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Monitoring and Forecasting of Coastal Erosion in the Context of Climate Change in Saint Louis (Senegal)

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Abstract: Owing to its unique physical and socio-economic characteristics, the Saint Louis region stands out as one of the most susceptible areas in Senegal to the adverse impacts of coastal erosion. The dynamics of erosion in this region are significantly influenced by the Langue de Barbarie (LB), a sand spit formed at the mouth of the Senegal River. Initially, in 2003, a 4 m wide artificial breach was strategically introduced to mitigate flooding; however, sediment dynamics expanded it to 6 km by 2020, thereby affecting the entire region. This study delves into the coastline change of the LB, specifically divided into three zones (LB-1, LB-2, and LB-3), spanning the period from 1994 to 2042. Leveraging Geographic Information System (GIS) and remote sensing techniques, our investigation reveals that, prior to the breach's creation, the average dynamic coastline rates in zones LB-1, LB-2, and LB-3 were estimated at 4.4, 5.9, and 4.4 m/year, respectively. Subsequent to the breach, these rates shifted to −1.2, 8.4, and −2.7 m/year, with the most significant erosion observed alongshore of LB-3 at −6.6 m/year during the period 2002–2012. Projecting into 2032, LB-1 and LB-3 are anticipated to experience erosion rates of −11.5 and −26.8 m/year, respectively, while the LB-2 records an estimated accretion rate of 8.41 m/year. Eroded areas are expected to total 571,458 m^2, while accumulated areas are expected to total 67,191 m^2. By 2042, zones LB-1, LB-2, and LB-3 are expected to experience erosion rates of −23 and −53.6 m/year, resulting in the erosion of 1,021,963 m^2 and the accumulation of 94,930 m^2 with a dynamic rate of 168.2 m/year in zone LB-3. These results have significant implications for solving the urgent issue of coastal erosion in LB.

Keywords: coastal erosion; erosion rate prediction; climate change; Saint Louis; West Africa

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1. Introduction

Due to the continual processes of erosion, deposition, and the effect of tides, waves, and currents, sand spits are dynamic landforms that change over time. They have the potential to be ecologically significant since they serve as homes for a variety of plant and animal species, and they are essential in forming coastal landscapes [1]. Coastal spits are often seen where the coast's orientation abruptly changes, such as on a headland [2]. The coastal current splits from the beach as it runs around the southeast promontory, owing to the centrifugal force of inertia and an unfavorable pressure gradient. Sediment delivered via coastal currents is deposited beyond the headland due to the flow separation process, resulting in the creation of an arrowhead. In other words, sediment is deposited where the longshore current meets the offshore current [3].

Sand spits are formed mostly by wave action; some sediments have moved inland, while others have stayed in place or moved seaward. The sediments are carried along the coast from river mouths or eroding cliffs [4]. It has been observed that erosion is now common on sand spits and that this retreat is caused by net losses of sediment offshore, along the coast, or inland. The occurrence of this phenomenon can be attributed to both decreased sediment supply and rising sea levels [5]. The relationship between wave transformation, tidal exchange, longshore sediment transport, and river flow is crucial to the morphological changes seen in sand spits [6]. Sand spit morphological changes were mostly caused by wave-induced current processes, as demonstrated by Allard et al. [7]. Additionally, two general mechanisms for the generation of sand spit were identified by Aubrey and Gaines [8]. The first mechanism involves longshore sediment movement leading to accretion, and the second mechanism is related to tidal inlet migration [9,10]. In addition, the complexity of sand spit morphological evolution is further illustrated by the geological context, sea level rise, sediment availability, and human activities [6,11,12].

