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VULNERABILIDADE DO DELTA DO RIO JEQUITINHONHA (NORDESTE DO BRASIL) ÀS MUDANÇAS CLIMÁTICAS

MILENA REIS NERVINO

SALVADOR

2023

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Milena Reis Nervino

Orientador: Prof. Dr. José Maria Landim Dominguez

Dissertação de Mestrado apresentada ao Programa de Pós-Graduação em Geologia do Instituto de Geociências da Universidade Federal da Bahia como requisito parcial à obtenção do Título de Mestre em Geologia, Área de Concentração: Geologia Marinha, Costeira e Sedimentar.

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MILENA REIS NERVINO

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“Os melhores cientistas e exploradores têm os atributos das crianças! Eles fazem perguntas e têm uma sensação de admiração. Eles têm curiosidade. 'Quem, o que, onde, por que, quando, e como?’ Eles nunca param de fazer perguntas!”

- Sylvia Earle

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RESUMO

Deltas são regiões mais baixas do relevo que se formam onde o rio desemboca no mar. São "hotspots" das mudanças climáticas uma vez que são sensíveis a qualquer variação no nível do mar e alterações climáticas. Nesse sentido, os deltas brasileiros têm recebido pouca atenção na literatura internacional em relação às mudanças climáticas em curso. As projeções de aumento do nível do mar pelo IPCC em até 1,1 m até o final deste século coloca em risco a existência dos deltas uma vez que um aumento do nível do mar dessa magnitude será capaz de inundar cerca de 40 % da área da planície do Jequitinhonha. Adicionalmente, alterações nos padrões de precipitação sobre a bacia de drenagem também são capazes de alterar drasticamente o comportamento da linha de costa. Verificou-se uma redução de aproximadamente 15% da precipitação sob a bacia hidrográfica do Jequitinhonha desde 2006 e o rio Jequitinhonha tem apresentado vazões cada vez mais reduzidas, que desencadeou erosão severa da linha de costa principalmente na desembocadura deste rio. Considerando as previsões do Instituto Nacional de Pesquisas Espaciais (INPE) que indicam redução de 48% na precipitação desta bacia até o final deste século, a estabilidade da linha de costa da planície deltaica será drasticamente afetada. Os insights adquiridos com o presente estudo trazem à luz o entendimento sobre a vulnerabilidade de deltas dominados por ondas frente às mudanças climáticas.

Palavras-chave: mudanças climáticas; regularização fluvial; erosão costeira; inundações costeiras.

ABSTRACT

Deltas are low-lying plains that form where the river flows into the sea. They are “hotspots” of climate change since they are sensitive to any variation in sea level and climate change. In this sense, the Brazilian deltas have received little attention in the international literature in relation to ongoing climate changes. The projections of sea level rise by the IPCC of up to 1.01 m by the end of this century put the existence of deltas at risk since a rise in sea level of this magnitude will be able to flood about 40% of Jequitinhonha’s plain area. Additionally, changes in precipitation patterns over the drainage basin are also capable of drastically changing the shoreline behavior. There has been a reduction of approximately 15% in precipitation over the Jequitinhonha watershed since 2006 and the Jequitinhonha river has had increasingly reduced flows, which has triggered severe erosion of the coastline, mainly at the mouth of this river. Considering the forecasts of the National Institute for Space Research (INPE) that indicate a 48% reduction in precipitation in this basin by the end of this century, the stability of the coastline of the deltaic plain will be drastically affected. The insights gained from the present study shed light on the understanding of the vulnerability of wave-dominated deltas to climate change.

Keywords: climate change; river regulation; coastal erosion; coastal inundation.

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INTRODUÇÃO GERAL

Deltas são planícies baixas que se formam onde os rios encontram o oceano (WOLTERS; KUENZER, 2015). São naturalmente moldados pelas forças dos rios, ondas e marés (OVEREEM, I. E SYVITSKI, 2009). Por serem naturalmente dinâmicos e complexos moldados por processos marinhos e fluviais (NIENHUIS *et al.*, 2012; WRIGHT E COLEMAN, 1973), e por constituírem regiões mais baixas do relevo (WOLTERS; KUENZER, 2015), são sensíveis a qualquer variação no nível do mar e alterações climáticas (OVEREEM, I. E SYVITSKI, 2009; DOMINGUEZ; GUIMARÃES, 2021), sendo os efeitos das mudanças climáticas em curso sob os deltas um tema de interesse mundial (SYVITSKI, 2008; SZABO *et al.*, 2016).

Muitos cientistas consideram as mudanças climáticas forçadas pelo aquecimento global como a mais séria ameaça ambiental que o mundo enfrenta atualmente (IPCC, 2007), tendo potencial de alterar os padrões de temperatura, precipitação, nível do mar, frequência de tempestades, e outras condições climáticas (OVEREEM, I. E SYVITSKI, 2009). Nas projeções climáticas do Painel Intergovernamental de Mudanças Climáticas (IPCC) estima um aumento no nível do mar de até 0,76 m em um cenário intermediário de emissões de Gases de Efeito Estufa (GEE), podendo alcançar um pior cenário com um aumento de até 1,1 m (IPCC, 2021).

Esse aumento do nível do mar, previsto para ocorrer até o final deste século, impacta diretamente na estabilidade das planícies deltaicas e sua população, resultando em riscos de inundação costeira, perda das áreas que atualmente se encontram úmidas, erosão costeira e perdas de infraestruturas (OVEREEM, I. E SYVITSKI, 2009). No entanto, não somente o aumento do nível do representa risco par os deltas, mas também alterações no regime de ventos, ondas e precipitação na bacia de drenagem e regime hidrológico, sendo este último raramente considerado em estudos da zona costeira (NEVES; MUEHE, 2010). Ainda, outros fatores naturais (ex.

variabilidade climática, subsidência) e antrópicos (ex. construção de barragens e mudanças no uso do solo) exercem pressão no sistema deltaico tornando-o hotspots de vulnerabilidade (IPCC, 2007).

Os deltas, devido à sua baixa topografia, alta produtividade, rica biodiversidade e fácil transporte ao longo abundantes vias navegáveis, são locais preferidos de habitação humana (WOLTERS; KUENZER, 2015), abrigando cerca de 7% da população mundial, ou meio bilhão de pessoas, mesmo representando apenas 1% da área terrestre global (ERICSON *et al.*, 2006). Do ponto de vista econômico, essas regiões são frequentemente os maiores contribuintes para a economia nacional (SZABO *et al.*, 2016). Os deltas do Ganges-Brahmaputra, Yangtze e Nilo são densamente povoados e a maioria dos estudos sobre vulnerabilidade dos deltas em função das mudanças climáticas são focadas nestas regiões (OVEREEM, I. E SYVITSKI, 2009). Os deltas brasileiros, por serem relativamente menores e menos povoados tem recebido pouca atenção na literatura internacional em relação às mudanças climáticas em curso.

Nesse contexto, o presente trabalho tem por objetivo avaliar a vulnerabilidade do delta do rio Jequitinhonha às mudanças climáticas em curso com foco principalmente no comportamento da linha de costa e na identificação das regiões da planície mais vulneráveis a inundação. A planície deltaica do Rio Jequitinhonha, situada no Nordeste do Brasil, é a maior planície litorânea do Estado da Bahia e nela desagua o Rio Jequitinhonha, um dos maiores rios do Brasil (DOMINGUEZ *et al.*, 2009). A planície do Jequitinhonha abrange os baixos cursos dos rios Jequitinhonha e Pardo apresentando uma área de aproximadamente 800 km^2 (DOMINGUEZ; MARTIN; BITTENCOURT, 2003) e é composta ao sul por cordões litorâneos, e ao norte, por extensos manguezais, zonas úmidas e canais de maré que, de certo modo, contribuem ainda mais para a vulnerabilidade deste ambiente.

Na desembocadura do Rio Jequitinhonha Dominguez, Guimarães e Bittencourt (2018) identificaram erosão severa da linha de costa, a qual tem sido atribuída a retenção de sedimentos decorrente da construção da barragem da Usina Hidrelétrica de Itapebi (UHE Itapebi) (DOMINGUEZ; MARTIN; BITTENCOURT, 2003), localizada cerca de 80 km da foz. A construção da UHE Itapebi foi iniciada em 1999 e entrou em operação fevereiro de 2003 com capacidade de geração de 450MW (NEOENERGIA, 2022).

O barramento de rios apresenta um mecanismo para uma redução severa ou mesmo eliminação da descarga de sedimentos fluviais para a costa, agravando e/ou acelerando processos de erosão (OVEREEM, I. E SYVITSKI, 2009). A redução da descarga de sedimento para a costa inicia o decaimento da cúspide deltaica (NIENHUIS *et al.*, 2013), de modo que, quando o suprimento de sedimentos não é suficiente para sustentar a posição da linha de costa do delta, as ondas atuam retrabalhando e redistribuindo o sedimento ao longo da linha de costa, acarretando erosão no delta e nas suas adjacências. Por outro lado, desde 1993, o rio Jequitinhonha tem apresentado vazões cada vez mais reduzidas, que possivelmente desencadeou um processo de erosão severa da linha de costa principalmente na desembocadura deste rio.

Nesse contexto, verificou-se redução de aproximadamente 15% da precipitação sob a bacia hidrográfica do Jequitinhonha desde 2006, e considerando as previsões do Instituto Nacional de Pesquisas Espaciais (INPE), que indicam redução de 48% na precipitação desta bacia até o final deste século, a estabilidade da linha de costa da planície deltaica será drasticamente afetada, uma vez que a linha de costa é sensível a alterações climáticas (DOMINGUEZ; GUIMARÃES, 2021).

Ressalta-se que o desenvolvimento socioeconômico desta região está ocorrendo no cenário de mudanças climáticas, como por exemplo, a implantação de empreendimentos de criação de camarão (carcinicultura), ressortes, ampliação da rodovia BA-001 que dá acesso aos municípios costeiros, implantação de instalações portuárias, e a própria expansão urbana nas cidades.

Nesse sentido, este trabalho contribui com a gestão costeira local uma vez que traz um mapeamento do comportamento da linha de costa, fenômeno que tem causado perda de área a prejuízos econômicos para a região, e identificação das áreas vulneráveis a inundação costeira, aspecto essencial para minimizar os impactos associados à elevação do nível do mar na região. Essas informações podem ser utilizadas pelos gestores seja na elaboração de um plano de gerenciamento costeiro municipal, plano de uso e ocupação do solo e nas tomadas de decisões, principalmente frente às projeções das mudanças climáticas em curso.

Os insights adquiridos com o presente estudo trazem à luz o entendimento sobre a vulnerabilidade de deltas dominados por ondas frente às mudanças climáticas. Este trabalho deu origem a um artigo apresentado em sua estrutura original no capítulo 2 desta dissertação e que será submetido a revista Marine Geology.

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CAPÍTULO 2
VULNERABILIDADE DO DELTA DO RIO JEQUITINHONHA (NORDESTE DO BRASIL) ÀS MUDANÇAS CLIMÁTICAS

Climate change and the vulnerability of the Jequitinhonha River delta (northeast Brazil).

