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Short-time analysis of shoreline based on RapidEye satellite images in the terminal area of Pecém Port, Ceará, Brazil

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ABSTRACT

Coastal environments are highly dynamic and sensitive to interference and variations caused by the numerous natural and anthropogenic agents. The northern coast of Northeastern Brazil has undergone intense erosion in recent years. However, the construction of the Pecém Port modified the beach and shoreline features differently from the adjacent areas. This article describes using remote-sensing images integrated with a Geographic Information System to evaluate the sedimentary balance and morphological changes observed in the sandy beach area that was affected by the construction of Pecém Port. Two methods were applied to the RapidEye images to quantify the short-time changes that occurred on the coast. The Digital Shoreline Analysis System method showed that the beach width increased west to the port, which was calculated by the Change Polygon Approach determined by intersecting and uniting polygons to estimate the difference between the areas over time. The short-time analysis results showed changing coastal morphology, demonstrating that the anthropic interventions in the region are transforming significantly the natural elements that make up the region landscape. Between 2011 and 2014, the investigated beach stretch of approximately 3 km suffered an accretion process of more than 102,000 m^2 over 3 years. The high spatial resolution of satellite images, digital processing imaging techniques and geostatistical methods were effective in this study, allowing understanding the recent changes in the area.

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1. Introduction

The sea-level rise and sediment sources are the primary agents of natural geomorphologic changes while weather waves and currents are the drivers of local sediment transport, changing the coastal geomorphology in different timescales. These elements modify the coastal geomorphology in different timescales including individual events, such as storms, cyclical events and changes in short- and long-term trends.

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The wider availability of image-processing technology now provides coastal investigators the ability to objectively map a range of robust and repeatable shoreline indicators using digital coastal imagery (Boak and Turner 2005). Studies examining short- and long-term shoreline changes have generally utilized satellite data and use GIS (Geographic Information System) techniques to detection, extraction and monitoring of shoreline changes (Gens 2010; Klemas 2011; Ford 2013; Kankara et al. 2015). Therefore, the monitoring of shoreline changes is very important for coastal management while time series of remote-sensing images are extremely useful for this kind of monitoring.

The geological and structural arrangement of the underlying units, the offshore topography, and the conditions of the sources and sediment sinks interacting with hydrodynamic forgings affect the sedimentation rates and the changing geomorphology of the coastal systems. Besides the action of natural agents, human interference commonly accelerates shoreline modification, being prone to change the propagation pattern of waves and currents and interfere with sediments availability and mobility (Honeycutt and Krantz 2003).

The design of the Pecém Port terminal has an offshore structure with facilities for berthing of vessels located far from the coast, connected by a bridge between the berthing piers and onshore facilities. Because it is an artificially sheltered offshore port, an 'L'-shaped breakwater was built to create an artificial bay of calm waters where the berthing piers are situated (Figure 1). Duarte et al. (2015) conducted preliminary investigations using a long series of Landsat images to show that changes in the natural coastal dynamics and the shoreline in the Pecém Port region have been quite intense in recent years.

Currently, the port terminal is in the process of expansion, and the construction of a new bridge to access the mooring berths (Figure 2) has been modifying the local surroundings and coastline.

Figure 1. Aerial view of the Port of Pecém, showing the pier in 'L' and the bay of calm waters.
Source: Tecer (2014).

Figure 2. Aerial view of the Port of Pecém, showing the construction of a new bridge to access the berths piers.
Source: Lima (June 2017).

This research was motivated by previous studies that demonstrated that, in contrast to the process of coastal erosion that is occurring in the northeast coast of Brazil, in the Pecém Port region sediment addition processes were observed, which could affect the activities of the port terminal in the future.

2. Study area

The Pecém Port is located in São Gonçalo do Amarante, 50 km from Fortaleza, the capital of Ceará state (Figure 3). Besides the excellent location, close to routes of the northern hemisphere, it has a natural draft of 17 m and therefore requires no dredging, allowing large vessels to be berthed in an area that is not subjected to strong tide variations.