Moreover, given that sand spits are composed of sediments that have been carried along the coast from river mouths or eroding cliffs, the deltas of the Niger, Volta, and Senegal rivers exhibit intricate patterns of morpho-dynamic evolution [5]. Some sand spits are observed along the coast of West Africa, especially in the Volta and Niger Deltas. The Senegal River delta's LB sand spit, located at its mouth, results from significant longshore drift that has affected one of the best instances of a wave-dominated delta [1]. The spit evolved alongside the delta and appears to have relentlessly spread downwards in conjunction with river-mouth diversion but with rare breaches, the oldest of which is only preserved north of Saint Louis. The spit had a downdrift migration range of about 30 km, after which alongshore sand drift and river discharge circumstances stabilized the position of the river mouth [1]. The tidal range and river flow are two conflicting forces that strive to dominate for most of the year. The upper basin's seasonal rainfall distribution is intimately associated with the Senegal River regime. One characteristic that distinguishes the humid tropical hydrological regime is the turbid waters with significant solid charges that occur during the June to July and October to November flood seasons. Additionally, it is distinguished by a low water season, which runs from December to June and has significantly lower river charges [13].

Therefore, the installation of the Manantali (1960) and Diama (1985) dams has made the hydrological system of the Senegal River artificial [14]. This has changed the lower estuary's water circulation, which has an impact on the processes of sedimentation and erosion. According to several studies, the retention zone of the dam is subject to almost critical sedimentation, and the river estuary is subject to an erosion regime [15]. The spit hindered a quick evacuation of the river waters during flooding and acted as a natural barrier to protect the beach from hydrodynamic agents [16].

However, the effects of human activity are clearly visible on the LB's spit. For instance, the 2003 breach opening altered and called into question the LB's existence as well as the estuary's natural functioning. At first, the breach helped to avoid flooding by making it easier for the river to reach the ocean. But, because of the breach, marine currents have drastically altered the hydrological regime. The levels of water are now determined by the tide's rhythm because of the tide's major increasing effect [16]. Significant changes in coastal hydrodynamics, such as tidal patterns, have been recorded. There is a large rise in seawater during high tides, with significant evacuation of river flows during low tides. The area is being threatened by increased coastal erosion [17]. The breach caused an increase in the salinity of the water table, making the gardens unusable. Additionally, the loss of mangrove stands, an ecosystem that provided hatching grounds for fish, and the pH reduction in the water have affected fishing operations [18]. Moreover, the Senegalese lower estuary is at a critical point in its history due to the accumulation of several risk factors, such as the development of a marine dynamic and the over-salinization of both the land and the water [19]. Extreme coastal erosion has caused a fast change in the shape of the LB sand spit [19].

Climate change will accelerate the loss of biodiversity and dwindling freshwater and land resources and increase societal vulnerabilities, particularly in areas where the economies are highly dependent on natural resources [20]. Extreme weather, heat waves, storms, flooding, disappearing human settlements, ocean acidification, declining fisheries, an imbalance between water supply and demand, and coastal erosion leading to rising sea levels are just a few of its consequences [21].

Sea level rise is one of the most significant effects of climate change on the coastal regions of many countries. It is among the most challenging effects of global warming. Along with hydrodynamic, geomorphological, and climatic factors, it is the primary driver of coastal erosion. The latter is often illustrated by the retreat of the shoreline, leading to a reduction in coastal areas and the destruction of coastal ecosystems.

One of the main causes of coastal erosion is coastal flooding, a condition when ocean water inundates normally arid coastal areas. It is caused by a number of variables, including storm surges, high tides, prolonged rainstorms, and, most significantly, sea level rise. By removing sediments from the beach, the force of the water, especially during storm events, speeds up the erosion process. Coastlines then begin to gradually or quickly recede as a result [21]. In West Africa, a very small contribution to global climate change is noted, but, because of its position and poor capacity for adaptation, West African countries are extremely sensitive to the consequences of climate variability and change. As they rely on rainfed agriculture and ecosystem services, inhabitants in the dry parts of West Africa, in particular, suffer unfavorable effects from rising temperatures and fluctuating rainfall patterns. In various West African nations, flooding is another typical hazard brought on by the environment [22].

