0	100	0
0.87	183.8	100	0	120.9	100	0	68.6	100	0
1.15	225.7	81	19	149.1	81	19	81.6	84	16
1.49	238.8	77	23	166.8	72	28	84.6	81	19
2.00	256.2	72	28	172.8	70	30	87.3	79	21

necessary to achieve sustainable sand barrier management.

3.4. Short-term dynamics of the sand barrier and characterization of the breaching process

Laguna de Rocha is located on a stretch of micro-tidal coast, with semi-diurnal tides (amplitude of M2 tidal constituent is approximately 12 cm; Santoro et al., 2013), affected by moderate meteorological tides (historical maximum of the total sea level in 100 years of records is +1.7 m, see Fig. B2 in Appendix B). The analysis of the mean annual cycle (mean value and range of 10–90% quantiles) and the cumulative distribution function of the water level in Laguna de Rocha and in La Paloma harbor (Fig. 6) shows that sea level has little seasonal variability and varies mostly within the range ± 0.6 m and that water level in the lagoon presents an distinct annual cycle. In Fig. 7 total sea level and lagoon water level extreme regimes, obtained from empirical peak over thresholds and annual maximums respectively, including the generalized Pareto distribution fitted to the extreme sea level data (by means of the methodology proposed by Solari et al., 2017) (see Fig. B3 in Appendix B) are presented. No distribution was fitted to the lagoon water level as these extreme data were affected by the natural and artificial openings of the lagoon, and therefore, it made no sense to extrapolate to higher return levels with a statistical model that neglected this.

The foot of the dune (in those profiles with dunes) is between levels +1 and + 1.5 m (Fig. 8), and that this is approximately the maximum level reached in the profiles of the inlet area, where there are neither dunes nor vegetation. The +1.5 m level has a return period of less than 2 years in the lagoon and approximately 20 years at sea (Fig. 7); i.e., the level that exceeds the profiles of the inlet area and foot of the dunes has a return period of ca. 20 years in the sea level statistics and a return period of less than 2 years in the lagoon water level statistics.

The analysis of the local bathymetry, wave climate, and potential long-shore sediment transport is included in Appendix B. Results showed that: (a) as expected in a wave-dominated environment, there are shallow flood shoals but no ebb shoals (see Fig. B1 in Appendix B); (b) the wave climate in the study area is mild, with most of the waves coming from the SE and with extreme waves coming from the SSE with a mean period between 9 and 13 s (see Fig. B4 in Appendix B). Significant wave height and total sea level can be regarded as independent variables for extreme conditions; and (c) mean annual gross (potential) long-shore sediment transport is approximately $3 \times 10^6\, m^3\, yr^{-1}$, while mean annual net sediment transport is two orders of magnitude smaller (see Fig. B5 in Appendix B).

In the records of natural openings, there is no information as to whether they were caused by sea action (sea level and/or waves) or by the action of the water level inside the lagoon. However, it is noted that for all cases in which levels and wave information are available for the day of the opening, the water level in the lagoon is higher than the sea level and that the wave height at breaking always remained below 2.5 m (a value corresponding to approximately the 95% percentile) (Fig. 9). On the other hand, from the results obtained by modeling the response of the beach profiles in the inlet area using the 2DV model (Gonzalez et al., 2007), it is concluded that only when the berm level is close to the mean sea level it is possible for a 1-year return period storm to breach the barrier. Given that (a) all natural openings occurred with the lagoon level higher than sea level, and (b) that for wave and sea level conditions recorded during natural openings, the numerical model shows that beach profile erosion does not result in barrier breaching, it is concluded that all of the natural openings were caused by the action of high lagoon water levels that exceed berm height in the inlet area. Thus, it seems reasonable to assimilate the maximum lagoon water level reached at the time of opening to the level of the berm in the inlet area at that moment. This supported building a series of “pseudo-measured" berm levels that were used to compare with berm levels estimated by means of equation (2). Fig. 10 compares the probability distribution function of berm levels at the inlet obtained with the two approaches, and it can be appreciated that there is reasonable agreement between them.

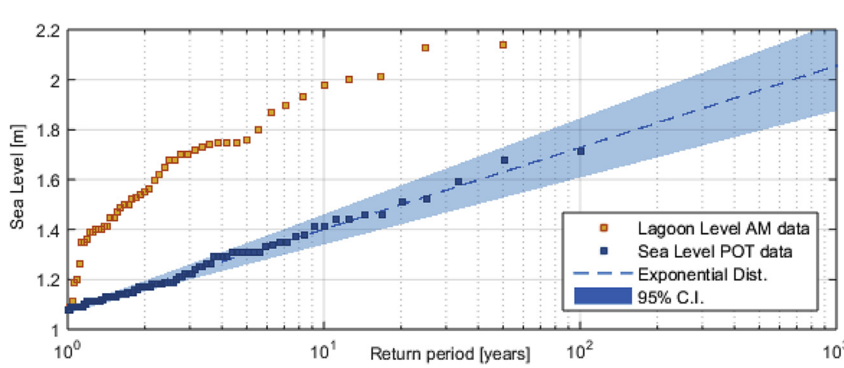

Fig. 7. Extreme value analysis of the lagoon water levels (red) and of sea level gauges at La Paloma harbor (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

