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EARTH SCIENCES

Wave energy distribution at inlet channel margins as a function of ebb tidal delta morphology: Cananéia Inlet, São Paulo, Brazil

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Abstract: Wave energy gradients between and along the margins of inlet channels play an important role in defining the inlet margins' evolutionary processes, mainly those related to spit erosion or accretion, and inlet migration. The aim of this study is to understand the wave power distribution along the margins of a tidal inlet (Cananéia inlet, São Paulo, Brazil), its variation over time, and the influences of the ebb tidal delta morphology on the incoming waves. To evaluate changes in bathymetry and morphology of submersed features, we apply geoprocessing techniques to analyze nautical charts from the Brazilian Navy from 1939, 1971, 1985 and 2004. The numerical model MIKE21 SW was applied to assess wave propagation and nearshore wave power. Hence, wave energy levels along the inlet margins were assessed in terms of decadal morphological changes. The results indicate a dynamic behavior of the inlet and ebb tidal delta, pointing to the ebb tidal delta as the main transforming agent of the waves that reach the inner portion of the channel. The morphological changes of the ebb tidal delta over the last decades are critical to define the action of waves on the margins of the inlet.

Key words: wave action, ebb tidal delta, tidal inlet, numerical modeling.

INTRODUCTION

Inlets are dynamic and complex systems that are controlled by the interaction of several factors, such as morphology, tides, wave energy and river discharge. The combined action of these processes produces complex circulation patterns that lead to a variety of depositional features (Wright & Coleman 1978, FitzGerald et al. 2000, Siegle et al. 2004, 2007, Pianca et al. 2014). The coastal inlet systems can be divided into three main regions that include the following: an oceanic portion, covering the outer sedimentary bodies (ebb delta) and one or more channels; the main channel, corresponding to the region with minimal cross-sectional area; and an inner portion, with its sandbars (flood delta) and channels (Bruun 1978).

Ebb tidal deltas are sedimentary features whose settings are determined by the interactions between continental drainage and drift currents (Oertel 1975). They can be classified according to the relative importance of the processes involved in their formation and maintenance as follows: tide-dominated deltas are characterized by more extensive channels and oriented transversely to the coast, and wave-dominated deltas are divided into three types, of which two are related to conditions of strong longshore currents and one occurs in situations of slow longshore currents (Davis Jr 1994).

The presence of the inlet and its associated features causes the interruption of sediment transport along the coast, affecting the supply of sediment to the adjacent coastline, creating erosive and depositional patterns on adjacent beaches (FitzGerald 1988). Ebb tidal deltas are also important as temporary or permanent sediment reservoirs and their morphology affects the distribution of wave energy along the coast, working as a natural barrier to the action of waves protecting the coast from erosion processes (FitzGerald 1996).

The Cananéia inlet is located in the southern portion of the Cananéia-Iguape estuary-lagoon system (south of São Paulo State, Brazil). The inlet margins are formed by the northern portion of Cardoso island and the southern portion of Comprida island, and it is the largest communication channel of this estuarine system. Due to its morphological characteristics, it is the main navigation channel in the region (Pisetta 2006). However, mainly due to the extreme mobility of submerged sandbars (Suguio & Tessler 1983), difficulties in navigation through this channel have been described by navigators since the 18th century (Geobrás 1966). Later, this set of mobile sandbars was described as an ebb tidal delta (Bonetti Filho & Furtado 1996).

The morphology of the inlet and its associated ebb tidal delta may affect the local coastal dynamics, navigation and land use. In this study we examine the wave action on the Cananéia inlet margins, assessing the importance of the ebb tidal delta on incoming waves. Such studies are unprecedented for the region and provide information on the importance of submerged morphology and inlet evolution, with consequences on adjacent coastline changes.

Study area

The Cananéia inlet, located between latitudes 24°37'S and 25°07'S and longitudes 47°23'W and 48°05'W, is part of the Cananéia-Iguape estuarine-lagoon system (Figure 1). The inlet is limited by Comprida island in the north and Cardoso island in the south. The channel is approximately 2 km wide and has an average depth of around 15 m in the estuary, which decreases toward the ocean, reaching 3-5 m in the wave action area due to the formation of sandbars. Difficulties navigating through the channel because of the continuous migration of sandbars have been reported since the 18th century (Geobrás 1966). Bonetti Filho & Furtado (1996) have described these mobile sandbars as an ebb tidal delta.

The region is subjected to a microtidal regime, with semidiurnal tides ranging from 1.3 m to 0.83 m during spring and neap tides, respectively (Miyao & Harari 1989). Regional climate is characterized by an average annual temperature of 23.8 °C and an annual rainfall average of more than 2,200 mm. Rain is distributed regularly throughout the year; although, there is a rainier period from December to April (rainfall above 200 mm) and a drier period from May to November (with lower precipitation values but never under 80 mm). The transition from one period to the next is gradual (Silva 1989).