Climate change has had a tremendous impact on Senegal's coastal areas, providing substantial challenges to both the ecosystem and human life. Climate models predict that West African countries would face higher temperatures, lower annual rainfall, increasing intensity and frequency of heavy downpour events, and rising sea levels. These changes will have a substantial impact on Senegalese socio-economic and environmental resources. Around 74% of Senegal's coastal housing is vulnerable to sea level rise. Erosion is expected to cause 1–2 m of shoreline loss per year along sand spit shorelines and 0.1–0.7 m per year along rocky coastline sections, exacerbated by sea level rise [23]. Rising sea levels of up to one meter by 2100 are affecting Senegal's cities coastal zone, which houses around 67 percent of the population and 90 percent of industrial production [24].

The LB's shoreline dynamics are very different from other Senegalese coastlines. The energy of the Senegal River, the structural condition of the LB sand spit as an estuary, and the hydrodynamic circumstances make it one of West Africa's most vulnerable coastal areas. Many studies have been conducted to forecast the dynamics of the shoreline as a result of sea level rise. In a study conducted by Fenster [25], he stated that, 'Several methods have been used to predict beach loss as a function of time or sea level rise' [25,26].

These investigations include an extrapolation of projected long-term erosion rates; superimposing sea level rise on varied coastal plain and barrier island slopes [27]; and employing the Bruun rule [28] and the Bruun rule variants [18,29]. Because of its simplicity and the fact that sediment movement is not taken into account, an extrapolation of a constant rate of change value is the most commonly employed method for future shoreline change prediction—the End Point Rate (EPR) or Linear Regression (LR) [25]. Using the End Point Rate (EPR), this study intends to monitor and anticipate coastal erosion at the LB sand spit in the context of climate change. The uniqueness of this study is the computation of future coastal positions and the forecast of lost areas of the LB sand spit's coast in 2032 and 2042.

2. Study Area

Built on an island in the Senegal River estuary, the city in the Saint Louis area is situated along the southern shore and is isolated from the ocean by the LB, a sand spit [16]. It is a notable example of a transboundary sand spit that connects Senegal and Mauritania's coastal territory. This 600 km length of sand marks the end of a long coastline expedition that began in Nouâdhibou, Mauritania, and ended in Saint Louis, Senegal [30]. The LB is a dynamic geological structure formed by the interaction of ancient marine sediments with more modern Quaternary deposits. These formations, which are originated with the basin's uplift, are further molded by the action of waves, currents, and sediment transport processes, resulting in the spit's transboundary nature, which is shared and shaped by Senegal and Mauritania [31].

More specifically, LB is a sandy spit in the northern part of the Senegalese coast, between longitudes 16°23′ and 16°35′ west and latitudes 15°45′ and 16°15′ north [32]. Due to its location parallel to the coast, from north to south, it constitutes a sand spit that has a width of between 200 and 400 m. Its length is variable due to the dynamics in the area but it has reached an extension of about 30 km along the Senegal River estuary's maritime margin [32].

The evolution of climatic, hydrologic, and geomorphologic factors characterizes the LB. Rainfall generally starts in June and lasts until September. Total annual rainfall is 79% higher in Saint Louis, which lies on the coast. The Senegal River delta's LB sand spit, located at its mouth, results from significant longshore drift that has affected one of the best instances of a wave-dominated delta [7]. The waves are of local origin and are more or less regular in shape, caused by local breezes and overlaid on distant swells. Their properties are heavily influenced by wind patterns. Their height ranges between 0.65 and 1.35 meters, with the highest values recorded during the northeasterly trade wind season. Their period ranges from 3 to 5 s. They produce huge sand accumulation [7]. Waves have only a minor impact on coastal dynamics, reinforcing or attenuating the action of swells [33–35]. Since the winds can only mobilize sandy sediment particles at speeds above 5 m/s on the LB, they would only be effective in the dry season, particularly in the second half of this period. Wind speeds exceeding this threshold represent 55.3% in March, 75% in April, and 66.1% in May. Throughout the year, especially from October to May, the LB north-to- north-westerly swells predominate in the seaward direction [5,10,36]. The periods vary from 8 to 12 s for northwest swells. These swells are responsible for a north–south coastal drift transporting 600,000 m^3 of sediment per year [37].

