PANAMJAS
Pan-American Journal of Aquatic Sciences

Climate Changes: effects of sea level rise on the municipalities of Rio das Ostras, Casimiro de Abreu, Cabo Frio and Armação dos Búzios, Rio de Janeiro, Brazil

FÁBIO FERREIRA DIAS[1,2,3*], CAMILA AMÉRICO DOS SANTOS[2,3], PAULO ROBERTO ALVES DOS SANTOS[4], RUAN VARGAS[3], ANDERSON DOS SANTOS PASSOS[1], LAIANA LOPES DO NASCIMENTO[3], THALITA DA FONSECA RODRIGUES[5], KAREN MARIELA BENCOMO SEGUERI[1], ORANGEL AGUILERA SOCORRO[1], PERLA BAPTISTA DE JESUS[1] & TAÍSA CAMILA SILVEIRA DE SOUZA[6]

[1] Universidade Federal Fluminense (UFF) – Programa de Pós-graduação em Biologia Marinha e Ambientes Costeiros, Instituto de Biologia. Rua Outeiro de São João Batista, s/n, Niterói, Rio de Janeiro, Brasil.
[2] UFF – Programa de Pós-graduação em Engenharia de Biossistemas, Av. Milton Tavares de Souza, s/n, Campus da Praia Vermelha, Niterói, Rio de Janeiro, Brasil.
[3] UFF – Núcleo de Estudos em Ambientes Costeiros- NEAC, Instituto de Geociências. Av. Milton Tavares de Souza, s/n, Campus da Praia Vermelha, Niterói, Rio de Janeiro, Brasil.
[4] UFF – Departamento de Analise Geoambiental, Av. Milton Tavares de Souza, s/n, Campus da Praia Vermelha, Niterói, Rio de Janeiro, Brasil.
[5] Universidade Federal do Rio de Janeiro – Programa de Pós-graduação em Geografia, Athos da Silveira Ramos, n° 274, Cidade Universitária, Rio de Janeiro, Brasil.
[6] UFF – Programa de Pós-graduação Dinâmica dos Oceanos e da Terra, Av. Milton Tavares de Souza, s/n, Campus da Praia Vermelha, Niterói, Rio de Janeiro, Brasil.

*Corresponding author: *fabioferreiradias@id.uff.br*

Abstract. The significant increase in mean global temperatures results in climatic changes that, among their consequences, point to a rise in the mean sea level– due to the melting of the icecaps. Such circumstances will cause impacts, as well as the requirement for adaptations and interventions by the end of the 21st century. It is estimated that if sea level rises by 60 cm in the next 100 years, it will be enough to flood large areas and cause diverse environmental impacts. It is noteworthy that the region between the municipalities of Rio das Ostras and Armação dos Búzios is characterized by an open beach arc, having in its rear a fluviomarine plain, being widely sensitive to a rise in sea level and its erosive processes. Thus, the present study sought to know the past transformations of the coastal landscape of the area along the Holocene, as their respective marine paleontology, in order to determine their evolutionary tendency and propose future scenarios. The analysis of sea level variations and their consequences in the coastal zone was carried out through simulation using a Digital Terrain Elevation Model, together with land use maps. Thus, it was possible to identify areas subject to changes and impacts resulting from a possible rise in sea level in the area. In this way, the implementation of monitoring programs and mitigation actions must be present or foreseen in a coastal management plan and the construction of programs that promote integration between public agencies and research entities.

Key words: Coastal Zone, Coastal Erosion, Remote Sensing, GIS, Coastal Management

Resumo: Câmbios climáticos: efeitos do aumento do nível do mar sobre os municípios do Rio das Ostras, Casimiro de Abreu, Cabo Frio e Armação dos Búzios, Rio de Janeiro, Brasil. O aumento significativo das temperaturas médias globais resulta em mudanças climáticas que, apontam entre suas consequências, uma subida do nível médio do mar – em virtude do degelo. Tais circunstâncias causarão impactos, e exigem adaptações e intervenções até o final do século XXI. Estima-se que, se o nível do mar aumentar 60 cm nos próximos 100 anos, será o suficiente para inundar grandes áreas e causar diversos impactos ambientais. É notório que a região entre os municípios de Rio das Ostras e Armação dos Búzios se caracteriza por ser um arco praial aberto, tendo em sua retaguarda uma planície flúvio-marinha, sendo amplamente sensível à uma subida do nível do mar e seus processos erosivos. Assim, o presente trabalho procurou conhecer as transformações passadas da paisagem costeira da área ao longo do Holoceno, como seus respectivos paleoníveis marinhos, com objetivo de determinar sua tendência evolutiva e propor cenários futuros. A análise das variações do nível do mar e suas consequências na zona costeira foi realizada através de simulação utilizando um Modelo Digital de Elevação do Terreno, junto a mapas de uso do solo. Assim, foi possível identificar áreas sujeitas a alterações e os impactos provenientes uma eventual subida do nível do mar no local. Dessa forma, a realização de programas de monitoramento e ações mitigadoras devem estar presentes ou previstas num plano de gerenciamento costeiro e a construção de programas que promovam a integração entre os órgãos públicos e as entidades de pesquisa.

Palavras-chave: Zona Costeira, Erosão Costeira, Sensoriamento Remoto, SIG, Gerenciamento Costeiro.

Introduction

The climatic changes that can occur due to the significant increase of mean global temperatures points to the rise of sea level (e.g. Suguio 2008, Nicholls et al. 2014). Martin et al. (1996) claim that the sea level will rise due not only to the partial melting of the ice masses stored on the continents but also to the thermal expansion of the oceans.

In fact, the Fifth Assessment Report of the Intergovernmental Panel on Climate Change – IPCC (Church et al. 2013) states that the thermal expansion of the oceans and the melting of the glaciers were the dominant factors (75% of the increase observed since 1971) that contributed to the rise of global mean sea level in the 20th century.

In addition to the IPCC, several authors approach sea level rise and its consequences (e.g. Al-Buloshi et al., 2014; Nicholls et al., 2014; Osiliere 2016). The estimative of sea level rise during the next century could range between 0.3 to 2.15 m (Grinsted et al., 2009; Vermeer & Rahmstorf, 2009; Rohling et al., 2008). Other more recent works that can be cited are those of Beckley et al., 2017; Nerem & Fasullo (2019) and NOAA (2019), based on tidal gauge data and observations of altimetric satellites, showing a rise of 3 mm yr^{1}, however, show that this rate is accelerating. Sea level changes and its consequence along the Brazilian Atlantic coast (e.g. Sampaio et al., 2003; Souza, 2005; Neves & Muehe, 2008; Lins-de-Barros & Muehe, 2010; Passos et al., 2017, 2018) remain an open discussion. However, the more plausible scenario to Rio de Janeiro sea level changes model (Armação dos Búzios and Cabo Frio region) could be the baseline curve of sea level proposed by Dias (2009) and Jesus et al. (2017) for Holocene Southeastern Brazilian coast.

Early geological interpretation of relative sea level changes were referred to Holocene marine transgression (e.g. Sant'anna, 1975; Brito & Carvalho, 1978; Cunha et al., 2012) following the axiom of Martin et al. (1996) based in the past and present evolutionary sea level change.

The causes and consequences of a sea level rise have gained increasing importance, as a large part of the world population is concentrated in coastal areas. An estimation of 20% of the global population live within 100 km of the coast and less than 10 m above sea level, and the projected population growth rates in the coastal zone are the highest in the world (McGranahan et al., 2007; Hawker et al., 2019). Furthermore, 21 of the 33 megacities (cities with more than eight million people)as Tokyo (Japan), Mumbai (India), Lagos (Nigeria), Los Angeles (USA), Dhaka (Bangladesh) and Karachi (Pakistan), for example, can be considered coastal cities (Small & Nicholls, 2003; Martinez et al., 2007; Masselink and Gehrels, 2014; Radford, 2014; IPCC, 2019).