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Deltas are considered "hotspots" of vulnerability to climate change. This vulnerability results from the fact that these areas are low-lying regions, making them susceptible to even small rises in sea level, and because the position of the coastline of the deltaic plain is extremely sensitive to variations in the solid discharge, which are controlled by the hydrographic basin's precipitation. The IPCC forecast of sea level rise of up to 1.01 m by the end of this century poses a relevant threat to the survival of deltas, as it increases the risks of coastal flooding, loss of wetlands, intensification of coastal erosion and infrastructure losses. Changes in the wind, wave and hydrological regime of the drainage basin due to ongoing climate changes also increase the vulnerability of deltaic systems. The Jequitinhonha delta is one of the 4 wave-dominated deltas in Brazil. This delta exhibits an asymmetry in the distribution of sedimentary environments because while the southern portion of the deltaic plain consists of deposits of regressive coastal sands, the northern portion is characterized by a chain of barrier islands, numerous tidal inlets, and extensive mangroves, which constitute an additional factor to increase the delta's vulnerability. A brief comparison of satellite images from 1976 to 2021 reveals that over this time, the delta's coastline in front of the Jequitinhonha River's mouth receded by around 1 km. T This erosion has been attributed to the sediment buildup in the reservoir of the Itapebi Hydroelectric Power Plant, which was constructed in 2003 and is located 80 kilometers from the river's mouth. On the other side, since 1993, precipitation has also dropped in the river's drainage basin, as well as the Jequitinhonha River flows, reducing the supply of sediments at the mouth. This reduction triggered a process of decay of the deltaic cusp, process that should continue in the next decades considering the forecasts of reduction in the precipitation in the hydrographic basins of the east coast of Brazil. In the northern portion of the deltaic plain, sea level rise in the coming decades, associated with the increase in

flooded areas and the tidal prism, should dramatically change the ebb tidal deltas associated with the sand barriers, implying in their greater segmentation and reduction of width with loss of area. Also, severe environmental and socioeconomic impacts will occur in this stretch very used for tourist activities and urban expansion of the city of Canavieiras.

Keywords: climate change; river regulation; coastal erosion; coastal inundation.

1. INTRODUCTION

Deltas are considered vulnerability hotspots to climate change (Syvitski, 2008; Syvitski et al., 2009; Wolters & Kuenzer, 2015; Szabo et al., 2016). Because they are low-lying regions, built over the last few thousand years, under conditions of approximately stable sea level, any rise in sea level can produce drastic changes in the geomorphology of the deltas (Stanley & Warne, 1994; Overeem & Syvitski, 2009). Also, the coastline position in the deltas is very sensitive to variations in solid discharge, which is controlled by precipitation in the watersheds and more recently by regulation works (Nienhuis et al., 2013).

The Intergovernmental Panel on Climate Change (IPCC) predicts an increase in sea level between 0.63 and 1.01 m by the end of this century depending on the greenhouse gas emission scenario (Fox-Kemper et al., 2021). This sea level rise directly impacts the deltaic plains and their population, by increasing risks of coastal flooding, loss of wetlands, intensification of coastal erosion and infrastructure losses (Overeem & Syvitski, 2009). Changes in the wind, wave and hydrological regime of the catchment also poses a risk to the world's deltas, as well as other natural (e.g. subsidence) and anthropic (e.g. construction of dams and changes in land use) factors, increasing their vulnerability to ongoing climate change (Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, 2007).

One of Brazil's four wave-dominated deltas, the Jequitinhonha delta is located on the east coast of Brazil, covering an area of 800 km^2 and been relatively little occupied. Its deltaic plain presents a marked asymmetry in the distribution of sedimentary environments. The southern half consists of continuous regressive coastal sand deposits, whereas the northern half is characterized by a chain of barrier islands, numerous tidal inlets and extensive mangroves (Figure 1). These features represent an additional factor for the vulnerability of the delta since, in addition to constituting the lowest areas of the deltaic plain, can have the balance between river flows and the tidal prism easily disturbed by climate changes (Syvitski et al., 2009; Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, 2007).

Moreover, the Jequitinhonha River's flow has decreased by around 64% over the past forty years, which has caused a process of severe coastal erosion, particularly at the river's mouth (https://www.snirh.gov.br/hidroweb/apresentacao). Since 2006, there has been a reduction of approximately 15% in precipitation in the Jequitinhonha watershed, and forecasts by the National Institute for Space Research (INPE) indicate a reduction of 48% in precipitation in this basin by the end of this century (Figure 2) (https://pclima.inpe.br/analise/), which will increase the vulnerability of the delta. Alongside this, the run-of-river type Itapebi Hydroelectric Power Plant (UHE Itapebi), which is only about 80 km from the river's mouth, began operating in 2003, which could affect the sedimentary equilibrium at the mouth.

The present study aims to assess the vulnerability of the Jequitinhonha River delta to ongoing climate changes, focusing mainly on the behavior of the coastline and the identification of the regions of the plain that are most vulnerable to flooding. The vulnerability to climate change of wave-dominated deltas built under conditions of very high wave energy, as is the case of the east coast deltas of Brazil, has received little attention in the international literature. So far, most of these works have been focused on the large deltas of Southeast Asia and the Mediterranean, characterized by high population numbers and intensive agricultural use (Overeem & Syvitski, 2009; Syvitski et al., 2009).

Figure 1: Geological-geomorphological map of the Jequitinhonha-Pardo River delta. Aib - Ibicaraí complex; PSsa - Rio Pardo Group - Salobro Formation; QHfl - Fluvial Sand - Clay deposits; QHI - Coastal Sands - Holocene Marine Terrace; QHm - Mangrove Clay-Organic Deposits; QHtu - Clay-organic wetland deposits; QPI - Coastal Sands - Pleistocene Marine Terrace; QPla - Deposits of Alluvial Fans; Qar – Residuals Sand Deposits ("Mussununga"); Tb – Barreiras Group. Data source: DOMINGUEZ, 2008 e DOMINGUEZ, 2011.

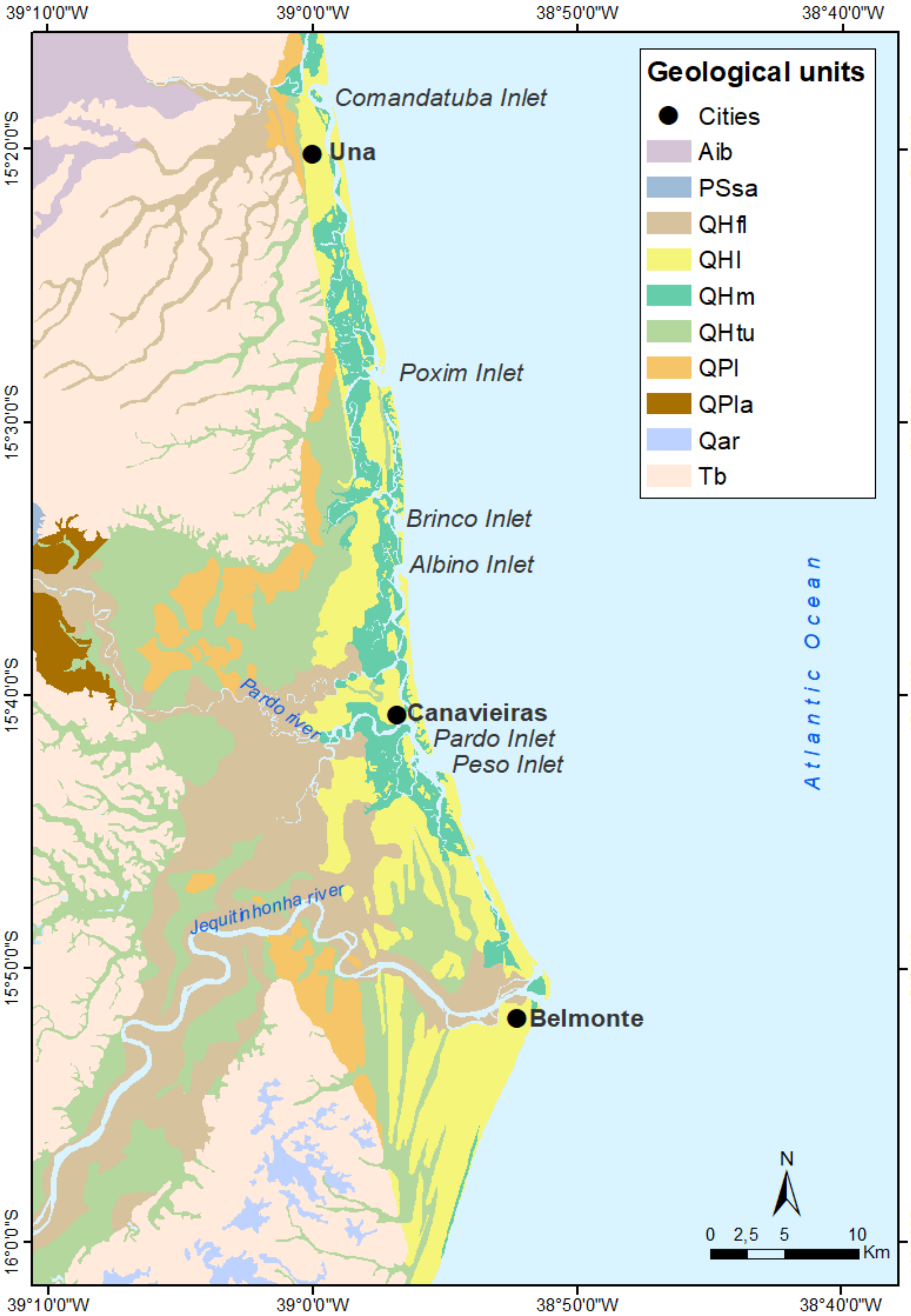
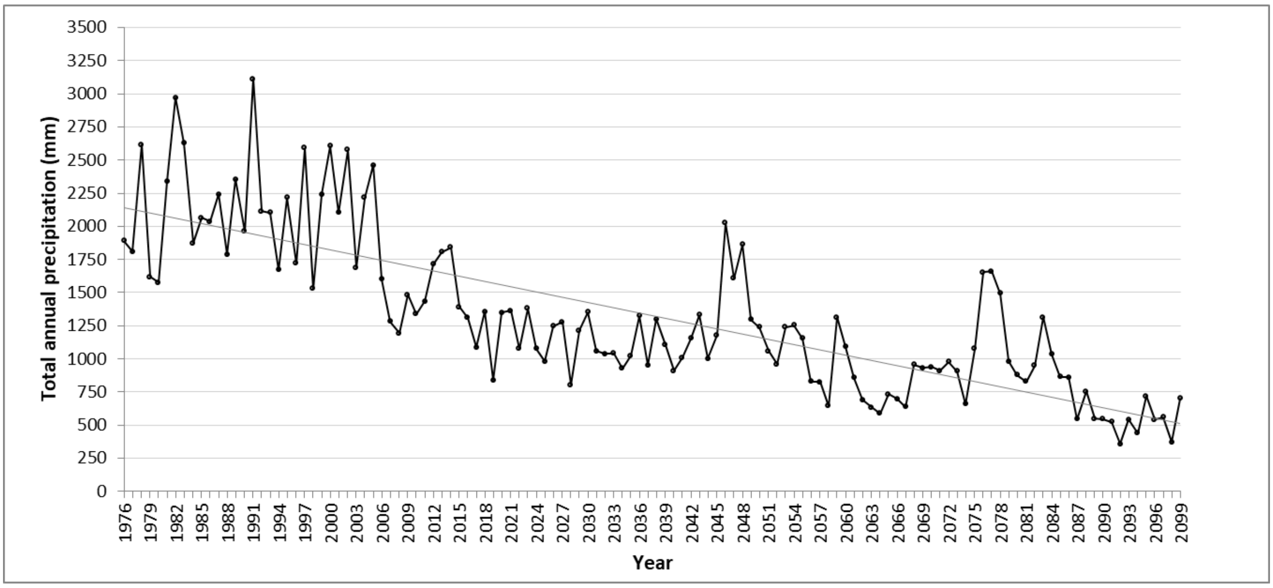


Figure 2: Average total annual precipitation in the eastern Atlantic watersheds of Brazil where the Jequitinhonha River watershed is located. Measured precipitation (1976 to 2005) and future projection until the year 2099. The future projection was obtained based on the Eta Regional Model of the National Institute for Space Research (INPE), simulations from the Brazilian Earth System Model (BESM) project of INPE using the Future Scenario RCP 8.5 (Representative Concentration Pathways) which corresponds to a scenario of high emission of greenhouse gases (GHG) in which the CO2 equivalent exceeds 1000 ppm by the end of the 21st century and, with that, the forcing radioactive energy will reach 8.5 W/m² by the year 2100. This scenario is closest to the trends observed in current measurements of GHG concentrations in the atmosphere. Source: https://pclima.inpe.br/analise/.