The study area is located on the promontory of Pecém, formed by the Precambrian rocks (quartzites and gneisses) of Ceará Group, surrounded and buried under Cenozoic coastal sediments of the Barreiras Group and recent dunes. This promontory geologically divides the area into two distinct regions, the southeast (SE), dominated by sediment transport processes and/or erosion and the northwest (NW) portion of the small Pecém bay, dominated by sedimentation processes (Magini, Martins, and Pitombeira 2013). The quartzites and gneisses occur in the post-beach to a depth of 20 m. The occurrence of Ceará headlands on the west coast forms small bays, creating beaches with asymmetrical NW-oriented dimples where sedimentation processes occur due to decreased energy waves and currents (Figure 4).

According to Morais et al. (2006), the waves that bathe the Ceará coast have a strong east component, with directions varying between the E, E-NE and E-SE quadrants, maintaining a close relationship with the prevailing wind directions. Magini, Martins, and Pitombeira (2013) suggest that in relation to the processes of sedimentation and coastal erosion of the area occurred two moments. In the period of construction of the temporary terminal, the environmental changes promoted coastal erosion, and in the post-construction period, a higher sedimentation occurred with increasing shoreline west of the terminal due to the contribution of sediments. This sedimentation variation is due to changes in coastal flow, controlled by waves and currents, since sediment

Figure 3. Location of the study area. (a) Detail of the situation of the Pecém Port Terminal; located in the municipality of São Gonçalo do Amarante; (b) Location of São Gonçalo do Amarante in the state of Ceará; (c) Map of Brazil, with the Northeast region and the highlight for the state of Ceará in red.

sources have not been altered. The beach has undergone progradation processes since 2001 after the implementation of protection structures and the removal of the temporary berthing terminal.

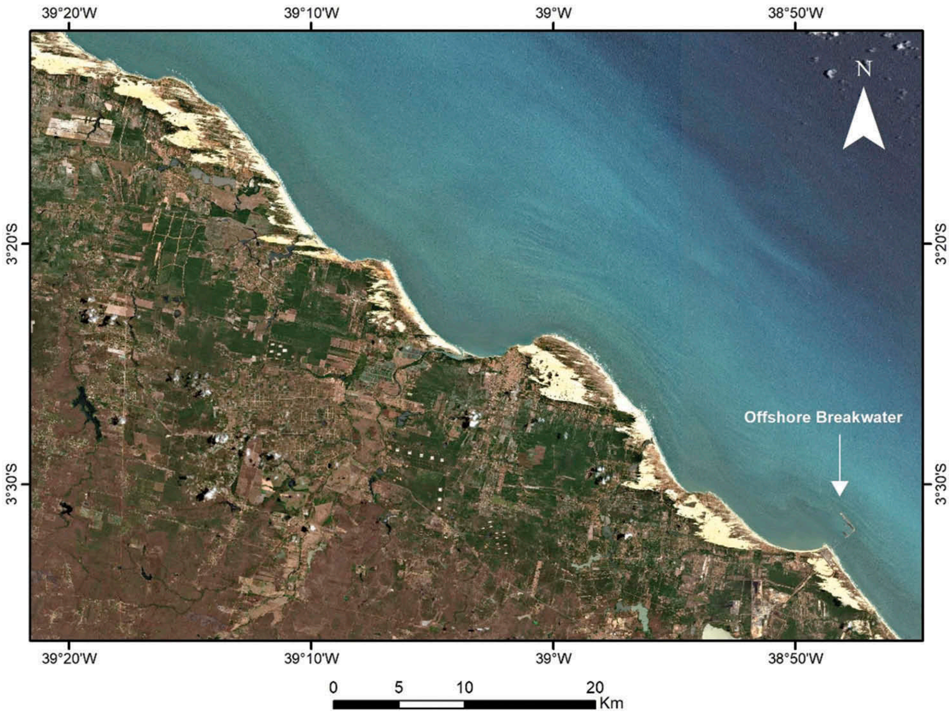

Figure 4. Image of the satellite Sentinel 2 (true colour composition), showing the asymmetrical concavity of the beaches to NW of the Port Terminal of Pecém, generated by the presence of the promontory.

3. Methods

The applied methodology was based on the use of high spatial resolution images for extraction of the shoreline in different periods. For this, was used the definition of Bird (2008) to demarcate the shoreline in the images, which defined the coastline as the edge of the land at the limit of normal high spring tides; the subaerial land margin, often marked by the seaward boundary of terrestrial vegetation. Amaro, Santos, and Souto (2012) concluded that the boundary of the coastline on sandy beaches is marked by wet and dry areas caused by tidal variation.

