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Research article

Coastal dynamics and risk assessment in the Gambia

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Abstract: West African coasts are experiencing a significant retreat on average, albeit highly variable according to sections. Shoreline changes were analyzed in ten sections along the Gambian coast between 2011 and 2023. The results indicated a predominant retreat, ranging from 1.27 to 4.51 m per year, with the most severe retreat occurring in the northern part of the country. However, localized accretion zones were also detected, where the coastline has expanded by 0.54 m per year. Coastal vulnerability is linked not only to the intensity of erosive processes but also to the degree of urbanization. In areas with severe retreat but limited construction, sea advance forms new beaches inland, but in developed areas, it leads to the destruction of infrastructure and buildings, causing major social impacts. Coastal planning must be adjusted to accommodate the future evolution of the shoreline, enabling beaches to shift inland. While this may result in land loss, it will enable the preservation of beaches, a vital tourism resource for Gambia's economy.

Keywords: climate change; coastal retreat; coastal erosion; coastal hazard; coastal vulnerability

1. Introduction

Coastal erosion is a natural process, but it has been unusually intensified in many regions of the world, with the sea advancing further inland at a faster rate in recent decades. In some areas, coastal changes appear to be due to human activities, such as mining or coastal defenses, which disrupt the movement of sand along the shores. Nevertheless, on a global scale, the primary cause seems to be sea level rise, associated with climate change [1,2]. Globally, 24% of beaches are eroding, 28% are accreting, and 48% remain stable [3]. Africa is one of the few continents with net erosion, showing an average rate of –0.07 m/year, although in many areas of the continent, these values are widely exceeded, as occurs in North Africa [4] or in West Africa, with values ranging from +7.68 to –6.67 in Senegal [5–10], –4.57 to –7.24 in The Gambia [11], –0.85 to –1.24 in Ghana [12–13], +15.00 to –12.00 in Togo [14–15] or –10.45 in Benin [16]. Data show a sea level rise in West Africa ranging from 1.5 to 3.3 mm/year [17–21], which could rise to 8 mm/year by 2100 [22], resulting in total increases between 36 and 86 cm, depending on the scenarios considered [19,23,24]. Human activities influence coastal erosion, but it is also intense in areas where they are absent [14]. Some areas experience accretion [9,11,15], although these are a minority, and do not offset the general regressive trend. The coastal dynamics in the area vary greatly, even between nearby sections. Understanding this variability is crucial when developing adaptation strategies.

Coastal vulnerability refers to the susceptibility of physical, social, and economic components to impacts such as sea-level rise, storms, or erosion [25]. Vulnerability largely depends on resilience, that is, the ability to adapt to new conditions, which is strongly influenced by naturalness and development levels. In natural environments, the landward movement of the coastline results in a gradual transformation of the coastal ecosystem. However, in urbanized areas, this creates conflict due to the destruction of infrastructure and the inability to modify the natural system. Current approaches to vulnerability assessment employ multidisciplinary tools combining remote sensing, geographic information systems, and multi-criteria decision analysis, facilitating the identification and weighting of factors that determine the sensitivity and exposure of coastal areas [26–29]. Methods such as the Analytical Hierarchy Process and the Best–Worst Method enable assigning weights to vulnerability indicators [30]. Integrated indices combining physical and socioeconomic aspects may be confusing, so applying indices that separate environmental and social dimensions is encouraged, enabling more rigorous analysis and the implementation of coastal management strategies that respond to local particularities [25–28].

Coastal vulnerability indices have limitations, including the mixing of hazard and vulnerability variables and a reliance on subjective weightings, which hinder the comparability and objectivity of results [28,31]. Risk assessment in coastal zones requires considering the hazard and the vulnerability of exposed systems. The application of advanced technologies in data acquisition and analysis enables significant progress in enhancing coastal risk studies. Tools such as drones, LiDAR sensors, and space geodetic technologies provide high-quality data that facilitate continuous monitoring of coastal zones [31,32]; however, these technologies are not always available.

Coastal dynamics vary significantly over time and space, requiring the study and frequent monitoring of numerous points along the coastline to enable effective management and timely decision-making regarding adaptation to coastal risks. Consequently, assessment models must be reliable, accurate, user-friendly, and feasible for implementation in regions with limited access to advanced technology. In this study, we address these challenges by presenting an integrated analysis of shoreline dynamics, social and environmental vulnerability, and coastal risk along the coastline of The Gambia. The aim is to provide practical tools to support robust climate change adaptation strategies and informed decision-making in coastal management.

2. Materials and methods

2.1. Study area

The coastline of The Gambia was divided into sections separated by geographical barriers. At least one study stretch was selected within each section to determine the evolution of the coastline (Table 1, Figure 1). The aim was not to provide an exhaustive assessment of every shoreline segment, but to apply and test a replicable methodology while capturing representative examples of the diversity and variability of coastal dynamics across the country. These stretches were in areas without human intervention affecting coastal dynamics (e.g., groins and sand mining), and with a visible erosion scarp. The total length of the Gambian coastline is 89,064 m, and 11,114 m have been surveyed, representing a sample of 12.5% of the total.

Table 1. Studied sections.