2. STUDY AREA

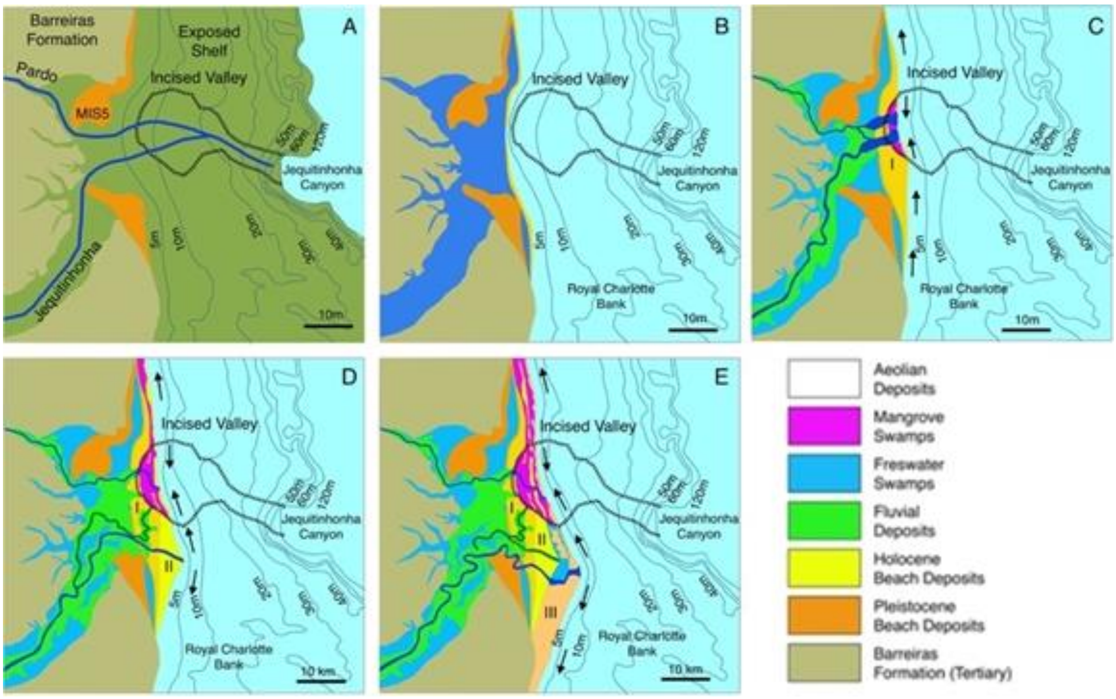
2.1. GEOLOGY-GEOMORPHOLOGY OF THE DELTAIC PLAIN

The Jequitinhonha River's deltaic plain is mainly constituted by deposits of regressive coastal sands that form two sets of Pleistocene-age (inner) and Holocene-age (outer) sandy terraces (Figure 1). The inner limit of the deltaic plain is marked by a line of inactive cliffs carved in the Lower-Middle Miocene Barreiras Formation (Rossetti et al., 2013). The regressive coastal sand deposits of Pleistocene age occupy the innermost region of the plain and have altitudes ranging between 6 and 11 meters (Dominguez, 2007; Dominguez & Bittencourt, 2012) and their deposition occurred during Marine Isotopic Stage 5e (MIS5e) (Dominguez & Bittencourt, 2012).

The Holocene regressive coastal sand deposits occupy the outer portion of the plain and are separated from the Pleistocene deposits by a low zone, occupied by wetlands that constituted a paleo-estuary during the maximum of the Holocene transgression (Dominguez & Bittencourt, 2012). The altitude of Holocene deposits decreases towards the coastline, ranging from about 6 meters in the innermost portion of the deltaic plain to 2.5 meters close to the current coastline (Dominguez, 2007; Dominguez & Bittencourt, 2012). This decrease is a result of the lowering of the relative sea level since the middle Holocene (Dominguez et al., 1982; Dominguez et al., 1981), a consequence of the fact that the delta is in a field region distant from the Glacial Isostatic Adjustment (GIA) (Mitrovica & Milne, 2002). Other deposits present in the deltaic plain include wetlands that occupy the lowlands of the plain, river deposits and deposits/mangrove forests, with the latter been restricted to the northern half of the deltaic plain, protected by a system of sandy barrier islands (Dominguez, 2007) (Figure 1).

DOMINGUEZ (2023) has recently summarized the Holocene evolutionary history of the Jequitinhonha delta plain (Figure 3). One important aspect of this evolutionary scheme is that the concentration of mangrove swamps in the Northern portion of the plain apparently resulted from a long-lasting control exerted by the Jequitinhonha incised valley head on the physiography of the delta plain.

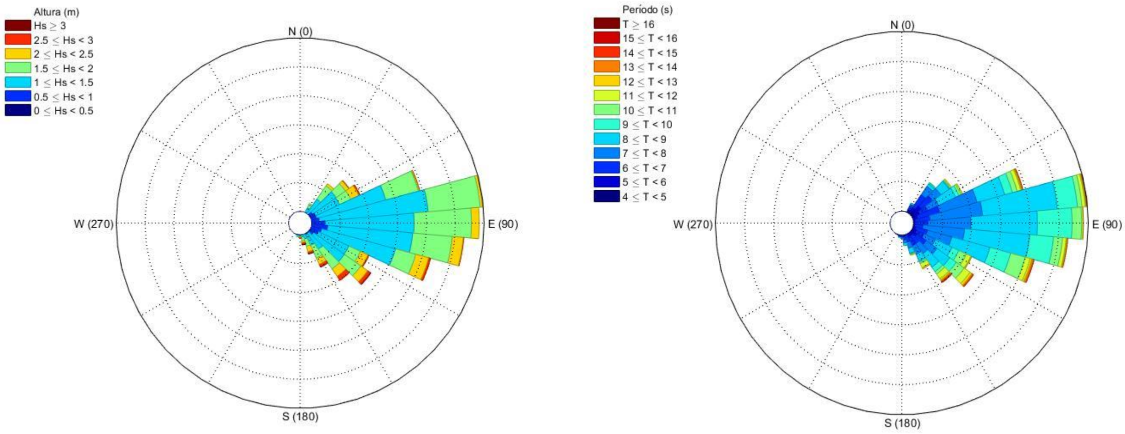
Figure 3: Proposed evolutionary scheme for the Jequitinhonha delta: a Last Glacial Maximum: shelf exposed subaerially and inception of the incised valley connecting the river to the Jequitinhonha canyon. b Maximum of the Holocene transgression (5.8ka). c, d and e During the Holocene 03 different episodes of delta construction (I, II, and III) occurred in association with the southward migration of the lower river course with the most recent episode beginning around 2.5ka (Based on Dominguez et al 1987). Most of the mangrove swamps in the delta are concentrated around the head of the incised valley which is also responsible for a slight concavity in the present-day shoreline. Small arrows indicate the regional longshore transport and local reversals. Source: DOMINGUEZ, 2023.



2.2. WAVES CLIMATE, CURRENTS AND TIDES

Based on data from 2012 to 2017, the wave climate is characterized by significant height between 1 and 3 m, peak period between 5 and 10 seconds, and propagation direction in the quadrants between NNE and SSE, with almost symmetrical distribution (https://www.marinha.mil.br/chm/dados-do-goos-brasil/pnboia-mapa) Figure 4. These data are consistent with data previously published by Pianca et al., 2010 based on WaveWatch III statistics. The tides in the region are semi-diurnal with a maximum amplitude at syzygy of 2.3 m and 1.4 m at quadrature (DHN, 2020).

Figure 4: Wave climate in the region. a) Significant height. b) peak period. Source: data collected in the period between 2012 and 2017 by a buoy of the National Buoy Program – PNBOIA (https://www.marinha.mil.br/chm/dados-do-goos-brasil/pnboia-mapa) located south of the study area (16°00,05’S e 37°56,42’W).



2.3. CLIMATE

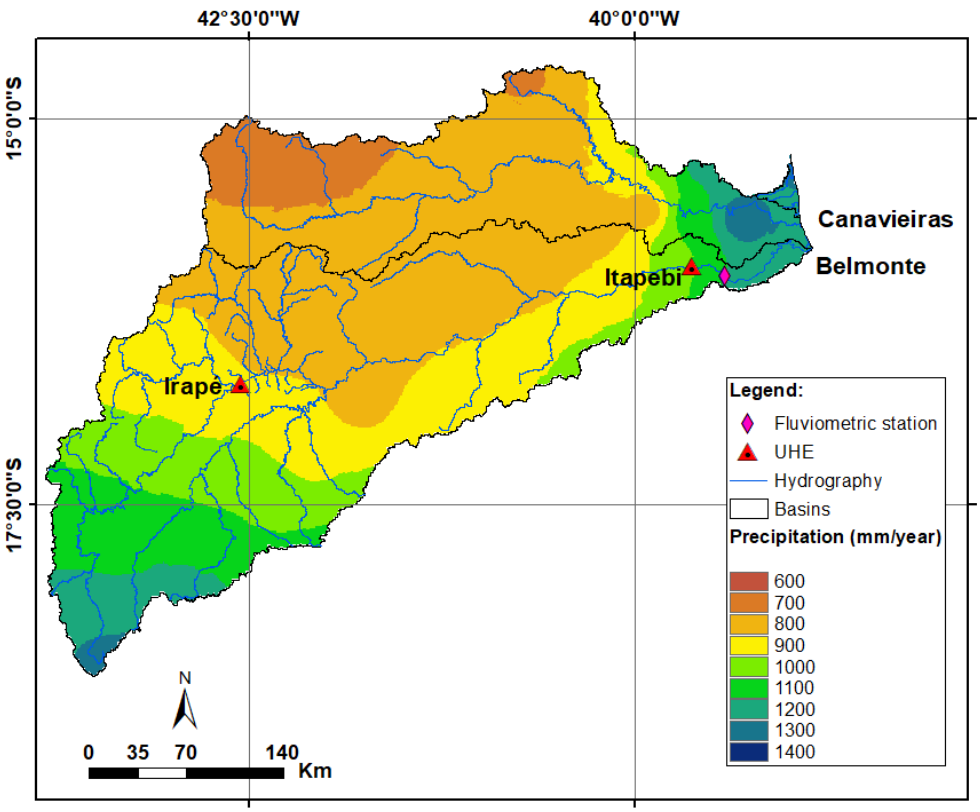
The hydrographic basins of the Jequitinhonha and Pardo rivers cross different climatic units (Ferreira & Silva, 2012) with total annual precipitation of 1300 mm in the headwaters, 600 mm in the medium course, and 1500 mm in the coastal zone (Figure 5). Precipitation in the upper and middle portion of the basin is mainly controlled by the South American Monsoon System (SMAS) associated with the southward shift of the Intertropical Convergence Zone (ITCZ) during the summer, and the development of the South Atlantic Convergence Zone (SACZ) is responsible for rainfall in the tropical zone of South America (Kousky, 1979; Vuille et al., 2012).