The pattern of incident waves is closely related to meteorological events. In southeastern Brazil, the meteorological events are characterized by the alternation of two domains of air masses. The first is tropical air masses coming from the Atlantic Tropical Anticyclone (ATA), which generate ocean winds to the continent throughout the year, producing waves from the NE-E quadrant that have a maximum height ranging from 0.5 to 1.0 m. The second is the domain of polar air masses associated with the Polar Mobile Anticyclone (PMA), preceded by the cold fronts, which produce waves from the SE-S-SW quadrant with a maximum height of more than 2 m (Santos 2005). The passages of frontal systems in the South Atlantic generate winds and waves from the eastern and southern

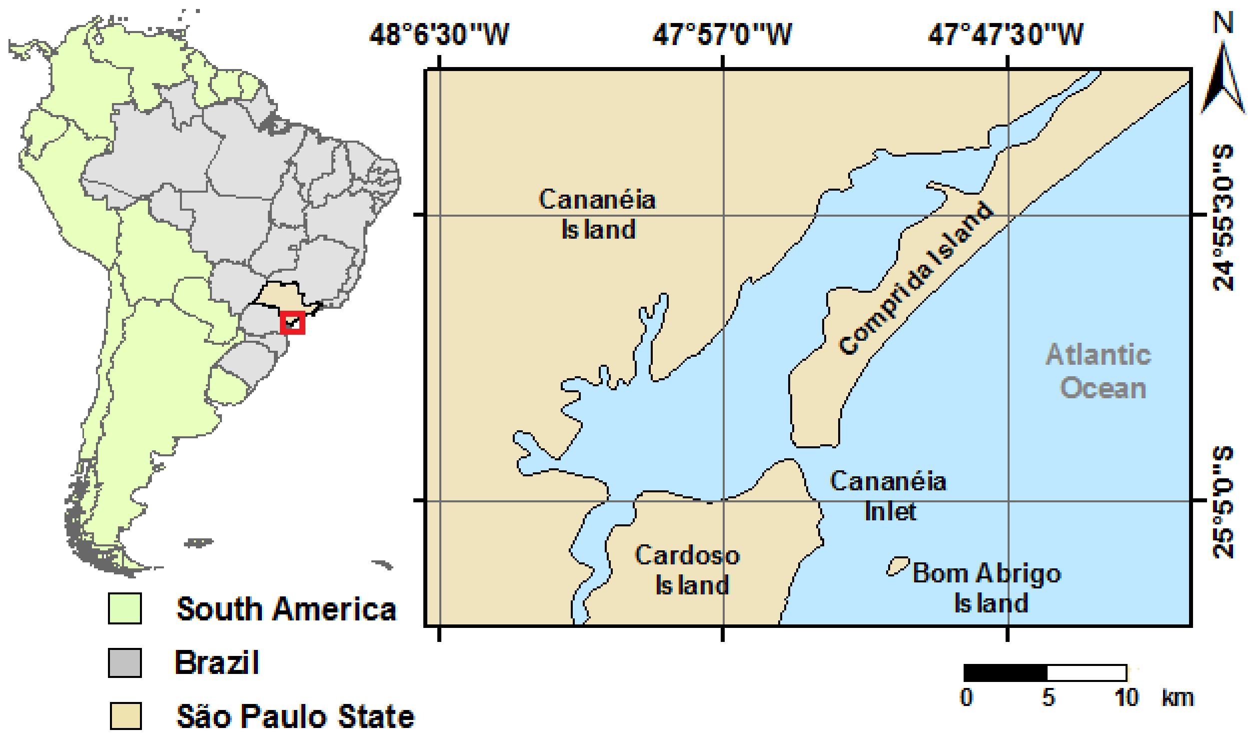

Figure 1. The Cananéia inlet at the southern portion of the Cananéia-Iguape estuarine system.

quadrants (Pianca et al. 2010), creating a seasonal pattern of longshore transport (Silva et al. 2016).

The main freshwater contribution to the system is that of the Valo Grande channel, an artificial channel opened in 1841 that connects the Ribeira de Iguape river to the estuary-lagoon system (Bonetti Filho & Miranda 1997), which has a watershed area of approximately 23,350 km^2 (Mishima et al. 1985).

METHODS

The applied methods combine geoprocessing tools and historical data (nautical charts) with the application of a numerical model in order to assess the morphological evolution of the channel, the associated ebb tidal delta, and its effects on the wave energy levels around its margins (Figure 2).

Geoprocessing techniques

Bathymetries have been extracted from the Brazilian Navy's nautical charts of the Directorate of Hydrography and Navigation (DHN). Four versions of nautical chart no. 1703 (Cananéia Harbour) for the years 1939, 1971, 1985 and 2004 were used to reconstruct the bathymetries for each year. The charts were georeferenced to the WGS 84 datum in UTM projection zone 23S using the ArcGIS® 9.3 georeferencing tool. Interpolation and further geoprocessing techniques, such as ebb delta volume and area definition were carried out with Surfer® 10 software. The delta was defined using the 5 m isobath as a baseline. Using the same software, cross-shore and alongshore bathymetric profiles have been extracted to compare and analyze morphologies from different periods. The total volume of the delta was calculated through the trapezoidal rule for each bathymetry.