Coastal sections of the country			Coastal stretches studied		
Section		Length	Beach	Length	Limits
1	Senegal border–Barra (Nuimi Nat. Park)	12526 m	Kayik	1082 m	13.580, −16.542/13.572, −16.556
2	Barra–Banjul (Gambia River)	4663 m	Banjul	463 m	13.459, −16.575/13.461, −16.578
3	Banjul–Bakau (Tanbi Wetland Nat. Park)	11583 m	Tanbi West	668 m	13.476, −16.647/13.474, −16.653
4	Bakau–Fajara	7889 m	Fajara	400 m	13.469, −16.700/13.472, −16.699
5	Kololi–Ghanatown	11722 m	Kololi (5a)	210 m	13.469, −16.700/13.406, −16.748
			Bijilo (5b)	1079 m	13.447, −16.724/13.449, −16.724
			Brufut (5c)	604 m	13.402, −16.751/13.449, −16.724
6	Tanji	5505 m	Tanji	416 m	13.346, −16.804/13.349, −16.802
7	Batokunku	7397 m	Batokunku	1661 m	13.312, −16.803/13.326, −16.805
8	Sanyang–Gunjur	14158 m	Sambuyang	1394 m	13.223, −16.783/13.210, −16.783
9	Gunjur Madina–Kartong	10335 m	Kartong	2460 m	13.106, −16.767/13.128, −16.768
10	Kartong–Senegal border (Halahin River)	3286 m	Halahin	677 m	13.071, −16.752/13.066, −16.749

2.2. Coastline change

To determine the coastline change, the erosive scarp was used, a methodology applied in Senegal [8], which is robust and reliable. The erosion scarp delineates the erosive line of the sea as it advances inland (Figure 2) and is identifiable on high-resolution orthophotos, enabling precise delimitation at a specific date. Unlike tidal fluctuations, the erosion scarp delineates the area where the sea is actively excavating than simply indicating the extent of a tide. Furthermore, it is not influenced by variations in vegetation cover, which are strongly determined by human action. One limitation of this method is that it is applicable to beaches with a certain degree of naturalness, but not in anthropized areas, where human action obscures the scarp, rendering it unrecognizable. For adequate assessment of such anthropized areas, this methodology should be combined with other measurement methods such as the placement of stakes or fixed markers to monitor shoreline change.

Figure 1. Location of studied coastal stretches.

Figure 2. Kartong Beach (coastal section 9), showing the erosion scarp.

To analyze the evolution of the coastline, orthophotos were selected that met two requirements: High resolution to enable precise delineation of the coastal scarp, and a consistent time interval between the images. The selected orthophotos were from 2011, 2017, and 2023, encompassing 12 years, including two six-year periods.

The delineation of the coastal scarp was carried out using a Geographical Information System (GIS), generating a layer for each year. By geoprocessing these layers, new ones were obtained, showing the coastline change, whether retreat or accretion, between 2011 and 2017, and between 2017 and 2023. Considering the length of the coastal stretch, and the decreased or increased area, the average coastline change in these periods was calculated.

2.3. Coastal vulnerability

To assess coastal vulnerability, a land buffer extending 200 m inland from the 2023 coastline was considered. This value corresponds to an average retreat of 2.5 to 3 m per year over the 21st century, up to 2100. This is consistent with results obtained in the region, as cited in the discussion, and is identical to or within the range used by other authors [33,34]. Coastal vulnerability integrates multiple dimensions [33,35]. In this study, vulnerability is approached from a social-ecological perspective [36,37], considering two complementary dimensions:

Social vulnerability. This dimension addresses the exposure and sensitivity of people and economic activities to coastal hazards. It was assessed by calculating the proportion of land within the buffer occupied by human uses, including urbanized areas, transport and industrial infrastructure, mining sites, and agricultural land. Areas with high population density, valuable assets, or productive croplands are at greater risk of direct damage and livelihood disruption [38,39].

Environmental vulnerability. This dimension considers the susceptibility of natural coastal ecosystems, which provide crucial services such as shoreline stabilization, flood buffering, and habitat provision. The proportion of land covered by sensitive ecosystems, such as wetlands, mangroves, dunes, and coastal forests, was used as an indicator. These habitats act as natural buffers but are highly threatened by erosion and sea-level rise [40,41].

Social and environmental vulnerability are essentially opposed, since a given area may have urban or productive uses, or environmental values, but rarely both at the same time, as human activities generate multiple environmental pressures [42]. They are not strictly opposites, because some areas do not have any particular social, productive, or environmental value.

This model carries out a simplified assessment of environmental and social vulnerability, enabling the rapid detection of potential significant environmental and social risks. Nevertheless, in risk areas, more detailed studies may be required, considering additional variables such as the uniqueness of flora or fauna, or the likelihood and severity of social issues such as community disruption, human rights violations, or reputational damage. The model is scalable, making it possible to identify the areas at greatest risk, so that more detailed and targeted evaluations can be undertaken.

A recent study in West Africa assessed coastal vulnerability by combining geophysical and socioeconomic variables, but concluded that socioeconomic factors, especially high population growth and unsustainable human development, play the most significant role [43]. Similarly, in Côte d'Ivoire, a vulnerability index was calculated, largely determined by geomorphology, wave energy, coastal population density, and land use [44]. In our study, geomorphological aspects and wave energy were not considered under vulnerability but under hazard, as they are related to coastal dynamics, that is, shoreline retreat or accretion. Vulnerability here focuses on assessing the potential consequences of a hazard occurring [35], in this case coastal retreat. We chose to analyze social and environmental vulnerability separately than as an integrated index, as this enables a more objective understanding of the specific issues in each area, which could otherwise be masked if both criteria were combined, since they are often nearly opposite and could cancel each other out.

2.4. Risk determination

The risk (*R*) was determined as the product of hazard (*H*), the coastal retreat, which defines the probability of occurrence, and vulnerability (*V*), which estimates the potential consequences of a hazard occurring, that is, the potential damage caused [45–47]. In a more elaborate approach, risk is considered to be the product of *H*, *V*, and exposure (*E*); *E* refers to the elements in the area where a hazardous phenomenon may occur, in this case, coastal retreat, while *V* is the propensity of those exposed elements to suffer damage. This work has a clear practical orientation, putting forward a solid and reliable yet easily replicable methodology that enables continuous assessment over time. For this reason, a simplified formulation was adopted, in which *E* and *V* were combined into a single factor. In this case, the values present in the area of potential impact (*E*), both environmental and social, were taken into account, insofar as they were particularly prone to being affected (*V*), so both aspects were considered, simplifying the model without losing rigour.

