Coastal Vulnerability Assessment Based on Multi-Hazardous Events. Case study: Northwestern Coastline of Guinea-Bissau (NC-GB)

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Coastal Vulnerability Assessment Based on Multi-Hazardous Events. Case study: Northwestern Coastline of Guinea-Bissau (NC-GB)

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Abstract

Guinea-Bissau coastlines are found highly vulnerable to coastal hazards, and this vulnerability will likely increase under future climate change scenarios. In addition, the multi-hazardous assessment studies have not yet been conducted to clarify the status of vulnerability index to coastal hazards. Therefore, we integrated eight bio-geophysical parameters and elaborate a comprehensive Coastal Vulnerability Index to coastal hazards, stabilish the rate of sea-level rise and determine the role of coastal habitats in protecting the shorelines in the Northwestern Coastline of Guinea-Bissau, by using the GIS and Coastal Vulnerability Index of InVEST Model. The study found that, out of 87 km of the studied coastlines, nearly 45 km lie in high to very-high vulnerability index. 17 km are found in a moderate vulnerability index and 25 km are found at low to very-low vulnerability index. The main responsible for high vulnerability registered in Zone-B were the wind and wave exposure, as this coastline is highly exposed to sea. The other reason was the storm surge and sea-level that rises 8.79/year, motivated by low coastal elevation. Mangrove ecosystem that are largely found in Zone-A, play very important role in protecting shoreline from coastal hazards with value 0.61, followed by forest and sand dune that are found mostly in Zone-C with 0.49 and 0.4 respectively, and saltmarsh that are relatively found in Zone-B with value 0.32. These findings can assist coastal managers in cost-effective adaptation plans, provide a scientific basis for sustainable coastal management and guidance for ecological conservation in coastal regions.

Keywords: Coastal vulnerability index, Climate change, Coastal hazards, Spatial Analysis Techniques

Introduction

Various coastal regions are vulnerable to coastal hazards due to their proximity to the sea (Sahoo and Bhaskaran 2018; Islama et al. 2016). Coastal hazards like sea storms, tidal flooding, coastal erosion, cyclones, saltwater intrusion, sea-level rise, and sea surface temperature occur frequently in coastal areas due to natural and human implication (Kantamaneni 2016). These coastal hazards constantly lead to extensive human, economic, social, and ecological damage. Several researches have projected that by 21st century, severity of the changes in coastlines will occur due to sea-level rise intensification (Djouder and Boutiba 2017; Pachauri et al. 2014; G houssein et al. 2018), as a result, coastal communities, properties, and coastal habitat are at constant risk (Pethick and Orford 2013). Several approaches have been employed, like the Coastal Vulnerability Index (Kumar and Kunte 2012a; Djouder and Boutiba 2017; Addo 2013; Islam 2015), coastal sensitiveness (Chalkias et al. 2014; Abudoda and Colin 2010) and others indexes such as, Comparative Coastal Risk and Coastal Risk Index-Local Scale (Calil et al. 2017; Komali 2016; Le Cozannet et al. 2013; Murali et al. 2013; Gallina et al. 2016) to link of coastal vulnerability to coastal hazards. These methods were initially suggested by Gornitz (1994), which was later taken up by various other authors (Djouder and Boutiba 2017; Addo 2013; Islam et al. 2016; Muralia 2015; G houssein et al. 2018). Being as an integral index, the CVI includes various pertinent parameters to produce relevant information for the management of the coastal regions (Bagdanavičiūtė and Kelpšaitė 2015; Denner et al. 2015). The CVI operates
as a numerical approach in categorizing coastal region's sections based on the strength of impact (González and Covarrubias 2018; Rani 2015). Prevention are one of the most risk management strategies to contain the coastal hazards impacts on coastal community, properties, and ecological environment (Hoque et al. 2017; Murali et al. 2013). In most coastal countries, researchers have made attempts to evaluate the level of coastal vulnerability by employing geophysical parameters like geomorphology, shoreline dynamic, relative sea-level change, wave regime, coastal slope and others (Kumar and Kunte 2012a; Gornitz 1994; Pendleton et al. 2005; Hamid et al. 2019; Islama et al. 2016; Shaji 2014) as well as population densities as a socio-economic parameter (Boruff† and Emrich†, 2005; Szlafsze† and Sterr, 2007; Kunte et al. 2014).

In Guinea-Bissau, approximately 65% of the entire territory are considered coastal area with continental shelf of 39,339 km² (seatemperatureinfo 2021), maximum wind speed of above 35 km/h and highest wave of above 14 meters height. The country is categorized into two distinct coastal regions, i.e., northwestern and southwestern those include Mimara, Tombali and Archipelago of Bijagos. The northwestern coastal region contains many important natural resources, like meandering rivers that form estuaries, the Heavy Sand Mining of Varela, deposited oil, and the Natural Park of Tarrafes do Rio Cacheu, one of the most extensive mangrove blocks in West Africa (del-Toro and López 2019). This Natural Park is important site for nature conservation established in the 1980s by the national authority and the World Conservation Union (IUNC 2018; Mendy and Lobban 2013). The low-lying land, the climatic condition and landform characteristic are seen as the main factors related to high coastal vulnerability that have led to considerable loss of properties and environmental destructions (Berman et al. 2020; Frumkin 2018). The coastlines in Guinea-Bissau are predicted to be negatively impacted by 21st century if sea-level rises 1 m which is above the one predicted globally (3.1 mm/yr.) (Buuiyan and Dutta 2012). The NC-GB is proven to be highly vulnerable to coastal hazards (Fandé 2018; Tebaldi et al. 2016). Although, no study on multi-hazardous assessment by integrating bio-geophysical parameters in this case “the natural habitat, geomorphology, relief, bathymetry, wind, wave, storm surge and sea-level rise” has been conducted to clarify the status of vulnerability index of this coastal areas. Therefore, in this study, we intend to 1) elaborate a comprehensive Coastal Vulnerability Index to coastal hazards, 2) establish the rate of sea-level rise in the shoreline of our study area and, 3) determine the role of coastal habitats in protecting the shorelines from coastal hazards in the NC-GB. Coastal stakeholders, policy makers and coastal managers can use the spatial findings as reference base in preparing mitigation and adaptation plans for sustainable coastal management (Hereher 2015; Ahammed and Pandey 2019; Hoque et al. 2017).