The SMAS is responsible for the annual precipitation cycle in South America with a wet season during summer and a dry season in winter. During the austral summer (December to February), eastern Brazil, where the drainage basin is located, receives more than 50% of the total annual precipitation. During the austral winter (June to August), the same region receives less than 5% of the total annual precipitation (V. B. S. . Silva & Kousky, 2012).

In the upper portion of the basin, the precipitation regime is intrinsically related to the activity of the SACZ that is formed in the summer and is the main SMAS mechanism in distributing moisture from the Amazon region to the interior of the continent. With the weakening of the SMAS, in April (Silva & Kousky, 2012), the dry period begins. The middle portion of the basin, in turn, is characterized by a semi-arid climate. On the other hand, precipitation in the lower portion of the basin is related to the advance of cold fronts, which are intensified in winter, resulting in a rainy season and dry summer.

In general, the historical analysis of precipitation between the years 1976 and 2005 indicates a reduction in the total annual precipitation in the Jequitinhonha-Pardo basin (https://pclima.inpe.br/analise/) (Figure 2).

Figure 5: Average annual precipitation in the Jequitinhonha-Pardo watershed. The two main existing dams in the region are also indicated. Precipitation data from the National Institute of Meteorology (INMET) available in the metadata catalog of the National Water Agency (ANA).



2.4. HYDROLOGICAL REGIME

The Jequitinhonha delta is jointly fed by the Jequitinhonha and Pardo rivers. The Pardo River basin has a total area of 33,000 km^2 (Dominguez et al., 2006) and has no dams along its course. The average flow of the Pardo River is 60 $m^3 s^{-1}$, while its solid flow is estimated at $0.23x10^6$ tons per year (Bernal, 2016).

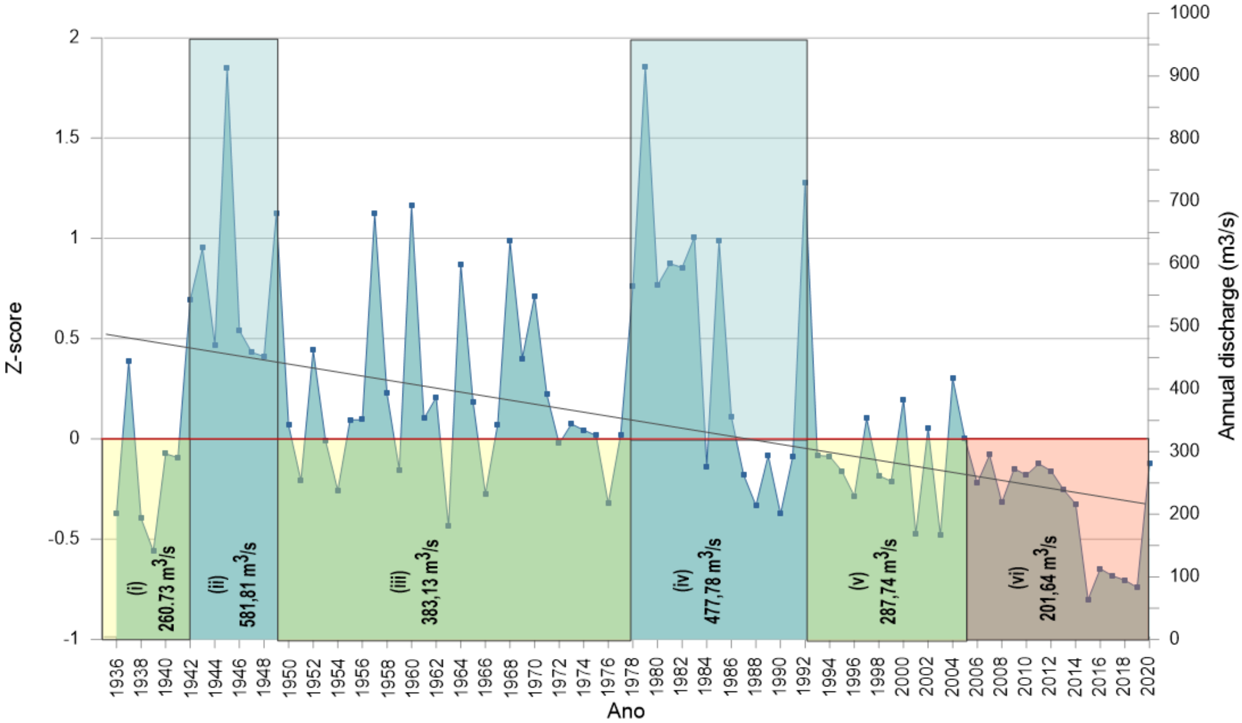
The Jequitinhonha River hydrographic basins have a total area of 70,000 km^2 (Dominguez et al., 2006; Bernal, 2016; Bernal, 2009). The average annual flow of the Jequitinhonha River is 320 $m^3 s^{-1}$ based on a historical series of data from the National Water Agency (ANA) from 1936 to 2020 (https://www.snirh.gov.br/hidroweb/ presentation). Bernal (2009) estimated a solid sediment discharge of about 23x106 tons per year to the Jequitinhonha River.

The only large dam on the lower course of the Jequitinhonha River is the Itapebi Hydroelectric Power Plant – UHE Itapebi, which is only 80 km from the mouth. UHE Itapebi started operating in 2003 with a generation capacity of 450 MW. This plant has a run-of-river operation, therefore without the ability to regulate liquid discharges from the river. On the upper course of the Jequitinhonha, about 570 km from the mouth, the Irapé UHE was built as an accumulation reservoir and has an installed capacity of 399 MW, which started operating in 2006.

The application of the standard score (Z-score) to the annual flow values for the period between 1936 and 2020 at the fluviometric station downstream of the UHE – Itapebi, allows identifying 6 very characteristic flow intervals (Figure 6): (i) 1936-1941, annual average flow 260.73 $m^3 s^{-1}$; (ii) 1942-1949, annual average flow 581.81 $m^3 s^{-1}$; (iii) 1950-1977, annual average flow 383.13 $m^3 s^{-1}$; (iv) 1978-1992: annual average flow 477.78 $m^3 s^{-1}$; (v) 1993-2005: annual average flow 287.74 $m^3 s^{-1}$; (vi) 2006-2020: annual average flow 201.64 $m^3 s^{-1}$.

In general, there were three intervals (i, iii and v) in which the average flow was around the annual average for the entire period (320.34 $m^3 s^{-1}$; z-score=0), and two intervals in which the flow average was anomalously above the annual average for the entire period (ii and iv) and an interval in which the average flow was much below the annual average (vi) (Figure 6). These data indicate a downward trend in average annual flows that has been occurring since the 1940s and which became more pronounced from 1993 onwards, with a more drastic and accelerated reduction from 2005 onwards (Figure 6).

Figure 6: Average annual discharge of the Jequitinhonha River and Z-score of the average annual discharge for the period 1936-2020 at the downstream station of UHE Itapebi, located 80 km upstream of the mouth (Figure 5). The red line indicates the average flow for the entire period (320.34 m^3/s) and the black line represents the trend line. Data source: ANA – Hidroweb (https://www.snirh.gov.br/hidroweb/apresentacao)



3. MATERIALS AND METHODS

3.1. ANALYSIS OF SHORELINE CHANGES

Images from the Landsat 5, Landsat 8 and Sentinel 2 satellites from the period between 1976 and 2021 were used for the analysis of the behavior of the coastline (Table 1).

Table 1: Satellite images used in the analysis of shoreline changes.

Data	Satellite	Spatial resolution (m)
22/03/1976	Landsat 1-5 MSS	60
21/01/1989	Landsat 1-5 MSS	60
10/08/1992	Landsat 1-5 MSS	60
31/07/2000	Landsat 4-5 TM	30
02/11/2005	Landsat 4-5 TM	30
24/05/2010	Landsat 4-5 TM	30
06/01/2015	Sentinel 2	15
20/05/2021	Sentinel 2	15

For each image, the coastlines were drawn manually directly on the monitor, using the composition of visible spectrum bands and using as a criterion the limit between dry sand and wet sand (Boak & Turner, 2006; Byrnes & Anders, 1991).

Quantitative temporal analysis of erosion and progradation trends was performed using the Digital Shoreline Analysis System (DSAS) tool, version 5.1 (Himmelstoss et al., 2021), which allows the calculation of several parameters, among which the net shoreline movement (Net Shoreline Movement - NSM), which expresses in meters the difference between the position of the oldest and most recent shoreline.

This methodology is susceptible to several errors due to differences in spatial resolution between the images, georeferencing, difficulty in tracing the coastline indicator used, in this case specifically, the line of contact between dry and wet sand, tide level in the date of acquisition of the image among others. However, errors associated with coastline tracing become negligible or acceptable when considering the spatial scale of the images used (60, 30 and 15 meters) (Boak & Turner, 2006) and the magnitude of the changes in the position of the coastline that occurred in the study area, which reach locally a few hundred meters.

3.2. PROJECTION OF THE FUTURE POSITION OF THE SHORELINE

The forecast of the future position of the shoreline was carried out using the “Shoreline Forecasting” module of the DSAS. This method is based on a statistical model called Kalman filter (Himmelstoss et al., 2021), which combines observed shoreline positions with model-derived shoreline positions to predict future shoreline position as well as the uncertainty associated with this estimate (Himmelstoss et al., 2021).

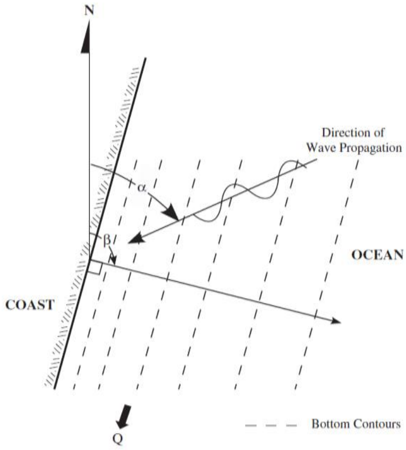
This methodology assumes that linear regression applied to past shoreline positions provides a good approximation for estimating the future shoreline position (Himmelstoss et al., 2021). Thus, other factors and processes that may influence the future position of the coastline are not considered. For this work, the future projection of the coastline for the year 2041 was used, since the last coastline used in the analysis was from the year 2021 and considering that the maximum projected by the DSAS module is 20 years.