RapidEye high-resolution satellite images were analysed to study the morphological and shoreline changes over the short-term, because they have five orthorectified spectral bands, with 5 m of spatial resolution, resulting in corrected images with precision of details compatible with 1:25,000 scale, and 12 bits of radiometric resolution (Table 1). The images used in this monitoring were imaged in four different periods (5 June 2011, 24 July 2012, 11 October 2013 and 18 June 2014), with a time interval established approximately per year, according to the availability of existing images, to analyse the changes occurred in an annual timescale.

The digital processing of the images employed was aimed at improving the gain in the process of recognition and interpretation of the coastline features. The colour composition employed to enhance the coastal features was R5G4B1, corresponding to the near-infrared, Red-edge and Blue bands, respectively (Figure 5). This composition

Table 1. RapidEye image resolutions.

Sensor	Spectral band	Spectral resolution (μm)	Spatial resolution (m)	Radiometric resolution (bits)
REIS	Blue	440–510	5	12
	Green	520–590		
	Red	630–685		
	Red-edge	690–730		
	Near-infrared	760–850		

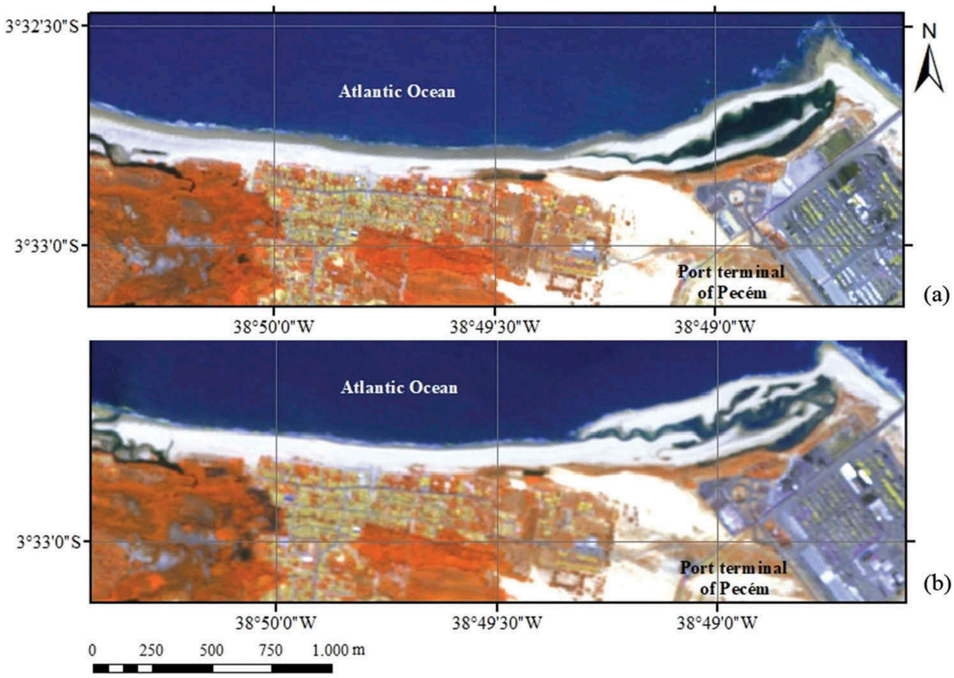

Figure 5. RapidEye colour composition RGB 541 for 2011 (a) and 2014 (b).

was adopted by showing very clearly the contrast between the wet and dry areas of the beach sediments, accurately marking the shoreline. The images were processed in the ENVI software and manually vectored in the ArcGIS® software, where the coastline area was extracted for each date, for later application of the Digital Shoreline Analysis System (DSAS) and Change Polygon Approach.

DSAS is an extension of the ArcGIS software that quantitatively analyses the evolution of erosion and deposition trends across multiple coastline locations. This extension uses a measurement baseline method to calculate the rate-of-change statistics for a time series of shorelines. The baseline is constructed by the user and serves as the starting point for all transects cast by the DSAS application (Figure 6). The transects intersect each shoreline at the measurement points used to calculate shoreline-change rates (Himmelstoss 2009).