2. Methods and Materials

2.1 Area of study

The study area is geographically located in the NC-GB, between 12° 16’ 14” N, latitude and 16° 9’ 57” W longitude (Fig. 1), covering an area of 1,035.1 km² with extended coastlines nearly 87 km long (Sintra 2016). The climate is tropical with temperatures variation from 20 °C (68 °F) to 30 °C (86 °F) in April to May, and annual average rainfall of about 2,000 mm. The study area is divided into three important ecological zones, considering different characteristic of this coastlines. Zone-A: area of high mangrove occupation covered by estuaries and rivers with the lowest coastal elevation and slope (Fig. 3a-b). Zone-B: Area with low coastal habitats quality and widely exposed to sea and contain low slope as well. Zone-C: the area with more coastal forests, dunes and sand beach with relatively higher cliff (De Faria et al. 2014).

Fig. 1 is fixed here.

2.2 Dataset and sources

In this study, we used the open-source United States Geological Survey (USGS) to acquire a year 2020 Landsat 8 Operation Land Imager (OLI) temporal dataset of the study area at an enhanced resolution of 15m (USGS 2020). The images were processed, mosaic, and clipped for parameters extraction using ArcGIS 10.5. We utilized a wide scope of both national and international data as shown in Table 1, and combined with field monitoring to assist in satellite images interpretation, coastal geomorphologies and natural habitats identification.
2.3 CVI parameters analysis and mapping

CVI is widely viewed as the most effective and direct method for assessing coastal vulnerability based-index (Djouder and Boutiba 2017). The CVI relates the degree to which the coastal environments are sensitive to the impacts of wind and wave exposure, surge potentials and rising of sea-level. The CVI was derived as a result of the exposure index (EI) and the sensitivity index (SI). The EI and SI are related to how prone coastal environment and communities are adversely affected by coastal hazards (Sajjad et al. 2020). EI and SI were computed based on the CVI model, designed by the Natural Capital Project (Naturalcapitalproject 2020). Such model was based on previous analytical framework approaches (Hammar-Klose and Thieler 2001; Gornitz 1990). It was applied to quantify the effects of sea-level rise and storm surges on the several coastlines, incorporating seven parameters such as coastal elevation, geomorphology, habitats, sea-level rise, wind, waves, and surge potential. In accordance with the criteria detailed by Nelson et al. (2016), 1 (very low) to 5 (very high) were ranked for different exposure levels, where each segment was calculated as:

\[
EI = \left( \frac{1}{7} R_{\text{Geomorphology}} \cdot R_{\text{Relief}} \cdot R_{\text{Habitats}} \cdot R_{\text{SLR}} \cdot R_{\text{Wind Exposure}} \cdot R_{\text{Wave Exposure}} \cdot R_{\text{Surge}} \right)^{1/7} \tag{1}
\]

More generally:

\[
Index = \left( \frac{1}{n} \sum_{i=1}^{n} R_i \right)^{1/n} \tag{2}
\]

where \( R_i \) means the classification of the \( i^{th} \) geophysical to calculate \( EI + SI \)

In this study, eight bio-geophysical parameters such as relief, geomorphology, natural habitat, bathymetry, wind, wave, storm surge potential, and sea-level rise were all considered following the related literatures. The conceptual framework of vulnerability index on the basis of an analytical hierarchy approach is presented in (Fig. 2).

2.3.1 Relief

Coastal relief performs a critical role in setting up and predicting the amplitude of landmass under threat of coastal hazards caused the potential rising of sea-level and storm surge (Murali et al. 2013; Kumar et al. 2010). Low elevation areas are thought to be a highly vulnerable, while high elevation areas are seen as less vulnerable (Hoque et al. 2018). In this study, we build the elevation and slope raster map (Fig. 3a-b) as an CVI input to calculate the relief of each shoreline segment. The average elevation radius numeric entry proposed by the user guide of InVEST package was assigned to “5000” in the model to determine the radius in meters around each shoreline point (Naturalcapitalproject 2020). The ArcGIS 10.5 was used to create this raster input.

2.3.2 Geomorphology

Coastal geomorphology is remarkably influential in assessments of the shoreline response to various hazards (Kumar and Kunte 2012a; Islam 2015). It’s noted that, rocky coastlines, provide greater strength in protection and they show to be less vulnerable to coastal hazards. In the contrary, sandy beaches, lagoons, and mudflats provide a limited resistance to coastal hazards (Murali et al. 2013). In this study, we considered four different coastal geomorphologies, including rocky, sandy beach, estuary, and cliff, as the input in the CVI model to define their potential in shoreline protection (Fig. 3c). Google-Earth was used for on-screen digitization considering approximately 1 to 3 km from the shorelines to interior of study area. Image improvement techniques were applied in histogram to increase the visualization and identify geomorphological features. This input was categorized into an attribute field called "RANK" based on the alternative scheme shown in Table 4 that classified with ranking 1 to 5, and the value was assigned according literature (Hammar-Klose and Thieler 2001; Gornitz 1990; Thakura et al. 2021) and field knowledge of the study area.
2.3.3 Natural Habitat

Sajjad and Chan (2020) natural habitats play a key role in minimizing effects of coastal hazards which may cause damage to coastal livelihoods. Mangroves, coral reef, seagrasses and coastal forest greatly reduce the height of waves in shallow water. Saltmarshes, coastal dune and seagrasses stabilize sediments and stimulate the accumulation of near coastlines beds and disperse wave power. This study considered four natural habitats, including mangrove, sand dune, salt marsh, coastal forest, areas without habitat to determine their vital role in protecting the shoreline from coastal hazards. The Google-Earth was used for on-screen digitization considering nearly 1 to 3 km from the shorelines to inland (Fig. 3d). The digitized data were exported to ArcGIS 10.5 for data processing. To add this variable into the CVI model, we provided a habitat table (CSV) to guide the model on the habitat inputs. The table contained headings "id" (text string without spaces applied to define the habitat uniquely), "path" (the file name and habitat location in the layer of GIS), "rank" (value from 1 to 5, as described in Table 4), "protection distance" (distance in meters beyond which this habitat will provide).

Table 2 is fixed here.

The CVI model computed a final natural habitat ranking for that point with the following formula:

\[
R_{Hab} = 4.8 - 0.5 \sqrt{\sum_{i=1}^{N} (5 - R_i)^2} + \left( \max_{i=1}^{N} (5 - R_i) \right)^2
\]

\[ (3) \]

Where \( R_{Hab} \) means the rank of habitats and \( N \) means the number of habitat types.