The hazard indicator is unique, but there are two separate indicators for vulnerability, social, and environmental. As noted, these are calculated independently and not integrated, in order to enable a more objective assessment of the specific issues in each area, without the risk of one criterion masking the other. Consequently, two risk values were also defined, social and environmental, depending on the vulnerability criterion applied. It was considered more appropriate to use these two indicators and handle them thoughtfully within a multi-criteria analysis than deriving a single risk indicator that might not be suitable for the changing reality of each coastal section.

Indicators of risk, hazard (*H)*, and vulnerability (*V)* were defined on a scale from 0 to 10, grouped into five classes, as usual in risk assessment [47,48]: Very low, low, medium, high, and very high. These indicators do not follow a linear scale but an asymptotic one, meaning they increase more sharply at first, especially in hazard. This better reflects how risk behaves in reality, where small changes at lower levels can lead to significant impacts. To model this nonlinear and saturating behavior, an arctangent-based transformation function was chosen because of its smooth, bounded, and monotonic nature naturally limits values within a finite range, providing gradual saturation appropriate for hazard and vulnerability indicators that asymptotically approach maximum levels instead of growing indefinitely (eq. 1):

$$H \text{ or } V = \pm a \cdot \text{atan}\,(0.85\,x) \tag{1}$$

where a is an empirical coefficient adjusted so that the maximum value of H or V reaches 10, and the independent variable (x) represents the annual coastal retreat (m/year) in the case of the hazard (H), or the proportion of the area occupied by land with social interest (built-up areas, crops, industries, mines) or environmental value (mangroves, wetlands, forested areas) in the case of the vulnerability (V). Coastline changes can be positive (accretion) or negative (retreat); accretion implies no risk, as no environmental or social values will be affected, so in these cases, H is set to 0. This transcendental function is applied because its monotonically increasing behavior has a maximum initial slope that gradually decreases and approaches asymptotic limits, enabling a realistic modeling of the behavior of hazard, vulnerability, and risk.

The risk (R) is calculated as the square root of the product of the hazard (H) and the vulnerability (V), so that it will also have a value ranging from 0 to 10. However, this general formulation assigns equal weight to H and V, which is quite rigid and does not always reflect reality. Therefore, a formulation is proposed that enables assigning differentiated weights to each factor, providing greater capacity to reflect their relative contributions to risk and enabling sensitivity analysis under different assumptions [48]. As a result, risk (R) is calculated as the (a + b) root of the product of hazard (H) raised to the power of a and vulnerability (V) raised to the power of b (eq. 2)

$$R = \sqrt[(a+b)]{H^a \cdot V^b} \tag{2}$$

where the exponents a and b enable adjusting the relative weight of each factor. The (a + b) root balances the combined effect so that the final risk value remains within a comparable scale.

To explore how risk estimates change depending on the relative influence of hazard and vulnerability, a sensitivity analysis was conducted by varying the values of a and b. The objective was to simulate plausible scenarios in which one of the components plays a more dominant role than the other in determining the overall risk. Three scenarios were tested:

- Scenario I ($a = b = 1$). Baseline scenario where hazard and vulnerability contributed equally to risk, reflecting a neutral assumption with no dominant factor.

- Scenario II ($a = 1$; $b = 4$). In this scenario, vulnerability was given significantly more weight than hazard, accounting for 80% of the total weighting versus 20% for hazard. This scenario reflected situations where social or environmental susceptibility (e.g., population exposure, limited adaptive capacity, or ecosystem degradation) was considered the key driver of risk, while the hazard remained moderate or relatively uniform. The ratio between b and a (4:1) served to highlight this asymmetry.

- Scenario III (*a* = 4; *b* = 1). This scenario, the opposite of the previous one, assumed that hazard dominates risk, while vulnerability had a secondary role. This configuration was particularly relevant in areas with low vulnerability or experiencing pronounced coastal retreat.

This parametric approach evaluated how risk responds to different assumptions without altering the underlying data. It also helped assess the robustness of the results and identified the conditions under which risk patterns may shift due to changes in hazard intensity or vulnerability. The three proposed scenarios, balanced, vulnerability-dominant, and hazard-dominant, enabled a robust sensitivity analysis. In any case, specific analyses for each area could be refined by assigning different weights, depending on the particular characteristics of the local context.

3. Results

3.1. Coastline change

The results revealed significant local variations in coastline dynamics (Table 2, Figure 3). Average national coastline change rates were –1.33 m/year for 2011–2017, –1.95 m/year for 2017–2023, and –1.66 m/year for the entire period 2011–2023. These values indicated a widespread retreat on average, with an increasing trend over time; 46% in the later period compared to the former. However, changes were highly variable (Figure 3), with rates reaching –7.5 m/year in Tanbi between 2017 and 2023, while accretion occurred continuously throughout the period in Batokunku and Sambuyang.