There are more than one statistical method for calculating the rate-of-change by DSAS. In this work, the EPR (End Point Rate) and LRR (Linear Regression Rate) model were chosen to analyse the changes in the shorelines along transects per year. The EPR

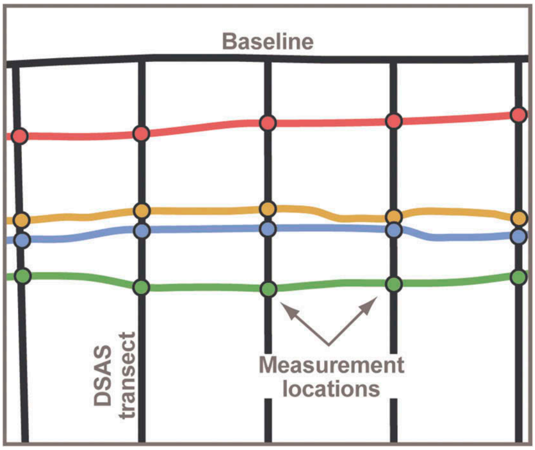

Figure 6. The measurement transects that are cast by DSAS from the baseline will intersect the shoreline vectors.
Source: Himmelstoss (2009).

statistical method was calculated by dividing the distance of shoreline movement by the time elapsed between the earliest and the most recent shoreline. This allows for a simple analysis between the longest time interval. The LRR method calculates the shoreline retreat rates in meters per year (m $year^{-1}$) considering all the shorelines of different years that intersect the transect (Himmelstoss 2009).

The mapping to measure the variations of shoreline area used the Change Polygon Approach Model (Smith and Cromley 2012), which considers the areas, instead of punctual values, to calculate the erosion percentages along the shoreline in each image. This model uses two binary images, erosional and accretional, for the estimation. In each of these images, the white pixels represented, respectively, the erosion and the accretion observed in the studied period. Maps showing the erosion/accretion areas around the Pecém Port were elaborated based on the data compilation from different times.

4. Results and discussion

The quantification and mapping of the coastal changes observed in the period under analysis were carried out in an average period, taking into account the natural behaviour of the region in relation to continental drift and tides. Morphological changes were classified as progradational and retrogradational.

From a baseline, the DSAS calculates the shoreline variation by dividing the distance between the earliest and the most recent data, resulting in the generation of statistical data. The DSAS application provides some statistical methods to be applied according to the parsing parameter. In this study, the method used was the calculation with LRR that uses a linear regression statistic, taking into account the rates of change, since it is an analysis that is based on the set of all the data collected through the transects, thus estimating the changes that occurred in each year. With this, it was possible to identify areas of increase or erosion (Figure 7).