2.3.4 Bathymetry

Bathymetry means the depth of the ocean and the sea bed, from the coastline to deeper sea area (Kumar et al. 2010). It is useful for all types of wave, hydrology, and flood modeling (Islam 2015; Kumar et al. 2012a). For the purpose of this study, the bathymetry map was acquired from the GEBCO. This raster input was used to find average water depths required for wave height, and period calculations and bathymetry values were negative in units’ meters. The raster covered the entire offshore, extending beyond the study area by at least the distance of the Maximum Fetch. All nondate and positive values are masked before calculating the average depth along a fetch ray. The ArcGIS 10.5 was used to create this raster map as an input in the CVI model (Fig. 3f).

2.3.5 Wind exposure

WAVEWATCH-III is a third wave model edition produced by NOAA/NCEP in the spirit of the WAM model (NOAA 2009). Model WAVEWATCH-III provides data that is used to calculate the wind and wave variables. The wind variable is an output that categorizes segments of the coastline by their relative exposure. This variable was calculated as Relative Exposure Index (REI) by taking the maximum of ten percent wind speed measurements from a long record, dividing the compass into sixteen equiangular sections, and matching the wind and fetch characteristics that were taken from an eight-years (2008-2016) compiled dataset from the WAVEWATCH-III model by using this equation:

\[
REI = \sum_{n=1}^{16} U_n P_n F_n
\]

\[ (4) \]

where: \( U_n \) means the average wind speed in meters per second of the ten percent maximum in the \( n^{th} \) equiangular section, \( P_n \) means the percentage of the wind speed at the record that blows in the direction of the \( n^{th} \) sector, \( F_n \) is fetch range (the distance at which the wind blows over the surface of the water), in meters, in the sector \( n^{th} \). The ArcGIS 10.5 was used to create this vector point map as an input in the CVI model.
2.3.6 Wave exposure

The coastal areas exposed to the open sea commonly suffer greater wave exposure than sheltered ones, due to the fact that winds blow from a considerable distance, generate more giant waves (NOAA 2009). It calculates relative vulnerability of a coastal point to $E_w$ wave, attributing to it the highest of the average weighted wave power of ocean, $E_w^o$ and locally generated wind waves, $E_w^l$:

$$E_w = \max(E_w^o, E_w^l)$$  \hspace{1cm} (5)

For ocean waves, the average weighted power was calculated as:

$$W_w^o = \prod_{k=1}^{16} H[F_k] P_k^o O_k^o$$  \hspace{1cm} (6)

Where $H[F_k]$ means a single function for all sixteen equiangular sectors of the Heaviside pitch $k$ wind. Then, $P_k^o O_k^o$ gets the average of the highest ten percent of the wave power index ($P_k^o$) that were seen in the angular section $k$ orientation, with the average of the time percentage ($O_k^o$) when such waves were seen in that section. For waves produced locally by the wind, $E_w^l$ was calculated as:

$$W_w^l = \prod_{k=1}^{16} H[F_k] P_k^l O_k^l$$  \hspace{1cm} (7)

Where $H[F_k]$ is the opposite of the definition in Equation (7), meaning $E_w^l$ that only accumulate along rays that do not reach max fetch distance, $E_w^l$ means the total out over the sixteen wind sectors of the wave power that was produced by averaging the ten percent highest $P_k^l$ values of wind speed propagating in the $k$ orientation, weighted by the occurrence percentage $O_k^l$ of these high wind in such sector. The locally generated power of the wind's wave was calculated by using Equation (6). The ArcGIS 10.5 was used to create this vector point map as an input in the CVI model.

2.3.7 Storm surge

The storm surge is the speed of wind and the distance over which the wind can blow over the shallow water (Hoque et al. 2018). The storm surge inundation is primarily causing great damage and losses of human life in coastal regions. In general, the greater the extent of continental shelf fronting a segment of coastline, the greater the potential for tide surge during the storm (Jennifer et al. 2011). This model calculates the relative storm exposure from the distance of the point on the shoreline to the continental shelf boundary. This polyline input describes the location of the continental margin or other bathymetric contours that are locally important. The ArcGIS 10.5 was used to create this polyline map as an input in the CVI model.

2.3.8 Sea-level rise

Rising of sea-levels are a serious threat to coastal environment and communities (Khan et al. 2020). The effects of sea level change are likely to get worse with changes in climate (Mills et al. 2020). To map our annual sea-level rise, the tide data from 2008 to 2020 were collected from the Hydrographic Institute of Portugal (Hidrografico.pt 2021).

Table 3 is fixed here.

In the procedure, millimeter conversion of the data was carried out, the averaged high tide values taken were sorted and calculated using the spreadsheet to generate the rate of sea-level rise rate in the NC-GB. For this input, the elevation raster dataset was used as a mask to and the estimated high tide (2.8m) and low tide (0.1m) were plotted in ArcGIS 10.5 using Map Algebra under Special Analyst of Arc Toolbox to create the inundation map (Fig. 3e). This raster dataset was then converted into a point vector as required by the model with numeric field values representing a sea-level rise metric as rate, net rise and fall. The relevant parameters were first screened and then...
mapped out from various sources of data using spatial analysis techniques. An example of six mapped parameters is shown in Fig. 3 including relief, coastal slope, coastal geomorphologies, natural habitats, coastal inundation and bathymetry.

Fig. 3 is fixed here.

2.4 CVI parameters ranking and calculation

The rankings were attributed on each alternative mapped parameters layer, thus giving the vulnerability scores of 1 to 5 (Nelson et al. 2016). A ranking of 1 indicates very-low vulnerability index, while a ranking 5 shows very-high exposure index. On the basis of the proposed methods by Gornitz et al. (1990); Hammar-Klose and Thieler (2001), we outlined the alternative vulnerability ranking under each parameter, considering the literatures and local knowledge of the study area (Table 5). The alternatives for each parameter were given according to their potential contribution increasing the vulnerability index. Thereafter, the CVI was then computed as the root square of the ranked parameters and divided by the total number of parameters using the equation "1" (Islama et al. 2016; Kumar et al. 2010). An equal weighting was applied to each parameter for the final CVI calculation. The CVI outputs were then categorized by employing the quantile option of ArcGIS 10.5 tool platform. The quantile classifying method is alleged to be both consistent and effective in displaying the result of CVI outputs (Naturalcapitalproject 2020).

Table 4 is fixed here.

