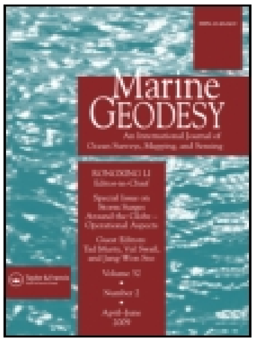

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Multitemporal Analysis of Coastal Erosion Based on Multisource Satellite Images, Ponta Negra Beach, Natal City, Northeastern Brazil

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This paper describes the use of moderate and high-resolution remote sensing images integrated with a Geographic Information System to evaluate the sedimentary balance and morphological changes seen on the sandy beach of Ponta Negra in northeastern Brazil. High-energy forces such as wind, tides, waves, and currents cause widespread erosion and morphodynamic instability along the shoreline. This investigation uses diverse images from multitemporal and multiresolution analyses and a Post-Processing Kinematic Global Positioning System (PPK GPS) survey as the primary resources to study the short and long-term effects of shoreline changes and the processes controlling the persistent horizontal and vertical erosion on the beach. We used moderate-resolution remote sensing images from 1973 to 2012 and high-resolution images from 2003 to 2011. Between 1973 and 2012 a total area of 121,494.52 m^2 was affected by erosion and 37,266.58 m^2 was affected by accretion. Shoreline progradation rates of 4.2 m/year and recession rates of -3.7 m/year were estimated for the period between 1973 and 1986 and mean erosion rates of 1.5 m/year were estimated from 1986 to 2012. Digital Elevation Model (DEM) comparison resulting from different PPK GPS surveys showed a negative sediment balance of approximately -3,261.94 m^3 in a plot of 12,500 m^2 between May and September 2012. The coast has also been facing a drastically increased human influence in recent decades. In summary, this article aims to

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contribute information to support the mitigation of coastal erosion and to protect seaside infrastructure.

Keywords Shoreline detection, remote sensing, digital elevation model, PPK GPS

Introduction

Sandy shores are prevalent in most coastal zones around the world (McLachlan and Brown 2006), but they are increasingly threatened by erosion and are not well understood. Small and Nicholls (2003) estimated that 23% of the world's population live within 100 km of the coast and less than 100 m above sea level. More recently, in 2010 the United Nations Atlas of the Oceans (www.oceansatlas.org) indicated that about 44% of the world's population live within 150 km of the coast as an inevitable consequence of economic progress. The ongoing human migration towards the coast, which started at least two centuries ago (Nordstrom 2000) and is expected to intensify in the coming decades, has resulted in several impacts and widespread modification of the sandy shores ecosystems. These are dynamic environments, and their characteristics are determined by the action of waves and tides on the available sediment. Within this dynamic setting there is an important exchange of sand, biological matter, and other constituents between the dunes and the intertidal zone and surf zone. Storms and the erosion they produce as well as anthropogenic activities represent the most significant hazards to sandy shores. Seaside infrastructure frequently installed without proper knowledge of coastal processes obstructs natural sand transport, affects the sediment budget and normally leads to severe erosion and serious socio-economic damage. These interventions have classically had a long-term trend of negative impact on the beach-dune system, an adverse effect that can also be detected in short-term analysis.

It is crucial to comprehend the physical processes behind coastal erosion to establish an effective mitigation plan, particularly in urban beach areas used for recreational and touristic purposes and where seaside infrastructure, such as boardwalks, kiosks, and even hotels, are at risk for damage. Assessment of beach erosion/accretion behavior based on multisource remote sensing images and systematic approaches to analysis and interpretation are effective resources that allow us to obtain information about the spatial and temporal evolution of the shoreline. Shoreline can be defined as a spatially continuous representation of the horizontal position of the land-water interface at a given instant (Parker 2003). Officially, the shoreline is the intersection between the Mean High Water Line and the beach as estimated by the nautical charts.

Currently, technological advancements in remote sensing, laser altimetry, spatial data surveys using a Global Positioning System (GPS) in its kinematic mode, and local tidal datum have been used to accurately map the morphological features and indicators of the shoreline. Multisensor, multiscale, and multitemporal remote images have contributed greatly to coastal geomorphological studies and have been used to measure both short- and long-term erosion/accretion processes (Moore 2000; Kumar and Jayappa 2009; Deepika et al. 2013).

Multisource database integration through Geographic Information Systems (GIS) promotes the understanding and quantification of the erosion/accretion rate from decade to decade and from year to year (e.g., Crowel et al. 1993; Boak and Turner 2005; Klemas 2011). Shoreline delineation based on available, cloud-free satellite images is an important task for long- and short-term coastal monitoring, and a high precision geometric method is also very important for the detection and multitemporal comparison of data.

When analyzing and interpreting satellite images the shoreline is defined by the High Water Line (HWL), which is the line of color change between the wet and dry areas of the beach that shows the maximum run-up from the last high tide (Anders and Byrnes 1991; Crowel et al. 1993; Pajak and Leatherman 2002; Robertson et al. 2004; Boak and Turner 2005). The HWL is the highest elevation on the shore reached by a rising tide. Therefore, climate conditions and seasonal changes, waves, tides and storms can all significantly affect the position of the wet/dry line and must be considered when evaluating its movement on the coast in the short and long term (Moore 2000; Boak and Turner 2005).

In addition to the precise definition of the constantly changing shoreline, it is also important to establish a specific indicator related to the vertical and horizontal changes of the beach face, as required by coastal monitoring and sediment balance (Krueger et al. 2011; Santos and Amaro 2011; Gonçalves et al. 2012). Thus, a local geodetic network provides a highly accurate referenced tidal datum when generating georeferenced models and facilitates comparisons between remote sensing images (Li et al. 2002).

On Ponta Negra sandy beach, perhaps the most famous spot in Natal, notorious erosive conditions have persisted for decades and if continues the ineffective remediation efforts to control erosion along this shoreline may lead to chronic socioeconomic impacts. In recent decades, Ponta Negra beach has experienced urban growth in the adjacent dune and backshore area (Hora et al. 2008). The progressive urban sprawl has resulted in substantial environmental problems such as the conspicuous effects of soil sealing with streets and pavements. Furthermore, the popularity of this tourist destination has led to an increase in seaside facilities, such as boardwalks, kiosks, a pluvial drainage system and sewer lines too close to the shoreline. Another relevant effect of urban densification was the interruption in the longshore and beach-dune sediment exchange, a key condition for the regular beach face nourishment. An Expert Report written by Amaro et al. (2012a) for the Federal Court formally focused on the coastal vulnerability and erosional difficulties found on Ponta Negra beach. This report made a statement about the erosional issues and also presents some management alternatives that would decrease the vulnerability of the beach-dune system, namely seaside boardwalk relocation, beach nourishment and dune maintenance.

The present study describes an application of remote sensing multitemporal analyses based on moderate and high-resolution images, a postprocessing kinematic (PPK) GPS survey for 3D modeling of the beach face, GIS spatial analysis, and field studies to get the time-series shoreline database for the long-term study (from 1973 to 2012) and the short-term study (from 2003 to 2011) of the erosion/accretion patterns on Ponta Negra beach. We also tried to develop a systematic methodology to (i) visually identify and estimate shoreline offsets (sectors of main erosion/accretion rates); (ii) evaluate the planialtimetry based on a PPK GPS survey for 3D modeling the morphology and the erosion/accretion rate in the short-term scale over an area where erosion has been particularly accentuated; and (iii) describe Ponta Negra beach in the context of embayed shape geometry.

Our main interest is for this methodology to improve analyzes changes and furthermore to predict future shoreline positions based on multisource data of various spatial and temporal resolutions, which are essential to coastal planning and management. Similarly, it provides relevant information which helps in decision making about demarcation of a setback area in the littoral. Finally, it also defines coastal erosion risk areas and calls for appropriate intervention for coastal protection and urban sprawl.

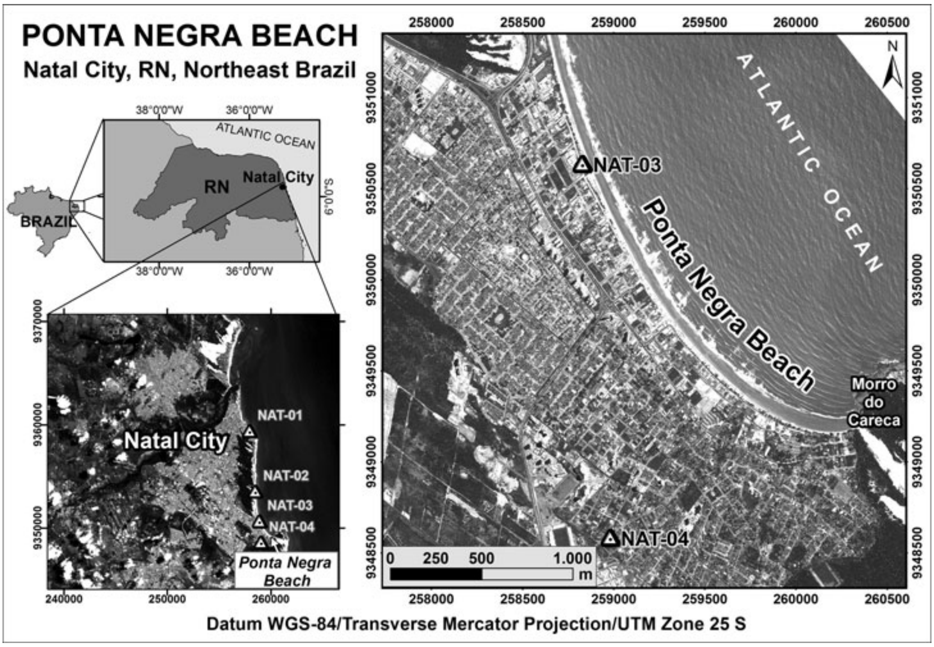

Figure 1. Map of Ponta Negra beach, city of Natal, state of Rio Grande do Norte (RN), Northeastern Brazil. Local geodetic stations: NAT-01, NAT-02, NAT-03 and NAT-04.