One of the evidences of a sea level rise is the coastal erosion. This phenomenon is observed and studied worldwide (e.g. Castelle et al., 2007; Pedrosa, 2013; Karlsson & Hovelsrud, 2015; Seino et al., 2015; Umar et al., 2015; Senevirathna et al., 2017; Leatherman, 2018) and can cause several consequences not only to the coastal environment but also to human activities.It is certain that in the coming decades coastal erosion will intensify around the entire world, and may lead to the disappearance of several coastal areas and regions (Snoussiet al., 2007; Peric & Zvonimira, 2015). According to Bruun (1962) sea level rise is accompanied by a retreat from the shoreline. The link between coastal erosion, flooding and sea level rise is that this process is the beginning of a major transformation in the coastal zone that is lowland drowning (Williams, 2013).

Souza (2009) points out that coastal erosion is an environmental problem that can cause several consequences for various natural and anthropic environments, such as retreats in the coastline. In agreement, Williams (2013) points out that coastal erosion is one of the main agents causing changes in the coastline. Coastal erosion can be caused by numerous factors, being they natural and/or anthropic, not being directly linked to the space and time scale (Souza et al., 2005). This phenomenon may become a problem when there are some infrastructure (as roads, houses, kiosks and boardwalks) within the active beach system. Indeed, this fact is referred to an idea of vulnerability of coastal erosion and storm surges, which can cause economic losses (Lins-de-Barros, 2005; Vargas, 2017; Bevacqua et al., 2018). Letherman (2001) describes the social and economics coasts of a sea level rise.

A beach is commonly defined as an accumulation of unconsolidated sediments formed in the interface of the ocean and land (but there are other kinds of beaches, as lacustrine and estuarine beaches), and it is eroded when it loses more sediments than it receives (when there is a negative sediment balance on the beach system). The beaches fringe about 40% of the world’s coastline (Komar, 1976; Bird, 2008; Davidson-Arnott, 2010). Bird (2008) shows the various sources of input and output of sediments on a beach. According to Davidson-Arnott (2010) 20% of the coastlines are composed of sandy beach, and others 10% are composed of gravel or cobble beaches, particularly in high latitude areas.

In this context, this study sought to verify the relative sea level variations in the municipalities of Rio das Ostras, Casimiro de Abreu, Cabo Frio and Armação dos Búzios, in the state of Rio de Janeiro, Brazil, through investigation of the repositioning of the coastline along the Holocene and simulate a future scenario with a sea level above the current one. Thus, it was possible to analyze the sea level variations and their consequences in the coastal zone, identifying in addition to the changes in the landscape, possible impacts resulting from a probable rise in sea level in the region.

Study Area: The study area is located in Região das Baixadas Litorâneas do Estado do Rio de Janeiro (Baixada Litorânea Region of the State of Rio de Janeiro, Fig. 1) and corresponds to the municipalities of Rio das Ostras, Casimiro de Abreu, Cabo Frio and Armação dos Búzios. For Sant'anna (1975), the region is characterized by an open beach arc, which extends from Barra do Rio das Ostras, to the north; until to the south of Barra do Rio Una (Una River).

Materials and methods

The first stage consisted of a survey of cartographic material. Orthophotos in the 1:25,000 scale and Digital Terrain Models were obtained on the website of the Brazilian Institute of Geography and Statistics (IBGE). Satellite images used correspond to the dates of May 07, 1984 (Landsat 5 TM) and September 18, 2015 (Landsat 8 OLI), path 216 row 076, were acquired on the Brazilian National Institute of Space Research (INPE) website. During the fieldwork in the study area, a Zênite Global Positioning System (GPS) tracker was used, and in the laboratory stage, it was used the software ArcGis 10.2 for data processing.

Indicators of Ancient Sea Level: This stage aimed to spatialize indicators of ancient sea level, cited by several authors, such as: active cliffs and ancient beach ridges (Sant'anna, 1975), and bioclastic accumulations (e.g., Anomalocardia brasiliana and Cerithium sp.), according to Cunha et al., (2012) and Brito & Carvalho (1978). The occurrence of each of these indicators was georeferenced (WGS84) in a single map to show the area that was flooded in Holocene.

Coastal Erosion Indicators: A survey was carried out in the field, which shows possible coastal erosion points through the methodology of Souza & Suguio (2003), and points out the presence of the coastal erosion indicators and the spatial distribution along the beaches (Table I). The indicators found at the beaches had their geographic coordinates recorded (WGS84 geodetic system) with a geodetic GPS. The information obtained was plotted on a map.

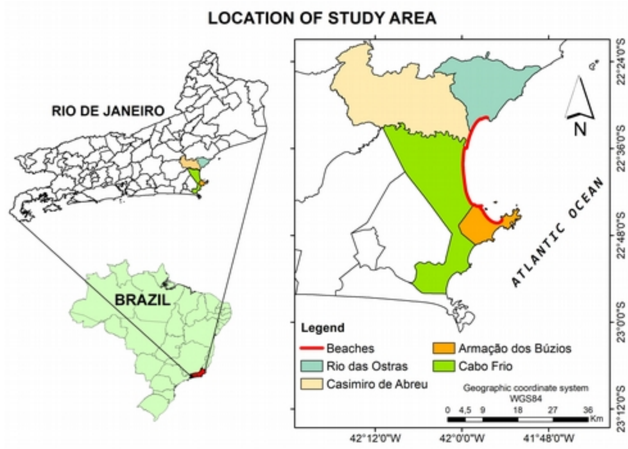

Figure 1. Location of study area. Municipalities of Rio das Ostras, Casimiro de Abreu, Armação dos Búzios and Cabo Frio in Rio de Janeiro, Brazil.

Landscape Transformations in Coastal Environments: Land Use Mapping: The urban occupation was mapped applying the Normalized Difference Built-Up Index (NDBI) (Zha et al., 2003) for the years 1984 and 2015 in order to analyze the urban and population growth. The images used correspond May 07, 1984 (Landsat 5 TM) and September 18, 2015 (Landsat 8 OLI), with bands that have 30 meters of resolution per pixel.

According to França et al., (2012) NDBI is a radiometric index used to identify urban and built areas, based on the spectral response of these areas between the near infrared and mid-infrared bands. The equation used was proposed by Zha et al., (2003):

$$NDBI = \frac{(MIR - NIR)}{(MIR + NIR)}$$

where: NIR corresponds to near Infrared and MIR to mid-infrared.

First, the near infrared and the mid-infrared bands were transformed into reflectance bands. The Landsat Tools softwaregives the reflectance equations for each band of the different sensors. The QGIS 2.14 software was used to perform the equations necessary for the transformation of the bands and also the NDBI.

“False color" compositions were made for each year using ENVI 4.5 software, applying the NDBI done for the two yearsaccording to the following configuration RGB: R (NDBI), G (band 4), B (band 3) for Landsat 5;and R (NDBI), G (band 5), B (band 4) for Landsat 8.

Other classes of land use as water, vegetation, wet areas, beach, mangrove, pasture, agriculture, restinga, exposed soil and rocky outcrop were mapped by visual interpretation, based on IBGE mapping and Cabo Frio Master Plan. This stage allowed the representation of the degree of anthropic intervention over the years and the verification of the areas to be impacted by the rise in sea level.

Simulation of Future Scenarios: Different methods in several studies were adopted for the simulation of sea level rise and its consequences: Snoussi et al., (2007) used satellite altimetry, aerial photographs, Digital Elevation Model (DEM) and ArcGIS software; Natesan & Parthasarathy (2010) employed in their methodology topographic maps in the scale of 1:25,000 and generation of the DEM of the area through ArcGIS; Akumu et al., (2010) used the Sea Level Affecting Marshes Model (SLAMM) together with the Landsat TM data, DEM, ER Mapper and ArcGIS; and Al-Buloshi et al., (2014) through the use of a GIS structure, developing a DEM together with a precise database of the coastal zone elevation reference points.

For the simulation of future scenario, the land use map was superimposed on the DEM acquired on IBGE website and the highest rate of sea level rise was adopted, proposed by Jones & Mann (2004), which indicates an extreme value of 2.15 m for the year 2100.