2.5 Field observation

This study applied qualitative field observation methods to find out the most vulnerable area of coastal hazards. We carried out on-site field observations in March to May 2021 for the purpose of identifying the coastal natural habitats and geomorphologies and their state of degradation due to coastal hazards intensification. This field observations were considered to help in interpretation of satellite images for on-screen digitisation natural habitat and geomorphology parameters. The in-depth self-observations were undertaken at site-specific places of the study area by using photographer, GPS and ‘Olho de Papagaio’ a high-resolution aerial image device.

3 Results

3.1 CVI parameters and mapping

The CVI results and description of the selected eight parameters that impact the coastal structures of the study area are presented below. The study area was divided into three important zones based on their ecological characteristic. Each parameter was assigned to a ranking one to five according to the alternative classification scheme given in Table 5. In this study, the high and very-high Exposure Index was largely occurred in Zone-A and B with a CVI model result 3.89% and 3.20, respectively. The very-low EI was mostly noted in Zone-C with value of 1.30 and the moderate EI was both identified in Zone-A and C of our study area with value 2.50 (Fig. 4). Out of 87 km of the studied coastline, nearly 24 km corresponding (27.59%) registered very-high vulnerability index. This area covers almost the entire coastline of Zone-B (Fig. 4). 17 km (19.54%) showed a moderate vulnerability index, and the segments of very-low vulnerability lie in approximately 11 km (12.64%). These areas are found both in Zone-C and A.

Fig. 4 is fixed here.

Zone-B recorded the highest vulnerability index due to its highly exposure to wind and wave (Fig. 5). Low relief of the coastlines made zone-A more vulnerable to storm surge and sea-level rise, however, the coastal habitats found in these areas mainly mangroves, play very important role in protecting the coastlines from coastal hazards (Fig. 7). In contrast, the very-low vulnerability registered in Zone-C was due to high relief of this area associated with some coastal geomorphology structures and natural habitat such as flat rocky, low cliff, coastal forest and abundant sand dune (Fig. 8).
3.1.1 Relief

A higher elevation shoreline is at less risk of being flooded than a lower elevation shoreline. In this assessment, areas with ranking 1 were classified as very highly vulnerable area, while those of ranking 5 was categorized as very low vulnerable area. This result shows that the relief ranking is lower in Zone-A, indicating high vulnerability (Fig. 7a). Approximately 38 km of the coastlines (ranking 4 to 5), lie in low to very-low vulnerable areas. Nearly 22 km of the coastlines (ranking 3), shows the moderate vulnerability index, and about 27 km (ranking 1 to 2) lie in a very-high to highly vulnerable. The high and very-high vulnerability index registered in Zone-A are due to low elevation of the coast seen in Fig. 3a.

3.1.2 Geomorphology

Coastal geomorphology plays a key role in resistance against coastal hazards. The flat rocks, the low-lying cliff and estuary offer a moderate protection, and were ranked 2 to 3 in this study. However, low cliffs and flat rocky units were observed only in a small area of Zone-C, unlike estuary occupying almost two-thirds of all coastlines that are found largely in Zone-A. Sand beach provides less protection, and it was ranked 4, standing approximately 31 km, occupying above one-third of entire coastlines of Zone-B and C. In this analysis, the result showed that, nearly 43 km corresponding (49.43%) of the coastlines are under a high geomorphology protection, 39 km (44.83%) are under moderate geomorphology protection and only 05 km (4.35) are under low geomorphology protection. Very-low and very-high were not observed in our results (Fig. 7b).

3.1.3 Wind Exposure

This analysis shows the relative wind exposure in the coastline of our study area. We can see that almost the entire coastline is somehow exposed to high wind. Approximately 47 km of the coastlines, under ranking 4 to 5 lie in a high to very-highly vulnerable areas (Fig. 7c). Nearly 17 km (ranking 3), are found in moderate vulnerable areas. Around 23 km of coastlines (ranking 1 to 2), lie in a very-low to low vulnerable area. The high and very high wind exposure registered in Zone-B and C, were due to their high exposition to open Atlantic Ocean and inconsistent natural habitat in the shorelines. The low and very-low wind exposure registered in Zone-A, has to do with notable sheltered areas by the river Cacheu and mangrove ecosystem in the shoreline.

3.1.4 Wave Exposure

From this analysis, relative wave exposure on the coastlines of the study area is shown. We found that almost two third of the coastlines are highly exposed to wave. Nearly 47 km of the coastlines under ranking 4 to 5 lie in high to very-highly vulnerable areas (Fig. 7d). Roughly 24 km under ranking 3 were located in a moderate vulnerable area, and approximately 17 km of the coastlines under ranking 1 to 2 lie in a low and very-low vulnerable areas. The registered high and very-high vulnerability index in Zone-B and C, were due to their exposition to Atlantic Ocean and continental shelf. The low and very-low vulnerable areas found in Zone-A has to do with notable sheltered areas by the river Cacheu and estuary (Fig. 8).

3.1.5 Storm surge

In general, the greater the extent of the continental shelf fronting a section of coastline, the greater the potential for the surge to build up during a storm. This analysis reports that approximately 40 km corresponding (45.98%) of the coastlines under ranking 4 to 5, are in a high to very-highly vulnerable area (Fig. 7e). Nearly 16 km (18.39 %), under ranking 3, present moderate vulnerability index. 31 km (35.63 %), under rank 1 and 2 are in a low to very-low storm surge exposure. The high and very-high vulnerability registered in Zone-A were due to low elevation and slope of the coastlines (Fig. 3a-b). The registered low and very-low vulnerable areas were due to relatively high elevation of this coastline.

3.1.6 Sea-level rise

Changes in climate contribute to rising sea levels, making a terrible effect on the environment and coastal community. In this study, we made the first assessment of sea-level change in the NC-GB, recorded at the Cacheu
river tide station and found a significant change rate of 8.79 mm/year (Fig. 6). This rate of calculated change in sea-level is higher than the global predicted rate of sea-level change of 3.1 mm/year (Bhuiyan and Dutta 2012). Therefore, in this analysis, ranking 5 determines the areas with a very-high vulnerability to sea level rise, while rank 1 determines the areas with a very-low vulnerability. Approximately 41 km (47.13) under rank 4 to 5 lie in high to very-highly vulnerable areas (Fig. 7f). Nearly 18 km (20.69 %) under rank 3 are in moderate vulnerability index. 28 km (32.18 %) under rank 1 to 2 are in a low to very-low vulnerability index.