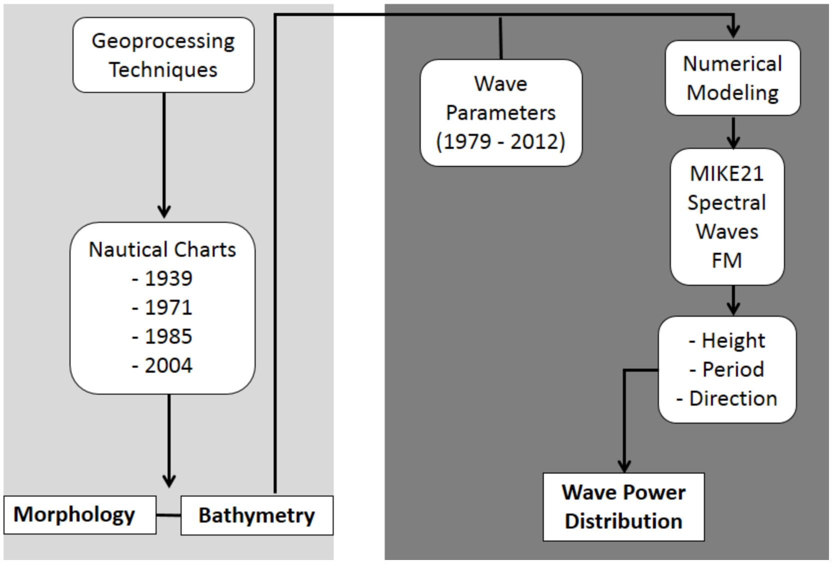

Figure 2. Schematic flowchart synthesizing the applied methods.

Wave parameters

Wave parameters (significant wave height, direction and peak period), from 1979 to 2012 were obtained from the global wave generation model WaveWatch III (NOAA/NCEP - National Oceanic and Atmospheric Administration/ National Centers for Environmental Prediction). The model used is based on the balance equation of the spectral action density for the directional wave spectrum and considers the processes of growth, decay and refraction for each specific frequency. Additional information related to the model can be found in Tolman (1999). Then, wave information was extracted for coordinates 26°S and 45°W and used for wave climate characterization through basic statistics.

Numerical modeling

To propagate the waves onshore, the two-dimensional third-generation numerical model MIKE21 Spectral Waves FM, developed by Danish Hydraulic Institute (DHI), was applied. This model describes the growth, decay and transformation of wind-generated waves and swell in oceanic and coastal waters (DHI 2007). The basic equations in MIKE21 SW are derived from the conservation equation for the spectral wave action density based on the approach proposed by Holthuijsen et al. (1989). Additional information about the model formulation can be found in Holthuijsen et al. (1989), Komen et al. (1994) and Young (1999).

The model domain is approximately 100 km alongshore and 80 km offshore. It is limited to the north by the Icapara inlet and to the south by the Superagui channel, and from the coastline to the continental shelf up to depths of approximately 60 m (Figure 3).

Four unstructured and flexible computational meshes were generated for the simulations, one for each morphological situation. We used three different resolution levels, increasing towards the area of interest (Figure 3). All meshes were created to be as similar as possible, making adjustments only related to differences in morphology and coastline position.

Combining wave scenarios and the four different morphological conditions, a set of simulations was run. To analyze the influence of the ebb tidal delta in wave propagation toward the margins of the inlet, ten simulation

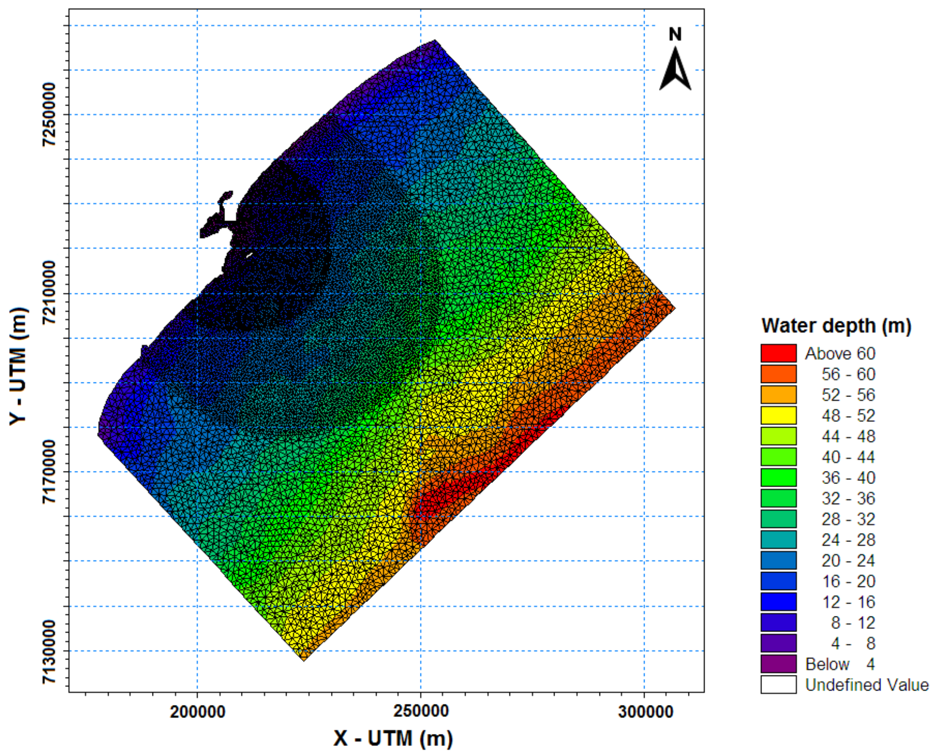

Figure 3. Model domain representation with elements of the computational mesh and interpolated bathymetry of the situation found in the 2004 nautical chart.