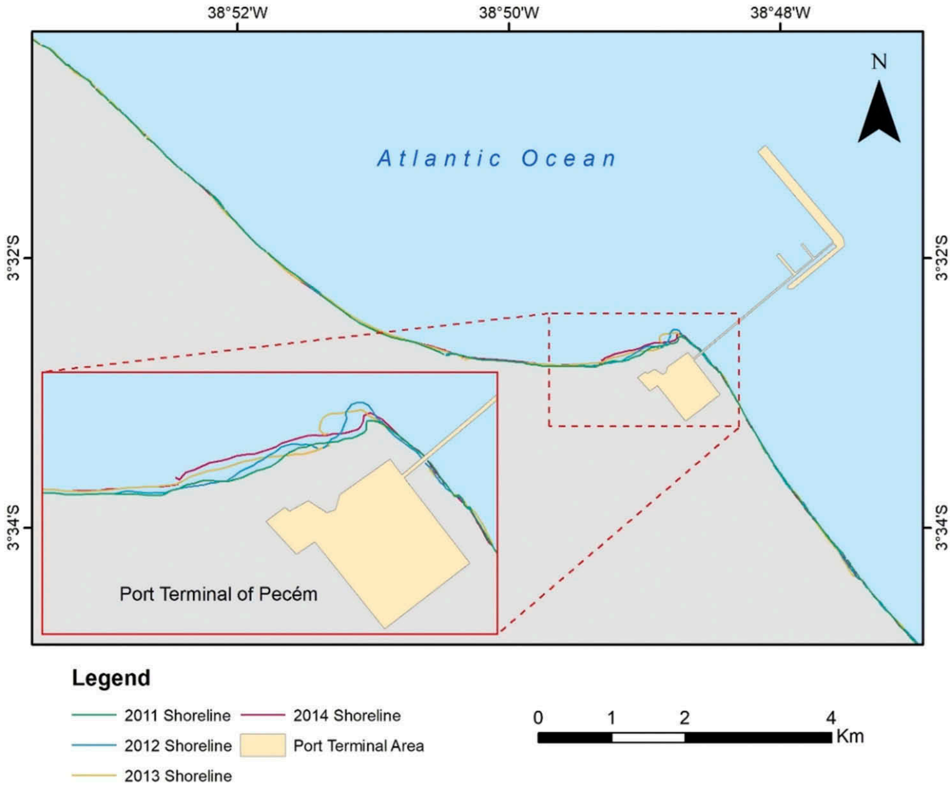

Figure 7. Shorelines interpreted in RapidEye images and used for DSAS.

The DSAS method consisted of generating transects, arranged every 10 m along the shoreline, showing that the sediment volume increased to the west of the port, causing the beach to widen (Figure 8). In the study region, a sedimentation trend was observed west of the port, reinforcing the natural process of sediment transport caused by the longshore drift, which occurs from east to west in Ceará.

Figure 9 shows that the variation of the morphology of the beach near the Port of Pecém shows a general tendency of accretion of sediments, especially in the region of the promotory, where the access bridge to the mooring berth is located, by the EPR. Figure 10 shows the coastline variation rates for the period between 2011 and 2014 where the method used was the LRR calculation, and negative values indicate erosion.

Figure 11 shows EPR and LRR graphs and comparison of the values obtained with the EPR and LRR methods between 2011 and 2014. Negative values denote erosion and positive values denote accretion. The EPR and LRR results for all three regions were very close to each other.

The study area was analysed in more detail through the Change Polygon Approach (Figure 12), whose objective was to calculate the accretion or erosion, through the intersection and union of polygons, and by means of calculations to determine the difference between them, thus measuring the area modified.

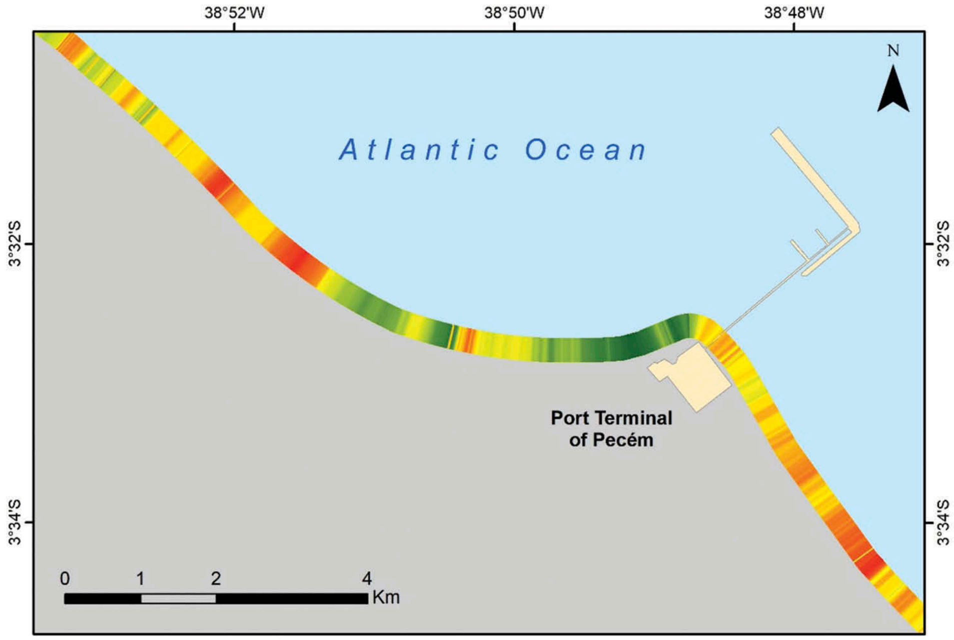

Figure 8. Transects employed in the DSAS and modified area in the period between 2011 and 2014.