**Fig. 6 is fixed here.**

### 3.1.7 Habitat role

The coastline habitats play the key role in reducing effects of coastal hazards. They reduce the wave and wind currents force, stimulate the coastal banks to rise, and disperse wave power. In this study, the higher and lower scores showed the relative contribution of habitat in protecting the coastline. 0.49 to 0.61% represent high to very-high habitat contribution in protecting the coastline from coastal hazards, respectively. These areas are found in Zone-A, covering mostly mangrove that were ranked 1 in habitat Table 2. 0.40%, represent moderate habitat contribution in protecting the coastline occupying a small area of Zone-A and C. These areas are mostly covered with coastal forest which were ranked 2 in habitat Table 2. 0.32% to 0.16 represent the low to very-low habitat contribution. These areas cover Zone-A and B, they include mainly sand dunes, salt marsh and area with almost no coastal habitat that were ranked 4 and 5 in habitat table.

**Fig. 7 is fixed here.**

**Table 5 fixed here.**

### 3.2 Field observation

The qualitative method provides us with useful data to verify the vulnerability index in the NC-GB. Over ten sites were observed, but we only seven specifics were highlighted and we found similarities between CVI model results and field observations results. As shown in Fig. 8, the zone-A presented a high vulnerability index of surge and sea-level rise as confirmed in the image 3 and 7 of observed places. Our CVI results indicated that zone-B is highly vulnerable to wind and wave due to its exposition to open sea as confirmed in image 6. We also observed that, Zone-C is slightly vulnerable to coastal hazards due to its relatively high elevation supported by geomorphological structures as seen in image 4 and 5. Image 1 shows the coastal dune build up around Sucujaque community due to the coastal accretion generated by sea-level rise and storm surge. Our CVI model showed a relatively comparable vulnerability index.

**Fig. 8 is fixed here.**

### 4 Discussion

Naturally, this study builds on previous studies to assess CVI (Pendleton and Theiler 2005; Islama et al. 2016; Hoque et al. 2019; Shaji 2014); however, it is the first coastal vulnerability assessment covering a large part of the NC-GB that relates to coastal hazards. This index-based analysis has been applied in several coastal countries around the world to assess the vulnerability of the coastal regions to coastal hazards (Djouder and Boutiba 2017; Addo 2013). Coastal hazards are putting NC-GB at greater risk of damage. Traditional approaches to combat coastal erosion and inundation, such as seawalls and jetties, are often expensive to construct and maintain, especially in variable weather conditions (Harman et al. 2015). A growing body of evidence suggests that mangrove, coral reefs, coastal forests, saltmarsh and seagrass beds can buffer coastal waves and currents and retain sediment, providing protection for coastal communities and infrastructure, maintaining the benefits of coastal habitats for people and ecosystems. The potential role of ecosystems depends on a variety of factors, such as habitat and geomorphology types, magnitude of coastal hazard, shoreline type and elevation. Several of these factors also affect the suitability of an area for habitat restoration.
The deltaic coastlines with a low elevation and flat slope are seen more susceptible to coastal hazards mainly the sea-level rise, storm surge and wave action (Tripathi and Resmi 2018). NC-GB, contains the lowest coastal elevation of -10m below the sea-level rise which registered a change rate of 8.79mm/year, significantly higher than the globally predicted average of 3.1mm/year (Bhuiyan and Dutta 2012). Due sea-level rise and storm surge, the sand beach and dunes are transported to the coastal habitats placed at low elevations, obstacle the fertilization of the land and the spread of seeds, and this sediment transport route system relies heavily on wind and wave activity that largely occurred in the Zone-B of our study area. Storm surge is a function of wind speed and direction, and also the distance over which wind blows across shallow water. Guinea-Bissau contains ones of the largest continental shelf in West Africa extending to 39,339 km², allowing the generation of wind speed above 35km/h (seatemperatureinfo 2021). In general, the greater the extent of the continental shelf fronting a section of coastline, the greater the potential for surge to build up during a storm (Jennifer et al. 2011). The NC-GB is potentially influenced by southwesterly monsoonal winds as well as waves (Hidrografico.pt 2021). The sediments from various sources are circulated and resettled by hydrodynamic processes based on wind and wave directions. This has led to a gradual increase in coastal erosion mostly in the cliff lands and coastal accretion in the flat slope areas, consequently increasing the vulnerability of the coastlines. The geomorphological and habitat diversity inherent to this coast also explains coastal variations, as it favors local accumulation in certain areas, resulting in famine in other areas, as seen in Zones-B and C of our study area, where the habitat and geomorphological structures are weak. Another element that promotes this coastal vulnerability is the degree of human implication in the coastal land transformation, contributing in greater extent of sediments supply after deforestation. Human pressures on the coastal plain have resulted in the removal of mangroves, conversion of wetlands and coastal forests to large-scale of cultivation areas, putting the shorelines in a serious vulnerability situation (del-Toro and López 2019). These situations also prevented the formation of barriers on the beach crest that could trap sediment. Significant coastal dunes and beach crest plains characterize these sandy shores, as largely found in Zones-C of study area.

In this study, we observed that poor coastal management combined by the socio-economic situation and lack of proper coastal structures to protect the coastlines, could significantly increase the vulnerability. Although, it is important to highlight that, the conservation activities carried out in these coastal areas by several governmental and non-governmental organizations (IUNC 2018) have contributed to the gradual restoration of wetlands, fundamentally allowing for the significant growth of the mangrove ecosystem, highly observed in Zone-A of our study area. In the early 2000s, five natural parks and protected areas, covering a total area of around 5000 km², were created in Guinea-Bissau, including the Natural Park of Tarrafes de Rio Cacheu (PNTC), which was established in 2000 under Decree law 12/2000. The PNTC management is currently under the authority of a council, the Board of Park Management, composed of park leaders, local representatives, State and government representatives from the Institute for Biodiversity and Protected Areas (IBAP), created in 2004 as the national unit responsible for managing the protected areas network, as well as other stakeholders working in the field (NGOs, associations, etc.). Despite the extraordinary efforts of these organizations, the coastlines of NC-GB continue to suffer from coastal hazards as confirmed by the results of CVI model associated with our field observation findings. Based on these findings, it is clear that coastal vulnerability in the NC-GB, could increase with this global climate change dynamics, therefore deep conservation is required in this coastal country to minimize the impact of coastal hazards.