The ocean tide at Saint Louis is semi-diurnal. The water mass oscillates according to a period corresponding to half a lunar day, i.e., about 24 h 50 min, for about 6 h and then spreads out for a few minutes: this is the high tide. It then falls again for 6 h and spreads out for a while: this is the low tide. The range of tides is 1.1 m in spring and 0.5 m in neap [5,27]. A significant littoral drift that occurred between 4000 and 1800 B.C. also resulted in the formation of offshore sand bars that stretch from west to east. Thus, until the sub-actual period, north–south–south currents caused by the reflection of northwest swells along the coast were formed. The interaction between three drivers (swell, tide, and river) forms the deposit of sand in the shape of a spit [38]. There is a significant amount of sediment available for sedimentary dynamics [14,39].

The coastline of Saint Louis and the Langue de Barbarie experiences extensive southward sediment flow, resulting in major morphological changes and, eventually, erosion [40]. Longshore sediment transport rates resulted in a drift volume from north to south ranging from 600 to 700,000 m^3/year, which appears to be the direct cause of the sand spit's southward lengthening and narrowing in the northern half [41,42]. From 2019 to 2020, a substantial amount of the inland sand spit remained steady, with vertical changes of less than 1 m. The largest morphological alterations may be seen at the southern extremity of the Langue de Barbarie, as well as other locations along the sand spit's Atlantic face. From 2015 to 2020, the sand spit's alongshore migration is expected to average 230,000 m^3/year. This accounts for 35% of the north–south drift volume [40,43], implying that the sand spit expansion has the ability to catch a significant amount of the alongshore sand drift [36].

Geomorphologically, the LB sand spit is mainly the result of continuous sedimentation from the sub-actual to the present. The setting up of the different geomorphological and geological units obeys several sequences ranging from subsidence tectonics to eustatic movements and climatic oscillations of the quaternary period, which is verified by the continuous subsidence of the delta. Consequently, the lower delta of the Senegal River has been shaped by different eustatic movements and climatic oscillations [44]. The LB is a sedimentary transit area that stretches from north to south in terms of dynamics and sediment. On the outside shore, estimates of the sedimentary transfer range from 1.5 million to 365,000 m^3/year. According to Kane's calculations from 1985 to 1997, the LB's foreground receives an average annual sediment movement of about 600,000 m^3 [45]. For mobilized materials with dimensions ranging between 0.1 and 0.5 mm, Barusseau (1980) provides more precise estimations with values between 223,000 and 495,000 m^3/year [46]. Suspended sediments were evaluated along the internal coast, which corresponds to the river zone. From 1989 to 1990, flows of continental origin transiting to the river mouth totaled 725,000 tons. This discharge of continental sediments takes the shape of a turbid plume, which is distinctive of the Senegal River mouth. The sediment load ranges from 10^6 tons in moderate flooding to 2.8×10^6 tons in extremely high flooding. These suspended particles are primarily made up of clay (92%), fine silt (6%), and coarse silt (2%) [19]. The following figure is about the location map of the study area.

The study area is divided into three zones because the contribution of human activities (such as settlement and the breach implementation) to the coastline dynamic is different along the coast of the Saint Louis region (Figure 1). These zones are as follows: LB-1 is from Guet Ndar to the Hotel La Saint Louisienne; LB-2, the area influenced by the breach, is from Ngaina Lebou to Mouit; and LB-3 is from Gouye Rene to Mbaw and corresponds to downstream of the Langue de Barbarie. Two periods were considered: pre-breach (before 2003) and post-breach (after 2003).