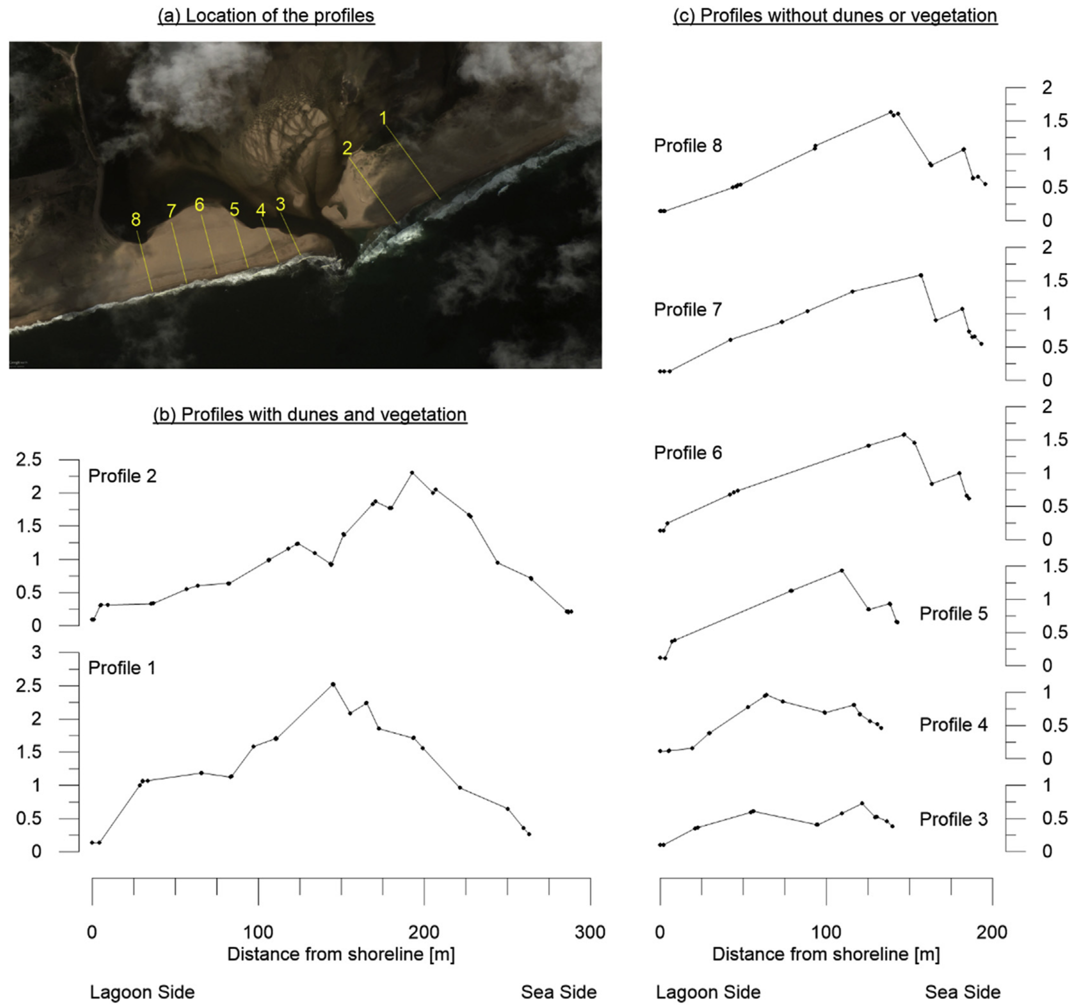

Fig. 8. Profiles of the sand barrier. (a) Location of the profiles; (b) Profiles with dunes and vegetation, located outside of the area where the lagoon usually opens; (c) Profiles without dunes or vegetation, located in the area where the lagoon usually opens.

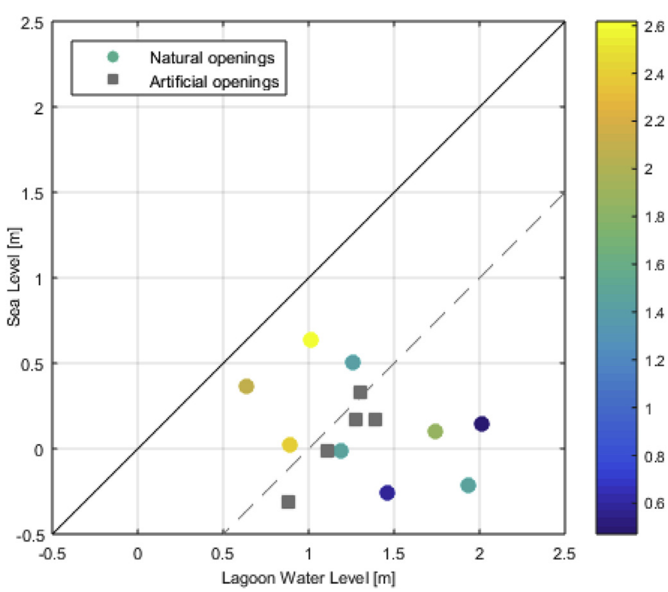

Fig. 9. Lagoon water level (LWL), sea level (SL) and significant wave height (Hs) during natural (in color) and artificial (in gray) opening events. SL = LWL and SL = LWL - 1 m lines are given as reference (continuous and dashed lines, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