scenarios have been prepared for each of the four bathymetric situations. Eight of them were based on the parameters of incident waves with frequency of occurrence greater than 5%, and the other two were hypothetical scenarios of an extreme situation, with varying incidence direction of the highest observed wave condition. The specifications of the wave parameters, direction (in degrees), significant height (in meters) and peak period (in seconds), used in each scenario are presented in Table I.

From the results obtained in the simulations, the significant height, peak period and wave direction were extracted at specific points along the coastline of the channel margins (at a distance of approximately 100 m from the shoreline), as well as before and after the ebb tidal delta. Then, the wave power (P) was calculated for these points, according to the linear wave theory exposed in Holthuijsen (2007) and estimated from Equation (1):

$$P=\frac{\rho g^2 H^2 T}{32\pi} \quad (\mathrm{W/m}) \qquad (1)$$

where ρ is the density of sea water (1,027 kg/m^3), g is the acceleration of gravity (9.8 m/s^2), H is the significant wave height (in meters) and T is the peak period (in seconds). Results are presented in the form of wave power distribution maps and comparative plots of wave power at different points in the region of interest.

RESULTS AND DISCUSSION

Through the visualization of bathymetric data, presented in maps and digital terrain models, we could identify the ebb tidal delta (Figure 4). This feature is composed of curved shallow sandbars in front of the inlet and it has an asymmetric morphology, as the sedimentation is more intense in the vicinity of Cardoso island than Comprida island. This is probably due to the differentiated wave action in the region, caused by the presence of Bom Abrigo island to the south, which protects this portion of the most energetic waves coming from ESE, SE and SSE, as well as by the effect of the hydraulic jetty caused by the action of the inlet flows on the longshore currents.

The digital terrain models also show that the northern margin is characterized by a steeper relief and with greater depths in relation to the southern margin. This is due to the presence of the main channel of the inlet, a channel constantly excavated by the tide, and located in the northern part of the inlet.

Comparing the cross-shore profiles (Figure 5) some morphological changes in the ebb tidal delta can be identified, as there is migration to the northeast and growth seaward. The growth of the submerged features towards the ocean may be related to the depositional processes observed at the eastern limits of both margins by some authors such as Tessler et al. (1990), Conti et al. (2012) and Gagliardi (2013), pushing the inlet migration in that direction. Furthermore, the largest extension of the main channel in the oceanic direction, carrying more sediment to offshore, results in seaward growth of the ebb tidal delta.

Table I. **Wave parameters used in each simulation scenario.**

Scenario	Direction (°)	Height (m)	Period (s)
Case 1	86.58	1.29	7.44
Case 2	85.15	1.73	7.74
Case 3	134.54	1.74	9.21
Case 4	182.12	1.30	10.89
Case 5	183.20	1.76	10.67
Case 6	184.55	2.23	10.87
Case 7	186.34	2.72	11.29
Case 8	85.79	2.21	7.99
Extreme 1	185.00	6.76	13.01
Extreme 2	85.00	6.76	13.01

From the analysis of alongshore profiles, it was found that the channel migration has been in the northeast direction (Figure 6). The migration to the northeast is consistent with the erosive tendency of the northern margin of the inlet and with longshore currents with a predominant direction to the northeast, according to regional wave climate and agreeing with Silva et al. (2016). The western end of the northern margin, known as Ponta da Trincheira, presents an expressive erosive tendency that has been identified by other authors since the 1950s, such as Sadowsky (1953, 1954), Tessler et al. (1990) and Conti et al. (2012). In terms of morphology it was possible to observe that the main channel of the inlet became narrower and longer over time, and the maximum depths were reduced but staying around 20 m.

Figure 7 shows some of the morphological changes of the inlet and delta mentioned above, such as the erosion of the northern margin of the inlet, northeasterly migration of the channel and delta, and seaward growth of the delta. It was possible to verify expressive depth changes in the region of the inlet, reaching vertical variations greater than 4 m, and the accentuated predominance of erosive processes in the north margin and depositional ones in the south margin. The widening of the seaward portion of the inlet is also observed. This may have contributed to the increase of depositional processes in the outer part of the channel, with consequent depth reduction. Over the years, the main channel migrated to the northeast and narrowed concomitantly, as observed in the bathymetric profiles parallel to the coast. Additionally, analyzing bathymetric maps, we observed that the channel increased in extension toward the ocean and reduced its maximum depths.