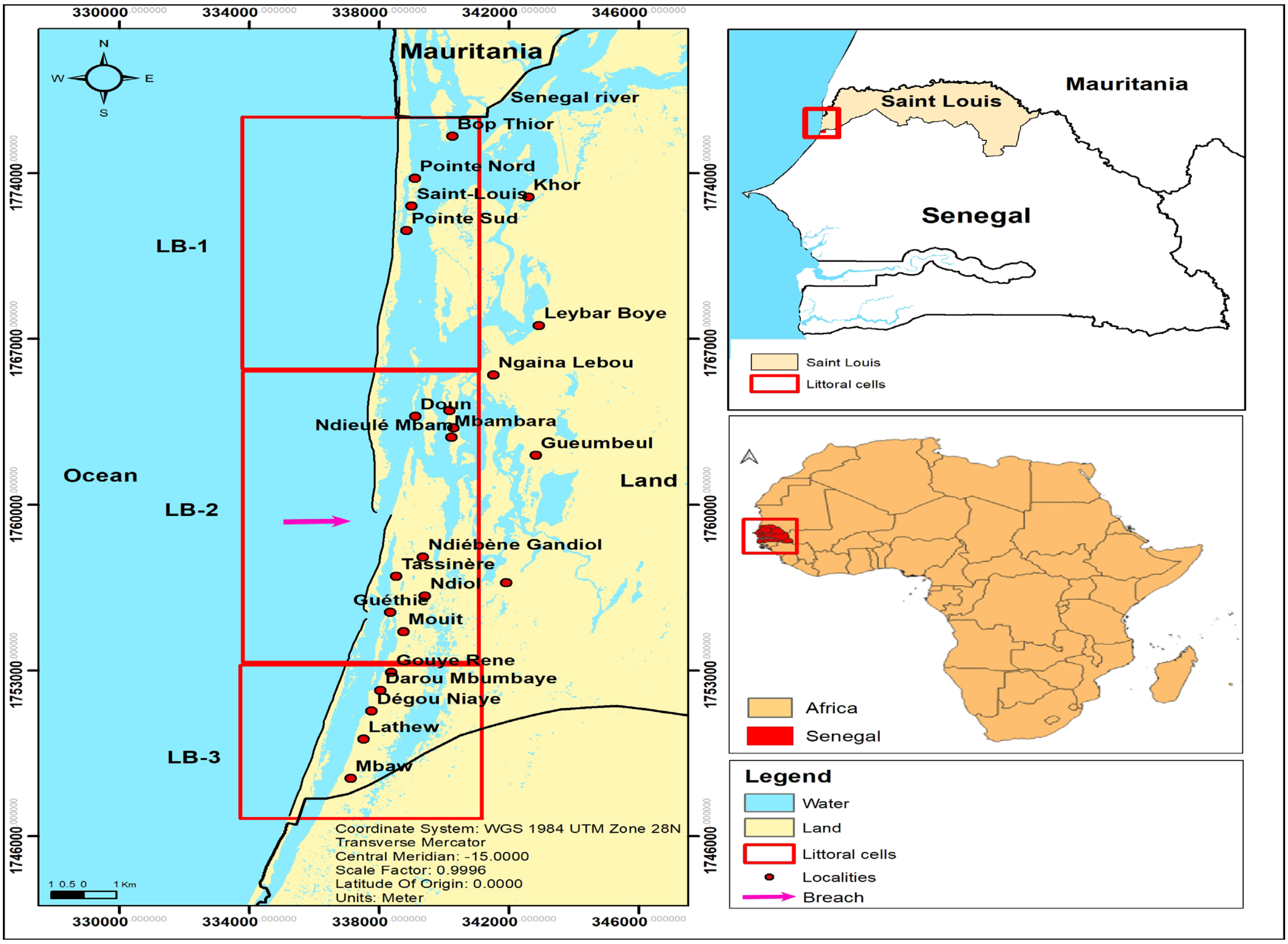

Figure 1. Location map of the study area.