3.3. ESTIMATE OF TRANSPORT AND DIRECTION OF COAST DRIFT

A mathematical model written in Python language and based on the method proposed by (Walton & Dean, 2010; Dean & Walton, 1975b) was used to estimate the volume and direction of sediment transport along the coastline in the study area. The input information in the model was the period data, height, and direction of incident waves measured at 100 km from the coast and at a depth of 200 m (Marinha do Brasil, 2016) together with the azimuth (β) of each shoreline segment, 100 m long, for which the intensity and direction of the littoral drift were calculated.

This method provides the average values of the volume of transported sediments as a function of the azimuth of the coastline, where transport to the right (with the observer facing the sea) is defined by positive values, and to the left, by negative values (T. L. Walton & Dean, 2010) (Figure 7).

Figure 7: Elements used in the estimation of the transport and direction of the littoral drift. β - azimuth from the external normal to the coastline. α - azimuth of wave propagation direction. Q – volume of transported sediments. Source: Walton and Dean (2010)



The estimate of the magnitude and direction of the littoral drift was calculated using the equation of (Walton & Dean, 1973), which is based on the equation of CERC - US Army Engineer Waterways Experiment Station (1984), assuming shallow water for breaking waves.

$$Q = \frac{K H_b^{5/2} \sqrt{g/\gamma}}{16\left(\frac{\rho_s}{\rho_w} - 1\right)(1-p)} \sin 2(\beta - \alpha_b) \qquad (2)$$

Where,

K: empirical dimensionless transport coefficient (0,77 - 1);
H_b e α_b: wave data (height and angle) in the surfzone;
β: azimuth (angle referred to the North direction) of the external normal to the coastline;
g: gravity (9,81 m/s^2);
γ: breaker index, H_b/h, (~0,8);
h: depth;
ρ_s: sediment density (2650 kg/m^3);
ρ_w: density of sea water (1025 kg/m^3);
p : porosity (0,4).

In this work, H_b was estimated using the method proposed by Komar & Gaughan (1972) and α_b was considered as the angle between the propagation direction of waves in deep water and the coastline, since wave transformation studies (refraction-diffraction) were not carried out.

3.4. ESTIMATE OF THE AREA OF THE DELTAIC PLAIN VULNERABLE TO FLOODING

The area of the deltaic plain vulnerable to flooding in the face of a rise in sea level was determined from a simulation of a 2 meter rise in this level in the Copernicus numerical terrain model (https://doi.org/10.5069/G9028PQB) using the ArcGis software. It is known that sea level rise projections by the end of this century are less than 2 m, but as Copernicus DEMs do not differentiate vegetation from bare soil, a 1 m rise in sea level produces irrelevant results. In addition, the areas occupied by mangroves were manually traced in Landsat 8 images and later incorporated into the areas vulnerable to flooding.

3.5. DETERMINATION OF THE TIDE PRISM AND VOLUME OF EBB TIDAL DELTA

The tidal prism (P) corresponds to the volume of water that enters the estuary during the rising tide and is expressed by the product between the height of the tide and the flooded area (O'Brien, 1931; Jarrett, 1976).

For the current scenario (actual sea level), the floodplains areas in m^2 was determined by mapping the mangrove area associated with each tidal inlet, in a Sentinel 2 satellite image taken on May 20, 2021 (Table 1), using the ArcGIS software. These areas were multiplied by the height of the tide, thus allowing to determine the P associated to each mapped tidal inlet. For sea level rising scenario, the tidal prism was estimated using the areas vulnerable to flooding after sea level rise (item 3.4) for each tidal inlet.

The sediment volume of ebb tidal deltas (V) is intrinsically related to P and can be calculated from the empirical relationship proposed by Dean & Walton (1975) and Walton & Adams (1976):

$$\boldsymbol{V = 6.6 \times 10^{-3} P^{1.23}}$$

The volume of the ebb tidal deltas was calculated considering the current sea level and the sea level rise scenario.

4. RESULTS

4.1. SHORELINE BEHAVIOR

The analysis of the behavior of the coastline for the last 45 years (1976 - 2021) allowed us to subdivide the coastline of the deltaic plain into 5 sectors, as described above and shown in Figure 8.

Sector A – corresponds to the section at the southern limit of the deltaic plain with a total length of 13 km (Figure 8), where the behavior of the coastline is characterized, for the most part, by erosion, with some segments close to stability.

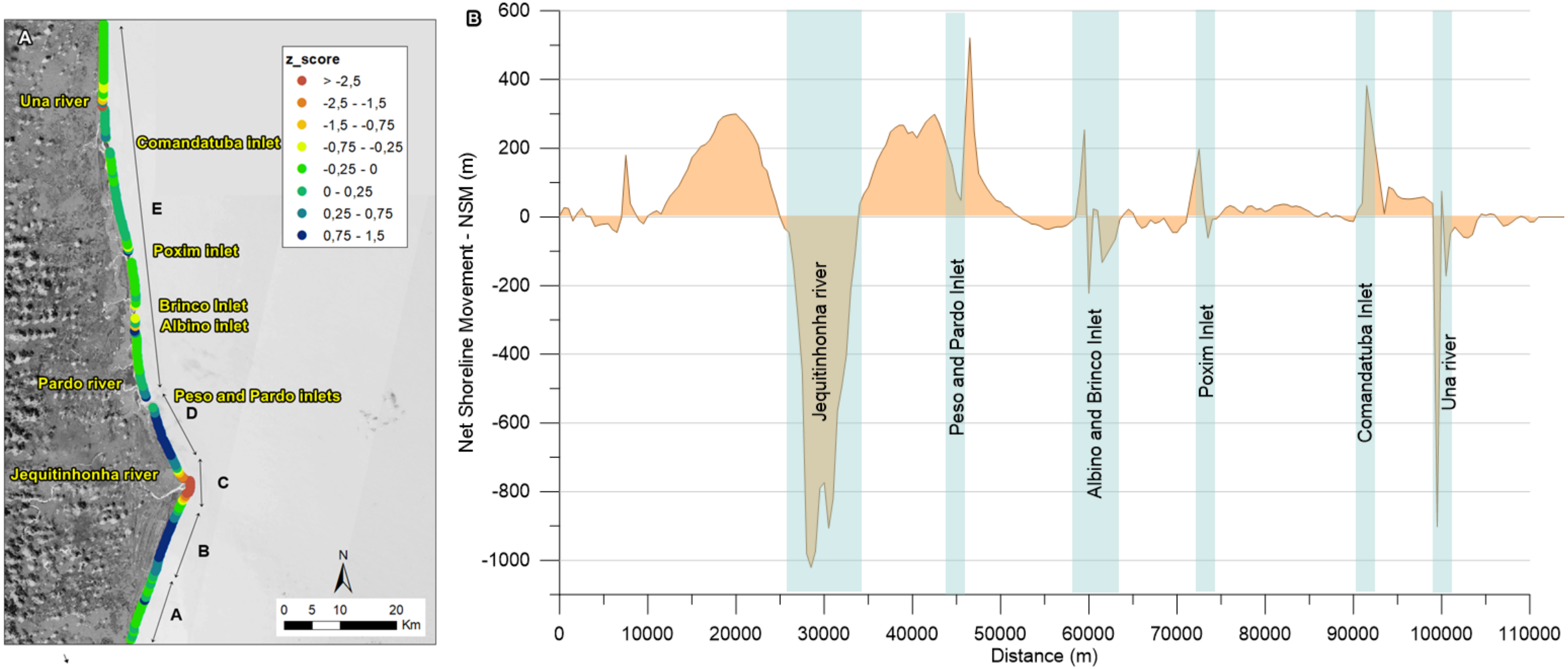
Sector B – corresponds to the stretch of coastline that extends from the mouth of the Jequitinhonha River for approximately 11 km in a southerly direction. In this sector the coastline experienced progradation of up to 250 meters (Figure 8).

Sector C – this sector, with a total length of 6 km, corresponds to the mouth of the Jequitinhonha River and its immediate surroundings (Figure 8). In this stretch, erosion rates of retreat greater than 30 m $year^{-1}$ were measured, with a total retreat in the last 45 years of up to 1030 meters. This erosion resulted in considerable loss of commercial and residential developments as well as public urban facilities (Figure 9).

Sector D – corresponds to the portion of the coastline, 12 km long, situated to the north of sector C and coincides with a sandy point that deflects the mouth of the Peso inlet to the North. The mouth of this channel has moved northwards by about 4 km over the last 45 years, forcing it to currently flow into the right bank of the Pardo River. In this stretch, the coastline progressed by up to 250 meters in the analyzed period (Figure 8).

Sector E – corresponds to the stretch of coastline located to the north of Sector D, with 67 km in length (Figure 8). In this Sector there are several mouths of tidal inlet, and the coastline has exhibited, over the last 45 years, high variability, being characterized by stretches in erosion alternating with stretches in progradation.

Figure 8: Net Shoreline Movement (NSM) in the delta plain for the period 1976 to 2021, illustrated as standard deviation of the mean NSM value or z-score (mean: 8.91, standard deviation: 223.50), B. Shoreline movement values. The light blue bars on the bottom panel indicate the positions of the mouths.



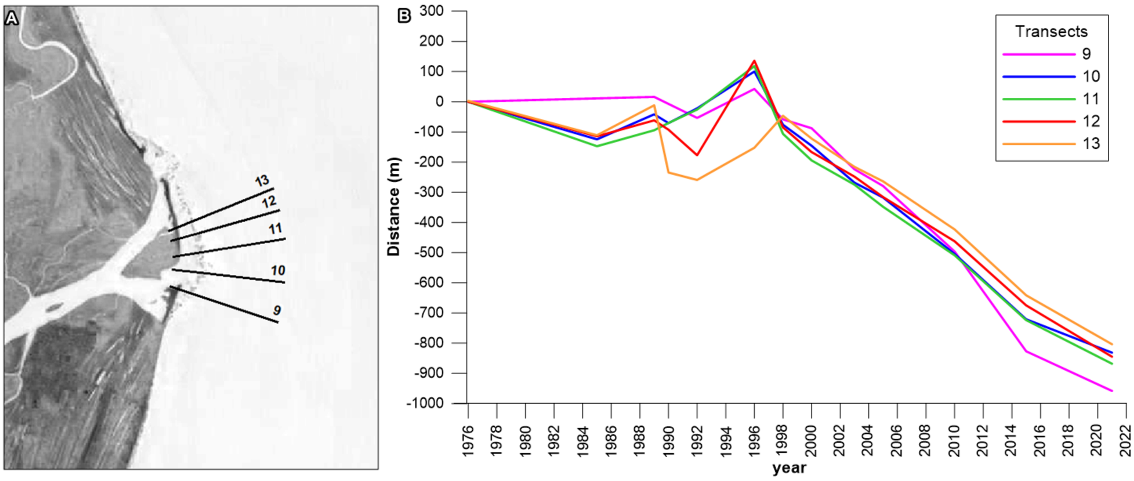
4.2. CHANGES IN THE SHORELINE AT THE MOUTH OF THE JEQUITINHONHA RIVER (SECTOR C)

The behavior of the coastline at the mouth (stretch C) was analyzed in more detail, as this stretch experienced the most severe erosion affecting urban infrastructure and causing economic losses (Figure 9).