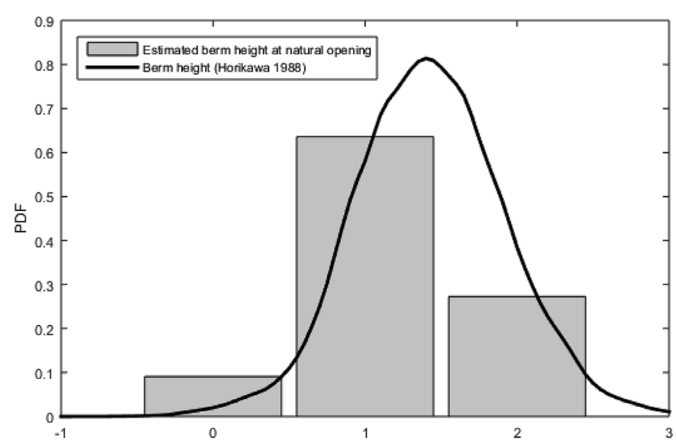

Fig. 10. Probability density function (PDF) of berm heights calculated with equation (2) (continuous lines) and frequency of berm heights estimated assuming berm heights equal to lagoon water levels during natural openings (bars).

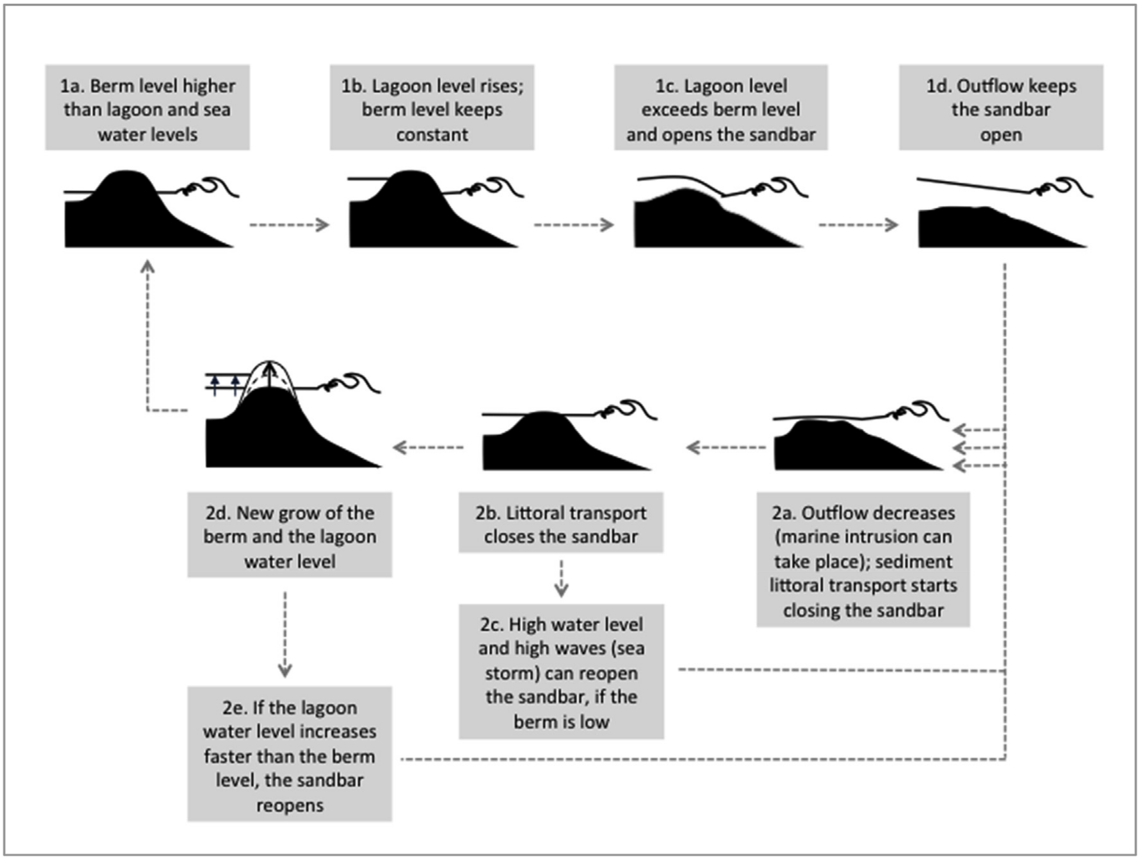

Fig. 11. Conceptual diagram of the dominant natural opening/closing mechanisms of Laguna de Rocha sand barrier (modified from Conde et al., 2015) (see text for explanation).

3.5. Conceptual model for short-term dynamics of the inlet

From the results obtained here, it is concluded that Laguna de Rocha inlet dynamics are in agreement with ICOLL dynamics as described by Haines and Thom (2007): "… catchment rainfall and associated runoff result in increasing water levels until levels reach the crest of the entrance sand berm. Once the sand berm becomes overtopped, high velocity outflows cause scour and rapid channelization. Discharge from the ICOLL continues to enlarge the entrance channel … The resulting open entrance allows tidal exchange between the ocean and the lagoon until marine sands, reworked under the action of tides and waves, once again infill the channel." A schematic for the conceptual model describing these dynamics for Laguna de Rocha is shown in Fig. 11. Starting from a condition where berm height is higher than both lagoon water level and sea level, (Fig. 11, inset 1a), the lagoon water level starts to increase until it exceeds berm height, producing the breaching of the barrier (Fig. 11, inset 1b-1c). Outflow maintains the inlet opening (Fig. 11, inset 1d) until lagoon water level and sea level equalize (Fig. 11, inset 2a). When the lagoon water level is approximately equal to mean sea level, coastal sediments progressively block the channel again, and the regrowth of the berm begins (Fig. 11, insets 2a-b and d). At this point, two situations that may lead to the re-opening of the barrier: (i) the combined action of high sea level and waves may lead to natural openings when the berm is not high enough (Fig. 11, inset 2c), and (ii) when the lagoon water level increases (e.g., rainfall event) faster than berm regrowth (Fig. 11, inset 2e).