3. Data Source

To facilitate this investigation, Landsat images from four specific dates (1994, 2002, 2012, and 2022) were procured (Table 1). To ensure data consistency and minimize the impact of the rainy season on image quality, the analysis focused on the period from January 1st to May 31st for each respective year. The selection of 1994, instead of 1990, was made due to the unavailability of images for the latter year, as well as for the years 1991, 1992, and 1993 within the designated timeframe.

Table 1. Characteristics of earth observation data used.

Satellite/Sensor	Path/Row	Number of Bands	Spatial Resolution (m)	Acquisition Date
Landsat 5/TM	205/049	7	30	22 May 1994
Landsat 7/ETM	205/049	8	30	12 January 2002
Landsat 7/ETM	205/049	8	30	24 January 2012
Landsat 8/OLI_TIRS	205/049	11	30	28 February 2022

4. Methodology Approach

Over time, two primary methodologies have been employed in Senegal to analyze shoreline dynamics. The initial approach predominantly involved the interpretation of an antiquated geological map, utilizing sea level as a reference point. Subsequently, a second method was adopted, leveraging contemporary geospatial tools such as satellite imagery, cadastral maps, and aerial photographs [47]. Numerous studies on shoreline dynamics in the Saint Louis region, particularly within the Langue de Barbarie (LB), have utilized modern geospatial tools, as evidenced by previous research [5,16–19,21,25]. This study builds upon previous examinations of LB's coastline dynamics, encompassing both pre- and post-implementation of the breach (Figure 2). A distinctive contribution lies in the proactive forecasting of future coastline dynamics, anticipating areas of accumulation and erosion based on the current state. The investigative approach integrates Geographic Information System (GIS) and remote sensing techniques. Initially, Landsat images were processed to delineate coastlines. Subsequently, dynamic calculations were performed to forecast coastline positions and estimate areas to be gained or lost in 2032 and 2042.

4.1. Landsat Image Processing and Coastline Detection

Landsat image processing and coastline detection were conducted using a semi-automatic categorization plugin integrated into the QGIS software 3.36.0 [48]. This plugin incorporates a semi-automated classification tool developed using Python programming, which systematically identifies and tracks land cover. In this context, the plugin was applied to process Landsat images, utilizing its inherent land cover categorization tool to ascertain the shoreline. Furthermore, the program allows for post-processing activities, offering tools to enhance and assess categorization accuracy or integrate additional data. The resultant processed images were subsequently categorized to outline the coastline. To distinguish between land and sea, the Landsat images were partitioned into two distinct land cover groups, namely land and water (sea and river) (Figure 2). Subsequently, the coastlines were digitally mapped using vector layers derived from the classified images.

4.2. Coastline Dynamic Calculation and Forecasting

The analysis of shoreline dynamics in the Saint Louis region spans the period from 1994 to 2022 and was executed through the implementation of the Digital Shoreline Analysis System (DSAS), an extension integrated into the ArcGIS software 10.8. The dynamic rate is gauged using the End Point Rate (EPR) parameter. The computation of Net Shoreline Movement (NSM) is accomplished through the application of the End Point Rate (EPR) statistical method, which involves dividing the time interval between the oldest and youngest shorelines via the Net Shoreline Movement (NSM) (Equation (1)).

$$\text{EPR} = \text{NSM}/\text{Elapsed time between the oldest and youngest coastline} \quad (1)$$

Projections for coastline dynamics in 2032 and 2042 were initially extrapolated from the post-dynamic breach rate, considering both anticipated accretion and loss zones. The velocity concept served as the initial framework for predicting future coastline positions, with the year 2022 serving as the baseline. Utilizing the current position as a reference, the coastline is projected to recede by a distance of Y meters in 2032, with an estimated coastal retreat rate of X meters per year. Subsequently, to forecast areas of loss, the coastlines for 2022, 2032, and 2042 were amalgamated. The resulting integrated shapefile was then converted into a polygon, facilitating the calculation of areas gained or lost along the coastline [49].