Study Area

Location

Ponta Negra beach is located in the urban area of Natal, the capital of the state of Rio Grande do Norte, in the Northeastern region of Brazil (Figure 1). It is an open coast and sandy shore approximately 4.0 km long. Behind it, there is a dune field of erodible sandy sediments extending to below present sea level and many well-developed residential neighborhoods. An important vegetated dune known as Morro do Careca lies in the southern portion of the beach, which is a popular tourist attraction.

Geological and Morphological Aspects

The east coast of Rio Grande do Norte is made up of cretaceous sedimentary rocks that belong to the Sedimentary Coastal Basin of Pernambuco, Paraíba, and Rio Grande do Norte (Neuman et al. 2009). This area is covered by sandstone from the Barreiras Group dating back to the Miocene-Pleistocene period and also by quaternary sediments such as sandy beaches, dune fields, and marine and alluvial terraces (Vital et al. 2006). The structural framework of the Eastern seaboard, characterized by neotectonic reactivation, is marked by alternating horsts and grabens that can be seen in a general NE trend. In the coastal area they form the rocky cliffs of the Barreiras Group (Bezerra et al. 2001) and the morphological structure of zeta curved bays (Silvester and Hsu 1993, 1997). Zeta curved bays are formed by differential headland erosion and active cliffs due to the complex interaction between offshore wave refraction and diffraction, the distribution of wave energy and longshore currents.

The morphological components on Ponta Negra beach present a wide selection of sand particle size. The diameter varies from very fine to medium on the shoreface, fine to medium on the foreshore and medium on the backshore. The beach is dissipative and it is marked by the presence of fine sand predominantly near Morro do Careca. The beach slope gradually increases which leads to coarser sand on the northern stretches of the beach and shows a reflective component (Almeida et al. 2013).

Meteorological and Oceanographic Forces

Weather and climate conditions regulate high-energy coastal processes. The climate of Natal's coastal region is classified as Tropical humid (Köppen-Geiger climate classification Af). From 1992 to 2012, the annual average temperature was 26.2°C and the annual average precipitation was 1,724 mm/year, with rainfall concentrated between February and May, according to the meteorological database of the Brazilian Weather Bureau (INMET 2013). The rainy season is related to seasonal migration of the Intertropical Convergence Zone (ITCZ) and occurs only when it moves over Northeastern Brazil. The trade winds pattern has an extremely strong southeasterly trend, varying seasonally between SSE and ESE. Ponta Negra beach is exposed to locally generated wind-waves that may develop considerable erosive power when driven by northeasterly or southeasterly winds (average 5.0 to 9.0 m/s). The highest wind speed for 2012 was registered between July and October, with a variation of 9.0 m/s to 9.4 m/s. The tidal regime is mesotidal semidiurnal. This coastal region is mostly wave-dominated and the gentle slope of the continental shelf contributes to sediment circulation along the shore (Testa and Bosence 1998).

During a time series of 60 years (1948–2008), the climate conditions on Ponta Negra beach were studied using tidal wave and weather reanalysis databases available from the Coastal Monitoring System of Brazil and developed by the Environmental Hydraulics Institute of Cantabria -Spain (González et al. 2007; Almeida et al. 2013). The numerical model used for wave simulation was the WAVEWATCH-III^{TM} from the National Oceanic and Atmospheric Administration–National Center for Environmental Prediction (Tolman 1999, 2009). The offshore wave climate was characterized by significant heights ranging from 1.7 to 1.8 m in average conditions and 2.7 to 3.2 m during storms. Ninety-four percent of the waves occurred in an ESE, E, ENE, and SE direction, with decreasing occurrence probability; furthermore, 75% of the sea states come from an ESE and Easterly direction. The wave spectrum showed peak periods from 8–10 s under normal conditions and from 13–17 s during storms. As the waves approach the shore they lose energy due to bottom friction and upon arriving at the shallow region near Morro do Careca, the wave heights decrease significantly to 1.0 m with peak periods of 7.5 s under normal conditions. In situ measurements taken 2.0 km from shore at a depth of 8.0 m averaged a wave height of 0.78 m ranging from 0.54–1.0 m and a peak period of 4.3 s with wind direction varying between SE and NE (Amaro et al. 2012a). The continuous action of trade winds, wave climate and tides are responsible for promoting coastal drift and for transporting sediment northward, parallel to the shoreline at an average speed of 0.05 to 0.8 m/s.

Socio-economic Conditions

Ponta Negra beach, located in the tropical Atlantic coastal zone, is one of the most popular tourist destinations in Northeast Brazil. Such favorable environmental conditions have

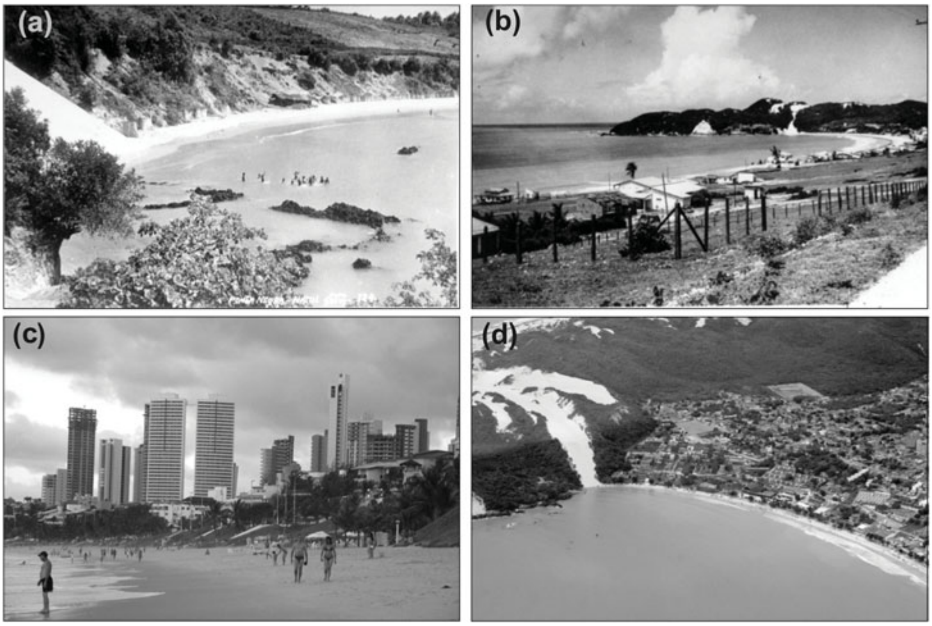

Figure 2. Ponta Negra beach: (a) View of the beach area and Morro do Careca dune showing the low density of surface occupation in the early 60s, mostly closer to the Morro do Careca dune, and low cliffs and rocky outcrops (Barreiras Group) along Ponta Negra beach's backshore covered by sand dunes; (b) Summer houses, access roads and vegetated dune surface in the early 60s; (c) Urban verticalization in the neighborhood around Ponta Negra beach in the early 2000s; (d) Aerial view in 2010, showing the urban sprawl over the vegetated dunes and the high density of construction too close to the shoreline. Source: Jaecy and GEOPRO.

led to a boom in real estate investment and a rise in several infrastructural and technical services provided by the municipality. However, some of the seaside constructions are totally inadequate due to a lack of time series data about the evolution of a beach-dune system and its natural erosion. The tourism sector provides a wide range of employment in Natal, and on Ponta Negra beach the economy is completely driven by the tourism industry. Thus, the newly established tourism industry and the recent urbanization of the area have made the complex environment even more fragile.