3.6. Sand barrier artificial breaching protocol

The results of this study allowed us to develop a multi-dimensional decision-making model concerning when, where, and how the artificial opening can be done in the best way possible, considering the social and ecological implications. The purpose of the model is to minimize the artificial opening events in the lagoon along an annual cycle, and only restrict it to those occasions when all criteria and thresholds are met. The new opening mechanism is considered to be more restrictive in comparison to the previous procedure, and the justification is the evidence, locally and elsewhere, of potentially severe changes when arbitrary, uninformed, and frequent openings are done in this type of vulnerable site, as shown in the introduction.

The protocol was developed as a choice diagram, to enable comprehension and realistic use by decision makers or local people, and it ultimately addresses the fundamental issue of deciding when an artificial opening can be authorized or not. Although this is the most critical aspect of the whole problem, other relevant facets (i.e., where and how) were also addressed during the study, but they are not presented here. A reduced number of variables was used to build up the protocol, derived from the hydrological and the morphological results of the study. Nevertheless, it must be noted that the final model is heavily based on the complete set of results. For example, the protocol could not have been developed without understanding the sand barrier historical management, the stakeholders perception or the potential extension of the flooding areas along the littoral).

A string of choices is driven through simple questions (Fig. 12). The initial point considers the lagoon isolated from the ocean and a progressive increase in the water level after precipitation events in the basin. The primary question in the protocol refers to the water level of the lagoon. Presently, the water level is both measured automatically by means of a continuous water quality buoy located in the southernmost part of the lagoon and also recorded with a limnimeter placed on the shore of the sand barrier. Until the water level reaches 1.57 m OZ (value corresponding to the four "flooding marks" agreed upon in

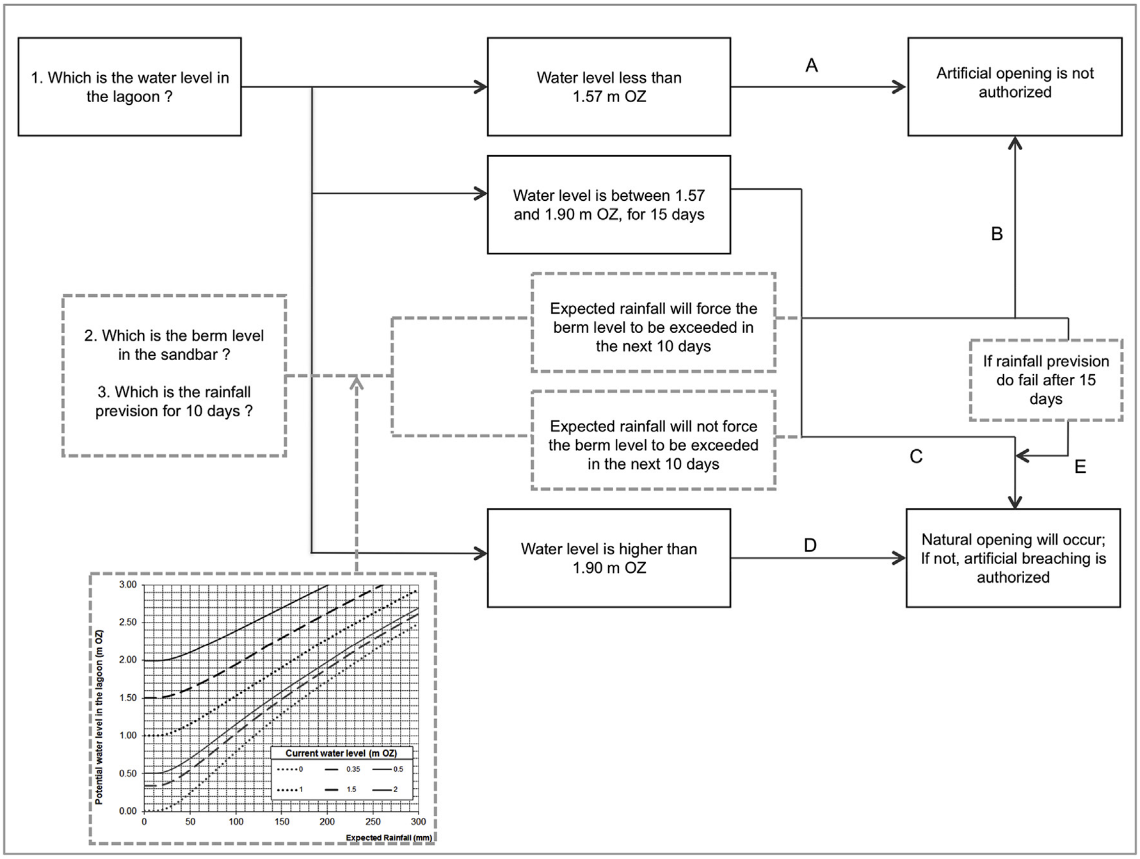

Fig. 12. Decision-making model for the artificial opening of Laguna de Rocha sand barrier (modified from Conde et al., 2015). Questions 2 and 3 arise in the protocol 5 days after water level enters the 1.57–1.90 m OZ range. Inset left below is a chart for the estimation of the probable water level of Laguna de Rocha, derived from the actual water level and the rainfall prediction.