Results and Discussion

Indicators of Ancient Sea Level: According to Sant'anna (1975), the geological indicators (ancient beach ridges and cliffs) are represented in Fig. 2. In relation to the biological evidence, two studies were consulted to make this representation. According to the study done by Cunha et al., (2012) in the region of Cabo Frio and Armação dos Búzios, the biological indicators (bioclastic accumulations – Fig. 3) were found throughout the coastal plain of the study area, also represented in Fig. 2.

Mapping of Coastal Erosion Indicators: During the campaign, six different indicators were identified and their spatial distributions were represented by points in Fig. 4. Each point was observed and recorded according to the presence of a certain indicator, using Table I as base. Indicator II had already been verified by Castro et al., (2011), who used images from different dates (1975 and 2003) to determine the shoreline retrogradation.

Figure 5 illustrates a sequence of recorded photographs of the coastal erosion indicators found on the beaches. A great destruction of the boardwalk and a very narrow backshore zone, among other aspects, were observed.

On Praia das Tartarugas (Tartarugas Beach)

Table I. Coastal erosion indicators monitored on the beaches of the State of São Paulo, Brazil (Souza, 1997; Souza & Suguio, 2003).

Indicator	Description
I	Backshore zone very narrow or nonexistent due to flooding by the spring tides (beaches urbanized or not).
II	General retrogradation of the coastline in the last decades, with a clear decrease in the beach width, in all its extension or more sharply in certain places of it (beaches urbanized or not).
III	Progressive erosion of Pleistocene or Holocene marine and / or aeolian deposits bordering beaches, without the development of cliffs (urbanized or unpopulated beaches).
IV	Intense erosion of Pleistocene or Holocene marine / aeolian deposits bordering the beaches, causing the development of cliffs with heights up to tens of meters (urbanized beach or not).
V	Destruction of frontal sandbanks or mangrove vegetations and / or presence of roots and trunks in position of life buried in the beach, caused by the accentuated erosion or the burial of the vegetation due to the retrogradation / migration of the coastline on the continent.
VI	Exhumation and erosion of paleolagunal deposits, turfs, beach sandstones, Holocene and Pleistocene marine deposits, or basement on the present foreshore and / or beach face due to the removal of beach sand by coastal erosion and extremely negative sedimentary deficit (urbanized beach or not).
VII	Frequent exposition of “terraces or artificial cliffs”, presenting packages of thickness up to metric, formed of successive layers of buried landfills by beach/aeolian sands, in the contact between the beach and the urbanized area.
VIII	Destruction of artificial structures built on the Holocene marine or aeolian deposits, which border the backshore zone, the foreshore, the beach face, the nearshore zone and / or the offshore.
IX	Erosive recovery of old marine abrasion platforms, elevated from +2 to +6 m, formed on rocks from the igneous-metamorphic Pre-Cambrian to Mesozoic basement, at times when the sea level was above the current level during the Holocene and the end of the Pleistocene (urbanized beaches or not).
X	Presence of concentrations of heavy minerals in certain locations of the beach, in association with other erosive indicators (urbanized beaches or not).
XI	Development of beach cusps formed by the presence of concentrated return currents or centers of divergence of littoral drift cells located at a more or less fixed location (s) of the coastline.

and Praia do Abricó (Abricó Beach), in Rio das Ostras, the monitoring between 1999 and 2008 and the comparison of aerial photographs point to retreats between 8 and 12 meters according to Muehe (2006) and Lins-de-Barros & Muehe (2010), corroborating with some sections observed in the survey of this study.

Highlighting coastal erosion events, in 2001 a storm event destroyed kiosks at Praia das Tartarugas and in an attempt to retain erosion a wall was built, as reported by Muehe (2006).

In the stretches C, D and E (Fig. 5), the presence of fallen trees, exposed concrete pipes, beach sandstone and well development of cliffs were noticed. As already presented in the study of Muehe (2006), at north of the mouth of São João Riverto

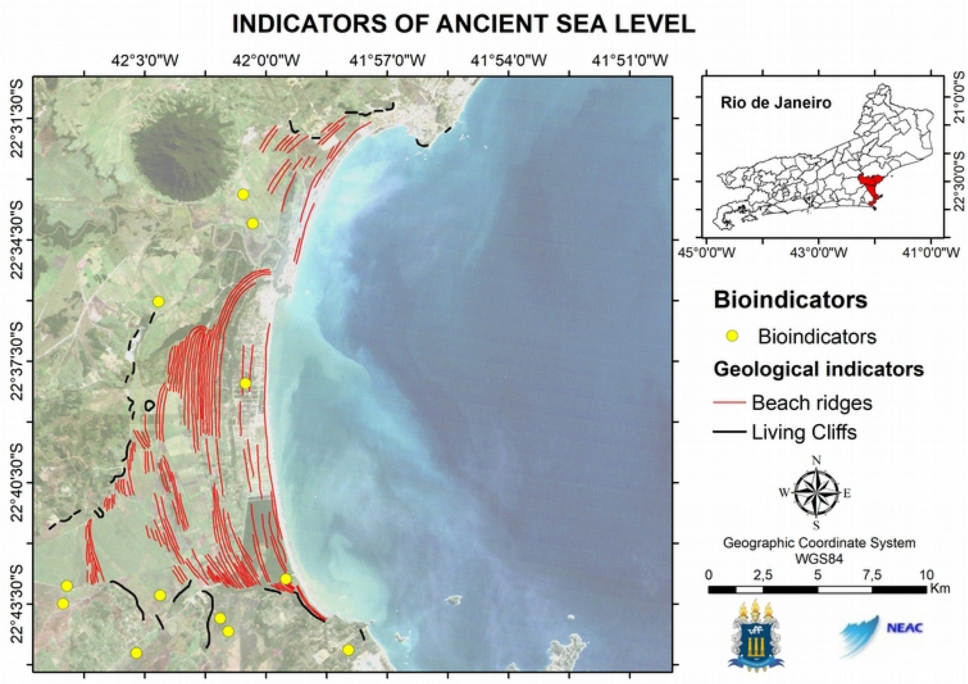

Figure 2. Distribution of geological and biological indicators along the coastal plain of the study area.

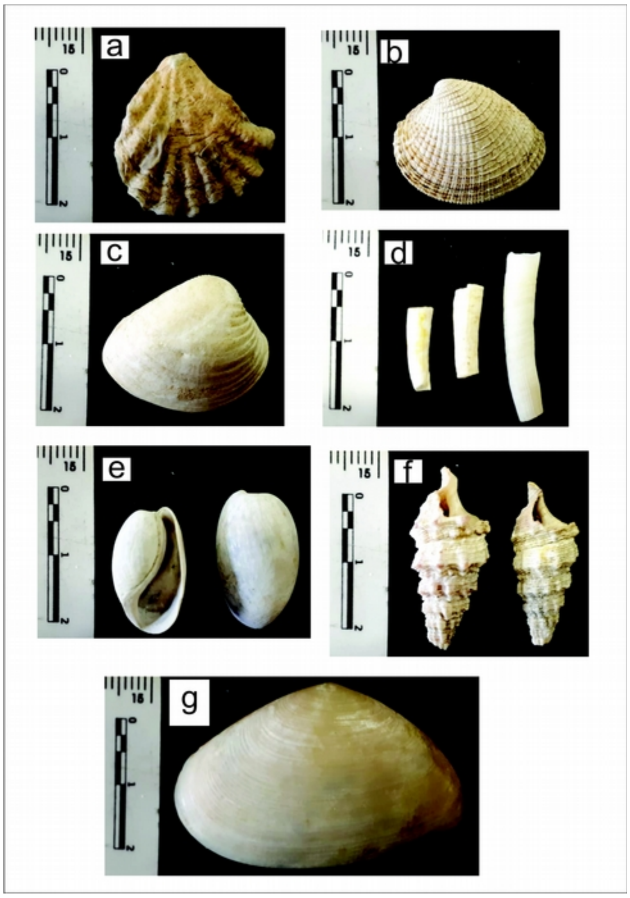

Figure 3. a) *Plicatulagibbosa*; b) *Chione* sp.; c) *Anomalocardia brasiliana*; d) *Dentalium* sp.; e) *Bullastriata* sp.; f) *Cerinthium* sp.; g) *Telinalineata* sp.