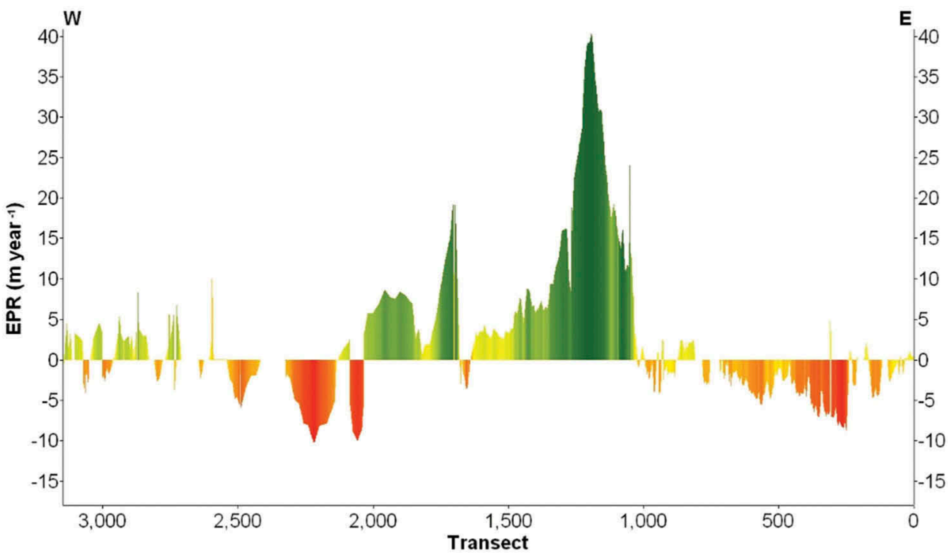

Figure 9. Rates of change of the shoreline for the period between 2011 and 2014 by the EPR method (negative values indicate erosion).

For the Pecém region, the method was considered satisfactory, since it allowed verifying, through the symmetrical estimate of the polygon, the increase of the sedimentation in the area. The purpose of the port breakwater is to absorb the energy of the waves, thus minimizing wave and tide effect in the adjacent regions, generating an artificial bay of calm waters for mooring ships.

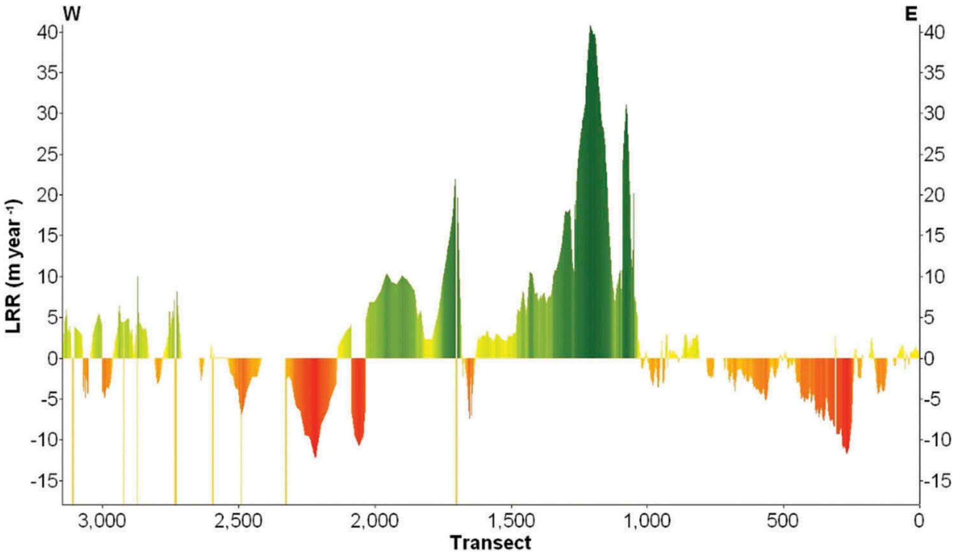

Figure 10. Rates of change of the shoreline for the period between 2011 and 2014 by the LRR method (negative values indicate erosion).