2011), no action is suggested, as a low water level would hamper the viability of artificial opening. Consistently, at this value the water level would not yet reach private land limits, according to the hydrological model, and also no flooding occurs according to the perception of stakeholders (Fig. 12, route A).

The critical section addressed by the protocol is when the water level lays between 1.57 and 1.90 m OZ, properly considered a flooding event both technically and according to the perception of stakeholders. Inundation of cattle-raising fields as well as houses in the floodplain, and a generalized social perception of a flooding phase, triggers the request to breach the sandbar. This perception is additionally influenced, when Rocha city is flooded, by misperception of people that a closed sand barrier acts as a stopper for the water from being drained from the city sooner. Nevertheless, hydrological modeling has already demonstrated that even if the water level of the lagoon would ascend to a totally unrealistic level of e.g. 4 m, there would be no influence upstream that would worsen a flooding event occurring in Rocha city (see details in Conde et al., 2015).

Once water level enters the 1.57–1.90 m OZ range, the protocol triggers an alert to prepare to eventually proceed to the artificial opening, but only if the water level remains in the reported range for more than 15 days. It is assumed that most of the beneficial ecological processes associated with the flooding phase will be already attained in this period. The value 1.90 m OZ represents the maximum water level observed in a recent artificial opening (June 2013), and indicates roughly when sand barrier houses start to flood. This value is assumed as a typical water level prior to a natural opening. After 5 days inside the range, the next questions arise, concerning rainfall prediction and if the water level in the lagoon is getting close to the berm height, enabling natural sand barrier breaching. If a rainfall event is likely to occur in the watershed in the next 10 days (a prediction with acceptable accuracy), and the concomitant increment of the water level is estimated to exceed the height of the berm (monitoring of the berm height is done permanently by rangers), the assumption is that it is highly probable that a natural opening will occur within the 15-day period, so no sand barrier control action should be taken (Fig. 12, route B). If the rainfall predicted is low, or if the berm is very high, the natural opening is not likely to happen, so the artificial opening has to be authorized to alleviate flooding (Fig. 12, route C). A specific rainfall-runoff model based on NRCS (USDA, 2010) was formulated to estimate a probable water level, derived from a given water level and expected rainfall in the watershed (Fig. 12, inset left below). If the predictions that the berm would be exceeded failed, the opening should also be authorized (Fig. 12, route E).

The protocol assumes the sand barrier will open naturally immediately after the water level reaches 1.90 m OZ (Fig. 12, route D); therefore, only monitoring is required. If a natural opening does not occur after a prudential time (e.g., several hours), the protocol prompts opening the lagoon artificially. This situation can particularly occur when extreme rainfall events strike in a few hours when the lagoon already has a high-water level (e.g. in August 2013; water level increased from 1.90 to 2.17 m in less than 12 h). Although the return period of a similar flooding event is 5–10 years or higher, acceptable land planning in this lagoon should strongly promote the migration of littoral houses to safer places, particularly in the sandbar, to promote pile-dwelling type of structures, and to definitely ban new urbanization sites in the floodplain (Conde et al., 2105).

4. Conclusions and perspectives

Despite a diversity of human disturbances affecting the Laguna de Rocha sand barrier during the last decades, its deliberate artificial opening probably exhibits as its most critical threat, because of the fragility and uniqueness of this zone (Rodríguez-Gallego et al., 2013). The present study shows how this disturbance has introduced a new physical dynamic equilibrium to the lagoon and has defined attractors that could generate points of non-return to pre-disturbance conditions if management actions are not taken. The product of our study is a protocol which has been legally endorsed by the Ministry of the Environment of Uruguay. The protocol is being tested now and it is assumed that adjustments will be necessary to cope with changes due to natural variability (e.g., changes in precipitation pattern or dune dynamics), new research evidence (e.g., effects of the lagoon-ocean connection on ecosystem services provision), or emerging new social circumstances (e.g., evolution of littoral urbanization, application of the protected area management plan). Forthcoming steps concerning protocol adjustments include permanent monitoring of its practical implementation (e.g., simplification of the decision tree for managers; improvement of the rainfall forecast through refined models) as well as of the final environment results (e.g., water quality; fisheries evolution).

From a technical point of view, consistent results between changes in historical images, lagoon hydrology, and the sedimentological data of the sand barrier area, combined with historical information and local ecological knowledge, were obtained. Combined geomorphological and hydrological results indicate that the sand barrier of the lagoon is a recent sedimentary sequence of extreme vulnerability, both to natural- and human-driven changes. Although its opening mechanism has been modified by a progressively incremented marine energy relative to hydraulic lacunar forcing, the inner forces still do prevail. It is highly reasonable to argue that this ongoing imbalance is a consequence of the long-term artificial breaching. It is assumed that the new artificial breaching mechanism will contribute to recovering the lost hydraulic energy and, at the same time, maintaining the flooding period as close to the natural conditions as possible, along with ecological and social benefits.

To further understand the evolution of the sand barrier system in Laguna de Rocha, as well as the success of the new protocol, variables linked to climatic change and variability should be better integrated into the model (i.e., sea level and wave energy escalation, modification of coastal wind pattern, or persistent expansion of internal banks). A predicted increase in sea level of approximately 15 cm for 2030 in this coast has been reported (Nagy, 2012), suggesting an amplified erosive effect on the sandbar, especially when occurring simultaneously with wind tides of 2 m above sea level. These potential alterations indicate the possibility of scenarios where previous natural breaching zones along the sand barrier could be reactivated, modifying the connection dynamics between the lagoon and the sea. It is expected that under more intricate scenarios like the ones expected in this latitude, consequences will depend not just on the response of the natural system but also on the management actions implemented. This will eventually lead to major modifications in the present breaching protocol.