Rio das Ostras region, the beach presents an exposure of sandstones, indicating erosion occurrences that are accentuate towards Rio das Ostras.

In sections F and G, the point that is in the region of Armação dos Búzios, present a very narrow backshore zone as coastal erosion indicator (indicator I), where there was no emerged sand (no backshore zone).

As result of NDBI processing and visual interpretation, 13 classes of land use were mapped for the years 1984 and 2015. It is important to note that the mapped area corresponds only to the coast zone that is of interest for this study. Therefore, the results show only the values based on this delimitation. Figure 6 illustrate the land use of 1984 and 2015 and the TableII shows the area (km² / percentage) corresponding to each class mapped.

According to Fig. 6 and Table II, the three most representative classesin 1984 were: Pasture, urban occupation and forest. For this year, the urban growth was beginning to develop, corroborating with the work of Oliveira et al., (2015).

In the mapping of 2015, the three most representative classes were: Urban occupation, agriculture and pasture. Comparing the two dates, it can be observed that the urban occupation in 2015 increased by 126% in relation to 1984, more than doubled. The study by Oliveira et al., (2015) allusive to the relative rate of increase per mesoregion corroborates with the land use mapping made in this

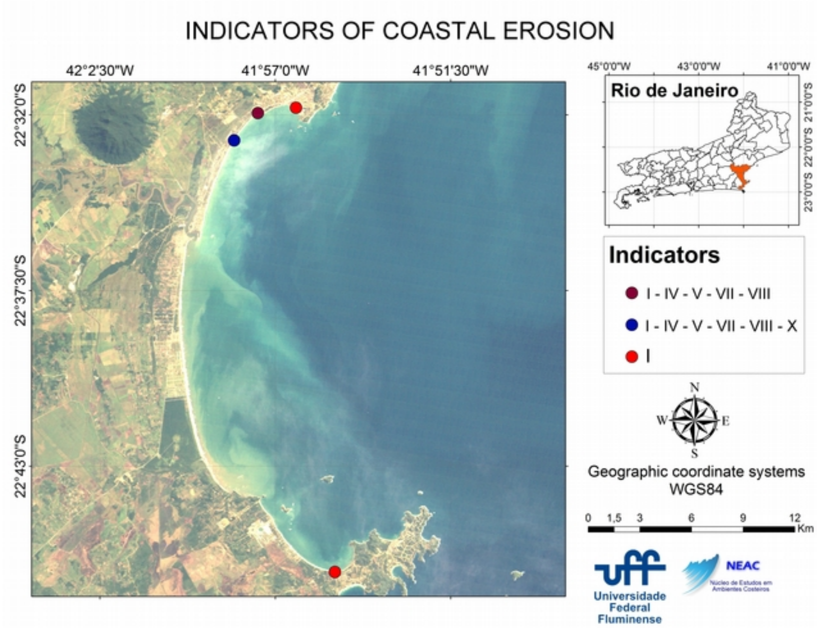

Figure 4. Indicators of coastal erosion observed in situ, according to Table I.

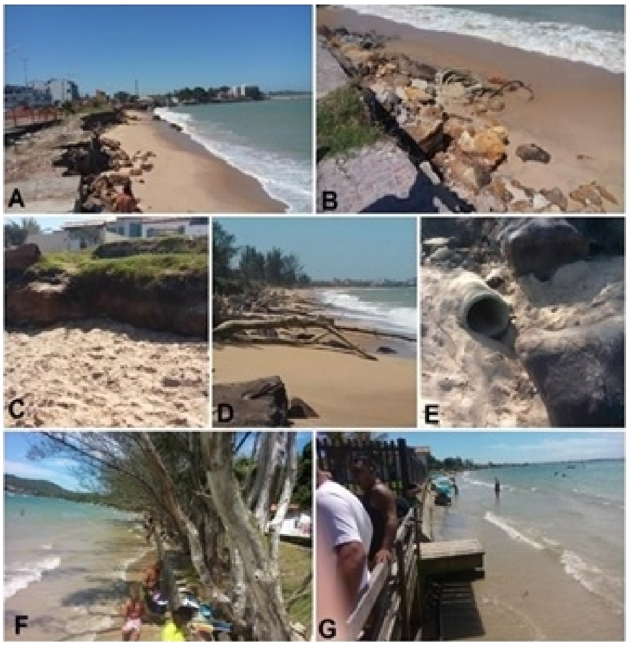

Figure 5. Coastal erosion indicators in Rio das Ostras to Armação dos Búzios. Point A and B: Indicators I, IV, V, VII and VIII. Point C, D and E: Indicators I, IV, V, VII and X. Point F and G: Indicator I.

study, which shows that since 1980, the coastal region of Baixada Litorânea, which comprises the follow municipalities: (1) Araruama, (2) Armação de Búzios, (3) Arraial do Cabo, (4) Cabo Frio, (5) Casimiro de Abreu, (6) Iguaba Grande, (7) Rio das Ostras, (8) São Pedro da Aldeia and (9) Saquarema, has experienced an accelerated growth over the years.

Other information that helps to understand the urban growth of concentrated linear character along the Amaral Peixoto highway is directly linked to the economic dynamism, driven initially by the tourism industry and later also by the oil industry, which became more accelerated since the 1990s (Alentejo, 2005).

Simulation for Future Scenarios: Throughout this study it was possible to know the past evolution of the study area and thus to project a future critical scenario coming from a potential rise of sea level. The simulation (Fig. 7) was elaborated following the rate of sea level rise proposed by Grinsted et al., (2009). Figure 8 shows the classes of land use that will be flooded.

Through the simulation (Fig. 9), it is possible to observe an extensive flooded area of 303.359 km² of the total area mapped. The geomorphology of the area favors flooding since it is a coastal plain, characterized by low declivities. In relation to the urban occupation of 2015, an area of 32.291 Km² was flooded in this simulation, representing approximately 38.60% of the total urban occupation mapped.

Several studies like this are carried out around the world, considering a sea level rise as a simulation to show the possible impacts. In the work carried out by Al-Buloshi et al., (2014), in Oman, the authors projected three scenarios, being considered the worse of 5 meters of elevation that shows a great impacted area.

According to Nicholls et al., (2014), sea level rise can cause several social and physical impacts