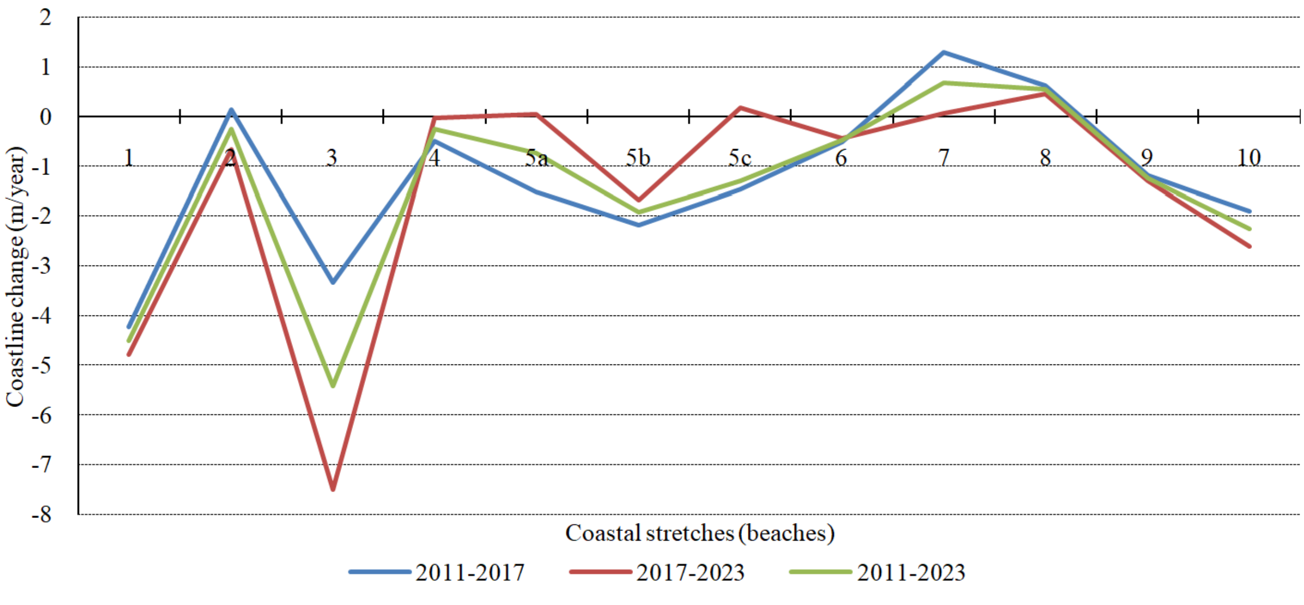

Figure 3. Shoreline change in the studied stretches (2011–2017; 2017–2023; and 2011–2023).

Table 2. Shoreline change between 2011 and 2023 (hazard).

No	Name	Period	Area change		Shoreline change		Valuation	
			Loss	Win	Period	Annual	Indicator	Value
1	Kayik	2011–2017	27449 m²	0 m²	−25.37 m	−4.23 m	9.18	Very high
		2017–2023	31078 m²	0 m²	−28.72 m	−4.79 m	9.40	Very high
		2011–2023	58527 m²	0 m²	−54.09 m	−4.51 m	9.30	Very high
2	Banjul	2011–2017	619 m²	990 m²	+0.80 m	+0.13 m	0	Accretion
		2017–2023	1843 m²	0 m²	−3.98 m	−0.66 m	3.61	Low
		2011–2023	2462 m²	990 m²	−3.18 m	−0.26 m	1.54	Very low
3	Tanbi	2011–2017	13 404 m²	0 m²	−20.07 m	−3.34 m	8.71	Very high
		2017–2023	30 059 m²	0 m²	−45.00 m	−7.50 m	10.00	Very high
		2011–2023	43 463 m²	0 m²	−65.06 m	−5.42 m	9.59	Very high
4	Fajara	2011–2017	1179 m²	8 m²	−2.93 m	−0.49 m	2.79	Low
		2017–2023	302 m²	226 m²	−0.19 m	−0.03 m	0.18	Very low
		2011–2023	1481 m²	234 m²	−3.12 m	−0.26 m	1.54	Very low
5	Kolili (5a)	2011–2017	1903 m²	0 m²	−9.06 m	−1.51 m	6.42	High
		2017–2023	113 m²	158 m²	+0.21 m	+0.04 m	0	Accretion
		2011–2023	2016 m²	158 m²	−8.85 m	−0.74 m	3.97	Low
	Bijilo (5b)	2011–2017	14 089 m²	0 m²	−13.06 m	−2.18 m	7.60	High
		2017–2023	10 901 m²	0 m²	−10.10 m	−1.68 m	6.78	High
		2011–2023	24 990 m²	0 m²	−23.16 m	−1.93 m	7.23	High
	Brufut (5c)	2011–2017	5336 m²	0 m²	−8.83 m	−1.47 m	6.33	High
		2017–2023	553 m²	1180 m²	+1.04 m	+0.17 m	0	Accretion
		2011–2023	5889 m²	1180 m²	−7.80 m	−1.30 m	5.90	Medium
6	Tanji	2011–2017	1264 m²	0 m²	−3.04 m	−0.51 m	2.89	Low
		2017–2023	1090 m²	0 m²	−2.62 m	−0.44 m	2.53	Low
		2011–2023	2354 m²	0 m²	−5.66 m	−0.47 m	2.69	Low
7	Batonkunku	2011–2017	490 m²	13 351 m²	+7.74 m	+1.29 m	0	Accretion
		2017–2023	878 m²	1615 m²	+0.44 m	+0.07 m	0	Accretion
		2011–2023	1368 m²	14 966 m²	+8.19 m	+0.68 m	0	Accretion
8	Sambuyang	2011–2017	584 m²	5789 m²	+3.73 m	+0.62 m	0	Accretion
		2017–2023	63 m²	3814 m²	+2.69 m	+0.45 m	0	Accretion
		2011–2023	647 m²	9603 m²	+6.42 m	+0.54 m	0	Accretion
9	Kartong	2011–2017	18358 m²	793 m²	−7.14 m	−1.19 m	5.59	Medium
		2017–2023	19132 m²	0 m²	−7.78 m	−1.30 m	5.90	Medium
		2011–2023	37490 m²	793 m²	−14.92 m	−1.24 m	5.74	Medium
10	Halahin	2011–2017	9510 m²	1765 m²	−11.44 m	−1.91 m	7.20	High
		2017–2023	10597 m²	0 m²	−15.65 m	−2.61 m	8.11	High
		2011–2023	20107 m²	1765 m²	−27.09 m	−2.26 m	7.71	High

Accretion	Retreat				
	Very low	Low	Medium	High	Very high
0	0–2	2–4	4–6	6–8	8–10

To calculate the hazard indicator (H), an asymptotic function (eq. 2) was applied as described above, where the independent variable (x) represents the annual coastal retreat (m/year). The dependent variable (H) takes a value of 0 when no retreat occurs and of 10 for the highest recorded retreat (7.5 m/year) (Figure 4):