Efficient long-term implementation of the new system poses, at the same time, challenges to management, the local participatory process, and scientific research. The management recommendations derived from this study are significant progress towards a consensus-based and knowledge-base decision-making practice concerning the artificial opening of the sand barrier of this lagoon, and it is of note that they could be transferred or adapted to other coastal lagoons, once successful testing of the effectiveness of the present mechanism is completed in Laguna de Rocha. A plan to reallocate houses to a non-flooding safe area is also urgently needed. The new protocol will be a significant contribution, given the contrasting evidence concerning the benefits and costs of manipulating sand barriers and also because results from lagoons in other coastal contexts cannot be directly extrapolated (Esteves et al., 2008).

Acknowledgements

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Appendix A. Sand barrier sedimentary description

Table A1
Mineral frequency of the fine-grained fraction in several sediment sampling sites along the sand barrier of Laguna de Rocha (locations of sampling sites are shown in Fig. 5 in the main text, upper panel with correlative numbers; samples 0 and 10 come from the holocenic ends of the sandbar; samples 1 to 9 were obtained from inner and younger sectors of the bar). Qz = Quartz; KF = K-Feldspar; Pg = Plagioclase; Amp = Amphibole + Pyroxene; Gr = Garnet; Tu = Tourmaline; Sph = Sphene; Zr = Zircon; Mta = Magnetite and other opaque minerals; Ep = Epidote; Biot = Biotite.

Sample	Qz	KF	Pg	Amp	Gr	Tu	Sph	Zr	Mta	Ep	Biot	Field description
0	59	15	5	1	1	1	0	1	16	0	1	Very coarse sand well-graded
1	47	16	8	3	3	2	0	1	20	1	0	Coarse sand well graded
2	47	16	8	2	4	2	0	1	20	1	0	Medium sand well graded
3	48	16	8	3	4	3	1	0	15	2	0	Medium sand well graded
4	49	16	8	3	3	2	0	1	16	1	0	Medium sand well graded
5	52	17	9	3	3	0	0	0	16	0	0	Inorganic silt/Medium sand
6	46	15	8	3	5	3	0	1	16	2	0	Mud/Medium sand well graded
7	45	15	7	4	4	3	0	1	20	1	0	Organic silts low plasticity
8	50	17	8	3	4	0	0	1	16	1	0	Medium sand well graded
9	48	16	8	4	4	2	0	1	16	1	0	Organic soil/Medium sand

Table A1 shows that the grain size of the sediments of the sand barrier was characterized as coarse to very coarse sand, rich in quartz; however, occasional strata of sandy silts and organic-plastic muds were also found, suggesting the existence of several openings in the past. The lithic fragments were angular, fresh, and of continental (metamorphic) origin, and the sedimentary sequence exposed, at its base, a histic Gleysol horizon located 1 m above actual mean sea level, dated 2660 ± 50 ^{14}C yr BP (2795 ± 39 cal yr BP). Over this deposit, the sedimentary sequence that currently closes the lagoon is built up of sand ridges interbedded with organic clayey silt, and it was observed to have a thickness of more than 120 cm.

Appendix B. Wave climate and potential long-shore sediment transport analysis

This Appendix includes the analyses of local bathymetry data, wave climate, and potential long-shore sediment transport. Fig. B1 shows the bathymetry from the nautical chart and the bathymetry of the Laguna de Rocha and the nearshore area performed during this study. Location of lagoon water level and sea level gauges (blue dots) and of the wave virtual buoy (red dot) are included in the map. It is noted that although there are shallow flood shoals (i.e., a flood delta), there are no ebb shoals (i.e., there is no ebb delta), something characteristic of inlets located in wave-dominated environments (see e.g., Davis and Fitzgerald, 2004).

Figs B2 to B4 show characterizations of the waves at the virtual buoy, including both normal or mean annual conditions and extreme conditions. Fig. B2 shows the scatter plots of significant wave height and sea level and significant wave height and mean wave period. From these results, it is noted that wave climate in the study zone is mild, with most of the waves coming from the SE quadrant and with short periods. During storm conditions waves come mainly from the SSE direction (normal to the coast in the lagoon area) and have a mean period between 9 and 13 s. Regarding the joint occurrence of extreme sea levels and waves, it is noted that although high waves tend to occur with sea levels above average, there is no clear correlation between extreme waves and extreme sea level; it can be observed that extreme sea levels occur with moderate waves while extreme waves occur at sea levels below the threshold considered to determine the sea level extreme regime (shown in section 3.4). Fig. B3 shows the extreme regime of significant wave heights along with the generalized Pareto distribution fitted to the data, following the methodology of Solari et al. (2017). Fig. B4 shows two wave roses, one for all data and the other for waves with significant wave height greater than 3 m.

Fig. B5 shows the series of accumulated sediment volume transported through a beach profile at the inlet area. Although the net sediment transport in the whole period is negative, there are cycles in which the net transport fluctuates between positive and negative values. This could explain the periods of migration of the inlet in both directions; however, the study of inlet migration is outside the scope of this work.