5 Conclusion

In this study, we comprehensively elaborate a Coastal Vulnerability Index to coastal hazards by integrating biological parameters such as sand dune (new integrated parameter), mangrove, salt marsh, coastal forest; geomorphology parameters such as rocky, sandy beach (new integrated parameter), estuary and cliff; and physical parameters such as relief, bathymetry, wind, wave, storm surge and sea-level rise. For the first-time, we establish rate of sea-level rise in our study area, considering the coastline of approximately 87 km long and determine the role of coastal habitat in protecting the shoreline from coastal hazards. For these assessments we employed both GIS spatial datasets and CVI of InVEST model, and we found a considerable coastal vulnerability index in the NC-GB,
motivated mainly by sea-level rise, storm surge, wind and wave exposure. The main reasons for high vulnerability index registered in were due to the high wind and wave exposure, as this coastline is highly exposed to open sea. The other reasons were the storm surge and sea-level that rises 8.79/year, due to low coastal relief and flat slope, associated with inconsistent coastal habitats in the shorelines. The Zone-A, shows to be more resilient than Zone-B and C, due to the largely mangrove ecosystem that play very important role in protecting shoreline from coastal hazards. The Zone-B and C, deserves special attention from the conservation bodies and coastal community.

These findings, will assist policy makers or coastal managers in defining strategies that aimed to minimize the coastal vulnerability and help in developing a pro-active adaptation plans for the safeguard of the coastal community and ecological environment from destructive coastal hazards. The present study can also provide a scientific basis and practical reference for sustainable coastal management and guidance for ecological conservation in several coastal countries. For example, Senegal and Gambia located in the north of Guinea-Bissau, which contain very important marine conservation areas such as, Saloum Delta Biosphere Reserve (Senegal) and Tanbi Wetlands National Park (Gambia), all classified as RAMSAR site, like Natural Park of Tarrafes de Rio Cacheu in our study area (USAID and BA NAFAA 2012). As well Guinea, located in the south of Guinea-Bissau that comprises large river estuaries in “Lower Guinea” (UNDP 2019); and Sierra-Leone, that comprises four primary mangrove ecosystem regions such as, Scarcies River Estuary, the Sierra Leone River Estuary, Yawri Bay and Sherbro River Estuary (Trzaska et al. 2018). All these countries presented almost the same coastal landform characteristics, relatively low spatial elevation and vulnerability patterns. They are all exposed to the Atlantic Ocean and their ecosystem and biodiversity are highly threatened by coastal hazards, mainly the wind and wave, sea-level rise and storm surge. These coastal zones require special attention for better conservation by referencing our findings. We believe that these findings may be of interest to the readers concerned about coastal vulnerability studies which involved multi-parameters for multi-hazards assessment index.

5.1 Recommendations for coastal management

The recommended management strategies to protect the NC-GB based on the current CVI result are summarized in Table 6. For management recommendation, the study area is divided into three zones (Fig. 4) according to their specified vulnerability index situation. The detailed for coastal management is highlighted below:

1. **Zone-A**: the coastlines are very vulnerable to sea-level rise and storm surges. Coastal inundation and saltwater intrusion are frequent on these coastlines due to very low elevations and flat slope. Implementing set-back zones through dike construction can prevent coastal inundation (Harman et al. 2015). Buffers can be created alongside tidal channels, which can resist saltwater to intrude the agricultural and community’s lands.

2. **Zone-B**: these shorelines are widely exposed to sea and highly vulnerable to wind and wave exposure, due to low spatial elevation associated with lack of consistent habitats and geomorphologies in the shorelines (Fig. 7a-b). Promoting natural habitat conservation, mangroves restoration and native wood forests plantation, can reduce excessive wind speed (Harman et al. 2015). As well as implementing soft technology such as sand fences, dikes or polders can be an efficient step to provide protection of this area by reducing the strength of wave exposure.

3. **Zone-C**: these coastlines are comprised of a long natural beach of about 15 km, and it is relatively vulnerable to storm surge and wave exposure. Coastal erosion is highly observed on this coastline due to the stand cliffs and also the coastal accretion due to flat slope. The construction of sea walls or geotextile bags filled with sand beach can help prevent coastal erosion or accretion build by storm surge and wave exposure (Harman et al. 2015). Since Zone-C is a site of tourist interest, we observed several downfalls and unplanned infrastructures alongside coastlines. Such kinds of constructions pose significant threats to coastal ecosystems; therefore, the National authorities together with coastal managers should take proactive actions and policies to discourage such kind of constructions for the benefit of the nature.

Table 6 is fixed here.
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Authors contributions First author, Namir D. R. Lopes developed ideas, formulated the research aims, design the methodology, analyzed the results and writing the manuscript. Tianxin Li, and Rui M. Sa, equally contributed in planning of the research, reviewing the manuscript and provided helpful comments and suggestions. Nametso Matomela, contributed in language correction and data interpretation. All authors have agreed with submission of this manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Abuodha PAO, Woodroffe CD (2010) Assessing vulnerability to sea-level rise using a coastal sensitivity index: A case study from southeast Australia. Journal of Coastal Conservation 14: 189–205. doi.org/10.1007/s11852-010-0097-0

Addo K (2013) Assessing Coastal Vulnerability Index to Climate Change: the Case of Accra – Ghana. Journal of Coastal Research 165: 1892–1897. doi.org/10.2112/si65-320.1

Ahammed KKB, Pandey AC (2019) Geoinformatics based assessment of coastal multi-hazard vulnerability along the East Coast of India. Spatial Information Research 27: 295–307. doi.org/10.1007/s41324-018-00236-y

Bagdanavičiūtė I, Kelpšaitė L, Smeoore T (2015) Multi-criteria evaluation approach to coastal vulnerability index development in micro-tidal low-lying areas. Ocean and Coastal Management 104: 124–135. doi.org/10.1016/j.ocecoaman.2014.12.011

Berman M, Baztan J, Kofinas G, Vanderlinden JP, Chouinard O, Huctin JM, Kane A, Mazé C, Nikulkina I, Thomson K (2020) Adaptation to climate change in coastal communities: findings from seven sites on four continents. Climatic Change 159: 1–16. doi.org/10.1007/s10584-019-02571-x

Bhuiyan Md. JAN, Dutta D (2012) Analysis of flood vulnerability and assessment of the impacts in coastal zones of Bangladesh due to potential sea-level rise. Natural Hazards 61: 729–743. doi.org/10.1007/s11069-011-0059-3