In the ebb tidal delta, coastal erosion processes predominated in the southern part

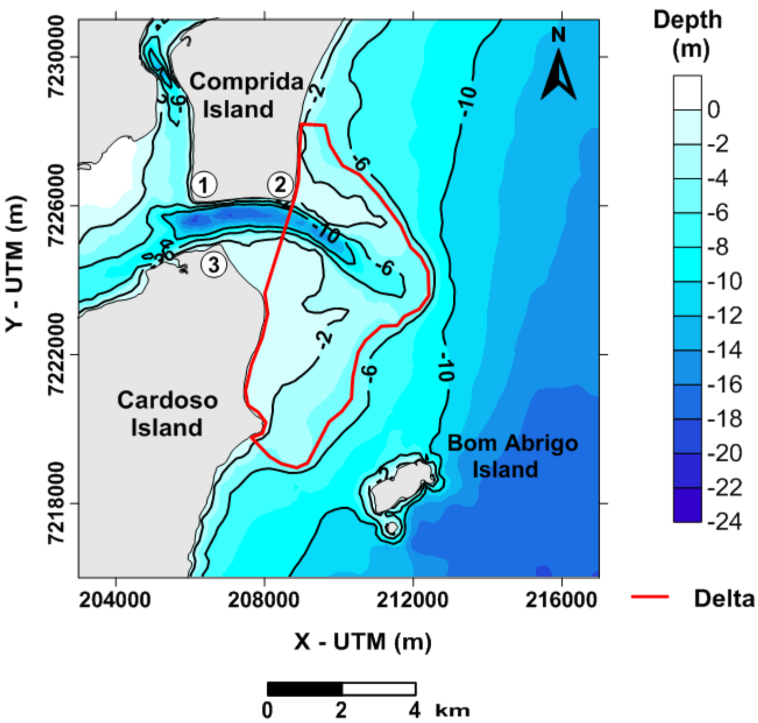

Figure 4. Bathymetric map of the Cananéia inlet region, generated from the data of nautical chart no. 1703 (2004), showing the location of the Ponta da Trincheira (1), Pontal de Fora (2) and Ponta do Perigo (3).

and depositional processes predominated in the north and central parts, which may be related to a higher sediment input in these portions due to the migration of the channel to the northeast.

Figure 8 shows that during the analyzed period there was a predominant increase in the total volume of the ebb delta, which almost doubled. In 1939, the total volume was estimated at 22 million m^3 and in 2004 its volume increased to approximately 40 million m^3. Such a volumetric increase may be related to a higher sediment supply coming from the adjacent coastal area through longshore drift currents and also coming from the inlet, which have a river origin or result from the erosion of the inlet margins. The relative decrease of the wave forcing in compare to the tidal currents can also contribute to the volumetric increase of the sedimentary feature. Another important factor in determining the size and morphology of the ebb delta is a tidal prism change (Elias & Van der Spek 2006, Dallas & Barnard 2011).

As observed in Figure 9, the wave climate of the region is characterized by predominant waves from the south (42.88%), east (25.16%) and southeast (18.05%), with waves from the southern quadrant presenting larger amplitudes and periods. Moreover, the most frequent significant heights are in the range of 1.5 to 2.5 m (54.73%), and the peak periods are more frequent between 6 and 10 s (59.89%). In this region, waves from the southern quadrant are more frequent in the winter period and are the most energetic waves.

By analyzing the wave power distribution maps along the margins of the Cananéia inlet, weighted as a function of the frequency of occurrence (Figure 10), it is verified that wave power which reaches the northern margin is higher in relation to the wave power on the southern margin. The presence of Bom Abrigo island to the south generates a shadow zone that protects the northern portion of Cardoso island from waves coming from the south and southeast, in addition to the orientation of the