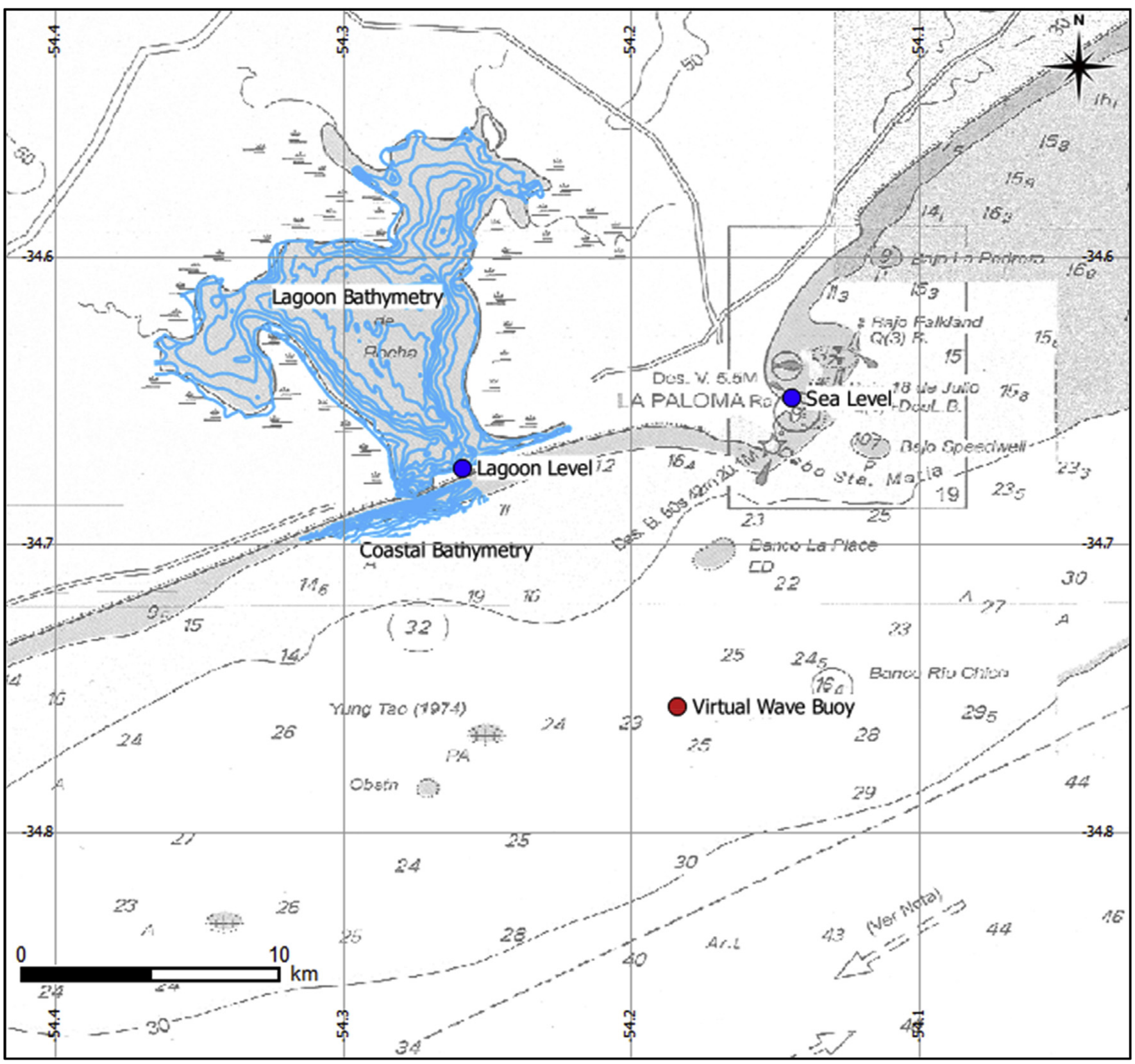

Fig. B1. Bathymetry from the nautical chart (in gray scale), Laguna de Rocha and nearshore area surveyed bathymetry (light blue), location of lagoon water level and sea level gauges (blue dots) and location of the wave virtual buoy (red dot).

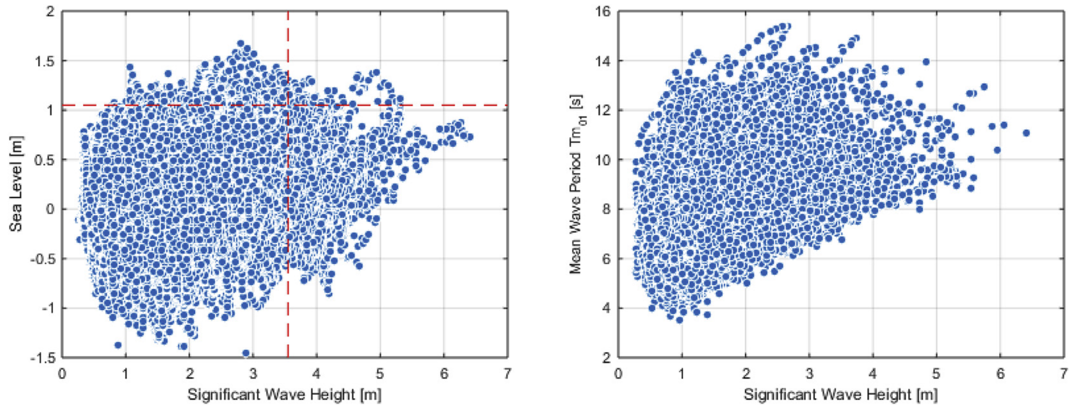

Fig. B2. Scatter plots of significant wave height (Hs) and sea level (left) and significant wave height (Hs) and mean wave period (right).