Boruff† BJ, Emrich† C (2005) Erosion Hazard Vulnerability of US Coastal Counties. Journal of Coastal Research 215: 932–942. doi.org/10.2112/04-0172.1

Calil J, Reguero B, Zamora A, Losada I, Méndez F (2017) Comparative Coastal Risk Index (CCRI): A multidisciplinary risk index for Latin America and the Caribbean. PLOS ONE, 12: e0187011. doi.org/10.1371/journal.pone.0187011

De Faria ML, Ferreira PM, Melo JB, Vasconcelos MJ (2014) A social assessment of forest degradation in the “Cacheu Mangroves Natural Park”, Guinea-Bissau. Forests 5: 3327–3343. doi.org/10.3390/f5123327

del Toro EMG, López MIM (2019) Changes in land cover in cacheu river mangroves natural park, guinea-bissau: The need for a more sustainable management. Sustainability (Switzerland) 11: doi.org/10.3390/su11226247

Denner K, Phillips MR, Jenkins RE, Thomas T (2015) A coastal vulnerability and environmental risk assessment of Loughor Estuary, South Wales. Ocean and Coastal Management 116: 478–490. doi.org/10.1016/j.ocecoaman.2015.09.002

DIVA-GIS (2021) Select and download free geographic (GIS) data for any country in the world. Diva-Gis.Org. https://www.diva-gis.org/gdata. Accessed 13 June 2021.
Djouder F, Boutiba M (2017) Vulnerability assessment of coastal areas to sea level rise from the physical and socioeconomic parameters: case of the Gulf Coast of Bejaia, Algeria. Arabian Journal of Geosciences 10: 1–20. doi.org/10.1007/s12517-017-3062-5

Fandé L (2018) Quantificação e mapeamento da extensão de inundação costeira em Bissau, Guiné-Bissau: perspetiva em cenário de alterações climáticas | Publication details | BIBLIOS - Ciências ULisboa. Ciências References Management System, 2. https://biblios.ciencias.ulisboa.pt/detalhes/41166

Frumkin H (2018) The US Health Care Sector’s Carbon Footprint: Stomping or Treading Lightly? American Journal of Public Health 108: S56–S57. doi.org/10.2105/AJPH.2017.304160

Gallina V, Torresan S, Critto A, Sperotto A, Glade T, Marcomini A (2016) A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. Journal of Environmental Management 168: 123–132. doi.org/10.1016/j.jenvman.2015.11.011

Ghoussein Y, Mhawej M, Jaffal A, Fadel A, El-Hourany R, Faour G (2018) Vulnerability assessment of the South-Lebanese coast: A GIS-based approach. Ocean and Coastal Management 158: 56–63. doi.org/10.1016/j.ocecoaman.2018.03.028

González B. A, Covarrubias OA (2018) Vulnerability assessment for supporting sustainable coastal city development: a case study of La Paz, Mexico. Climate and Development 10: 552–565. doi.org/10.1080/17565529.2017.1291406

Gornitz DW (1994) A coastal hazards data base for the US Gulf Coast. United States doi.org/10.2172/10164054

Gornitz V (1990) Vulnerability of the East Coast, U.S.A. to future sea level rise. Journal of Coastal Research 9: 201–237. https://www.jstor.org/stable/44868636

Guerra ACY, Botero CM, Arrizabalaga M, Vásquez JG (2019) Methodological proposal for ecological risk assessment of the coastal zone of Antioquia, Colombia. Ecological Engineering 130: 242–251. doi.org/10.1016/j.ecoleng.2017.12.010

Hamid AI, Din A, Yusof AHM, Abdullah N, Omar NM, Khanan AH, Abdul MF (2019) Coastal Vulnerability Index Development: a Review. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives 42: 229–235. doi.org/10.5194/isprs-archives-XLII-4-W16-229-2019

Hammar-Klose ES, Thieler ER (2001) Coastal vulnerability to sea-level rise. A Preliminary Database for the U.S. Atlantic, Pacific, and Gulf of Mexico Coasts. U.S. Geological Survey Digital Data Series 68. doi.org/10.3133/ds68

Harman B, Heyenga S, Taylor BM, Fletcher CS (2015) Global Lessons for Adapting Coastal Communities to Protect against Storm Surge Inundation. Journal of Coastal Research 31: 790–801. doi.org/10.2112/JCOASTRES-D-13-00095.1

Hereher ME (2015) Coastal vulnerability assessment for Egypt’s Mediterranean coast. Geomatics, Natural Hazards and Risk 6: 342–355. doi.org/10.1080/19475705.2013.845115

Hidrografico.pt. (2021) Previsão da Altura da Maré. Hidrografico Marinha Portugal. https://www.hidrografico.pt/m.mare. Accessed 12 June 2020.

Hoque MA, Ahmed N, Pradhan B, Roy S (2019) Assessment of coastal vulnerability to multi-hazardous events using geospatial techniques along the eastern coast of Bangladesh. Ocean and Coastal Management 181: 104898. doi.org/10.1016/j.ocecoaman.2019.104898

Hoque MA, Phinn S, Roelfsema C, Childs I (2018) Assessing tropical cyclone risks using geospatial techniques.
Murali RM, Ankita M, Amrita S, Vethamony P (2013) Coastal vulnerability assessment of Puducherry coast, India, using the analytical hierarchical process. Natural Hazards and Earth System Sciences 13: 3291–3311. doi.org/10.5194/nhe ss-13-3291-2013

Muralia RM, Kumar PKD (2015) Implications of sea level rise scenarios on land use /land cover classes of the coastal zones of Cochin, India. Journal of Environmental Management 148: 1–10. doi.org/10.1016/j.jenvman.2014.06.010

Naturalcapitalproject (2020) Habitat Quality of InVEST model. Stanford University. https://naturalcapitalproject.stanford.edu/. Accessed 11 July 2020.