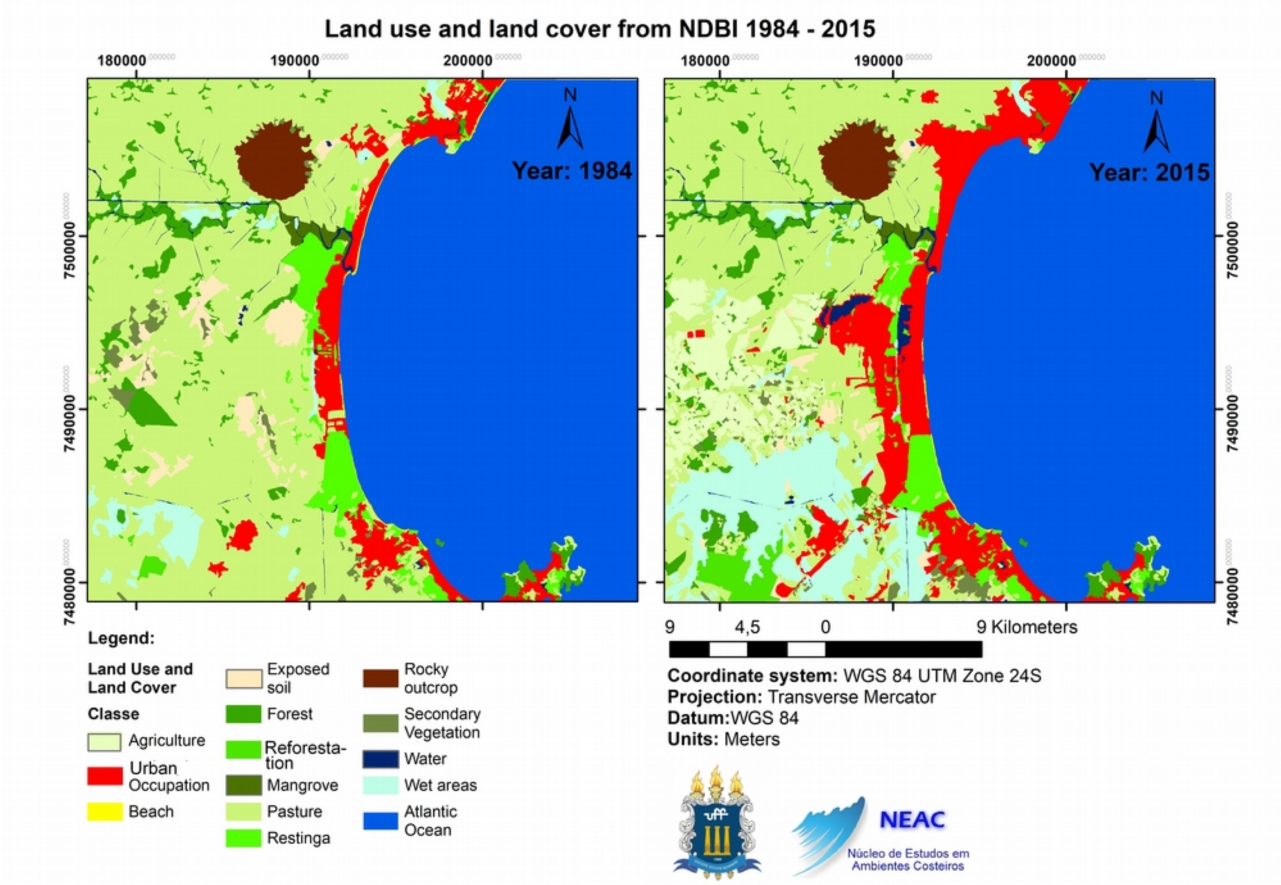

Figure 6. Land use and land cover map from NDBI of 1984 and 2015. The classes were chosen based on data from the Environment State Institute of Rio de Janeiro (INEA) (2015) land use and land cover map. Some addenda are in the Secondary vegetation, which has been mixed the secondary vegetation in the early stage, mid-advanced vegetation. In the wet areas, which are areas covered by grass or periodically flooded shrub vegetation.

Table II. Areas of land use classes – comparison between the years 1984 and 2015 in km² and percentage.

Classes	Area / 1984		Area / 2015	
	km^2	Percentage (%)	km^2	Percentage (%)
Agriculture	0.2	0.03	40.37	7.53
Urban occupation	36.905	6.88	83.65	15.60
Beach	1.68	0.31	0.94	0.18
Exposed soil	22.28	4.16	9.75	1.82
Forest	35.25	6.57	37.358	6.97
Reforestation	1.8	0.33	10.36	1.93
Mangrove	3.35	0.62	2.745	0.51
Pasture	356.5	66.49	40.16	40.16
Restinga	28.47	5.31	4.91	4.91
Rocky outcrop	15.012	2.80	15.012	2.80
Secondary vegetation	10.23	1.91	9.762	1.82
Water	9	1.66	12.66	2.36
Wet areas	15.65	2.92	72.01	13.43
Total	536.327	100	536.327	100

Figure 7. Oblique view of the 3D Model of the study area, simulating a sea level rise by 2.15 m proposed by Grinsted *et al.*, (2009). (A) shows the current region and (B) represents the area flooded. The yellow line represents the present coastline.

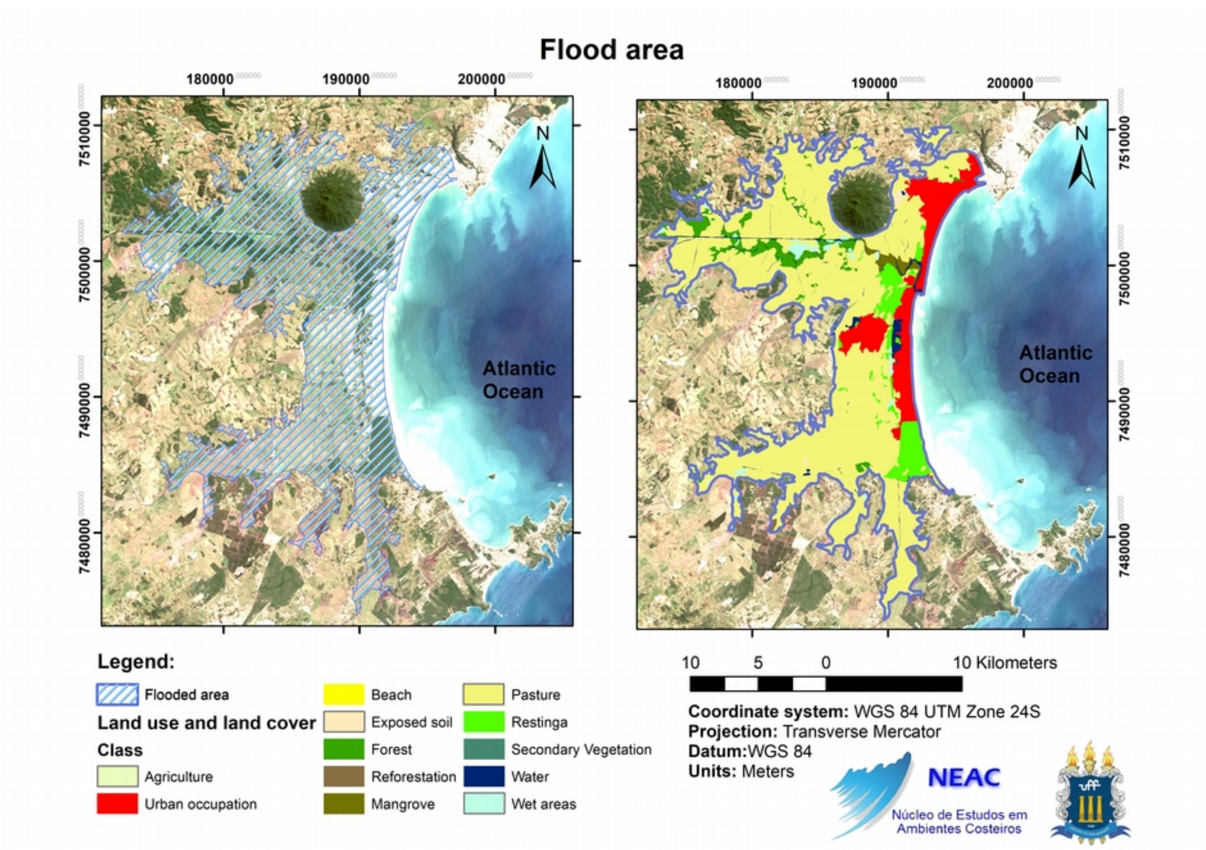

Figure 8. Land use map of 2015 with the flooded area overlaid. As observed in this Figure, it is possible to see the areas that will be impacted by a 2.15 m sea level rise.