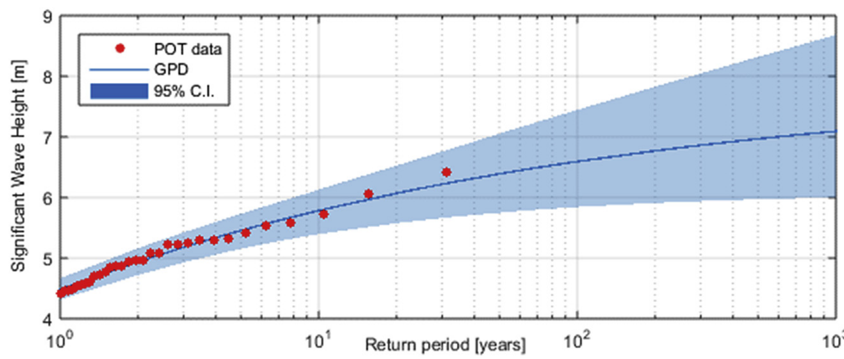

Fig. B3. Extreme value probability distribution of wave height (Hs) at the virtual buoy: data (dots) and generalized Pareto distribution (line) fitted to the data, along with the 95% confidence interval.

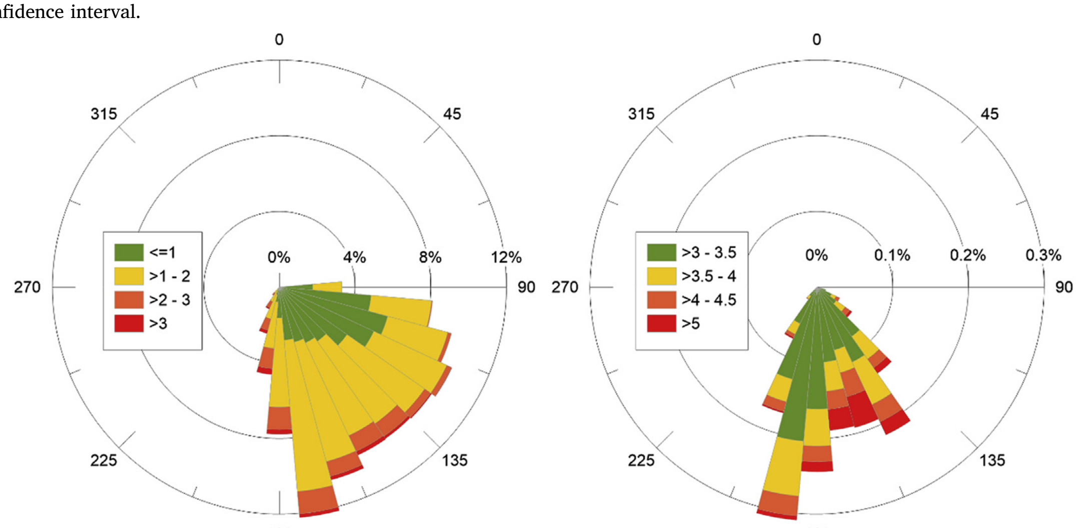

Fig. B4. Wave roses at the virtual buoy (see Fig. 2). Left: all data. Right: data with wave height (Hs) > 3 m. Colors refer to significant Hs.

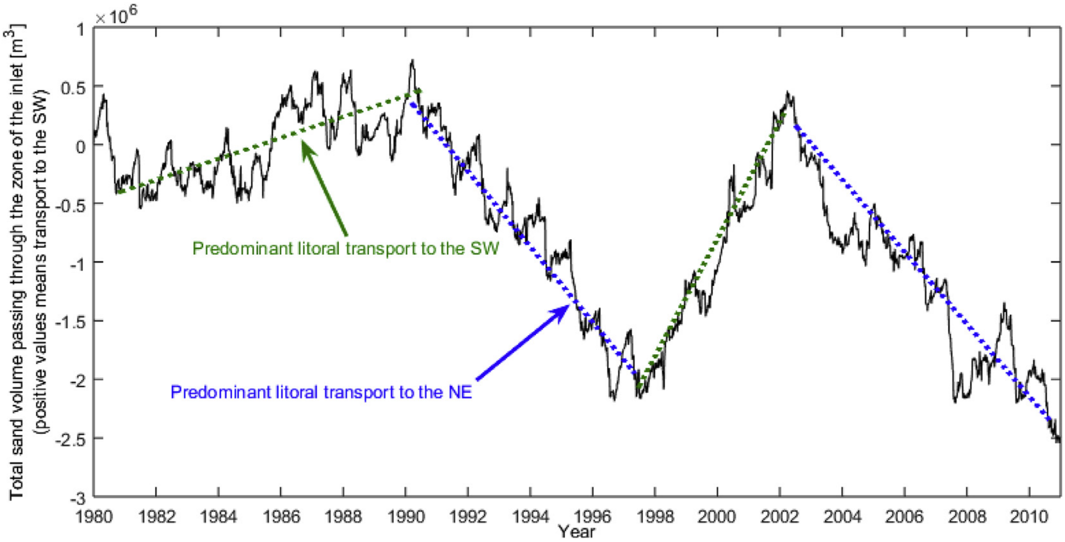

Fig. B5. Accumulated potential long-shore sediment transport through a beach profile at Laguna de Rocha inlet. Increasing values correspond to westward net transport and decreasing values correspond to eastward net transport.

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