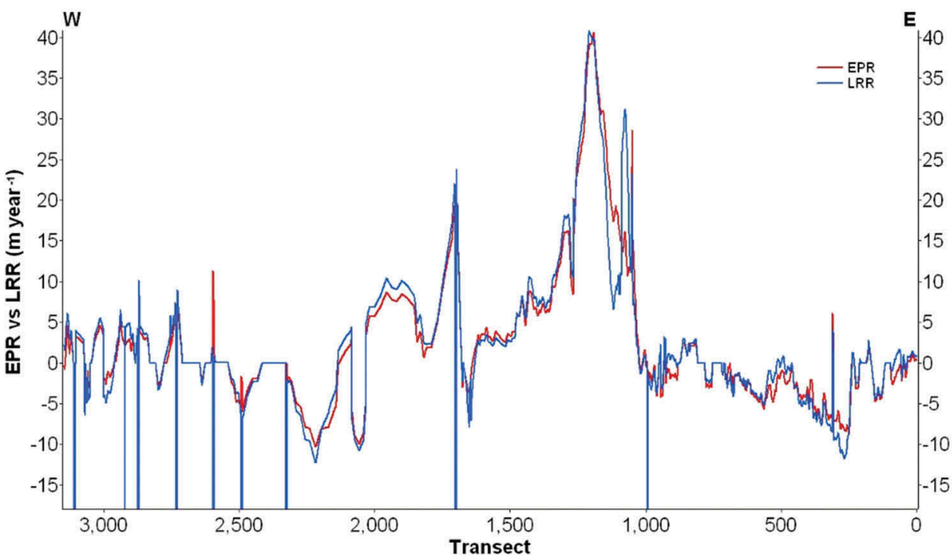

Figure 11. Comparison of the values obtained with the EPR and LRR methods between 2011 and 2014. Negative values denote erosion and positive values denote accretion.

However, despite the fact that the natural process of longshore drift act from east to west in the study area, the results show that the variation of the beach shoreline near the terminal has been intensified, with the occurrence of beach progradation process, due to the port infrastructure built in the region. The breakwater promotes a beach protection effect, minimizing the flow lines of the coastal drift current. In conjunction

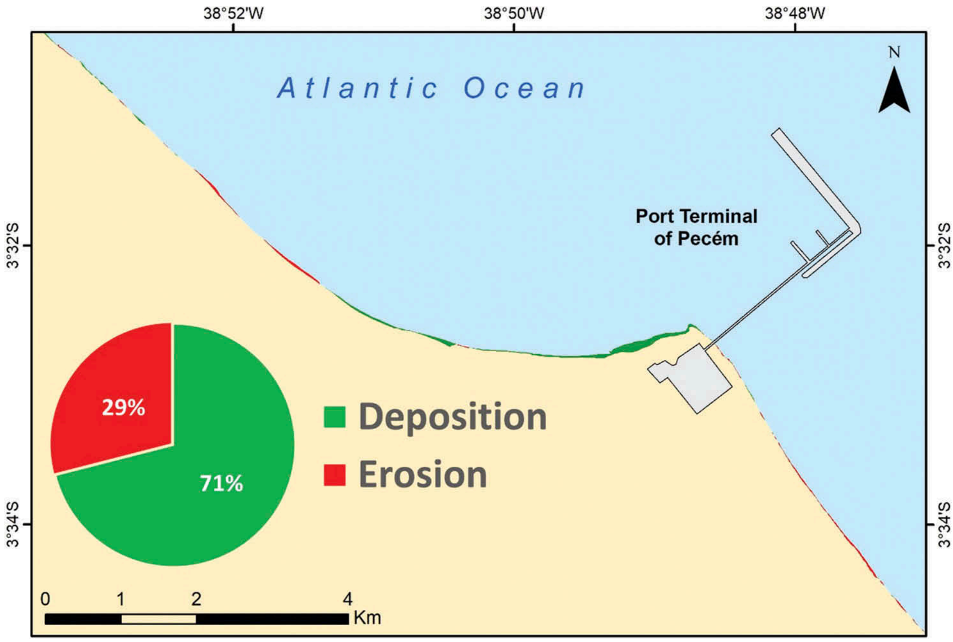

Figure 12. Result of the Change Polygon Approach method, used to calculate area changed between 2011 and 2014.

with the promontory, it promotes a vortex in the opposite direction of the coastal drift, favouring the deposition in the west portion (Figure 13).

The short-term analysis results showed a changing coastal morphology, demonstrating that the anthropic interventions in the region are transforming considerably the natural elements that make up the region landscape.

Between 2011 and 2014, the area underwent an accumulation process of 106,498 m^2 and an erosive process of 4,391 m^2, in a beach stretch of approximately 3 km over a time interval of 3 years. A positive sedimentary balance was verified, with an accumulation of more than 102,000 m^2 of sediments, contrary to the erosive process that has been taking place in most of the northeastern coast of Brazil.