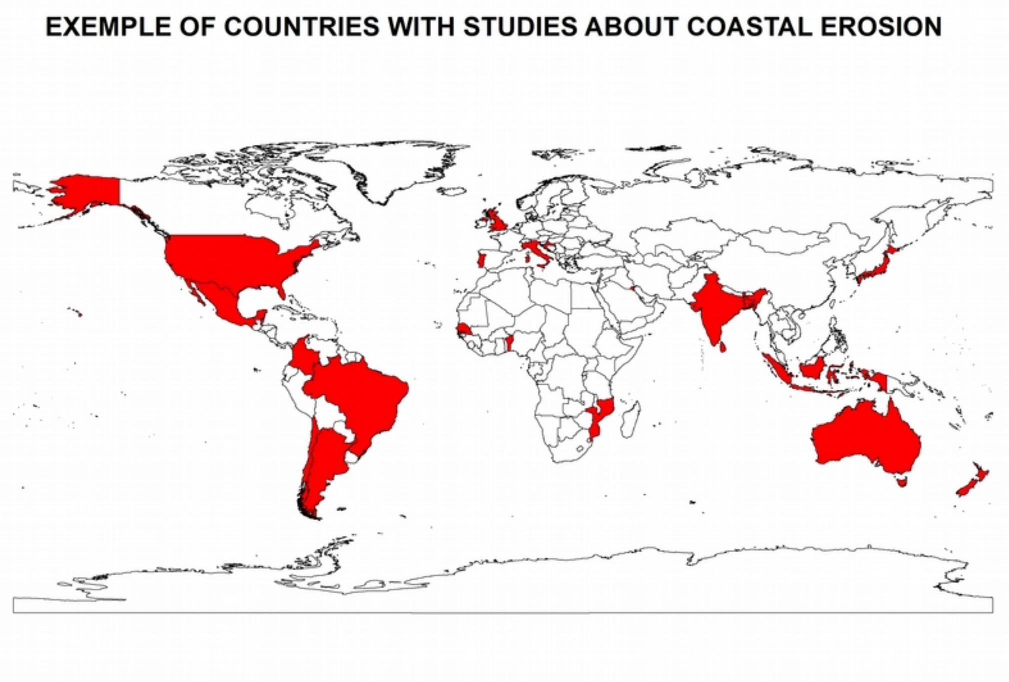

Figure 9. Example of countries with studies about coastal erosion: 1- Argentina (Isla et al., 2018), 2 – Australia (Castelle et al., 2007), 3 – Bangladesh (Paul & Rashid, 2017), 4 – Belize (Karlsson & Hovelsrud, 2015), 5 –Benin (Ndour et al., 2018), 6 – Brazil (Lins-de-Barros, 2005; Souza 2009; Muehe, 2011; Pereira et al., 2017), 7 – Chile (Martínez et al., 2018), 8 – Colombia (Rangel-Buitrago et al., 2015), 9 – Croatia (Pikelj et al., 2018), 10 – India (Ramakrishnan et al., 2018), 11 – Indonesia (Umar et al., 2015), 12 – Italy (Anfuso et al., 2011), 13 – Japan (Seino et al., 2015), 14 – Kuwait (Neelamani, 2018), 15 – Mexico (Escudero-Castillo et al., 2018), 16 – Mozambique (Cabral et al., 2017), 17 – New Zealand (Gibb, 1978), 18 – Portugal (Pedrosa, 2013), 19 –Senegal (Ndour et al., 2018), 20 - Sri Lanka (Senevirathna et al., 2018), 21 – Scotland (Fitton et al., 2016), 22 – USA (Hapke et al., 2009; Leatherman, 2018).

such as flooding and storm damage; loss of wetlands in the long-term; long-term erosion (direct and indirect morphological change); and potential intrusion of salt water. Neves & Muehe (2008) consider the following impacts on the coastal zone in Brazil: coastal erosion; damage to coastal protection constructions; damage to urbanization constructions of coastal cities; structural damage or operational damage to sanitation constructions; exposure of buried pipelines or structural damage to exposed pipelines.

Snoussi et al., (2007), Akumu et al., (2010), Zhang et al., (2011), Bosello et al., (2012), Nicholls et al., (2014) and Peric & Zvonimira (2015), presented the possible impacts resulting from a probable rise in sea level in different parts of the world. As mentioned, coastal erosion is one of the impacts that a sea level rise may cause in coastal cities. This phenomenon is observed and regarded by many studies in several countries. Figure 9 illustrates examples of countries that have studies about coastal erosion.

Leatherman (2018) shows in his study examples of some beaches in USA that suffer coastal erosion as in Miami Beach and Cape Hatteras, with a discussion related to a sea level rise. Indeed, about 80%-90% of the sandy beaches are experiencing erosion along the U.S Atlantic and Gulf coasts (Heinz Center 2000).

Conclusion

The regional mapping of sea level indicators allowed to identify the area that underwent several changes along Holocene, related to ancient sea level in the study area. The study led to the creation of a reference baseline for the estimates and the potential impacts with of a sea level rise, which allowed assessing the vulnerability of these coastal cities of strategic and economic importance.

The urban occupation of Rio das Ostras and Cabo Frio has increased significantly in recent years. In fact, there was an advance of areas built close to the coast, causing a severe modification in the environment and making it more sensitive to potential impacts of eventual extremes events.

Through the future simulation of a sea level rise, it is possible to highlight that an extensive area is sensitive to an eventual flood due to the natural topography. Thus, it is extremely important to monitor the evolution of coastal erosion processes, seeking to understand the phenomenon and to develop methodologies to mitigate it. It is also necessary that cities located in the coastal plain have appropriated management to support a sustainable urban growth – the mapping of land use in the years of 1984 and 2015 could be used as baseline.

This work allowed to strengthen the methods, the use of techniques and analyzes that generated more accurate data, offering a set of tools for the prevention of catastrophes and urban security in coastal areas. It is essential to make programs that promote integration between public agencies and research entities to promote studies on the coastal systems, establishing partnerships with higher education institutions in the preparation of environmental and urban studies, and finally, awareness and environmental education for the population of these regions.

Acknowledgements

The authors would like to thank the Núcleo de Estudos em Ambientes Costeiros (NEAC) for the support to carry out this work. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – Finance Code 001.

References

Alentejano, P. R. R. 2005. A evolução do espaço agrário fluminense. **Revista Geographia**. Universidade Federal Fluminense. Ano 7, n.º 13. Available in: <http://www.uff.br/geographia/ojs/index.php/geographia>. Accessed in November 2019.

Akumu, C. E., Pathirana, S., Baban, S. & Bucher, D. 2010. Examining the potential impacts of sea level rise on coastal wetlands in north-eastern NSW, Australia. **Journal of Coastal Conservation**, 15(1): 15-22.

Al-Buloshi, A., Al-Hatrushi, S. & Charabi, Y. 2014. GIS-based framework for the simulation of the impacts of sea level rise and coastal flooding on Oman. **Journal of Earth Science &Climatic Change**, 5(10): 1.

Anfuso, G., Pranzini, E. & Vitale, G. 2011. An integrated approach to coastal erosion problems in northern Tuscany (Italy): Littoral morphological evolution and cell distribution. **Geomorphology**, 129(3-4): 204-214.

Bevacqua, A., Yu, D. & Zhang, Y. 2018. Coastal vulnerability: Evolving concepts in understanding vulnerable people and places. **Environmental Science and Policy**, 82:19-29.

Bird, E. 2008. **Coastal geomorphology an introduction**. 2 ed. England: John Wiley and Son.

Bosello, F., Nicholls, R. J., Richards, J., Roson, R. & Tol, R. S. 2012. Economic impacts of climate change in Europe: Sea-level rise. **Climatic Change**, 112(1): 63-81.

Brito, I. A. M. & Carvalho, M. G. P. 1978. Distribuição de invertebrados marinhos na planície costeira do rio São João, Estado do Rio de Janeiro. **Anuário de Geociências**, 2:56-70.

Bruun, P. 1962. Sea level rise as a cause of shore erosion. **Proceedings American Society of Civil Engineers**, Waterways and Harbour Division, 88: 117-130.

Cabral, P., Augusto, G., Akande, A., Costa, A., Amade, N., Niquisse, S., Atume, A., Cuna, A., Kazemi, K., Mlucasse, R & Santha, R. 2017. Assessing Mozambique`s exposure to coastal climate hazards and erosion. **International Journal of Disaster Risk Reduction**, 23: 45-52.