Urban sprawl has led to dune deforestation, sand extraction and the construction of houses and hotels too close to the shoreline. These circumstances have drastically amplified the coastal vulnerability and are currently causing frequent destruction of infrastructures by erosion. Starting in the 1980s, urbanization in the immediate vicinity of Ponta Negra beach has developed intensely and has led to an increase in population density from 2,490 to 4,800 people/km^2 between 1986 and 2010 (Hora et al. 2008). Thus, longitudinal vegetated dunes gave way to artificial terraces, built with allochthonous sedimentary material, which was intended for the installation of residential buildings and recreational activities (Figures 2a, c). During the early 2000s, verticalization began in the urban neighborhood of Ponta Negra beach (Figure 2c), due to real estate appreciation of the region and the development of commercial activities linked to tourism. These activities have promoted the defacement of vegetated dunes (Figure 2b, d) and of active shoreline, stirring apprehensions about urban expansion without suitable appreciation and knowledge of the geomorphic and hydrodynamic complexity of the beach-dune system. Urban sprawl occurs regardless of coastal evolution studies and nowadays, there is heavy damage to seaside infrastructure caused by coastal changes (Figure 2d). For example, in 2012, high tides damaged more than 3.0 km of boardwalk and kiosks installed on Ponta Negra beach. The construction of the boardwalk and other seaside structures was completed in 2000 and since then, they have been suffering successive destructions and restorations. The main reason is a significant and rising deficit in the beach-sediment balance over the past few decades, which is noticeable both on the vertical and horizontal scale (Busman and Amaro 2012). In addition to this, soil sealing has interrupted sediment transfer in the beach-dune system and has caused an increase in rainwater runoff into the sea in the urban area adjacent to Ponta Negra beach. Consequently, this has increased the erosive effects on the beach face (Amaro et al. 2012a). Figure 2a also highlights the fact that before the extreme urbanization there were low cliffs and rocky outcrops (Barreiras Group) along Ponta Negra beach's backshore, which were mainly covered by sand dunes. Such morphology supplied the beach-dune system with sediment and consequently, provided a better balance between the destructive and constructive cycles.

Methods

Moderate and high-resolution satellite images from 1973 to 2012 were analyzed to study the morphological and shoreline changes over the short and long term. PPK mode geodetic surveys were also carried out between May and September 2012 using satellite imaging on the beach sector where erosion was the most severe. The progradation/recession of the shoreline was estimated to evaluate long-term (1973–2012) and short-term (2003–2011) changes. The rate of erosion/accretion was also calculated for beach sectors categorized according to the damage caused to seaside infrastructure by erosion, as studied by Amaro et al. (2012a), confirmed by field checks every month between May and September 2012.

Remote Sensing Images

The interdecadal analysis from 1973 to 2012 used moderate-resolution imaging sensors (80 m, 30 m and 23.5 m) LANDSAT 1 – Multi Spectral Scanner (MSS), LANDSAT 5 – Thematic Mapper (TM), LANDSAT 7 – Enhanced Thematic Mapper Plus (ETM+), and Indian Remote Sensing Satellites 6-LISS-3 (IRS 6). High-resolution images from IKONOS-2, QUICKBIRD, and WORLDWIEW-2 (spatial resolutions of 1.0 m, 2.0 m, and 60 cm, respectively) were applied to the interannual analysis from 2003 to 2011. Such analysis has allowed for standardizing the multisource images and thus comparing the shoreline changes between 1973 and 2012 in a GIS environment. Once the wet/dry interface was derived as a vector line using pixels from digital images, the average accuracy was estimated to be less than 0.5 pixels. In moderate-resolution images, the accuracy of the shoreline position depends on the range of the tidal height at the time the satellite takes the image. Remote sensing images for Ponta Negra beach were acquired on different dates and selected according to the height of the tide, presented on Table 1. HWL has been considered a shoreline indicator. Table 1 also introduces the basic specifications of satellite images used in shoreline recognition calculated in Universal Transverse Mercator (UTM), datum WGS-1984, and Zone 25 South.

This study follows the methodology mentioned in previous references (e.g., Fletcher et al. 2003; Souto et al. 2004; Batista et al. 2009; Amaro et al. 2012b) mainly regarding the multitemporal mapping of shorelines changes. These authors proposed image preprocessing

Table 1
Specifications of moderate and high-resolution sensors and tide height at acquisition date

Satellite	LANDSAT 1	LANDSAT 1	LANDSAT 5	LANDSAT 5	LANDSAT 5	IRS-6	IKONOS-2	QUICKBIRD	WORLD VIEW-2
Sensor	MSS	MSS	TM	TM	TM	LISS-3	—	—	—
Acquiring Date	08/30/1973	06/21/1976	09/20/1986	01/29/1994	04/14/2004	07/07/2012	02/21/2003	04/04/2007	02/05/2011
Hour (Brasília, D.C.)	08 h 59 min	08 h 14 min	08 h 49 min	08 h 48 min	09 h 08 min	09 h 42 min	09 h 48 min	10 h 09 min	10 h 07 min
Spatial Resolution	80 m	80 m	60 m	30 m	30 m	24 m	1.0 m	0.6 m	2.0 m
Path/Row	230/064	230/064	214/064	214/064	214/064	338/080	230/064	230/064	214/064
Tide Height	1.14 m	1.15 m	1.06 m	1.01 m	1.1 m	1.28 m	2.3 m	2.3 m	2.2 m

Table 2
Georeferencing models and errors applied to moderate-resolution images

Satellite/Sensor	Imaging Date	Geometric Correction Methods	RMSE/Accumulated Error
LANDSAT 1/MSS	30 August 1973	Second Order Polynomial (1986)	0.723/5.028
LANDSAT 1/MSS	21 June 1976	Second Order Polynomial (1986)	0.682/4.987
LANDSAT 5/TM	20 September 1986	Orthorectified	4.305
LANDSAT 5/TM	29 January 1994	Second Order Polynomial (1986)	0.679/4.984
LANDSAT 7/ETM+	29 May 2000	Orthorectified	3.187
LANDSAT 5/TM	14 April 2004	Second Order Polynomial (2011)	0.611/3.365
LANDSAT 5/TM	24 August 2011	Orthorectified	2.754
IRS-P6/LISS 3	07 July 2012	Second Order Polynomial (2011)	0.797/3.551
IKONOS-2	21 February 2003	Second Order Polynomial (1986)	0.552
QUICKBIRD	04 April 2007	Second Order Polynomial (1986)	0.322
WORLDVIEW-2	02 May 2011	Second Order Polynomial (1986)	0.657

techniques using geometric corrections to reduce distortions caused by the curvature of the Earth, refraction, sensor motion, terrain relief, and atmospheric corrections. These procedures, when applied to the Ponta Negra beach data, provide sufficient detection of shoreline changes and present a high visual contrast between surface features. Therefore, accurate ground control points measured by geodetic positioning and leveling were used to orthorectify the entire resolution image dataset. Moderate-resolution remote sensing data is available at the United States Geological Survey site (USGS 2012). The high-resolution images come from the Geoprocessing Laboratory collection (GEOPRO/UFRN). The second-order polynomial transformation was applied to georeference images and the accepted Root Mean Square Error (RMSE) was less than 1. In each scene about 100 ground control points were used covering a surface area of about 1,987,190.00 m^2 and had a density of approximately 2.0 points per hectare. Table 2 shows polynomials and errors on georeferencing models. The atmospheric correction of the images was accomplished using dark-object subtraction techniques (Chavez 1988, 1989) which improve radiometric quality and thus the visual impact of the images, decreasing the additive effect of the atmosphere.

Digital optical image processing techniques using ER-Mapper© and ENVI© software were applied in order to highlight the land-water distinction while ArcGIS© (Environmental Systems Research Institute Inc., or ESRI) provided extensive functions for spatial analyses. In this research, the Normalized Difference Water Index (NDWI) and histogram enhancement were used to better distinguish between water and land. The NDWI is expressed as in Equation (1) by McFeeters (1996):

$$\text{NDWI} = (\text{Green} - \text{NIR})/(\text{Green} + \text{NIR}) \tag{1}$$

where Green is a green band such as LANDSAT 5 - TM or LANDSAT 7–ETM+ Band 2, and NIR is a near-infrared band such as LANDSAT 5 - TM or LANDSAT 7–ETM+ Band 4.

NDWI maximizes reflectance of water by using green wavelengths and minimizes the low reflectance of NIR in the water column (using mid-infrared wavelength such as LANDSAT 5 - TM or LANDSAT 7 - ETM+ Band 5), opposite to the high reflectance of NIR by vegetation and soil. Consequently, the index shows positive values for water, while vegetation and soil generally are suppressed due to negative values or zero. The results also rely on statistical analyses (mean values, dispersion values, amplitude variation, and minimum and maximum values). The delineation of the shoreline on high-resolution images appears as the maximum high water line making it easily recognizable. Tidal heights were around 2.3 m and amplitude differences were less than 10 cm on the date the high-resolution images were taken.

Visual interpretation and shoreline delimitation were applied to selected images using the ArcGIS© vector procedure. In order to detect the shoreline more precisely in moderate-resolution images, a cubic pixel resampling was applied with a 70% contrast that aided in delineating the wet/dry line. Multitemporal images were superimposed to classify the shoreline dynamic based on the erosion/accretion of the surface area. To this intent, ArcGIS *Spatial Analyst* (ESRI) was also applied for the calculations of sediment rates, area, perimeter, width, and length of the shoreline.