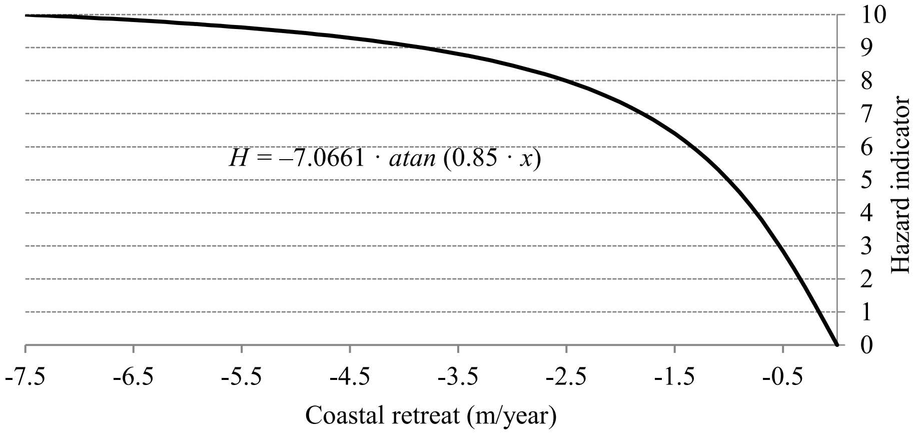

Figure 4. Hazard indicator.

3.2. *Coastal vulnerability*

To calculate social and environmental vulnerability indicators (V), the same type of asymptotic function used for hazard was applied (Figure 5). In both cases, the independent variable (x) represents the proportion of the area occupied by land with social or environmental interest, as described above. The dependent variable (V) takes a value of 0 when there is no occupation and reaches 10 when the entire area is occupied (i.e., proportion = 1). Thus, the same function was used for both vulnerability indicators, differing only in the land category considered in the numerator. These calculations are shown in Table 3.

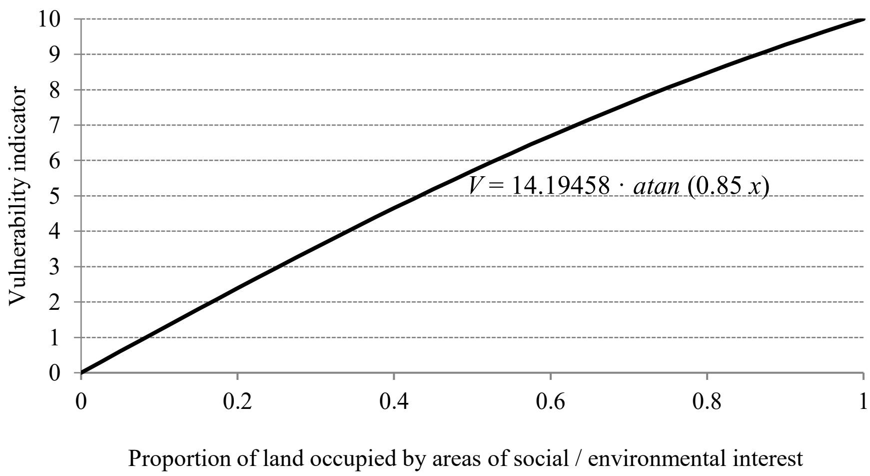

Figure 5. Vulnerability indicator.

Vulnerability values varied greatly across the country (Table 3). Social vulnerability was very high in Barra–Banjul and high in Bakau–Fajara, both densely built-up areas, and low between Kololi and Tanji, where urban development coexists with many undeveloped zones. In contrast, it was very low at the northern and southern ends of the country and between Batokunku and Gunjur, where human presence is limited. Environmental vulnerability was high or very high throughout most of the country, except in the most urbanized sections, Barra–Banjul and Bakau–Fajara, and, to a lesser extent, between Kololi and Ghanatown.

Table 3. Social and environmental vulnerability of coastal areas in 2023.

No	Description	Social vulnerability			Environmental vulnerability		
		Land occupation	Indicator	Value	Land occupation	Indicator	Value
1	Senegal border–Barra	0.004	0.04	Very low	0.985	9.89	Very high
2	Barra–Banjul	0.799	8.47	Very high	0.187	2.24	Low
3	Tanbi National Park	0.148	1.78	Very low	0.852	8.90	Very high
4	Bakau–Fajara	0.677	7.41	High	0.129	1.55	Very low
5	Kololi–Ghanatown	0.325	3.82	Low	0.500	5.71	Medium
6	Tanji	0.284	3.37	Low	0.582	6.52	High
7	Batokunku	0.149	1.78	Very low	0.740	7.97	High
8	Sanyang–Gunjur	0.103	1.24	Very low	0.747	8.03	High
9	Gunjur Madina–Kartong	0.215	2.56	Low	0.597	6.67	High
10	Kartong–Senegal border	0.043	0.52	Very low	0.879	9.11	Very high

Very low	Low	Medium	High	Very high
0–2	2–4	4–6	6–8	8–10

3.3. *Coastal risk*

To analyze coastal risk, the three scenarios proposed above were considered: Equal weight to hazard and vulnerability (Scenario I); greater weight to vulnerability (Scenario II); and greater weight to hazard (Scenario III). Risk was calculated for the periods 2011–2023 and 2017–2023 using eq. 2 with the exponents a and b defined for each scenario (Table 4).

Section 1 (Niumi National Park) had a very low social risk due to the near absence of human presence in the coastal area, but a very high environmental risk. The sensitivity analysis showed little variation, although in Scenario III, social risk rose to low. The area is an island, which increases its vulnerability. In the northern part, there are cultivated areas with scattered buildings just outside the risk zone: If the sea advances, the natural vegetation would be destroyed, leaving only these anthropized areas.

Section 2 (Barra–Banjul) showed a social risk ranging from low to high depending on the scenario, with higher values in the most recent period. Environmental risk was negligible, ranging from low to very low. Coastal retreat between 2011 and 2023 was moderate because there was accretion between 2011 and 2017; however, the area entered an erosive phase between 2017 and 2023. In Scenarios I and

III, social risk was low for 2011–2023 and medium for 2017–2023. In contrast, under Scenario II, greater weight on vulnerability, social risk became high. As this is a densely urbanized area, adopting the latter scenario is the most reasonable approach for decision-making. If the erosive trend continues, social risk could increase sharply.