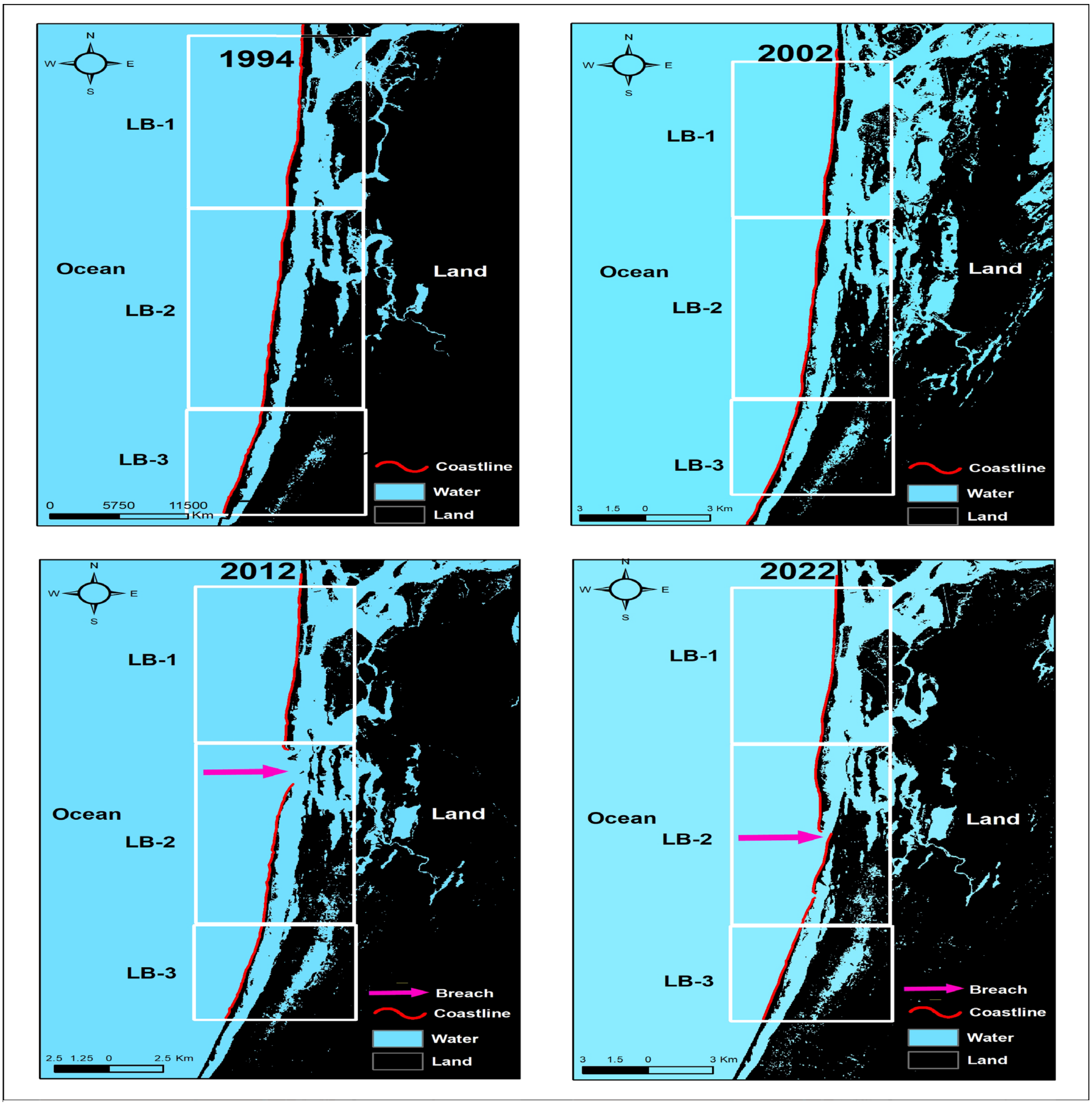

Figure 2. Classification and demarcation of coastlines using Landsat images from 1994, 2002, 2012, and 2023.