Postprocessing Kinematic GPS Survey

A PPK GPS survey was used for 3D accurate modeling of the beach face similar to methodology previously applied to other beaches in the state of Rio Grande do Norte (Santos and Amaro 2011). There are several advantages to performing a geodetic survey using GPS methodology compared with traditional methods based on Total Station (hereafter EDM, Electronic Distance Meter). The main advantage is its ability to map large coastal areas in short time intervals and show the geodetic coordinates and orthometric heights with an accuracy within a few centimeters of the Brazilian Geodetic System (BGS). It achieves these results by positioning and leveling the GPS using the relative mode (Santos et al. 2011). On Ponta Negra beach, geodetic surveys were carried out every month between May and September 2012 to observe areas under severe erosion impact. Such areas were categorized based on the destructive effects from strong to very strong (Amaro et al. 2012a). The methodology consisted of the following three steps: (i) installing local geodetic stations to support field surveys, (ii) a planialtimetric survey of the beach face using geodetic GPS for

Table 3
Specifications of local geodetic stations on Ponta Negra beach

Base Station	N (m)	E (m)	h (m)	sN (m)	sE (m)	sh (m)	H (m)
NAT-01	9, 359, 360.128	257, 873.766	0.012	0.003	0.004	0.012	8.9528
NAT-02	9, 353, 519.116	258, 434.202	8.492	0.030	0.030	0.082	13.3528
NAT-03	9, 350, 635.703	258, 826.872	3.572	0.003	0.004	0.010	4.8928
NAT-04	9, 348, 583.723	258, 979.12	39.7	0.003	0.003	0.01	42.7508

N – Northing; *E* – Easting; *h* – Ellipsoidal Height; *sN* – standard deviation to north coordinate; *sE* – standard deviation to east coordinate; *sh* – standard deviation to ellipsoidal height; *H* – Orthometric Height.

shoreline definition, and (iii) generating Digital Elevation Models (DEM) and calculating the sediment volume of erosion/accretion.

The local main positioning reference base (NAT-03) was established according to the technical regulations of the Brazilian Institute of Geography and Statistics NBR 14166 and fixed related to stations of the Brazilian Network of Continuous Monitoring of GPS System (RBMC). Execution of geodetic surveys used a geodetic GPS unit L1/L2 Trimble 5700 model and Topcon Tools software for post-processing adjustment and network analysis. Three others geodetic stations (NAT-01, NAT-02 and NAT-04) were installed along Ponta Negra beach at less than 3.5 km from each other to perform a high accuracy planialtimetric survey. Table 3 displays the coordinates, ellipsoidal elevation, and standard deviation from all the stations and the orthometric height calculated using the MAPGEO2004 system. The UTM coordinate system and the SIRGAS2000 geodetic reference system (with the GRS80 ellipsoid) were used in the application settings and DEM generation.

A PPK GPS survey was performed using a GPS antenna adapted in a quad-motorcycle as a rover receiver connected to a GPS antenna on the base station NAT-03 (Figure 3). The shoreline position and 3D conditions of the beach face and morphological features were determined with high accuracy and precision using a GPS receiver Trimble Model R3 L1 Frequency whose nominal horizontal accuracy was 5 mm + 1 ppm and a vertical accuracy of 5 mm + 2 ppm. Only the surveys that were executed on May 13 and September 14, 2012, were displayed because they specify main seasonal changes and clearly show the beach morphology alterations. They were performed just after maximum high water on neap tides because this area of the beach is inaccessible during spring tides. As a result, geodetic coordinates were obtained from each sampling point and had respective standard errors of 3.5 cm in the horizontal component and of 5.0 cm in the vertical component. Orthometric heights, referenced in the MAPGEO2004 geoid model, were calculated from the geometric heights and also related to the NAT-03 station (Figure 1). Triangulated Irregular Network (TIN) data structure was applied to generate DEM because results were better than the results from other methods (Amaro et al. 2013).

Classical cross-shore topographic profiles performed by EDM instruments were used as an evaluation procedure to the accuracy of the DEM obtained by geodetic GPS. The analysis is mainly focused on representation of the shore morphology with satisfactory accuracy. The DEM acquired by a geodetic GPS system optimizes the time needed for planialtimetric sampling using a quad-motorcycle. Among the advantages of this procedure are the easy organization of a survey that covers large areas and collects a wide range of points for the creation of DEM. From the DEM we can establish several cross-shore profiles with an

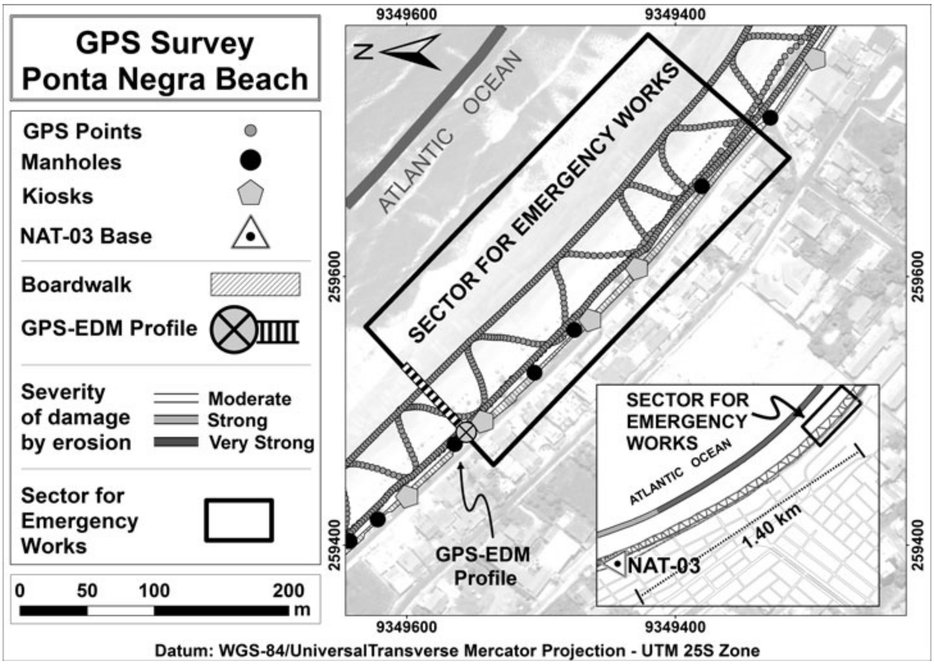

Figure 3. GPS survey points performed in May 2012 along the beach sectors that needed emergency repairs.

appropriate level of precision (maximum of 1.2 cm in the horizontal component and 2.0 cm in the vertical component). Then, a sequential DEM of the same area can be generated for change detection purposes or to estimate volume balance and sediment accretion or erosion rates.

Results and Discussion

The results of the comparison of moderate and high-resolution images were presented in multi-temporal maps demonstrating the progradation/recession of the shoreline on Ponta Negra beach based on a long-term study (from 1973 to 2012) and a short-term study (from 2003 to 2011). The results compared the various sectors assessed for damage caused to seaside facilities by erosion. These sectors were categorized as moderate, strong, and very strong according to indicators used to specify the intensity of destruction to sidewalks, kiosks, and rainwater or drainage discharge systems (Amaro et al. 2012a). The goal was to confirm the results obtained by satellite images of the shoreline progradation/recession rate and the erosion/accretion in the short and long term. These processes were seen as the most significant damaging factors for coastal infrastructure.

Moderate-Resolution Images

Figure 4 shows a comparative analysis of moderate-resolution remote sensing images from 1973 to 1986 (Figure 4a) and from 1986 to 2012 (Figure 4b). It reveals a sediment deficit of about 121,494.52 m^2 for whole beach, prevailing over segments with accretion of 37,266.58 m^2. This thus exhibits the erosion affecting the sea cliffs and the dune base of Morro do Careca in each of the analyzed time periods. Coastline geometry and wave and