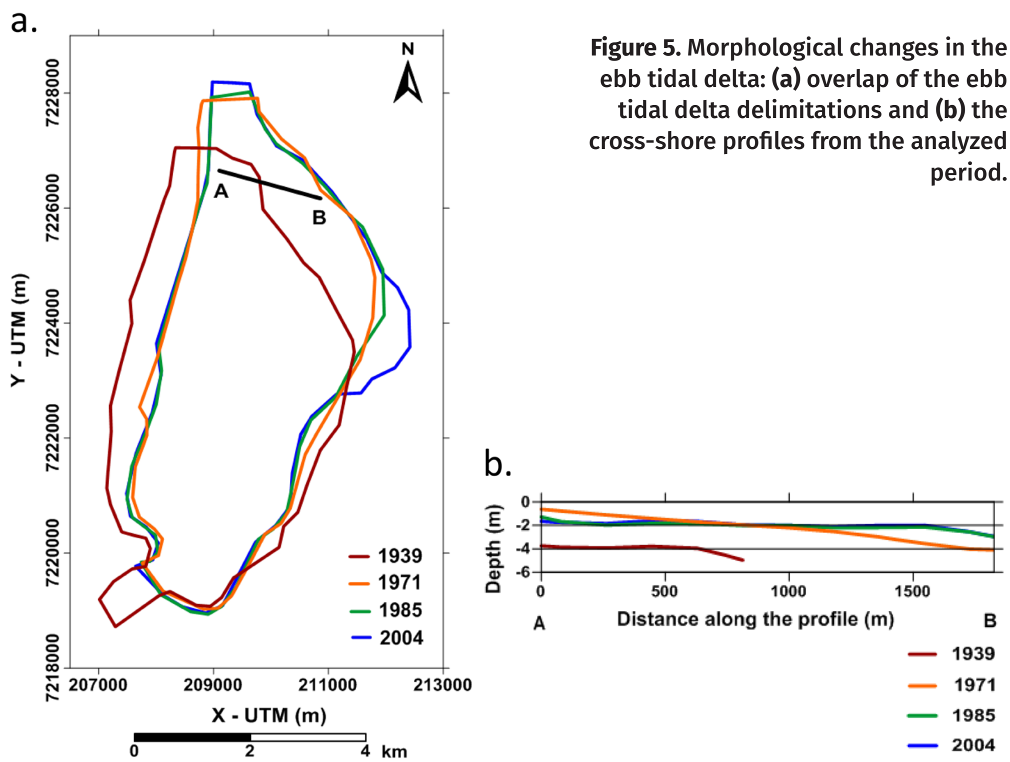

Figure 5. Morphological changes in the ebb tidal delta: **(a)** overlap of the ebb tidal delta delimitations and **(b)** the cross-shore profiles from the analyzed period.

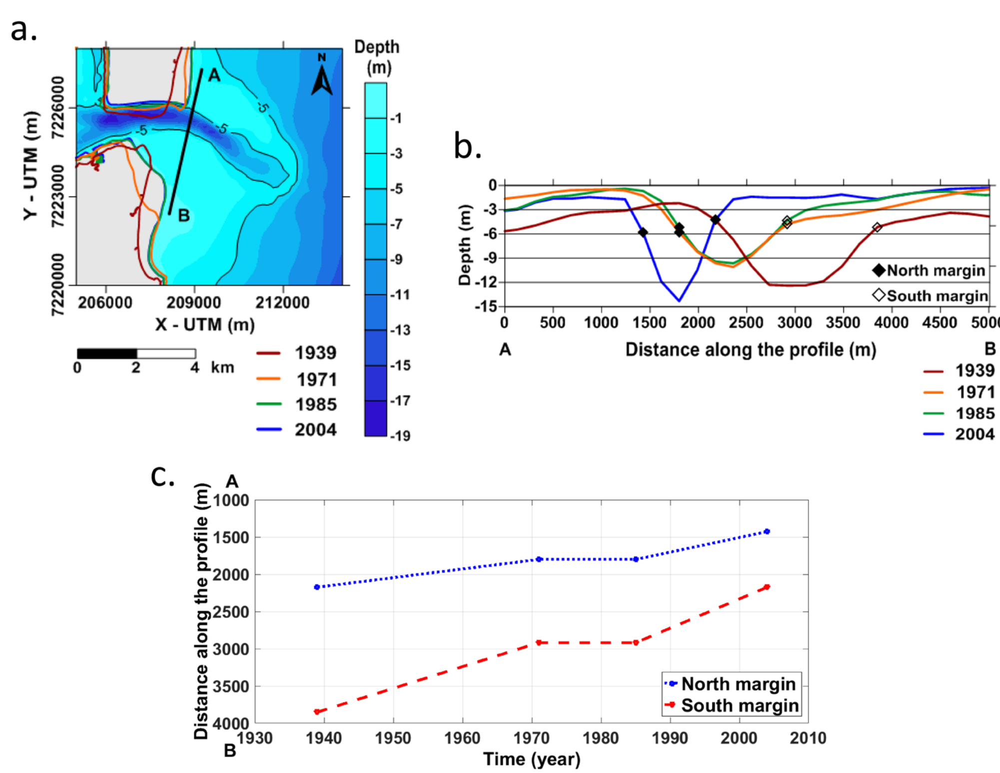

Figure 6. Migration of the channel over time for an alongshore profile NE→SW: **(a)** location of the profile, **(b)** channel margins identification from the 5 m isobath and **(c)** variation in the position of the margins over the period.