Erosion at the mouth persisted throughout the period of analysis, except for the interval between 1985 and 1996, when there was an alternation of erosion and progradation, but with a general trend of progradation of the coastline until 1996. Since, there was a continuous erosive retreat of the coastline at roughly the same rates (Figure 10).

Figure 9: Erosion in the vicinity of the mouth of the Jequitinhonha River. A. Oblique photograph of Belmonte beach in 2003; B. Vertical photograph of the beach from the same location in Belmonte in the year 2022. The red circle indicates a common element in the two photographs.

Figure 10: A. Location of the transects where a more detailed analysis of the coastline behavior was carried out for the period 1976-2022. B. Behavior of the coastline position over time with reference to the 1976 coastline. It can be noted that the coastline experienced a significant erosional decay, mainly from 1998 onwards.

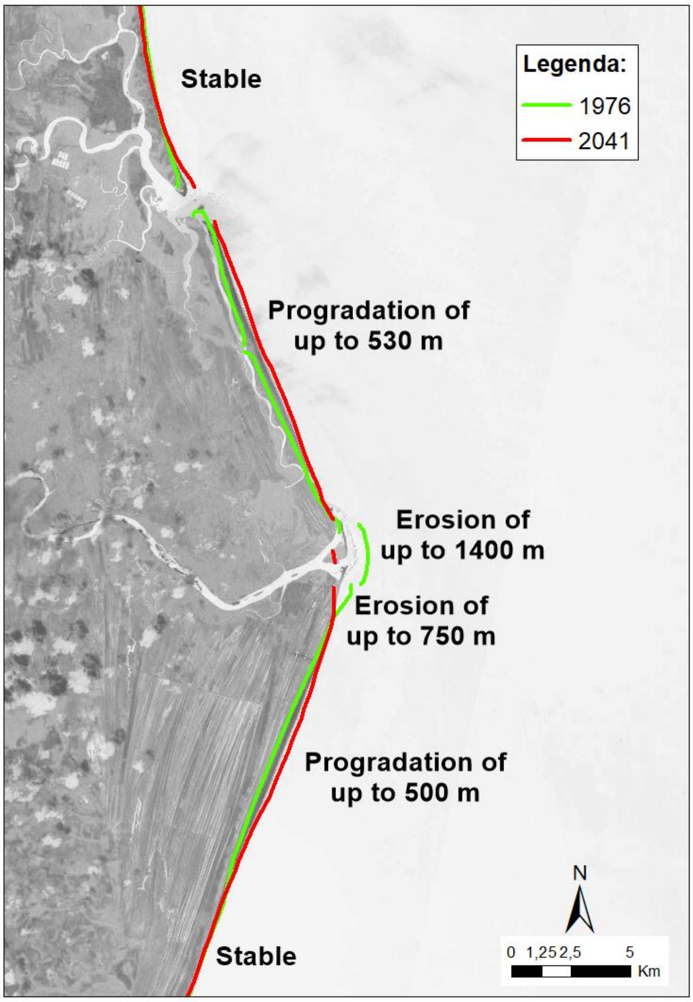


4.3. FUTURE PROJECTION OF THE SHORELINE POSITION

The predicted shoreline position for 2041 is shown in Figure 11. At the mouth of the Jequitinhonha River, erosion tends to continue with the shoreline experiencing a maximum retreat of approximately 1.4 km by 2041, on the river axis. In the immediate vicinity of the mouth, in the southern portion, erosion of around 750 m is expected by the year 2041.

In general, the future forecast is for the ongoing decay of the delta cusp to continue (Figure 8), with the eroded sediments from the mouth being redistributed to adjacent regions, both to the south (Sector B) and to the north (Sector D) of the mouth, in relation to the 1976 coastline.

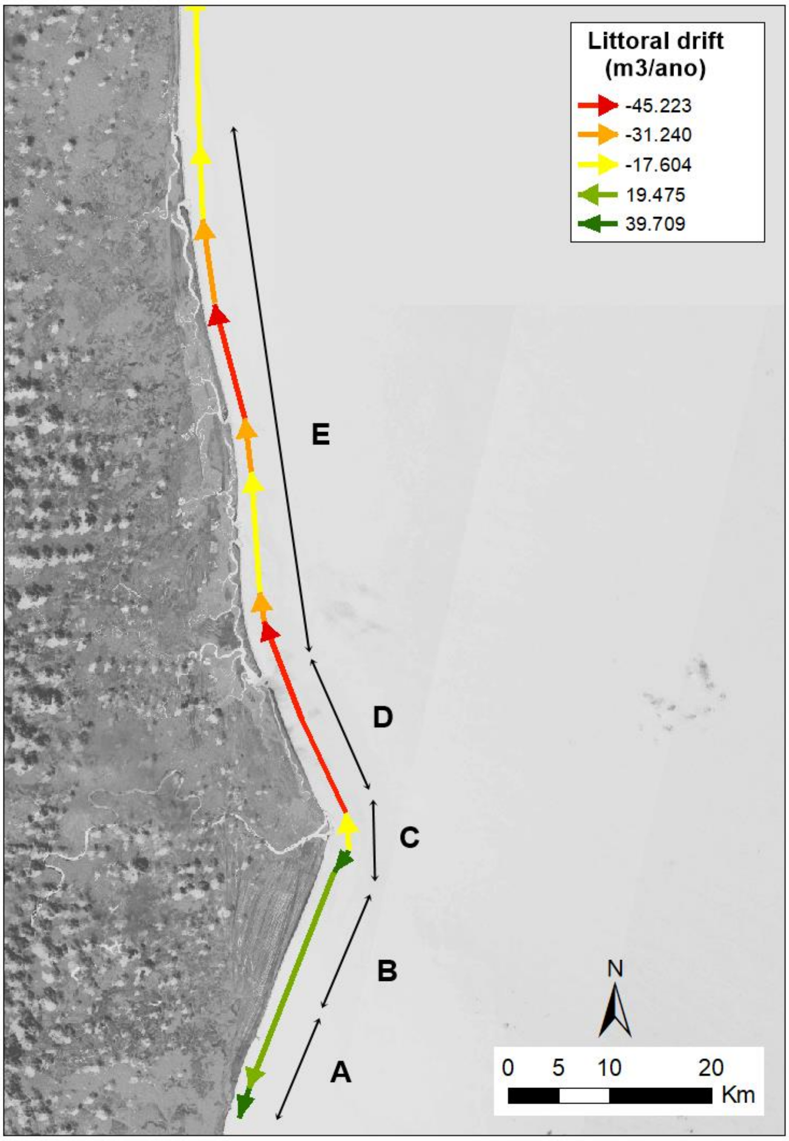
Figure 11: Coastline position in 1976 (green line) and future forecast for the year 2041 (red line) considering the retreat rates verified between 1976 and 2021.



4.4. LITTORAL DRIFT

Figure 12 shows the results of the modeling of littoral sediment transport. In general, there is a divergence in the transport of sediments from the mouth of the Jequitinhonha River, with the highest transport intensities observed immediately north of the mouth. The results obtained are consistent with those presented by Nascimento et al. (2007) for the region.

Figure 12: Littoral drift in the deltaic plain. The arrows indicate the drift direction, and the colors indicate the average intensity. Letters A to E indicate the same sectors in which the shoreline was compartmentalized in the shoreline behavior analysis (Figure 8).

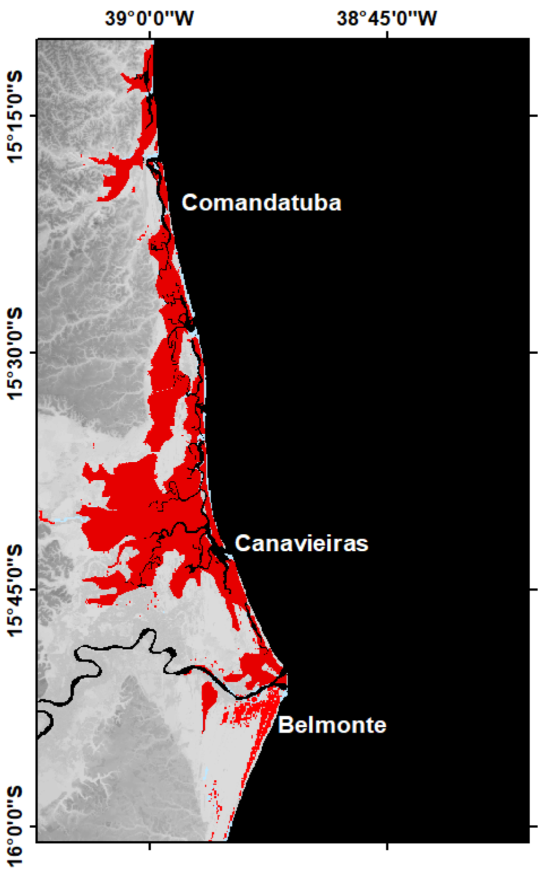


4.5. AREAS VULNERABLE TO FLOODING

Figure 13 shows the areas subject to flooding in the Jequitinhonha delta plain due to a 2 m rise in sea level. Note that the most vulnerable areas to flooding are in the northern portion of the deltaic plain, which is the lowest region where most of the mangroves and wetlands of the plain are concentrated.

The southern portion of the plain, made up of regressive coastal sands, is less vulnerable to flooding given that most of it is located at least 2.5 m above current sea level (altitude of the current berm).

Figure 13: Areas subject to flooding due to a 2m rise in sea level in the deltaic plain of the Jequitinhonha River.



4.6. TIDAL PRISMS AND VOLUMES OF EBB TIDAL DELTAS

With the predicted rise in sea level, there will be an increase in the flooded area associated with each tidal inlet in the northern portion of the plain (igure 14). The tidal prism is a function of the flooded area and tide height. Consequently, the tidal prism associated with each inlet should increase with sea level rise, as well as the volumes of sediment stored in the associated ebb tide deltas, due to these volumes are also controlled by the tidal prism.

The estimates of the tidal prisms associated with the tidal inlet present in the northern portion of the plain and the respective volumes of the ebb tide deltas were calculated both for the current situation and for a future scenario with the sea level 2 meters above the current one, using the empirical relationship proposed by Dean & Walton, 1975a and Walton & Adams, 1976) (Figure 15). As already mentioned, a sea level rise of 2 m was used due to the limitations imposed by DEM Copernicus that do not discriminate between bare soil and vegetation. It should be noted that the boundaries drawn of the contributing basins for each tidal inlet both for the current situation and for the scenario of a rise in sea level is to some extent arbitrary and based on "educated guesses". However, as our objective is to assess the vulnerability of the delta in a more general way, the precision in tracing these limits is a secondary aspect that does not compromise our objectives.

In the study area, the Pardo inlet was the one with the largest tidal prism and theoretically the largest ebb tide delta for the current situation. Likewise, it is also the most impacted by the 2 m rise in sea level, which could potentially result in an increase in the tidal prism of the order of 350% and in the volume of the ebb tide delta by 1000%.

igure 14: A. Floodplains in the current scenario corresponds to mangrove areas. B. flooded areas in the sea level rise scenario contributing to each tidal inlet.