Table 4. Sensitivity analysis of social and environmental risk.

Section		Period	Social risk			Environmental risk		
			Scen. I	Scen. II	Scen. III	Scen. I	Scen. II	Scen. III
1	Senegal border–Barra	2011–2023						
		2017–2023						
2	Barra–Banjul	2011–2023						
		2017–2023						
3	Tanbi National Park	2011–2023						
		2017–2023						
4	Bakau–Fajara	2011–2023						
		2017–2023						
5	Kololi–Gahanatown	2011–2023						
		2017–2023						
6	Tanji	2011–2023						
		2017–2023						
7	Batokunku	2011–2023						
		2017–2023						
8	Sanyang–Gunjur	2011–2023						
		2017–2023						
9	Gunjur Madina–Kartong	2011–2023						
		2017–2023						
10	Kartong–Senegal border	2011–2023						
		2017–2023						

Very low	Low	Medium	High	Very high
0–2	2–4	4–6	6–8	8–10

Scenarios. I: Hazard = Vulnerability; II: Hazard < Vulnerability; III: Hazard > Vulnerability

Section 3 (Tanbi National Park) had very high environmental vulnerability due to the presence of wetlands and mangroves that would be affected by marine intrusion, and is experiencing strong coastal retreat. As a result, environmental risk was very high under any scenario. Human presence is scarce; if greater weight was given to vulnerability (Scenario II), social risk was low, but in the other scenarios, risk increased significantly due to the strong coastal retreat in the area. It is reasonable to adopt Scenario II for social risk, and any scenario for environmental risk since they coincide.

Section 4 (Bakau–Fajara) was densely built-up, with high social vulnerability and very low environmental vulnerability. Coastal retreat was moderate and decreased during 2017–2023, reaching almost a balance along the coastline. This section included many stretches of coastal cliffs, where retreat problems were limited. As a consequence, environmental risk was very low, and social risk low to very low, except when vulnerability was prioritized, resulting in medium social risk between 2011 and 2023, due to the intense urbanization.

Section 5 (Kololi–Gahanatown) included three study beaches, Kololi, Bijilo, and Brufut, with local variations. Coastal dynamics were variable, but on average, retreat decreased by 72% in 2017–2023 compared to 2011–2017; Kololi and Brufut even experienced very slight accretion in the most recent period. The area is highly built-up toward the north, but less so toward the south, where natural areas predominate. The environmental and social risks were medium throughout the period, becoming predominantly low in the last six years. However, the presence of numerous beachfront hotel complexes in Kololi generated significant local issues; indeed, in Senegambia beach (just north of Bijilo Beach), a breakwater was built to protect the beach and maintain its tourist use.

Section 6 (Tanji) had high environmental vulnerability and low social vulnerability; although there were not many built-up areas, Tanji's urban center fell within the risk zone. Coastal retreat decreased by 14% between 2017 and 2023. This section presented a low social risk and a medium environmental risk, although if more weight was given to hazard, social risk would also be low.

In Sections 7 and 8 (Batokunku and Sanyang–Gunjur), there is currently accretion, so no coastal risk was identified. However, accretion has decreased in the most recent period, by 95% in Batokunku and 27% in Sanyang–Gunjur, so in the short term, accretion may cease and erosion may begin.

Section 9 (Gunjur Madina–Kartong) had low to medium social vulnerability and medium to high environmental vulnerability. Social risk was low but environmental risk was high; however, if hazard, coastal retreat was prioritized, the social risk increased slightly, and the environmental risk decreased.

Section 10 (Halahin) is a river mouth area with very high environmental vulnerability, low human presence, and consequently very low social vulnerability, and high coastal retreat. The environmental risk was mainly very high, while the social risk ranged from very low to medium depending on the scenario.

4. Discussion

As indicated, Africa is one of the few continents with net coastal erosion, at an average rate of –0.07 m/year [3], although in many areas, this rate is exceeded. In North Africa, the average retreat between 1887 and 2018 was −1.3 to −5.6 m/year [4]. In West Africa, most researchers found an average coastal retreat, although with some areas showing localized accretion [5–16] (Table 5).

The average shoreline change in Senegal ranges from −2.4 to −3.6 m/year, and around −1 m/year in Ghana. In Togo, variability is very high, with accretion extremes up to 15 m/year and erosion up to −12 m/year, with a general regressive trend [14,15]. In Benin, severe coastal retreat occurred between 2002 and 2013, followed by stabilization from 2014 onwards [16]. Regional data indicate retreat values in sandy areas between Senegal and Sierra Leone ranging from −1.2 to −6 m/year, with high variability along the coast and some points of accretion [13]. In Gambia, predictions made 30 years ago [49] pointed to a coastal retreat under a 1-meter sea level rise (corresponding to RCP8.5 by 2100) ranging from 840 m at Bald Cape to 57 m in the Sambuyang area; the second most significant retreat area was the northern part of the country, consistent with our findings. A study analyzed coastal dynamics in The Gambia between 1989 and 2019, dividing the period into two intervals: 1989–2009 and 2009–2019 [50], the latter quite similar to our timeframe (2011–2023). Their results showed disproportionately high coastal retreat figures: −16 m/year in the northern part of the country (where we recorded rates from −0.26 to −5.42 m/year), and −21 m/year in the central part (compared to our records of −0.47 to −1.93 m/year, and even accretion). In the southern part of the country the researchers reported accretion (+1 m/year), where we recorded accretion of +0.54 m/year to erosion up to −2.26 m/year, and other authors have also detected retreat [11].

Table 5. Results on coastal change in West Africa.