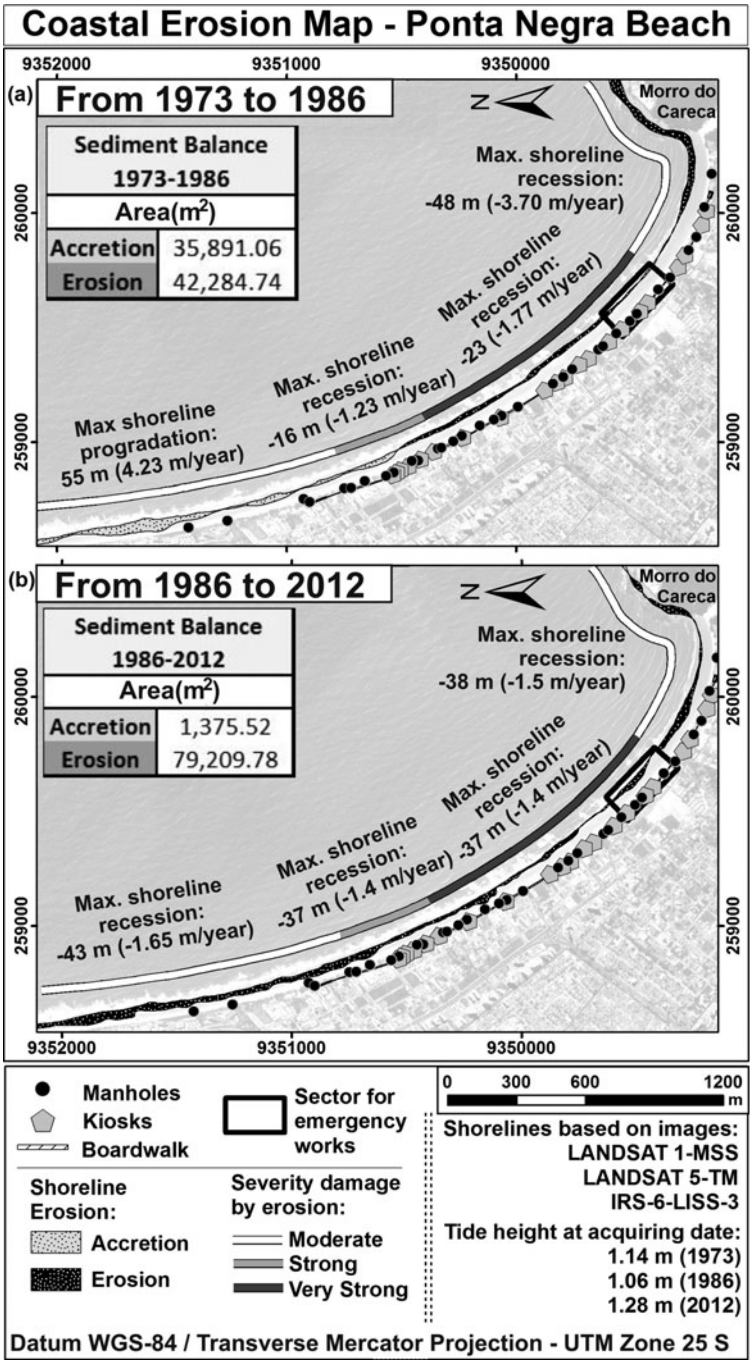

Figure 4. Coastal erosion map of Ponta Negra beach from (a) 1973 to 1986 and (b) 1986 to 2012 based on moderate-resolution images (LANDSAT 1-MSS, LANDSAT 5-TM and IRS-6-LISS-3). Shoreline changes (erosion/accretion area) is accompanied by classified beach sectors that experience different damage intensity to seaside infrastructure and are designated for emergency construction to repair infrastructural damage.

Table 4

Summary of sedimentary balance (erosion/accretion) per beach sector classified according to erosion damage to seaside infrastructure (such as boardwalk, kiosks, pluvial drainage system, and sewer lines) for periods from 1973 to 2012 and 1986 to 2012. Moderate* sector is the one closer to the Morro do Careca dune.

Period (Years)	Erosion Damage Sector	Moderate* (Area m^2)	Very Strong (Area m^2)	Strong (Area m^2)	Moderate (Area m^2)
1973–1986	Accretion	303.09	520.70	4,179.00	30,888.27
	Erosion	24,661.00	15,859.01	1,764.73	0.00
1986–2012	Accretion	1,004.89	370.63	0.00	0.00
	Erosion	16,378.09	15,993.22	8,040.64	38,797.83

wind interaction strongly indicate this segment as a supplier of sediments along the beach. The strong erosive conditions continue on the central portion of Ponta Negra beach, which is most densely urbanized area, as can be seen by the high number of kiosks and pluvial drainage system (manholes) installed at the seaside. Considering the damage severity to the beach facilities, this segment was categorized as strong to very strong according to the scale of damage intensity caused by coastal erosion. Only small portions of the beach revealed a positive balance related mostly to a temporary condition and controlled by sediment transport along the beach. Consistent semicircular contours indicate that erosion located in front of some pluvial drainage system (manholes) was caused the sediment removal from the beach face in runoff. During significant rainfall events, the excess rainwater is drained into the sea with an intense flow because the manholes have no attenuation storage. This negligence seriously affects the coastal morphology and causes beach face erosion (Amaro et al. 2012a). It also reflects a gentle beach gradient that facilitates strong waves and backwash action, subsequently increasing the fine sediment removal.

In Figure 4a, referring to the period from 1973 to 1986, an intense coastal erosion of approximately 42,284.74 m^2 and accretion of approximately 35,891.06 m^2 can be seen. The northern beach sectors categorized as strong and moderate on the intensity of destruction scale showed the highest accretion and made up 35,067.27 m^2 of the total. This can be seen in the areas of the frontal dunes in the backshore that were eroded by wave action along the beach face and the other areas alongshore, which maintained a sedimentary balance in the beach-dune system. In the 1990s, there was a dramatic increase in beachfront infrastructure due to a developing tourism industry and real estate speculation. By the year 2000, the boardwalk was extended 3.0 km and kiosks and a drainage system were added. In addition to the increase in construction along the shoreline, public works such as access roads and sewers were also installed to benefit the recent urbanization of the backshore dunes. Both the infrastructure and the public works reduced the sediment exchange in the beach-dune system and these areas displayed a severe erosion of approximately 46,848.47 m^2 (shown in Table 4) and a complete lack of sediment accretion between 1986 and 2012.

Table 4 summarizes the sedimentary balance on the beach (areas of erosion/accretion) according to the erosion damage categories (moderate, strong, and very strong) from 1973 to 1986 as well as from 1986 to 2012, as shown in Figure 4. These figures show the increase in erosion in these areas of approximately 42,284.74 m^2 between 1973 and 1986 and 79,209.78 m^2 between 1986 and 2012, and a reduction in accretion area from 35,891.06 m^2

to 1,375.52 m^2 from the first period to the second. The reason is that the first relevant seaside urbanization of Ponta Negra beach, which began in the 1970s and has developed until today, was focused mainly on seaside infrastructure and neighborhoods along the beach. The urbanization plan was completed around the year 2000 with an extension of the boardwalk northward and the installation of a pluvial drainage system and kiosks. The expansion of business activities linked to tourism and real estate appreciation in the area have also led to verticalization of urban space in Ponta Negra. This has led to continuous disfigurement in the vegetated dunes fields, uncharted changes of geological and geomorphological characteristics on the seaside and above all, the disruption of the dynamic interaction of coastal processes in the beach-dune system. Accordingly, the image analysis from 1986 to 2012 was included to demonstrate the conditions from an earlier period and the effects of seaside urbanization on erosion. Table 4 shows that the area near Morro do Careca, despite the fact that it showed the most erosion between 1973 and 2012 (41,039.09 m^2), was the only area that showed a reduction in erosion of approximately 24,661.00 m^2 between 1973 and 1986, and an increase in accretion of 303.09 m^2 to 1,004.89 m^2 in the two periods. This clearly shows the importance of the Barreiras Group sea cliffs below the dunes of Morro do Careca, both of which are sources of sandy sediments for Ponta Negra beach. These figures are corroborated by the studies in the Very Strong damage area, where there was intense coastal erosion of 31,852.23 m^2 between 1973 and 2012, even though it still receives sediments from Morro do Careca to the south. The main cause for the intense infrastructural damage along the coast is the poor planning of construction, which is now too close to the shoreline and the lack of coastal protection from wave action and tides.

From 1973 to 2012 there was a negative sedimentary balance for all the beach sectors. The area around the sea cliffs and the base of Morro do Careca, in the southern part of the studied area, suffered intense erosion of about 41,039.09 m^2. Between 1973 and 1986 the shoreline receded a total of −48 m at a rate of 3.7 m/year; between 1986 and 2012 the shoreline receded −38 m at a rate of 1.5 m/year.

Shoreline recession of around −23 m with erosion rate of 1.8 m/year was observed on sectors classified as strong and very strong between 1973 and 1986. This situation became more acute between 1986 and 2012 when the shoreline recession reached -37 m and had an erosion rate of 1.5 m/year. The sector in the central portion of the beach has been facing strong erosion since the early 1990s including a conspicuous destruction of its infrastructure during high tides. This means that the process of shoreline recession is prominent in this area.

For the beach sector classified as very strong, a highly destructive phase led to an erosion of about 31,852.23 m^2 between 1973 and 2012. The area where seaside facilities are being continuously destroyed by erosion due to the action of hydrodynamic driving forces is the main urban sector of Ponta Negra beach and it is crucial for tourism and the associated service sector.

In the northern portion of Ponta Negra beach, shoreline accretion reached 55m between 1973 and 1986 and had a progradation rate of approximately 4.2 m/year. Nevertheless, this moderate damage sector experienced a high shoreline recession of −43 m between 1986 and 2012 with an erosion rate of 1.6 m/year, a situation that is still occurring today.