Castelle, B., Turner, I. L., Ruessink, B.G. & Tomlinson, R.B. 2007. Impacts of storms on beach erosion: Broadbeach (Gold Coast, Australia). **Journal of Coastal Research**, 50(sp1): 534-539.

Castro, J. W., Fernandes, D., & Dias, F. 2011. Monitoramento do processo de erosão costeira na Praia das Tartarugas, Rio das Ostras-Estado do Rio de Janeiro/Brasil: Aplicação de metodologia quantitativa. **Revista da Gestão Costeira Integrada**, 11(3): 355-368.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D. & Unnikrishnan, A. S. 2013. Sea Level Change. In: **Climate Change 2013: The Physical Science Basis**. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T. F., Qin, D., Plattner, G. -K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cunha, A. M., Castro, J. W. A., Dias, F. F. 2012. A importância da preservação das acumulações bioclásticas da planície costeira do rio Una, municípios de Cabo Frio e Armação dos Búzios, RJ, Brasil. **Anuário do Instituto de Geociências - UFRJ**, 35(1), 58-67.

Davidson-Arnott, R. 2010. **Introduction to coastal process and geomorphology**. Cambridge University Press.

Dias, F. F. 2009. Variações do nível relativo do mar na planície costeira de Cabo Frio e Armação dos Búzios - RJ: Reconstrução paleoambiental holocênica e cenários futuros. **Tese de Doutorado**. Instituto de Geociências. Universidade Federal do Rio de Janeiro, Rio de Janeiro, 154 p.

Escudero-Castillo, M., Felix-Delgado, A., Silva, R., Mariño-Tapia, I. & Mendoza, E. 2018. Beach erosion and loss of protection environmental services in Cancun, Mexico. **Ocean & Coastal Management**, 156: 183-197.

Fitton, J. M., Hansom, J. D. & Rennie, A.F. 2016.A national coastal erosion susceptibility model for scotland. **Ocean & Coastal Management**, 132: 80-89.

França, A. F., Tavares Junior, J. R. & Filho, J.C.C.M. 2012. Índices NDVI, NDWI e NDBI como ferramentas ao mapeamento temático do entorno da lagoa olho d'água, em Jaboatão dos Guararapes-PE. **IV Simpósio Brasileiro de Ciências Geodésicas e Tecnologias da Geoinformação**. Recife, Pernambuco, Brasil, 001-009.

Gibb, J. G. 1978. Rates of coastal erosion and accretion in New Zealand. **New Zealand Journal of Marine and Freshwater Research**, 12(4):429-456.

Grinsted, A., Moore, J. C. & Jevrejeva, S. 2009. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. **Climate Dynamics**, 34(4): 461-472.

Hapke, C.J., Reid, D. & Richmond, B. 2009. Rates and trends of coastal change in California and the regional behavior of the beach and cliff system. **Journal of Coastal Research**, 25(3): 603-615.

Hawker, L.; Neal, J. & Bates, P. 2019. Accuracy assessment of the TanDEM-X 90 Digital Elevation Model for selected floodplain sites. **Remote Sensing of Environment**, 232.

Heinz Center. 2000. **The hidden costs of coastal hazards**. Washington DC, Island Press.

INEA. Uso e cobertura do solo. 2015. Infraestrutura Nacional de Dados Espaciais, Catálogo de metadados INDE.

Instituto Brasileiro de Geografia e Estatística. 2011. **Atlas Geográfico das Zonas Costeiras e Oceânicas do Brasil**. Rio de Janeiro. Ministério do Planejamento, Orçamento e Gestão.

Isla, F. G., Cortizo, L., Merlloto, A., Bértola, G., Albisetti, M. P. & Finocchietti, C. 2018. Erosion in Buenos Aires province: Coastal-management policy revisited. **Ocean & Coastal Management**, 156:107-116.

Jesus, P. B., Dias, F. F., Muniz, R. A., Macário, K. C. D., Seoane, J. C. S., Quattrociocchi, D. G. S., Cassab, R. C. T., Aguilera, O., Souza, R. C. C. L., Alves, E. Q., Chanca, I. S., Carvalho, C. R. A. C. & Araujo, J. C. 2017. Holocene paleo-sea level in southeastern Brazil: an approach based on vermetids shells. **Journal of Sedimentary Environments**, 2(1): 35-48.

Jevrejeva, S., Moore, J. C. & Grinsted, A. 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100?. **Geophysical Research Letters**, 37(7).

Jones, P. D. & Mann, M. E. 2004. Climate over past millennia. Reviews of Geophysics, 42: 1-42.

Karlsson, M. & Hovelsrud, G.K. 2015. Local collective action: Adaption to coastal erosion in the Monkey River Village, Belize. **Global Environment Change**, 32: 96-107.

Komar, P. D. 1976. **Beach process and sedimentation**. New Jersey: Prentice-Hall Inc.

Leatherman, S. P. 2018. Coastal erosion and the United States National Flood Insurance Program. **Ocean & Coastal Management**, 156: 35-42.

Leatherman, S. P. 2001. Social and economics coasts of sea level rise. In: Douglas, B. C., Kearney, M. S. & Leatherman, S.P. (eds). **Sea level rise history and consequences**. Academic Press, 75: 181-223.

Lins-de-Barros, F. M. 2005. Risco, vulnerabilidade física à erosão costeira e impactos sócioeconômicos na orla urbanizada do município de Maricá, Rio de Janeiro. **Revista Brasileira de Geomorfologia**, 2: 83-90.

Lins-de-Barros, F. M. & Muehe, D. 2010. Avaliação local da vulnerabilidade e riscos de inundação na zona costeira da Região dos Lagos, Rio de Janeiro. **Quaternary and Environmental Geosciences**, 1: 55-66.

Martin, L., Dominguez, J. M. L., Bittencourt, A. C. S. P., Flexor, J. M. & Suguio, K. 1996. Quais Seriam as Conseqüências de uma Eventual Subida Rápida do Nível do Mar? Considerações a partir da Análise de Exemplos Pretéritos. In: **XXXIX Congresso Brasileiro de Geologia**, Salvador, Bahia, Brasil, 275-277.

Martínez, C., Contreras-López, M., Winckler, P., Hidalgo, H., Godoy, E. & Agredano, R. 2018. Coastal erosion in central Chile: A new hazard? **Ocean & Coastal Management**, 158: 141-155.

Martínez, M. L., Intralawan, A., Vásquez, G., Pérez-Maqueo, O., Sutton, P. & Landgrave, R. 2007. The coasts of our world: Ecological, economic and social importance. **Ecological Economics**, 63, IS 2-3: 254-272.

Masselink, G. & Gehrels, R. 2014. Introduction to coastal changes and global changes. In: Masselink, G., Gehrels, R. (eds.). **Coastal environments and global changes**. United Kingdom, John Wiley & Sons.

McGranahan, G., Balk, D. & Anderson, B. 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. **Environment and Urbanization**, 19: 17-37.

Muehe, D. 2006. **Erosão e progradação do litoral brasileiro**. Ministério do Meio Ambiente. (press).

Muehe, D. 2011. Erosão costeiras – tendência ou eventos extremos? o litoral entre Rio de Janeiro e Cabo Frio, Brasil. In: **VI Congresso de Planejamento e Gestão das Zonas Costeiras**, Ilha Boa Vista, Cabo Verde, 1-12.

Natesan, U. & Parthasarathy, A. 2010. The potential impacts of sea level rise along the coastal zone of Kanyakumari District in Tamilnadu, India. **Journal of Coastal Conservation**, 14(3): 207-214.

Ndour, A., Laibi, R. A., Sadio, M., Degbe, C. G. E., Diaw, A. T., Oyédé, L. M., Anthony, E. J., Dussouillez, P., Sambou, H. & Dièye, E. H. B. 2018. Management strategies for coastal erosion problems in west Africa: Analysis, issues, and constraints drawn from the examples of Senegal and Benin. **Ocean & Coastal Management**, 156: 92-106.