Country	Area	Period	Coastal change (m/year)	Reference
Senegal	St Louis	2003–2016	–3.72	[7]
	Dakar	2006–2015	–4.79	[6]
	Rufisque	2008–2018	+7.68 / –6.67	[9]
	Joal	1989–2013	–0.82	[5]
	Palmarin Peninsula	1989– 2013	–3.83	[5]
		1987–2018	−1.07 / −2.37	[10]
		2005–2010	–2.45	[8]
		2010–2014	–2.60	[8]
		2014–2018	–3.05	[8]
The Gambia	Northern	2009–2019	−16.00	[5049]
		2011–2023	–0.26 / –5.42	This study
		2011–2017	+0.13 / –4.23	This study
		2017–2023	–0.03 a –7.50	This study
	Central	2009–2019	−21.00	[50]
		2011–2023	+0.68 / –1.93	This study
		2011–2017	+ 1.29 / –2.18	This study
		2017–2023	+0.17 / –1.68	This study
	Southern	1986–2004	–4.57 / –7.24	[11]
		2009–2019	+1.00	[50]
		2011–2023	+0.54 / –2.26	This study
		2011–2017	+0.62 / –1.91	This study
		2017–2023	+0.45 / –2.61	This study
Ghana	Central	1974–2012	–1.24	[13]
		2005–2012	–0.85	[13]
	Accra	1904–2002	–1.13	[12]
Togo	Togo coast	1986–2020	Max. –5.00	[14]
		2014–2020	Max. –10.00	[14]
		2015–2023	+15.00 / –12.00	[15]
Benin	Cotonu	2002–2013	–10.45	[16]

To assess the validity of the results obtained in this study, and the differing data available for The Gambia, the data in Table 5 were evaluated using the interquartile range (*IQR*) method to identify outliers. In this method, for the dataset considered, the first quartile (*Q1*), the third quartile (*Q3*), and the interquartile range (*IQR*) are calculated (eq. 3) [51]:

$$IQR = Q3 - Q1 \quad (3)$$

Normal values fall within the range between *Q1* − 1.5 *IQR* and *Q3* + 1.5 *IQR*; any values above or below this range are outliers (Figure 6). The median (*Q2*) is −2.18 m/year, with an *IQR* range from 0 to −4.68 m/year, resulting in normal value limits of +7.02 to −11.7 m/year. All values calculated in this study fall within the normal range. The high accretion and erosion rates reported for Togo and Benin are outliers, although they appear to result from localized phenomena that have now stabilized. Slightly atypical is the accretion recorded at Rufisque, although this is a localized value. However, the values calculated for central and northern Gambia by [50] stand out as outliers, falling well outside the normal range for West Africa, and should therefore be reconsidered.

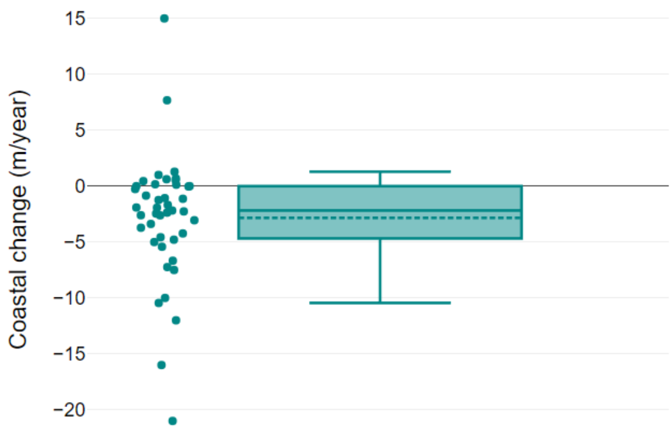

Figure 6. Boxplot of coastal variation in West Africa.

Our results do not show a clear trend in coastal dynamics over the last decade. At Kayik Beach (section 1), the retreat rate has increased by 13.2% in 2017–2023 compared to the previous period, while at Kartong Beach (section 9), it has increased by 4%. At Sambuyang Beach (section 8), accretion has decreased by 27.4% in this last period. However, Bijilo Beach (section 5b) shows a 22.9% reduction in retreat during 2017–2023, which may have been influenced by the construction of a breakwater at Senegambia Beach (not studied), located just to the north. Consequently, although the coastline is experiencing widespread retreat, there are significant local differences in its intensity and temporal dynamics; these variations are crucial when establishing adaptation measures.

The vulnerability of coastal territory varies greatly across the country and differs significantly depending on whether it is analyzed from a social or an environmental perspective, which are largely opposing; depending on the area, greater weight should be given to one aspect or the other. Thus, in densely populated areas, social vulnerability is essential, whereas in natural areas with low population density, environmental vulnerability should be the main criterion. A 2018 study proposes an Impact Risk Matrix for the coastal zone of The Gambia, but it does not include a hazard and vulnerability assessment, including just the latter; it provides interesting insights for adaptation (like restricting agriculture and livestock to improve land cover), but no results about coastline hazard or a real risk assessment [52]. Another study in Gunjur (Section 8) found that 90% of households in the area were highly vulnerable to coastal erosion, due to high levels of exposure and a limited adaptive capacity [53]. However, our results show that this section is currently experiencing accretion, so there is no risk. Identifying this vulnerability is useful, as erosion could occur in the future and increase the risk, but for now, it is not a priority area for action.

In West Africa, coastal erosion remains a problem for the socio-economic development of the coastal zone [13], and coastal environmental degradation is a major economic burden, with estimated costs equivalent to 5.3% of the region's GDP, 60% of which are linked to flooding and erosion [54]. In the coastal zone of The Gambia alone, a one-meter sea level rise would flood 12.46 km^2 of land, with a population density of 15,560 people/km^2 and estimated losses of US $788 million [55]. Significant investments have been made in beach nourishment in beaches such as Banjul or Kololi to preserve their aesthetic value and tourism potential, although the durability of these measures lasts only about two years [56]. While costly and of limited effectiveness, these efforts are necessary to prevent the loss of key beaches that sustain tourism, an important part of the national economy.