Recession on Ponta Negra beach since 2000 has been confirmed by intermittent beach monitoring and by the evident erosion of the beach profile and the destruction of seaside infrastructure, commonly reported by the local press. Over the past few years, the destruction of urban facilities during high water episodes has become chronic. Therefore, it is obvious

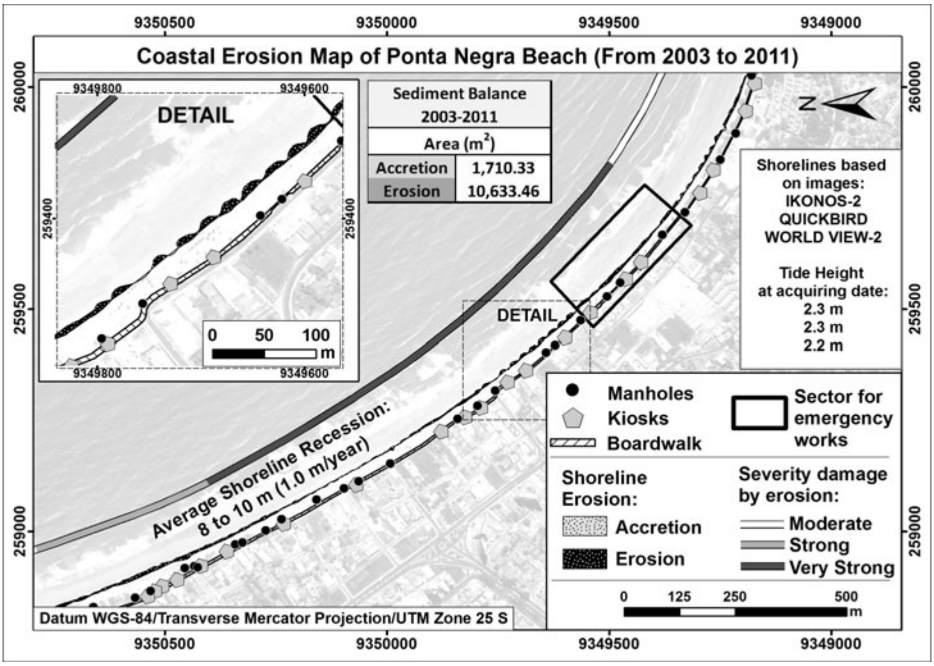

Figure 5. Coastal erosion map of Ponta Negra beach from 2003 to 2011 based on high-resolution images from IKONOS-2, QUICKBIRD and WORLDWIEW-2 satellites. Shoreline change (erosion/accretion area) is accompanied by classified beach sectors that experience different damage intensity to seaside infrastructure and are designated for emergency construction to repair infrastructural damage. The figure in detail shows the conspicuous semicircular forms which indicate erosion around the manholes.

that Ponta Negra beach's erosion was a natural process but since the early 1990s the rate of erosion has been accelerating. In the 1990s, urban plans were made that permitted the construction of seaside infrastructure that led to the disruption of the regular beach and dune sediment exchange. But it is also noticeable that in the early 1990s the main urbanized portion of Ponta Negra beach already had an intense negative sediment budget, which began in the early 1970s.

High-Resolution Images

Short-term shoreline changes and quantification of beach erosion/accretion were made by comparing high-resolution images from IKONOS-2 (acquiring date 21 February 2003), QUICKBIRD (4 April 2007), and WORLDVIEW-2 (2 May 2011). This generation of high-resolution satellite optical images allowed for coastal observation and beach feature detection mainly considering object-based analysis instead of only a spectral analysis of pixel values. The images were acquired under equivalent conditions and cover the same beach sectors of damage severity to beach facilities categorized from moderate to very strong.

Figure 5 shows a coastal erosion map of Ponta Negra beach between 2003 and 2011 supported by high-resolution images from IKONOS-2, QUICKBIRD, and WORLDWIEW-2 satellites. The image comparison analyses were completed in two phases: 2003–2007 and

2007–2011. Over a five-year period (2003–2007) there was a predominance of erosion with a deficit balance over an area of 2,886.52 m^2. The gain of 1,080.06 m^2 was restricted to portions of the sector, which required emergency repairs as indicated by Amaro et al. (2012a). To the North, the figure in detail displays the conspicuous semicircular forms indicate erosion around the drainage system and the natural dynamics of sediment removal from the beach face by waves and the current, which drive longshore sediment exchange.

The period between 2007 and 2011 showed that the sediment balance was also deficient by approximately 6.036,6 m^2 and widespread along the beach, but it was primarily seen in the sector that required emergency repairs. Therefore, the erosion losses outweigh the gains that occurred in the previous period for this beach segment. The evaluation of images also revealed intense erosion on the frontal dunes at the northern end of Ponta Negra beach. The erosion/accretion balance of Ponta Negra beach based on high-resolution satellite images from 2003 to 2011 indicates a deficit of around 8,923.13 m^2. Then, between 2003 and 2011, Ponta Negra beach was subjected to intense coastal erosion indicated by the shoreline retreat of 8 to 10 m, an average rate of around 1.0 m/year.

Therefore, the comparison between the moderate-resolution images and the high-resolution images that evaluates the long-term and short-term effects of the balance of erosion/accretion confirms that severe erosion on Ponta Negra beach began in the 1990s and became more acute in the 2000s. In conclusion, the sedimentary balance analysis on Ponta Negra beach indicates that erosion and accretion apparently occur accompanying sediment transport dynamics led by littoral drift and tidal currents. Therefore, the amount of erosion outweighs the gains from an earlier period for entire beach. Nowadays, Ponta Negra beach's northern sector is facing intense erosion on the remaining frontal dunes. All sectors are affected by sediment removal from the beach face due to natural driving forces (waves, currents and tides), but also as a result of runoff from the drainage systems and of anthropogenic action on beach landforms (such as the foreshore and frontal dunes), whose primary function is to protect the shoreline.

Digital Elevation Model

The DEM generated by the geodetic GPS survey evaluates the planialtimetric erosion/accretion rate on Ponta Negra beach. It was based on a PPK mode geodetic survey for 3D modeling of beach face morphology between May and September 2012. The DEM estimated that variations in the sediment volume on the beach face would occur in the area categorized as very strong on the destruction intensity scale. The beach zone is about 12,500 m^2 and has suffered continuous erosion as specified by the comparative analysis of moderate and high-resolution remote sensing images (Figures 4 and 5). This sector was selected for a geodetic survey because it required emergency works to repair damage of the seaside infrastructure and/or erosion control (Amaro et al. 2012a).

The DEM reveals remnants of frontal dunes and berms that are found distributed along the shore of Ponta Negra beach (Figure 6). They are in the end interrupted by a hollowing out in the beach face that are indicative of erosion resulting from rainwater runoff from manholes (Figure 7). Some beach cusps and low tide terraces, resulting from wave dynamics and the gentle slope that characterize this sector, can be seen on the lower level of the beach face.

A comparison of the DEM from different surveys revealed a negative balance of sediment volume of around $-3{,}261.94$ m^3 between May and September 2012 (Figures 6a, b). The height of the beach face varied from maxima of 2.20 m to 1.73 m, and minima of 0.50 m to 0.06 m, featuring a vertical erosion of around 0.47–0.44 m. This is translated

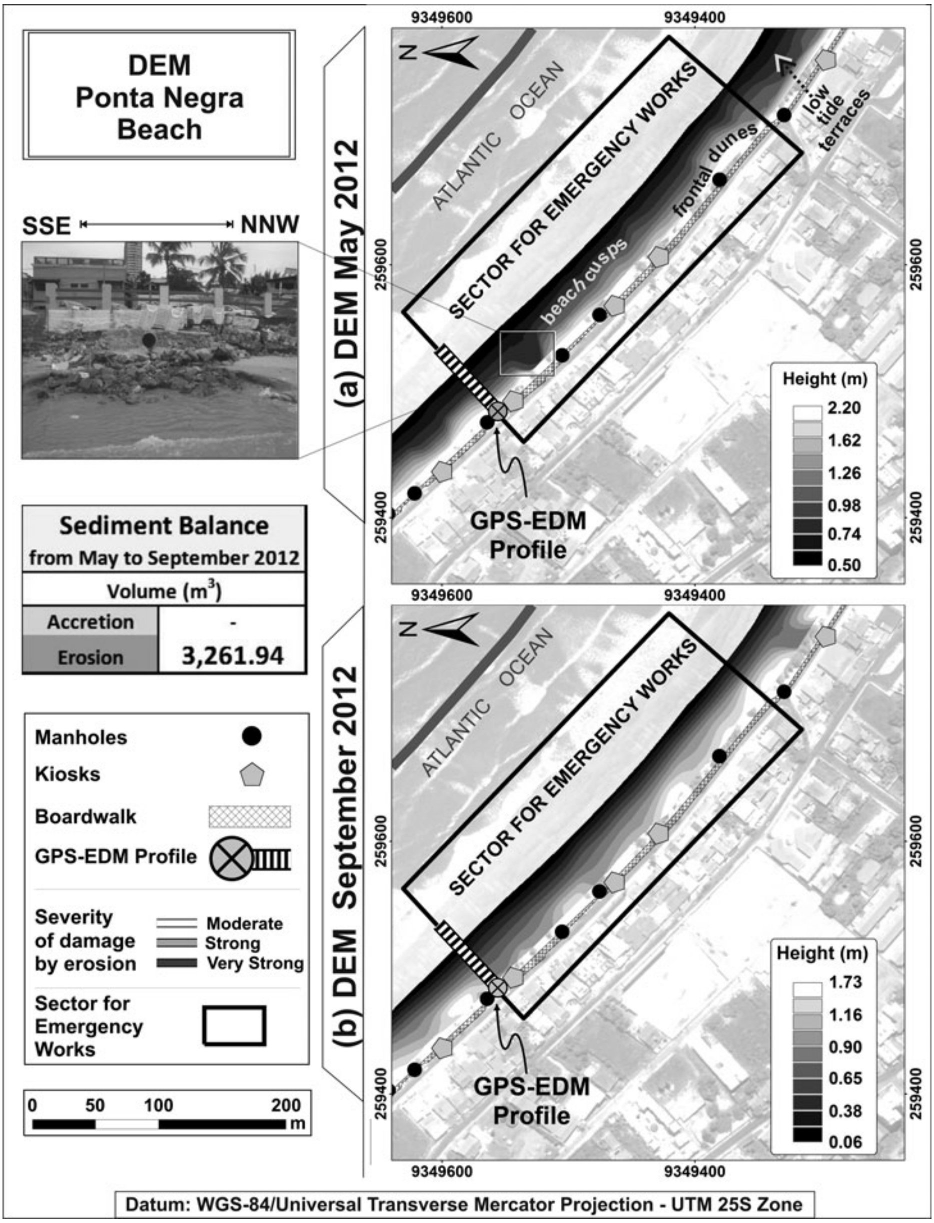

Figure 6. Digital elevation model derived from geodetic GPS surveys in May and September 2012 for classified beach Sector for emergency repair for seaside infrastructure damaged by erosion.