Neelamani, S. 2018. Coastal erosion and accretion in Kuwait - Problems and management strategies. **Ocean & Coastal Management**, 156: 76-91.

Neves, C. F. & Muehe, D. 2008. **Vulnerabilidade, impactos e adaptação a mudanças do clima: a zona costeira**. Parcerias estratégicas, 27(13): 217-296.

Nicholls, R. J., Hanson, S. E., Lowe, J. A., Warrick, R. A., Lu, X. & Long, A. J. 2014. Sea-level scenarios for evaluating coastal impacts. **Wires Climate Changes**, 5:129-150.

Oliveira, A. P., Lourenço, J. S. Q., Duarte, G. S., Souza, E. M. F. R. & Almeida, P. M. M. 2015. Dinâmica espacial da população do Rio de Janeiro entre 1970 e 2010 utilizando geotecnologias. In: **XVII Simpósio Brasileiro de Sensoriamento Remoto**, João Pessoa, Paraíba, Brasil, 3503-3510.

Osiliere, P. R. G. 2016. Vulnerabilidade costeira do arco praial de Maricá (RJ): Itaipuaçu – Ponta Negra. Rio de Janeiro. **Dissertação de Mestrado**. Instituto de Geociências. Universidade Federal do Rio de Janeiro, Rio de Janeiro, 113p.

Passos, A. S., Dias, F. F., Barros, S. R., Santos, P. R. A. & Rodrigues, T. F. 2017. Consequências de uma possível subida do nível do mar em Mangaratiba – RJ. **O homem e o litoral - Transformações na paisagem ao longo do tempo, TOMO VI - REDE BRASPOR**, p. 279-292.

Passos, A. S., Dias, F. F., Barros, S. R. S., Santos, P. R. A., Souza, C. R. G. & Vargas, R. 2018. Sea level rise and its likely impacts: a case study in the coast of Mangaratiba-RJ. **Pan-American Journal of Aquatic Sciences**, 13(4): 260-272.

Paul, B. M. & Rashid, H. 2017. **Climatic hazards in coastal Bangladesh Non-structural and structural solutions**. Butterworth-Heinemann.

Pedrosa, A. S. 2013. Risco de erosão no litoral norte de Portugal: Uma questão de ordenamento do território. **Sociedade & Natureza**, 1: 133-146.

Pereira, T. G., Filho, S. R. O., Moraes, C. P. R. A. & Lessa, A. C. P. 2017. Impacto das tempestades de 2016 em orla urbanizada: Arco praial de Piratininga, Niterói-RJ. **Revista do**

Departamento de Geografia- USP, volume especial 4: 75-84.

Peric, J. & Zvonimira, S. G. 2015. Economic impacts of sea level rise caused by climate change. **3rd International Scientific ConferenceTourism in Southern and Eastern Europe**, 3: 85-294. .

Pikelj, K., Ružić, I., Ilić, S., James, M. R. & Kordić, B. 2018. Implementing an efficient beach erosion monitoring system for coastal management in Croatia. **Ocean & Coastal Management**, 156: 223-238.

Radford, T. Rising sea levels threaten Los Angeles. 2014. Ecologist the journal for the post-industrial age. Available in: <https://theecologist.org/2014/mar/02/rising-sea-levels-threaten-los-angeles >

Ramakrishnan, R., Agrawal, R., Remya, P. G., NagaKumar, K. Ch. V., Demudu, G., Rajawar, A. S., Nair, B. & Rao, K. N. 2018. Modelling coastal erosion: A case study of Yarada beach near Visakhapatnam, east coast of India. **Ocean & Coastal Management**, 156: 239-248.

Rangel-Buitrago, N. G., Anfuso, G. & Williams, A. T. 2015. Coastal erosion along the Caribbean coast of Colobia: Magnitudes, causes and management. **Ocean & Coastal Management**, 114: 129-144.

Rohling, E. J., Grant, K.,Hemleben, C., Siddall, M., Hoogakker, B. A. A., Bolshaw, M. & Kucera, M. 2008. High rates of sea-level rise during the last interglacial period. **NatureGeoscience**, 1: 38-42.

Sampaio, A. C. F., Melo, A. A., Faria, A. P. & Menezes, P. M. L. 2003. Oscilação do nível do mar no futuro e possíveis consequências no Brasil: pequeno ensaio. In: **XXI Congresso Brasileiro De Cartografia**, Belo Horizonte, Minas Gerais, Brasil.

Sant'anna, E. M. 1975. Estudo geomorfológico da área da Barra de São João e Morro de São João. **Revista Brasileira de Geografia**, 3: 3-15.

Seino, S., Uda, T., Ohtani, Y. & Ohki, Y. 2015. Essentials aspects of beach erosion – Lessons from devastation of Ichinomiya coast, Japan. **Procedia Engineering**, 116: 446-453.

Senevirathna, E. M. T. K., Edirisooriya, K. V. D., Uluwaduge, S. P. & Wijerathna, K. B. C. A. 2018. Analysis of causes and effects of coastal erosion and environmental degradation in southern coastal belt of Sri Lanka special reference to unawatuna coastal area. **Procedia Engineering**, 212: 1010-1017.

Small, C. & Nicholls, R. J. 2003. A global analysis of human settlement in coastal zones. **Journal of Coastal Research**, 19(3): 584-599.

Snoussi, M., Ouchani, T. & Niazi, S. 2007. Vulnerability assessment of the impact of sea-level rise and flooding on the Moroccan coast: The case of the Mediterranean eastern zone. **Estuarine, Coastal and Shelf Science**, 77(2): 206-213.

Souza, C. R. G. 1997. As células de deriva litorânea e a erosão nas praias do Estado de São Paulo. **Tese de Doutorado**. Programa de Pós-Graduação em Geologia Sedimentar, Universidade de São Paulo, São Paulo, 184p.

Souza, C. R. G. 2005. Um sistema geográfico de informações para o litoral de São Paulo. In: **XI Simpósio Brasileiro de Geografia Física Aplicada**, São Paulo. Anais... CD-ROM (trabalho completo).

Souza, C. R. G. 2009. A erosão costeira e os desafios da gestão costeira no Brasil. **Revista da Gestão Costeira Integrada**, 9(1): 17-37.

Souza, C. R. G., Filho, P. W. M. S., Esteves, L.S., Vital, H., Dillenburg, S. R., Patchineelam, S. M. & Addad, J. E. 2005. Praias Arenosas e Erosão Costeira. **Quaternário do Brasil**, 130-152.

Souza, C. R. G. & Suguio, K. 2003. The coastal erosion risk zoning and the São Paulo state plan for coastal management. **Journal of Coastal Research**, Special Issue No. 35: 530-592.

Suguio, K. 2008. **Mudanças Ambientais da Terra**. São Paulo: Instituto Geológico, 339p.

Umar, H., Rahman, S., Baeda, A. Y. & Klara, S. 2015. Identification of coastal problem and prediction of coastal erosion sedimentation in south Sulawesi. **Procedia Engineering**, 116:125-133.

Vargas, R., Dias, F. F., Rodrigues, T. F., Nascimento, L. L., Passos, A. S. & Santos, P. R. A. 2017. Mapping of the vulnerability to storm surges in the municipality of Maricá, Brazil. **Shore & Beach**, 85(2): 14.

Vermeer, M. & Rahmstorf, S. 2009. Global sea level linked to global temperature. **Proceedings of the National Academy of Sciences**, 106(51):21527-21532.

Williams, S. J. 2013.Sea-level rise implications for coastal regions. **Journal of Coastal Research**, 63(sp1): 184-196.

Zha, Y., Gao, J. & Ni, S. 2003. Use of normalized difference built-up index in automatically mapping urban areas from TM imagery. **International Journal of Remote Sensing**, 24(3):583-659.

Zhang, K., Dittmar, J., Ross, M. & Bergh, C. 2011. Assessment of sea level rise impacts on human population and real property in the Florida Keys. **Climatic Change**, 107(1-2): 129-146.

Received: May 2019
Accepted: December 2019
Published: January 2020