Effective management and adaptation are essential to protect lives, property, and communities exposed to coastal hazards [57]. This need is heightened by the expectation that West African countries will experience some of the highest rates of population growth and urbanization in their coastal zones [58], further increasing the challenges faced in managing and protecting these areas. Adaptation plans must consider the risk by combining hazard with vulnerability, with no single criterion for decision-making. On the one hand, risk is influenced by the perspective adopted regarding vulnerability. On the other hand, it is strongly dependent on the weight assigned to hazard and vulnerability, which may not be equal. Assigning greater weight to hazard prioritizes actions in areas experiencing high coastal retreat, while doing so with vulnerability shifts the focus to areas of greatest social or environmental value. Each coastal section requires a sensitivity analysis and a tailored evaluation to support decision-making in an iterative process [59].

For example, the northern part of the country experiences significant coastal retreat. However, as this area is largely undeveloped, coastal retreat has led to the formation of new inland beaches without triggering major environmental changes. Despite the intense erosion, the coastal ecosystem is naturally adapting; the risk is that the coastal forest may eventually disappear. Just south of this area, the urban centers of Barra and Banjul, located on both banks of the Gambia River, have a radically different scenario. Although the hazard is moderate, social vulnerability is enormous; a one-meter sea level rise could displace the entire population of Banjul [49]. Relocation is not feasible, nor is natural adaptation of the ecosystem, making the construction of coastal defenses the only viable option. In contrast, in the first case such defenses would be inappropriate, blocking the natural recovery of the coastal ecosystem and causing a loss of naturalness.

Consequently, the hazard, coastal retreat , the social and environmental vulnerability, and the risk, are all useful tools to assess potential scenarios for a specific coastal stretch. It is essential to carry out tailored sensitivity analyses that enable selecting the best adaptation options, which can be active, involving engineering, non-structural or management options [60], or passive, enabling the environment to evolve naturally. Future strategies should learn from past experiences in West Africa, where many adaptation measures have ended up causing more setbacks than solutions [13].

A priority is to avoid or minimize new occupations in the coastal zone to prevent increased vulnerability, and to consider a managed coastal retreat where possible [61], at least for uses or activities that enable it, while properly addressing the environmental impacts that such retreat may generate [62]. For example, new tourist infrastructure should account for expected coastal changes, maintaining a sufficient distance between buildings and the shoreline to enable natural readaptation. Otherwise, hotels risk ending up close to seawalls, which is unattractive to tourists, or large sums will have to be invested in beach nourishment, which is, figuratively speaking, throwing money into the sea.

Wide buffer zones along the coast should also be guaranteed to maintain natural coastal dynamics without compromising environmental values, which can be lost where these areas are limited to a narrow strip. Vegetation conservation in the coastal zone does not appear to be a significant issue in the region, as plant cover has remained stable from 1979 to 2015 [63]. However, in the estuarine area of Tanbi Wetland National Park, a worrying decline in many fish species has been observed over the past few decades [64]. The more natural the coastal territory is, the greater its capacity to cope with changes induced by coastal dynamics; that is, the higher its resilience will be.

5. Conclusions

The Gambian coastline, like much of West Africa, is subject to significant retreat, although with notable local variability and even some localized accretion. Our findings are consistent with regional results and call into question some reported extreme values that require further validation.

Coastal dynamics are naturally highly variable, and more so under the impacts of climate change. Temporal variability shows that current accretion zones are not guaranteed to remain stable, as they may quickly shift towards erosion, and retreat rates can increase or decrease abruptly. Therefore, coastal adaptation requires extensive and recurrent studies to enable rapid detection of trend shifts, such as transitions between accretion and erosion, increases in shoreline change rates, or shifts in vulnerability. The model proposed in this study is simple yet robust, easily replicable without the need for advanced technology, making it particularly useful in West Africa. Its main limitation is that it is only applicable to beaches with a natural regime, and not to anthropized areas, where human activity prevents the identification of the erosion scarp. In such areas, it must be combined with other hazard assessment methods, such as the use of fixed stakes.

Coastal risk is complex and heterogeneous, resulting from the interaction between coastal retreat (hazard) and social and environmental vulnerabilities of each area. This study demonstrates the importance of independently assessing hazard and vulnerability in risk analysis, as well as the need to evaluate social and environmental risk separately, as they are often in tension. Each area requires a tailored analysis, where each of these factors, hazard, social vulnerability, and environmental vulnerability, may carry different relative weights. Sensitivity analyses also help evaluate the robustness of predictions. Prioritizing hazard focuses attention on areas experiencing the most intense coastal retreat, whereas prioritizing vulnerability shifts focus to zones of greatest social or environmental value. Effective coastal risk management must integrate hazard with social and environmental vulnerabilities within a multifactorial risk framework adapted to local conditions. Coastal zone management must learn from past mistakes in West Africa and prioritize flexible, context-specific measures, combining active interventions with passive strategies that enable natural coastal evolution where feasible.

Vulnerabilities vary significantly along the coast, requiring contrasting management approaches. While in undeveloped natural areas coastal retreat can enable ecosystems to adapt inland, in densely populated areas, even moderate erosion can generate severe social impacts, making coastal defenses unavoidable. This divergence underscores the importance of balanced adaptation strategies that integrate ecological preservation with human safety. It is necessary to reduce new development in vulnerable coastal zones and even consider a managed retreat when possible. Tourism infrastructure, essential for the country's economy, should be designed in accordance with the expected coastal dynamics, with enough buffer zones to prevent costly and unsustainable interventions such as repeated beach nourishment or poorly planned seawalls. It is also important to maintain wide natural buffer zones where possible to protect ecosystems and sustain natural coastal processes, which are often compromised where habitats are confined to narrow strips.

The study also reveals that, in contrast to the relative stability of vulnerability over time, hazard is much more variable. This underscores the need for continuous monitoring to enable adaptive management in this evolving context.

The proposed model is suitable for automation. Properly trained artificial intelligence could detect changes in both coastal scarp and land use, thereby automatically determining hazard, vulnerability, and risk in an efficient and highly cost-effective way.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of Interest

The author declares no conflict of interest.

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