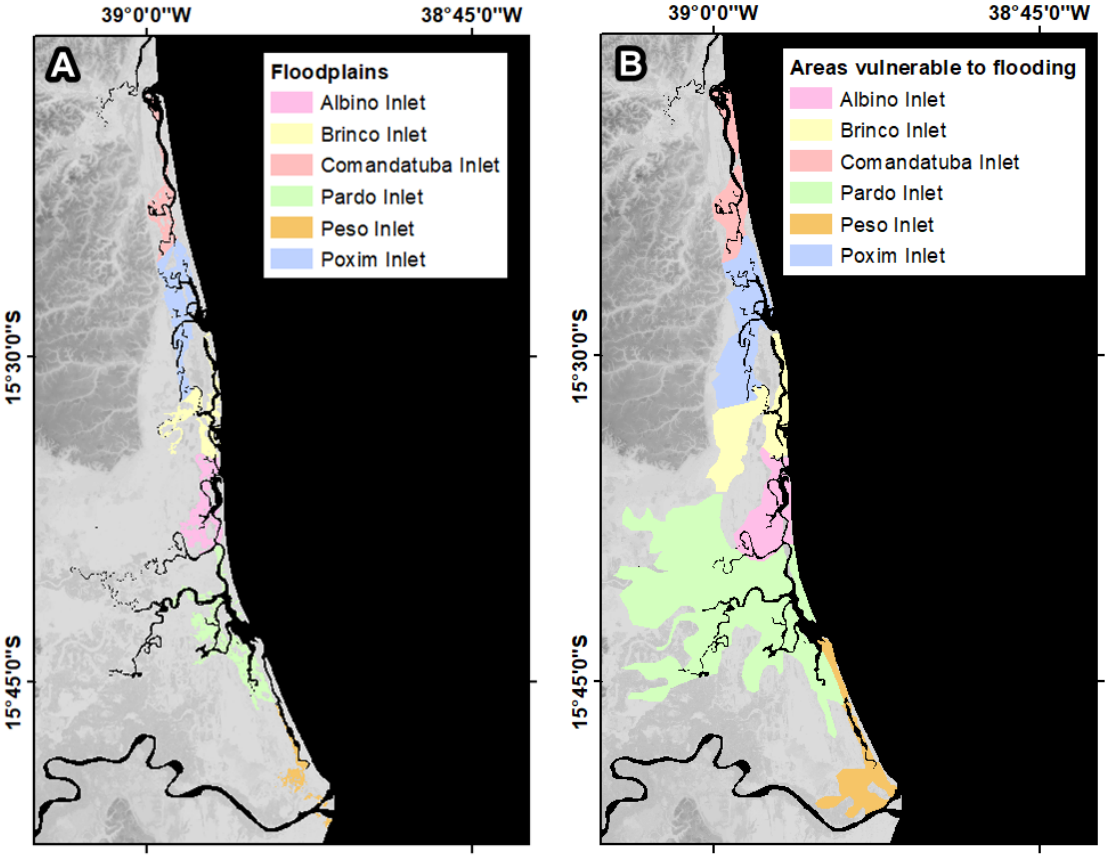
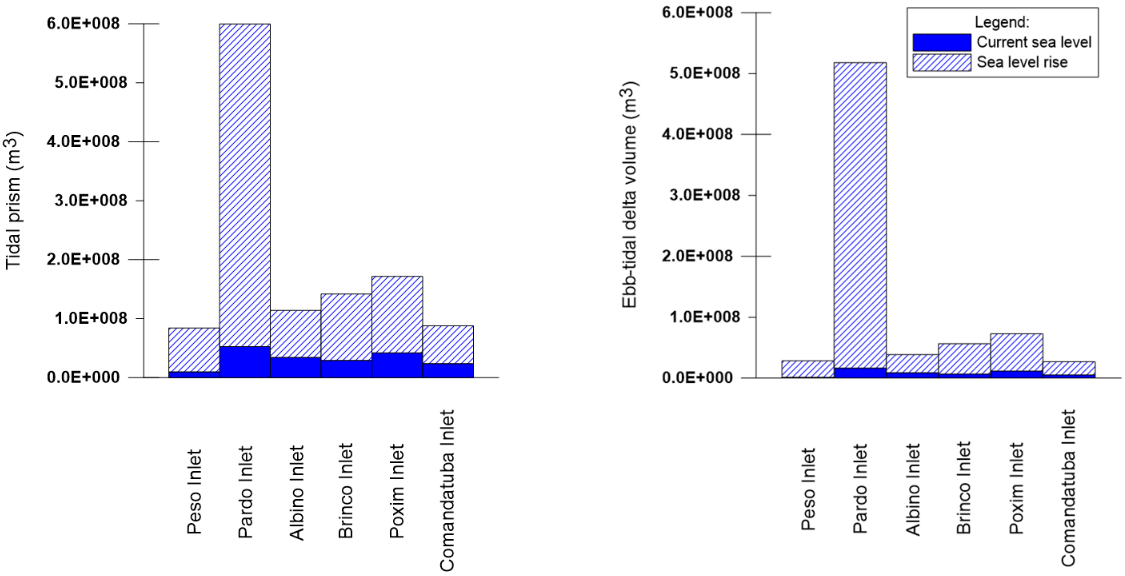


Figure 15: Tidal prisms and theoretical volumes of tidal deltas associated with existing tidal inlets in the delta plain for the current scenario and after a 2 m rise in sea level.



5. DISCUSSION

5.1. EROSION AT THE MOUTH OF THE JEQUITINHONHA RIVER

The analysis of the behavior of the coastline showed that the stretch that suffered the most erosion was the mouth of the Jequitinhonha River (Sector C) (Figure 8), with the eroded sediments redistributed to the flanks of the delta (Sectors B and D). The position of the coastline at the mouth remained almost the same position between 1985 and 1996. From 1996, the erosion process began, which persists until the present day, with relatively constant rates (Figure 10).

The hydrograph of the Jequitinhonha River has a flow regime marked by interannual and interdecadal variations (Figure 6). Since 1936, only two periods can be characterized as wetter than the overall average: (ii) 1942-1949 e (iv) 1978-1992.

In the periods (i) 1936-1941, (iii) 1950-1977 and (v) 1993-2005 the average flow was close to the general average for the entire period. In this last period (1993-2005), however, there was a 40% reduction in flow compared to the previous wet period (1978-1992). As of 2006, the outflows were reduced even more, being on average 58% lower than in relation to the wet period iv (1978-1992) (Figure 6). From 1996, the erosive process began at the mouth of the river, approximately concomitantly with the most dramatic reduction in river flow (Figure 6).

The coastal erosion that currently occurs has been commonly attributed to the implementation of the UHE Itapebi (Dominguez et al., 2006; Dominguez et al., 2003; Silva et al., 2021). In fact, the construction of dams on rivers intercepts the flow of sediments and is one of the causes of the reduction of sediment discharge to the coast, accelerating coastal erosion in the vicinity of river mouths (OVEREEM, I. & SYVITSKI, 2009). Classic examples include the acceleration of erosion at the mouths of the two distributaries of the Nile after the construction of the Aswan dam (Fanos, 1995), the case of the Volta River in Ghana after the construction of the

Akosombo dam (Ly, 1980), and the rivers Changjiang (Yangtze) (Yang et al., 2011) and Yellow (Chu et al., 2006; Wang et al., 2007) in China, Mississippi in the USA (Blum & Roberts, 2009), the Ebro in Spain (Sanchez-arcilla et al., 1998), the Godavari and Krishna in India (Rao et al., 2010) and the São Francisco River in Brazil (Dominguez & Guimarães, 2021). In addition to sediment retention, dams can significantly alter the hydrological regime of rivers by keeping average daily flows approximately constant throughout the year.

The construction of UHE Itapebi started in 1999 and started operating in 2003, slightly after the beginning of the erosive process. UHE Itapebi is a run-of-river type plant and, therefore, does not have the capacity to regulate river flows. Even though the plant's reservoir has the capacity to retain almost all of the riverbed's load, this does not seem to be the main cause of erosion at the mouth, given that in the stretch of approximately 70 km that separates the plant from the mouth, there is a volume expressive amount of sandy sediments in the bed of the Jequitinhonha river that could be mobilized and, therefore, feed the mouth for a few decades to come, if the river flows had remained close to their average values. Thus, apparently, the signal of sediment retention in the dam has not yet been able to propagate to the mouth.

The hydrograph of the Jequitinhonha River (Figure 6) shows a clear downward trend in average annual flows since the 1940s, which increased from 1993 onwards. This decrease in flow is associated with a progressive decrease in rainfall in the hydrographic basin (Figure 2), whose beginning precedes the construction of the Itapebi dam in 1999.

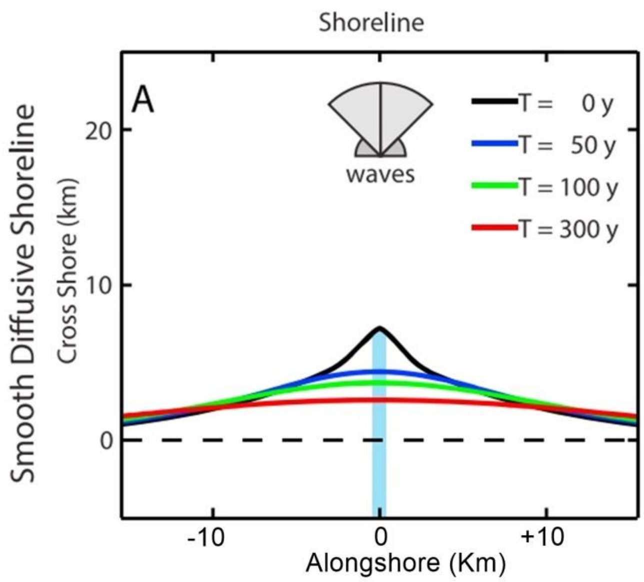
Thus, erosion at the mouth of the Jequitinhonha seems to result essentially from the reduction of rainfall in its watershed, which caused a decrease in flow and, therefore, the river's ability to remobilize the sediments stored in its lower course (Backwater Effect – LAMB et al. 2012). This erosion tends to get worse in the coming decades due to the conjunction of two factors:

(i) retention of sediments in the reservoir of the UHE Itapebi and (ii) additional reduction of rainfall in the hydrographic basin until the end of the century.

Nienhuis et al. (2013) proposed four shoreline decay models for wave-dominated deltas as a function of delta abandonment and reduction in solid discharge. In these models the shoreline decay is determined by the degree of asymmetry of the directional wave climate.

The so-called “smooth diffusive shoreline” model (Figure 16), characterized by a symmetrical directional wave climate (Nienhuis et al., 2013), with erosion at the mouth and re-deposition of sediments on both flanks of the delta, is what best applies to the Jequitinhonha river delta, thus allowing to predict that, if the conditions of reduction in flows verified in the last decades persist, the continued decay of the coastline will imply in the eventual disappearance of the deltaic cusp. This is the most likely future scenario considering the reduction of precipitation in the east coast watersheds of Brazil under the RCP 8.5 climate change scenario (Figure 2).