NOAA (2009) User Manual and System Documentation of WAVEWATCH-IIITM Version 3.14. Technical Note. https://polar.ncep.noaa.gov/waves/ensemble/download.shtml. Accessed 10 July 2020

O’Neill BC, Tebald C, Van-Vuuren DP, Eyring V, Friedlingstein P, Hurrey G, Knutti R, Kriegler E, Lamarque JF, Lowe J, Meehl GA, Moss R, Riahi K, Sanderson BM (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geoscientific Model Development 9: 3461–3482. doi.org/10.5194/gmd-9-3461-2016

Pendleton EA, Theiler ER, Williams SJ (2005) Coastal vulnerability assessment of Cape Hatteras National Seashore (CAHA) to sea-level rise. In Open-File Report. doi.org/10.3133/OFR20041064

Pethick J, Orford JD (2013) Rapid rise in effective sea-level in southwest Bangladesh: Its causes and contemporary rates. Global and Planetary Change 111: 237–245. doi.org/10.1016/j.gloplacha.2013.09.019

Rani NNVS, Satyanarayana ANV, Bhaskaran PK (2015) Coastal vulnerability assessment studies over India: a review. Natural Hazards 77: 405–428. doi.org/10.1007/s11069-015-1597-x

Sahoo B, Bhaskaran PK (2018) Multi-hazard risk assessment of coastal vulnerability from tropical cyclones – A GIS based approach for the Odisha coast. Journal of Environmental Management 206: 1166–1178. doi.org/10.1016/j.jenvman.2017.10.075

Sajjad M, Chan JCL, Lin N (2020) 18 - Modeling of coastal vulnerability to sea-level rise and shoreline erosion using modified CVI model. Environmental Science and Policy 106: 99–110. doi.org/10.1016/j.envsci.2020.01.004

Seatemperatureinfo (2021) Surf Forecast for Bissau. Sea Temperature Info. https://seatemperature.info/bissau-waves-forecast.html. Accessed 13 March 2021.

Shaji J (2014) Coastal sensitivity assessment for Thiruvananthapuram, west coast of India. Natural Hazards 73: 1369–1392. doi.org/10.1007/s11069-014-1139-y
Sintra (2016) Cooperação e Intercâmbio amigável de Sintra com Cacheu. Cm-Sintra.Pt. https://cm-sintra.pt/nomundo/relacoes-internacionais/cooperacao-e-intercambio-amigavel/cacheu. Accessed 12 June 2020.

Szlafsztein C, Sterr H (2007) A GIS-based vulnerability assessment of coastal natural hazards, state of Pará, Brazil. Journal of Coastal Conservation 11: 53–66. doi.org/10.1007/s11852-007-0003-6

Thakur S, Mondal I, Bar S, Nandia S, Ghosh PB, Das P, De TK (2021) Shoreline changes and its impact on the mangrove ecosystems of some islands of Indian Sundarbans, North-East coast of India. Journal of Cleaner Production 284: 124-764. doi.org/10.1016/j.jclepro.2020.124764

Tripathi S, Resmi KS, Baraik S (2018) Substantial land subsidence and its impact on Kalinagar, Sundarban Delta, West Bengal. Indian Journal of Geosciences 71: 589–598. file:///C:/Users/Lopes/Downloads/Documents/Paper4-IJGVol714.pdf

Trzaska S, de Sherbinin A, Kim-Blanco P, Mara V, Schnarr E, Jaiteh M, Mondal P (2018) Climate Change Vulnerability Assessment in Mangrove regions of Sierra Leone. http://www.ciesin.columbia.edu/wabice/SierraLeone_Coastal_VA_long-report_jan2018.pdf

UNDP (2019) Enhancing the Resilience of Guinea’s Coastal Rural Communities to Coastal Erosion Due to Climate Change. https://www.greenclimate.fund/sites/default/files/document/21890-enhancing-resilience-guinea-s-coastal-rural-communities-coastal-erosion-due-climate-change.pdf. Accessed 12 November 2021.

UNEP-WCMC.org. (2020) Ocean Data Viewer. United Nations Environment Programme - WCMC. https://data.unep-wcmc.org/. Accessed 12 June 2020.

USAID, BA NAFAA (2012) Vulnerability Assessment of Central Coastal Senegal (Saloum) and the Gambia Marine Coast and Estuary to Climate Change Induced Effects. https://www.crc.uri.edu/download/Climate_Change_VA_CR.pdf. Accessed 12 June 2021

USGS (2020) Science for Changing the World. https://earthexplorer.usgs.gov/. Accessed 10 July 2020.

**Ethical Statements**

Hereby, I Namir Domingos Raimundo Lopes, consciously assure that for the manuscript Coastal Vulnerability Assessment Based on Multi-Hazardous Events. Case study: Northwestern Coastline of Guinea-Bissau (NC-GB) the following is fulfilled:

1. This manuscript is the authors’ own original work, which has not been previously published elsewhere.

2. The paper is not currently being considered for publication elsewhere.

3. The manuscript reflects the authors' own research and analysis in a truthful and complete manner.

4. The paper properly credits the meaningful contributions of co-authors.

5. The results are appropriately placed in the context of prior and existing research.

6. All sources used are properly disclosed (correct citation).

7. All authors have been personally and actively involved in substantial work leading to the manuscript, and will take public responsibility for its content.

I declare that this submission follows the recommendations outlined in the Authors Submission guidelines and in the Ethical Responsibilities of Authors.
**Figures**

**Figure 1**

a) Location of the study area based on the world street map. b) The Northwestern Coastline of Guinea-Bissau divided in Zone-A, Zone-B and Zone-C, classified in eight land cover types using Landsat 15-meter resolution from 01/01/2020 and 01/02/2020.

**Figure 2**

The flow diagram of the coastal vulnerability approach used in this research.

**Figure 3**

Six bio-geophysical parameters maps: a) Elevation, b) Coastal slope, c) Geomorphology, d) Natural habitat, e) Coastal flood and f) Bathymetry.

**Figure 4**
Exposure Index values in the zone-A, B and C along the study area, defining very high to very low vulnerability index.

**Figure 5**

Exposure index’s variation of physical parameters in the Northwestern Coastline Guinea-Bissau. Wind, sea-level rise, storm surge and wave with higher exposure index in the study area.

**Figure 6**

Sea level rate in millimeter based on tide gauges of Cacheu Region port considered the reference years 2008 to 2020.

**Figure 7**

Coastal Vulnerability Index rankings in the Northwestern Coastline of Guinea-Bissau a) relief; b) Geomorphology; c) wind; d) wave; e) storm surge; f) sea-level rise and g) the habitat role.

**Figure 8**

Field observation sites in the study area. Image-1: Coastal dune formed by the accelerated accretion; Image-2: Coastal infrastructure degradation in Nhiquim shoreline; Image-3: Sea-level rise in Jobel community; Image-4: coastal elevation in Varela shoreline; Image-5: Flat rocky structure in Varela shoreline; Image-6: Cultivation and mangrove land in Igim community; Image-7: Landscape and sea-level in Bolol community.

**Supplementary Files**

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