into an erosive change of 5,600 m^3. The DEM for the May 2012 survey shows once again that the water from outside the drainage system (Figure 6a, 7) is an erosive factor, which caused a vertical loss of around 0.47 m as shown in the model. However, in September 2012, sediments were deposited at the entry to the drainage system most likely due to the dynamic sediment transport of waves and tidal currents during high waters (Figure 6b).

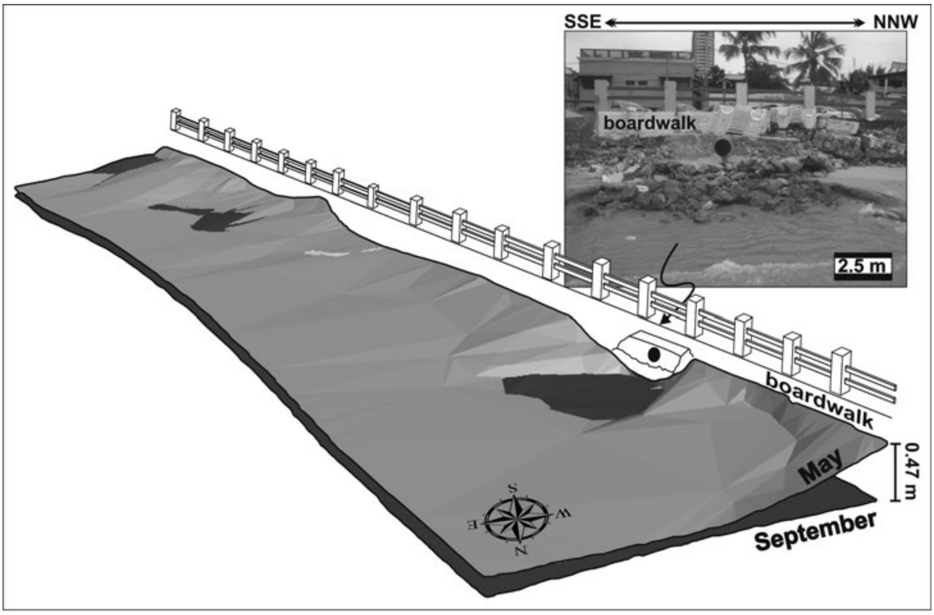

Figure 7. Perspective view of beach sector for emergency repair presenting a comparative overlay between the DEM from May (light grey) and from September 2012 (dark grey) emphasizing a vertical sediment loss due to the action of channelized water coming out of the drainage system.

Figure 7 displays a comparative overlay between the DEM from May (light grey) and September 2012 (dark gray).

The DEM from the GPS geodetic surveys were compared to traditional topographic profiles from EDM for improving reliability on data consistency. Then, statistical tests such as RMSE, Index of Agreement (*d*) and the Coefficient of Determination (R^2) were applied and indicated a correlation between the data from each survey. Both methods were performed at the same time in order to preserve environmental conditions and avoid bias. Profile 2 crossed the beach segment marked by intense erosion and categorized as a sector with Very Strong damage. It is used here as an example for this statistical procedure. The statistical parameters for July and August show a high correlation between profiling performed by both methods (Figures 8a, b). July is marked by index *d* of 0.9385, RMSE of 0.2210 and the R^2 of 0.9377 (Figure 8a). The profiles executed in August have index *d* of 0.9923, RMSE of 0.0655 and the R^2 of 0.9916, closely approaching a perfect correlation (Figure 8b). Even a visual analysis of both profiles allows recognizing the similarity between them, confirming the statistical analysis. Therefore, it can be confirmed that the DEM data obtained from a geodetic GPS survey is equivalent to the traditional topographic profiles carried out with the DEM systems, which is widely accepted for studies of coastal morphodynamics. Both procedures are highly accurate, as shown in Figure 8; however, the PPK GPS survey showed advantages in surveying time, large areas coverage and operational routines, with an error of only a few centimeters and comparable to EDM. A PPK GPS with a quad-motorcycle system as a rover is now considered an appropriate surveying method for examining the beach's planialtimetric and morphological changes in mesotidal conditions such as Ponta Negra beach.

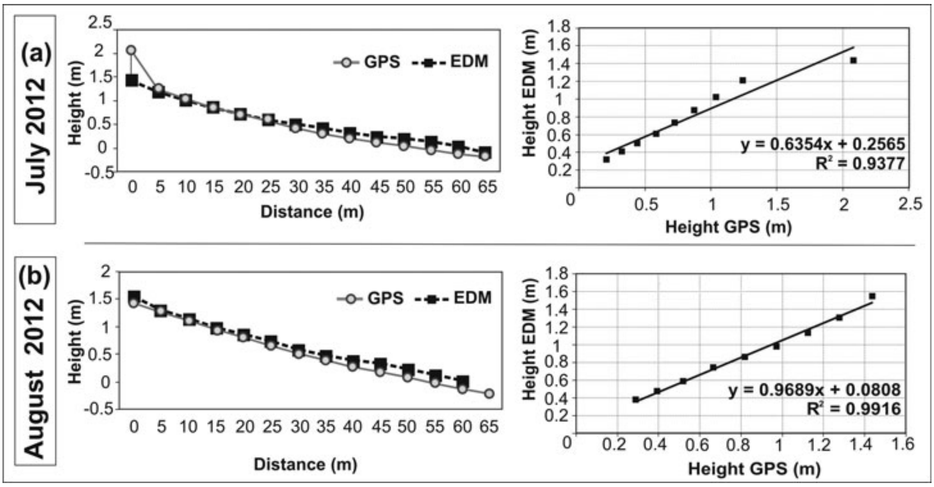

Figure 8. Comparison of cross-shore profile taken with geodetic GPS and EDM in (a) July 2012 and (b) August 2012, with its respective statistical index and adjustment equations.

Embayed Plan Shape Geometry

Ponta Negra beach's planform configurations were defined based on high-resolution satellite imaging taken in 2007 (spatial resolution of 20 cm) and the shoreline contour extracted from geodetic GPS field surveys. The objective of applying planform analysis in this study was to determine the tendencies of shoreline variations, an important measurement of the stability of Ponta Negra beach that allows predicting its behavior in the future. The stability of the shoreline shape has been categorized by Hsu et al. (2008) in four states: (i) static equilibrium, (ii) dynamic equilibrium, (iii) unstable, and (iv) natural beach reshaping. Figure 9 displays the comparison between the real Ponta Negra beach shape and predicted planform static equilibrium configuration according to the parabolic bay-shape. This can be seen in Eq. (2) by Hsu and Evans (1989):

$$Rn/R_0 = C_0 + C_1(\beta/\theta n) + C_2(\beta/\theta n)^2 \tag{2}$$

where β is the angle formed by the wave crest direction and the control line, which joins the wave diffraction point to the point where the straight section of the beach starts; R_0 is the length of the control line; θ_n is a range of angles incremented from β, the corresponding length R_n length of other lines that maintain the beach's stability; and C_0, C_1, C_2 are constants derived from regression analysis and are dependent on β.

The diffraction point of incident waves is located approximately 320 m from the promontory covered by the Morro do Careca dune. Therefore, wave diffraction starts just before reaching the promontory and is related to seafloor morphology. Remote sensing imaging together with a bathymetric chart revealed wave crests and a submerged feature at around 5.5 m in depth and also demonstrate a relevant change in the seafloor gradient.