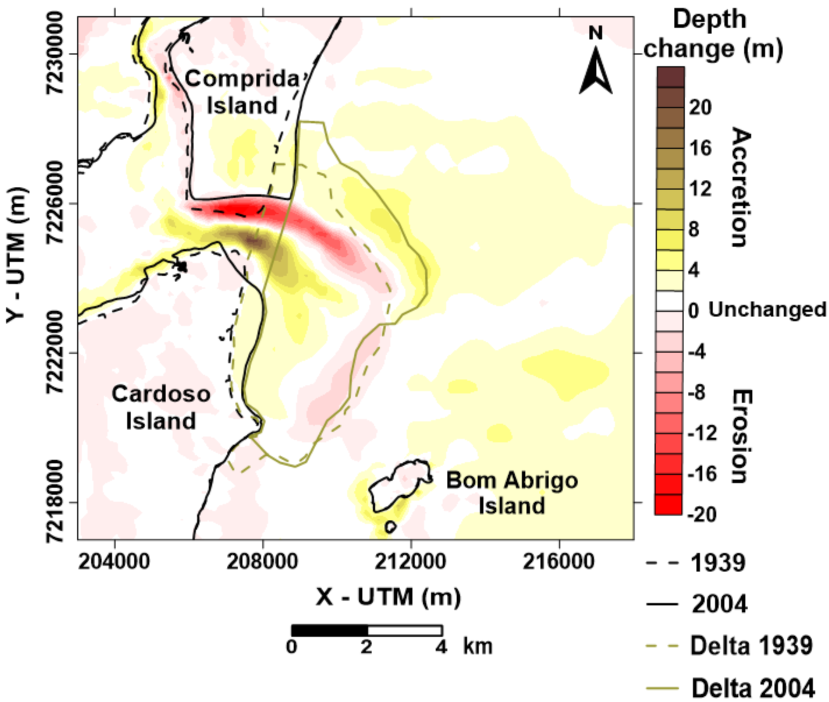

Figure 7. Erosion/accretion map showing the difference between the 1939 and 2004 digital elevation models.

coastline itself. The results also show that the wave power that reaches both margins tends to decrease over the years due to the increase in volume of the ebb tidal delta and the decrease in the depths around the inlet over the analyzed period.

Although they are not the most frequent type, waves from east are common in the winter season and have an important role in defining the inlet morphology. The scenario that contributes with the most wave power to both margins for the four bathymetric situations is represented by easterly waves, with 2.2 m height and period of 8 s (Case 8 - Table I). Under extreme conditions, the wave power increases on both margins, with the northern shore being more exposed to wave energy.

Through the numerical simulations of waves, processes such as refraction, shoaling, energy dissipation and breaking were also observed as the waves pass the ebb delta, leading to a significant reduction in wave power. As wave power is the wave energy flow, we can say that there is wave energy dissipation because of the delta. Over the ebb tidal delta, the water depth decreases and bottom friction, refraction and wave breaking dissipate more than 70% of the wave energy. This energy dissipation increases over time, being consistent with the morphological changes of the delta (Figure 11). Numerical modeling results suggest that the ebb tidal delta plays an important role in dissipating wave energy through wave refraction, and can reduce wave heights by about 50% (Barnard et al. 2007).

Despite limitations related to the numerical modeling process and the accuracy of the bathymetric data obtained from nautical charts, the applied methods proved to be adequate the proposed aims. Thus, it was possible to identify the main patterns and trends of morphodynamic process changes over the analyzed period. Similar methods were used by other authors such as Dallas & Barnard (2011) to study the ebb tidal delta in the San Francisco Bay coastal system (California, USA).

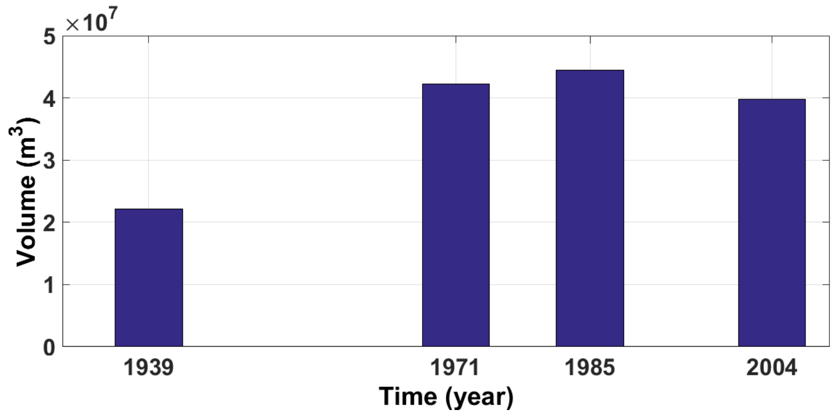

Figure 8. Change in the total volume of the ebb tidal delta over time.

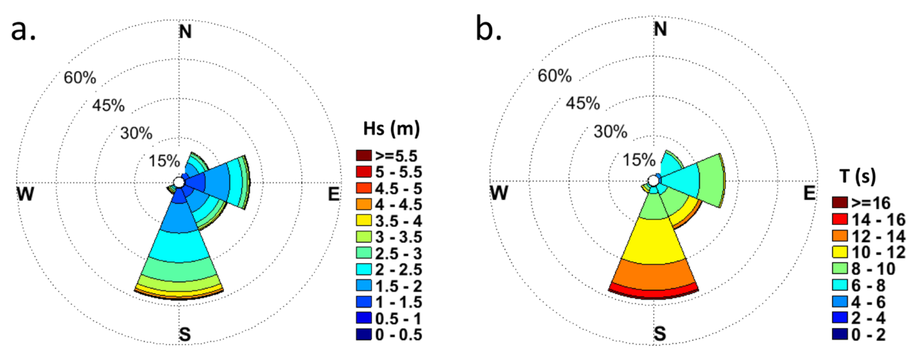

Figure 9. Directional histograms of (a) significant wave heights (Hs) and (b) peak periods (T) representing the waves of the period 1979-2012.