Figure 16: Decay model of deltaic cusp of type “smooth diffusive shoreline”. Source: (Nienhuis et al., 2013)



An important implication of this decay is that, ignoring other factors such as, for example, sea level rise or the increase in the frequency of extreme events, the total area of the deltaic plain will be preserved, as the eroded sediments of the mouth region they will only be redistributed to the lateral flanks of the delta by the littoral drift (Figure 8). Thus, from the point of view of coastal erosion, Sector C, which corresponds to the mouth of the river and its immediate surroundings, is the one that presents the greatest vulnerability to the reduction of river flows caused by ongoing climate change. This prognosis is corroborated by the results obtained in the analysis of the projection of the future position of the coastline until 2041 (Figure 11), which indicates behavior similar to that of the decay model of the deltaic cusp of the “smooth diffusive shoreline” type (Nienhuis et al., 2013).

5.2. VULNERABILITY OF THE NORTHERN PORTION OF THE COASTAL PLAIN (SECTOR E): FLOODING, ALTERATION OF THE TIDE PRISM AND COASTAL EROSION

The coastline in sector E, characterized by several mouths of tidal inlets (Figure 8), already presents a high variability in its position mainly due to the dynamics of the ebb tidal deltas associated with these channels, where large volumes of sediment are stored in tidal deltas and where changes in the channel thalweg and concomitant sandbar migration alternately trigger erosion and progradation in the vicinity of the tidal delta (Fitzgerald et al., 2001) (Figure 8).

In sector E, the rise in sea level and its effect in increasing the tidal prism could trigger dramatic changes in the geomorphology of the region with sectioning even of the barrier islands present there, like the changes described by (FitzGerald et al., 2008).

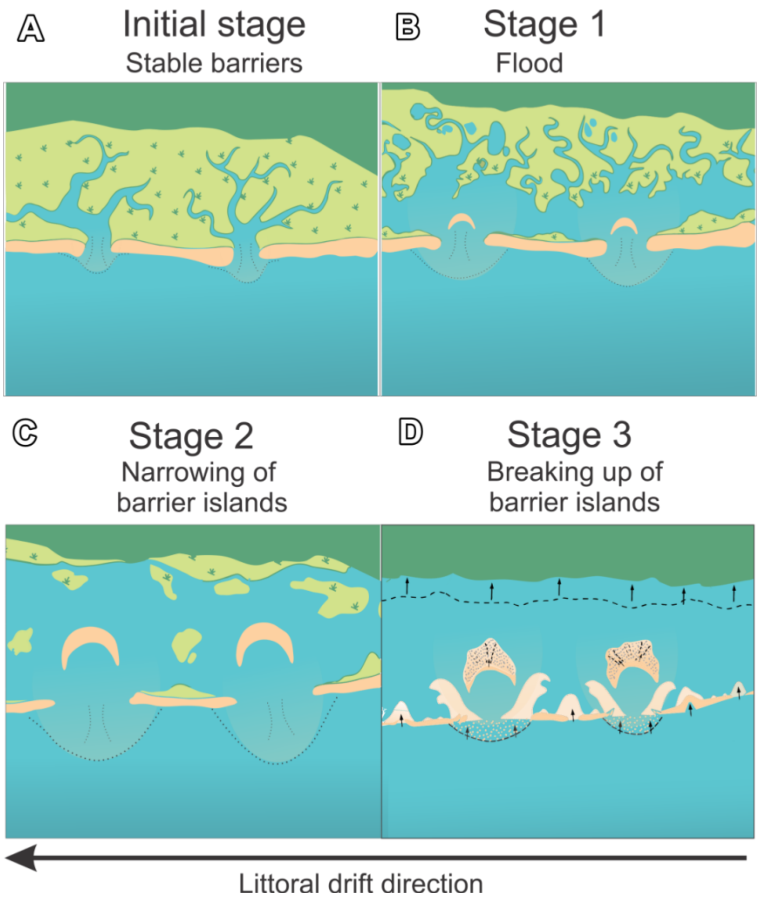
According to O’Brien, 1969 and Walton & Adams (1976) the tidal prism largely determines the cross-sectional area of the channel and the volume of the ebb delta, so that the increase in the tidal prism increases the volume of water exchange by the tides and intensifies tidal currents, expanding the dimensions of channels. In this sense, the tidal prism controls the dimensions of the channel, and the sediment transport trends in them (FitzGerald et al., 2008). This is a relevant aspect for estimating the effects of sea level rise on sand barriers.

In response to the rise of the tidal prism, the tidal channels widen, causing erosion of the shoreline adjacent to them and an increase in the volume of the ebb tidal delta (Figure 17B). The trapping of sediments by the ebb tidal delta until it reaches a new equilibrium volume (Walton & Adams, 1976), decreases the amount of sediments transported by the longitudinal current triggering erosion of the shoreline of the sandy barrier located downdrift (FitzGerald et al., 2008).

As seen, a sea level rise of around two meters has the potential to flood an area of about 16,089 km2 in the northern portion of the deltaic plain, theoretically increasing the tidal prism by around 350%. At the same time, the increase in water depth in the region located in the back area of the sand barriers generates an additional accommodation space that allows the expansion of flood tidal deltas (Figure 17C). The expansion of tidal deltas (ebb and flood) occurs at the expense of the transfer of sediments from the sandy barriers to these, which can result in accelerated erosion, narrowing and segmentation of these barriers (Hayes & FitzGerald, 2013), with the formation of new tidal channels and associated tidal deltas (Hayes & FitzGerald, 2013; (FitzGerald et al., 2008a) (Figure 17D).

A similar process of narrowing of sand barriers, rupture and formation of new channels occurred in Pass Abel (Fitzgerald et al., 2007) and in Isles Dernieres, Louisiana (Williams & Sallenger Jr., 1989), even causing the disappearance of barrier islands (FitzGerald et al., 2008a), like the barrier islands in Louisiana in the USA (Wright et al., 1999; List et al., 1997; Williams & Sallenger Jr., 1989; Fitzgerald et al., 2007), the barrier islands in the Mississippi delta also in the USA (Morton, 2007) and the Frisian Islands in the North Sea (FitzGerald et al., 2006).

Figure 17: Conceptual model of a barrier island coast in the rising sea level scenery. Adapted from D. M. FitzGerald et al., 2006.



6. CONCLUSIONS

The vulnerability of the Jequitinhonha River delta to ongoing climate change can be understood according to two main aspects:

The reduction in the amount of rain in the hydrographic basin resulted in a decrease in the flow of the Jequitinhonha River, reducing the input of sediments in its mouth, triggering a process of severe erosion that began in 1996. The erosion has caused a decay of the deltaic cusp, with eroded sediments being redistributed to the two flanks of the delta because of the symmetric directional wave climate that predominates in the region. However, it should be noted that the total area of the plain has not been affected so far, with only a redistribution of sediments. This decay tends to become more pronounced in the coming decades in view of forecasts of further reduction in rainfall by the end of the century. To this reduction in the input of sediments due to the reduction in flow, in the coming decades, the effect of sediment retention in the Itapebi dam reservoir, located 80 km upstream of the mouth, must be added. The effect of this sediment retention has not yet spread to the mouth, since the lower course of the river still has large stocks of sand that could be mobilized if the flows had not decreased (Backwater Effect - Lamb et al., 2012).

In addition to the mouth region, the northern portion of the deltaic plain is the most vulnerable to the effects of climate change, resulting from rising sea levels. This region is the lowest in the delta, with extensive mangroves and numerous sand barriers and tidal channels. This asymmetry in the vulnerability of the delta is probably controlled by the geological heritage, since the distribution of the mangrove areas is conditioned by the position of the head of the incised Jequitinhonha valley (DOMINGUEZ 2023), while the southern half is constituted by a continuous sheet of coastal sands regressive. Sea level rise by the end of the century could result in the rise of tidal prisms and consequent expansion of ebb tidal deltas associated with tidal channels. As the expansion of these tidal deltas takes place at the expense of eroded sediments from the sand barriers, this could trigger an erosion process on the coastline with the narrowing and sectioning of these barriers and the appearance of new channels and tidal deltas in a process that feeds back. The result may even be the elimination of sandy barriers, as already described in other regions of the world (FitzGerald et al., 2008b) with the formation of a haze on the coastline, approximately coinciding with the head of the former incised valley of the Jequitinhonha River.

As noted by Giosan et al. (2014) smaller deltas (area <1000 km^2) made up of sandy sediments, such as the wave-dominated deltas, have a larger portion of the delta plain located above sea level, and therefore are less vulnerable to sea-level rise deltaic plain, particularly its southern half, consisting mainly of regressive coastal sands, has relatively low vulnerability to climate change. In addition, due to the fact that the plain has developed in a field region distant from the effects of the GIA, where the relative sea level has dropped between 3 and 4 m since the Middle Holocene (Dominguez & Bittencourt, 2012), these coastal sands present varying altitudes between 2.5 m (height of the current berm) and 6 m in the innermost regions of the plain.

This study represents a contribution to understanding the vulnerability of wave-dominated deltas, built under high wave energy conditions, to ongoing climate change. This aspect has not yet been fully contemplated in the scientific literature, where case studies are more concentrated in the large deltas of Southeast Asia or in the wave-dominated deltas of the Mediterranean where wave energy levels are lower when compared to the Brazilian coast.

7. ACKNOWLEDGEMENT

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CAPÍTULO 3
CONCLUSÕES

O presente trabalho avaliou a vulnerabilidade do delta do rio Jequitinhonha às mudanças climáticas em curso com foco principalmente no comportamento da linha de costa e na identificação das regiões da planície mais vulneráveis a inundação.

Visto que o foco principal de estudos da vulnerabilidade dos deltas às mudanças climáticas tem sido os grandes deltas do sudeste asiático e do Mediterrâneo, este trabalho trouxe uma nova perspectiva no entendimento sobre a vulnerabilidade de deltas dominados por ondas, como é o caso dos deltas da costa leste do Brasil, frente às mudanças climáticas deltas.

Este trabalho também contribui com a gestão costeira local uma vez que apresentou o comportamento da linha de costa para os últimos 45 anos, projeção da posição futura da linha de costa e identificação das áreas vulneráveis a inundação costeira, aspectos essenciais para o planejamento de uso e ocupação do solo da região que está se desenvolvendo num cenário de mudanças climáticas.

Diante disso este trabalho, além de fornecer informações sobre a dinâmica costeira da região e propor ferramentas para auxiliar no gerenciamento costeiro local, também colaborou com a produção científica do Programa de Pós-Graduação em Geologia da Universidade Federal da Bahia.

ANEXO A – REGRAS DE FORMATAÇÃO DA REVISTA

PREPARATION

NEW SUBMISSIONS

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As part of the Your Paper Your Way service, you may choose to submit your manuscript as a single file to be used in the refereeing process. This can be a PDF file or a Word document, in any format or lay-out that can be used by referees to evaluate your manuscript. It should contain high enough quality figures for refereeing. If you prefer to do so, you may still provide all or some of the source files at the initial submission. Please note that individual figure files larger than 10 MB must be uploaded separately. Along with the Manuscript file, you will have to upload the following mandatory files during submission process:
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Divide the article into clearly defined sections.

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Please ensure the figures and the tables included in the single file are placed next to the relevant text in the manuscript, rather than at the bottom or the top of the file. The corresponding caption should be placed directly below the figure or table.

Peer review

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ANEXO B - COMPROVANTE DE SUBMISSÃO DO ARTIGO

06/03/2023, 17:09 Email – Milena Nervino – Outlook

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