The evaluation of real beach planform and the predicted static equilibrium shape proposed by the parabolic equation indicates that they do not match on Ponta Negra beach. Deviations from this predicted planform indicate areas that are vulnerable to erosion. In the study sector of Ponta Negra beach waves break at an angle to the shoreline which

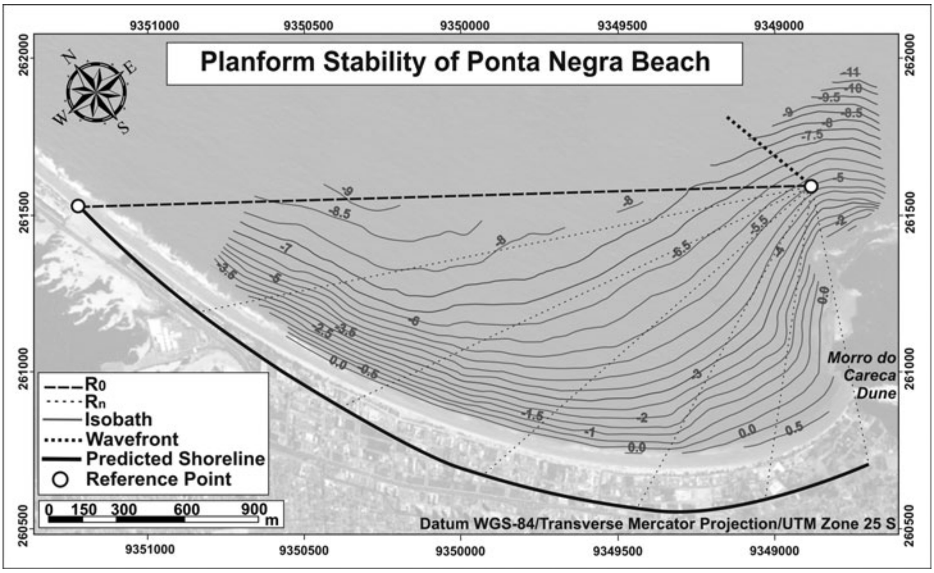

Figure 9. Map showing the comparison of the real shape and predicted planform stability of Ponta Negra beach based on Hsu and Evans (1989) and Hsu et al. (2008).

generates a longshore current that transports sediment causing shoreline retreat, sediment erosion, and significant destruction to seaside infrastructure. The curve predicted for Ponta Negra beach suggests a shoreline closer to the land situated on the area behind the headland formed by the Barreiras Group cliffs, below the Morro do Careca dune. It is predicted to reach altimetric levels with dense occupation of areas further north. In addition to this, the position of the predicted shoreline relative to the actual shoreline suggests that only the northern sector of Ponta Negra beach is in dynamic equilibrium, as illustrated in Figure 9. This shows that Ponta Negra beach is likely to be unstable in the long term and will be dependent on the maintenance of the present sediment supply in the bay.

Conclusion

The comparative analysis of shoreline changes based on multisource and multiple resolution remote sensing images showed widespread erosion in all the sectors of Ponta Negra beach and in the adjacent urban area with an increase in the erosion rate in recent years. It was demonstrated that the methods used in this study were satisfactory to make effective assessments of past shoreline progradation/recession on Ponta Negra beach between 1973 and 2012 (the long-term study) using moderate-resolution images (LANDSAT 1-MSS, LANDSAT 5-TM, LANDSAT 7-ETM+, AND IRS 6-LISS) and between 2003 and 2011 (the short-term study) using high-resolution images (IKONOS-2, QUICKBIRD, WORLDVIEW-2). The moderate-resolution images show that the erosion increased from 42,284.74 m^2 to 79,209.78 m^2 and the accretion area decreased from 35,891.06 m^2 to 1,375.52 m^2 between 1973 and 1986 and 1986 and 2012. The study reveals that the maximum recession on the shoreline, −48 m, was found at the base of Morro do Careca, thus indicating an erosion rate of 3.7 m/year between 1973 and 1986; between 1986 and 2012 the recession reached −38 m thus had an erosion rate of 1.5 m/year. The sector categorized as strong to very strong damage receded −23 m with an erosion rate of 1.8 m/year between 1973 and 1986. In the northern sector of Ponta Negra the accretion reached 55 m between 1973 and 1986 and had a shoreline progradation rate of about 4.2 m/year. However, this Moderate damage sector suffered a high shoreline recession of −43 m between 1986 and 2012 and the effects of erosion continue until today. In the short-term analysis based on high-resolution images of the whole beach, an erosion/accretion balance deficit of around 8,923.13 m^2 in area could be seen between 2003 and 2011.

A PPK GPS survey was taken for a 12,500 m^2 beach stretch that had been categorized as very strong on the destruction intensity scale between May and September 2012. A comparison of the DEM from this survey showed a negative balance of sediments of approximately −3,261.94 m^3 and significant vertical erosion of the beach face of about 0.47 to 0.44 m over these four months. These DEM were compared to the EDM profiles and a high degree of similarity could be seen between the two methods as shown in the statistical parameter study like in index *d* of approximately 0.9923, RMSE of 0.2210 to 0.0655, and R^2 of 0.9377 to 0.9916.

The comparison between the actual shape of the beach with its projected static equilibrium based on the proposal by Hsu and Evans (1989) showed an intense shoreline retreat in the studied area. The most intense erosion occurs near the headland where the dune, Morro do Careca, is located and in the northern sections of the beach where there is a high density of construction and public infrastructure such as sidewalks, drainage systems and sewers. Even if the parabolic bay shape equation is purely empirical, it can determine the approximate predicted static equilibrium shape and shoreline position and shape of Ponta Negra beach in the future. It reveals that the actual shape is completely unstable, something that can be confirmed by coastal erosion/accretion data.

Comparison of the long- and short-term periods showed that erosion is present in both periods and involves almost all of the shoreline. It has increased since early 1990s due to urban sprawl on the adjacent dune and in the backshore due to the construction of infrastructure closer to the shoreline. During the 2000s, the increase in seaside infrastructure intensified progressive soil impermeabilization and accelerated the erosion of the beach face. Results undoubtedly indicate that there has been a strong erosive character and an unstable sediment budget on Ponta Negra beach in recent years.

Sea cliffs, the Morro do Careca dune base, and most likely nearshore sediment bars formally serve as sand reservoirs for beach nourishment for remaining sectors. However, the sediment budget is not sufficient to nourish all of Ponta Negra beach and the erosive behavior continues to affect the sectors that are most relevant for recreational purposes with a high quantity of touristic infrastructure (such as boardwalks, kiosks, restaurants, hotels). Nevertheless this area was classified as a very strong damage sector and emergency construction was required to repair infrastructure damaged by erosion and strong waves. Few beach sectors clearly indicate a positive sedimentary balance but it is probably a temporary condition during sediment transport alongshore or related to preexisting frontal dunes that are being modified by human activities. The water table varies due to seasonal change, rainfall, beach topography and sea level fluctuation and it interferes with the patterns of sediment removal on the beach face. However, surface runoff is widespread alongshore due to the rainwater drainage system and it is a crucial agent in the erosion of sediments from the beach face. Although there were pre-existing conditions of intense erosion before 1986, the shoreline retreat indicated by remote sensing images shows that something substantial happened in early 2000s that made the destructive phase more intense than in all constructive and destructive past cycles.

The intense urbanization increases surface runoff by creating more impermeable surfaces that do not allow water percolation which is then conducted by a drainage system to the beach face increasing erosion. Decidedly this is a key factor for understanding patterns of sediment removal on the beach face and must be considered in solving the erosion problems on Ponta Negra beach.

This study specifically shows that Ponta Negra beach presents a complex erosion/accretion dynamic that is a function of wave conditions, nearshore morphology, bay geometry, seasonal wind variation and climate fluctuation and subaerial beach configuration related to the intense urbanization of the neighborhood. These factors are the main cause of beach instability and erosion. This study has also determined that the shoreline's movements have interfered with the changes and extension that the beach face has experienced, especially in the sector with the highest socioeconomic relevance.

However, the cause of erosion problems on Ponta Negra beach seems beyond the direct influence of significant wind, waves, tidal currents and progressive reduction in sediment supply. The population of Natal has recently put forth a lot of effort to solve the recurring destruction of the seaside infrastructure due to the socio-economic damage that this causes for property owners near the shore. The solution lies in appropriate environmental studies of the long-term and short-term impacts to improve knowledge of coastal processes and interactions of the beach-dune sediment exchange. We also must establish rules to assure adequate levels of urban growth in coastal areas. Furthermore, the negative balance of the sediment budget seen in long-term and short-term analyses based on remote sensing images and DEM by geodetic surveys must be taken into serious consideration.

Remote sensing technology has considerably improved the quality of digital images over the past decades, including temporal, spectral, radiometric, spatial resolutions improvements. In addition to this, it is easily available and sometimes free to the general public. This has facilitated the systematic and detailed monitoring of the evolution of sandy beaches and the mapping of morphological features and it has promoted a more accurate estimate of shoreline (progradation/recession) changes. The integration of studies on erosion/accretion rates in the long-term and short-term planialtimetric quantitative erosion data obtained by GPS survey and predictive analysis of static equilibrium of the beach are essential information in the development of public policy on the occupation of the coastal zone.

However, the most efficient use of this information about the densely populated coastal area should be accompanied by careful analysis of previous data, and greater investment in obtaining data on meteorological and oceanographic forces (winds, waves, currents, and tides) in a continuous time series, and using shallow bathymetry data. This is a high priority issue and a challenge for board decision makers, the scientific community and the community in general. Rapid coastal urbanization increases vulnerability, reduces the resilience of the environment, and consequently intensifies the exposure of socio-economic interests to disaster risk and increases hazards of future climate change scenarios.

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