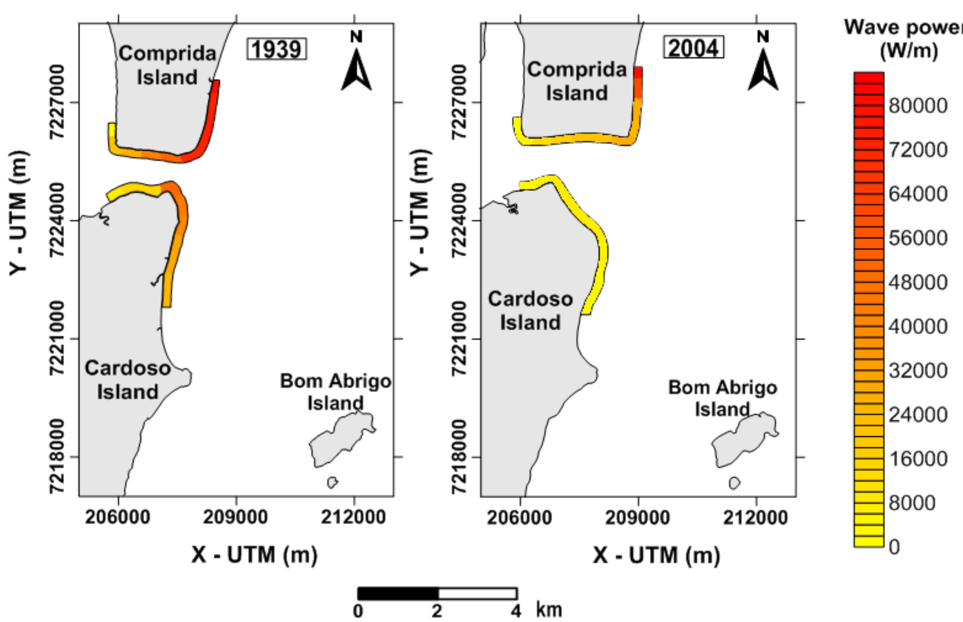

Figure 10. Wave power distribution along the margins of the Cananéia inlet in 1939 and 2004.

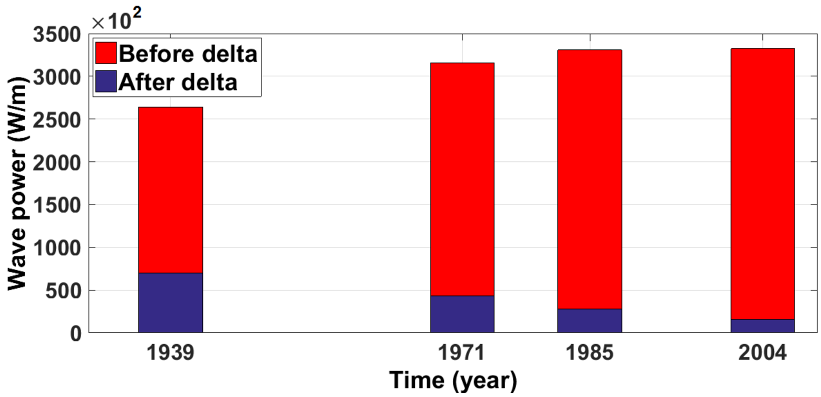

Figure 11. Wave power variation before and after crossing the delta, representing the wave energy dissipation caused by the delta in the different bathymetric situations.

We suggest that complementary studies be done considering other important environmental factors in the morphodynamic processes and consequently in the definition of the morphology of sedimentary features such as tides and coastal currents and considering also the tidal prism changes.

CONCLUSIONS

Based on historical morphological data and the application of a wave propagation numerical model, we assessed the effects of the ebb tidal delta morphology on wave propagation and wave power distribution along inlet margins. The Cananéia inlet is characterized by a well-developed ebb tidal delta and a main channel that presents a reasonable extension and depth. Although relatively stable in position, the inlet margins and ebb tidal delta are dynamic features subjected to different forcing conditions. Therefore, we can suggest, according to the classification proposed by Davis Jr & Barnard (2003), that this inlet suffers a mixed influence of the energy of waves and tides, subjected to a microtidal regime and protected from the most energetic waves.

The ebb delta is responsible for dissipating much of the energy of the waves that propagate towards the channel through the process of refraction and breaking waves, due to the reduced height of the water column on the delta and increased friction with the bottom. Thus, this sedimentary morphological feature determines the wave energy levels along the margins of the inlet and, therefore, its dynamics.

The margins of the Cananéia inlet have undergone significant morphological changes, being exposed differently to wave action, tidal currents and wind action. Such changes, evidenced by the erosion on the northern margin and accretion in the southern margin, show that its evolution during the last decades is well related to the waves that cross the ebb delta and reach the inner portions of the channel. Therefore, with the ebb tidal delta morphological changes over the past decades, the waves that reach the margins have had more or less influence on the margin's erosion and overall inlet dynamics. This process results in a constant adjustment between forcing conditions and inlet margins' position. In this study, we show the importance of evaluating the influence of the delta morphology, and its variability, when assessing the wave regime and erosion patterns inside inlet channels.

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Author contributions

BGA and ES designed the study. BGA performed the analyses with input from ES, PHGOS and MHG. BGA and ES wrote the paper with input from PHGOS and MHG.