The geometry and temporal evolution of the morphodynamics of the coastal position are of great importance in the evaluation of the spatial dynamics of the behaviour of the coastal system. The accelerated modification of the coast in recent years can be attributed to climate change and the degradation of the coastal environment caused by human activities, with increased occurrence of natural coastal erosion.

The installation of engineering works of the Port of Pecém dimensions can potentiate acceleration of these modifications, totally changing the local coastal dynamics, changing the natural regimes of accretion and erosion of marine sediments.

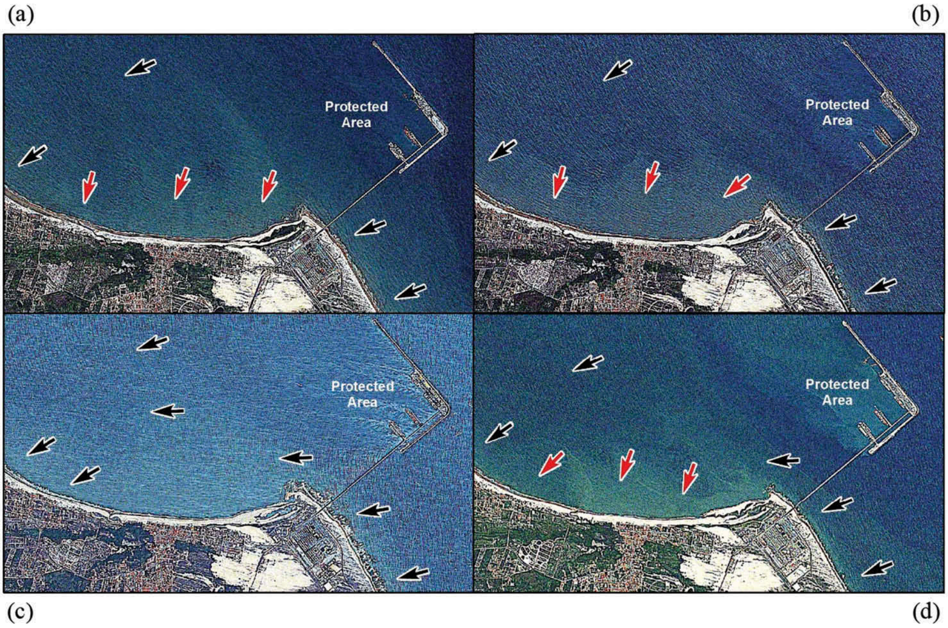

Figure 13. RapidEye images for the years 2011 (a), 2012 (b), 2013 (c) and 2014 (d), which were applied the 5 × 5 Laplacian filter, showing the influence caused by the wave pattern that reaches the shoreline due to the presence of the access bridge and the berthing piers.

5. Conclusions

The knowledge of the natural dynamics in coastal areas is of great importance because they are fragile ecosystems subject to diverse anthropic pressures, such as urbanization, installation of ports and other types of use and occupation.

The results of this RapidEye image-based short-time analysis showed a changing coastal morphology, demonstrating that the anthropic interventions in the region are leading to intense transformations of the natural elements that make up the landscape of the region. This modification can have undesirable consequences, including for the port terminal facilities, if the process of shoreline development increases to the point where it affects the port depth.

The use of digital image processing techniques, as well as the geospatial analysis methods applied to the area, allowed an understanding of the area evolution over time, from before the construction of the piers and breakwaters to the present moment.

The RapidEye images were effective since the high spatial resolution facilitated interpreting and mapping the investigated features, and determining the modifications that occurred over the evaluated period satisfactorily.

The use of both DSAS and Change Polygon Approach techniques allowed evaluating and comparing their advantages. The DSAS technique was the most efficient for the qualitative and regional analysis, while the Change Polygon Approach was the best tool for the quantitative and localized analysis. However, both methods are complementary and equally important to improve the understanding of coastal dynamics in the region.

Nowadays, the situation is different, since the second access bridge to the docking berth is in the final stage of construction, significantly altering the pattern of currents and waves and, consequently, sediment circulation. A new breakwater has already been planned to expand the port terminal in the near future, indicating the need for continuous monitoring of the region since the natural processes of the coastal dynamics will certainly be affected.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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