4.3. Calculating the Uncertainty

The analysis of any scientific experiment necessitates a scrutiny of uncertainties, as measurements inherently entail a margin of error. Scientists can gauge the precision of their findings and mitigate uncertainties, if necessary, by employing error analysis, which involves the assessment of uncertainties [34,35]. In this study, shoreline uncertainty is determined by summing the squares of individual uncertainties. To calculate the uncertainty associated with the End Point Rate, the square root of the sum of squares is taken and divided by the number of years between the two shorelines (EPRunc) (Equation (2)) [49].

$$\mathrm{EPRunc} = \sqrt{}((\mathrm{uncy\ A})2 + (\mathrm{uncy\ B})2)/(\mathrm{dateA} - \mathrm{dateB}) \quad (2)$$

uncy A represents uncertainty derived from shoreline A's attribute field.
uncy B represents uncertainty derived from shoreline B's attribute field.
Dates A and B represent the shoreline that is the oldest (B) and the most recent (A).

5. Results

The presented table encapsulates the evolving dynamics of the Saint Louis coastline in Senegal across distinct time intervals, elucidating the rates of both erosion and accretion alongside their corresponding uncertainties. The measurements, denoted in meters per year, offer valuable insights into the alterations within the coastal region. Furthermore, the results delineate two discernible periods in the dynamic rate—the period preceding and following the initiation of the breach—as outlined in Table 2.

Table 2. Coastline dynamics of the Saint Louis region from 1994 to 2022.

Coastline Dynamics and Uncertainties (m/year)						
Periods		**LB-1**	**LB-2**	**LB-3**	**Average**	**Uncertainty**
1994–2002		4.4	5.9	4.4	4.9	±1.9
2002–2012		−0.8	2.8	−6.6	−1.5	±1.4
2012–2022		−1.5	14	1.3	4.6	±1.4
1994–2022		1.6	4.1	−0.7	1.7	±1.5
Before Breach	1994–2002	4.4	5.9	4.4	4.9	±1.9
After Breach	2002–2022	−1.2	8.4	−2.7	1.5	±1.4

5.1. Coastline Dynamics before the Breach (1994–2002)

The LB-1, alongside LB-2 and LB-3, exhibited respective average dynamic rates of 4.4, 5.9, and 4.4 m/year during the period from 1994 to 2002. The overall average dynamic rate for the entire zone during this timeframe was 4.9 m/year. Uncertainty in measurements was estimated at ±1.9 m/year before the breach. The coastal dynamic rate is estimated to have averaged 3.6 m/year from 1994 to 2002 from Goxu Mbathie to Guet Ndar (north of LB-1), while it is reported to have averaged roughly −0.8 m/year from Guet Ndar to Hydrobase (south of LB-1). Furthermore, the downstream rate of the Langue de Barbarie is estimated to be 4.3 m/year (Figure 3).

5.2. Coastline Dynamics after the Breach (2002–2022)

Following the establishment of the breach in 2003, a notable transformation occurred in the region's hydrography. In specific coastal areas, the coastline dynamic exhibited an increased pace compared to the pre-breach period [39]. LB-1, for instance, recorded a dynamic rate estimated at −0.8 m/year from 2002 to 2012. Moving from Goxu Mbathie to Guet Ndar (north of LB-1), the dynamic remained relatively consistent with the pre-breach period, estimated at 2.7 m/year. Conversely, a rate of approximately −3.3 m/year was reported from Guet Ndar to Hydrobase (south of LB-1). Further downstream of the Langue de Barbarie, a dynamic rate of around −6.6 m/year was observed (Figure 4). The uncertainty in measurements was estimated at ±1.4 m/year after the breach period, reflecting the increased complexity and variability introduced by the breach's impact on the coastal dynamics.

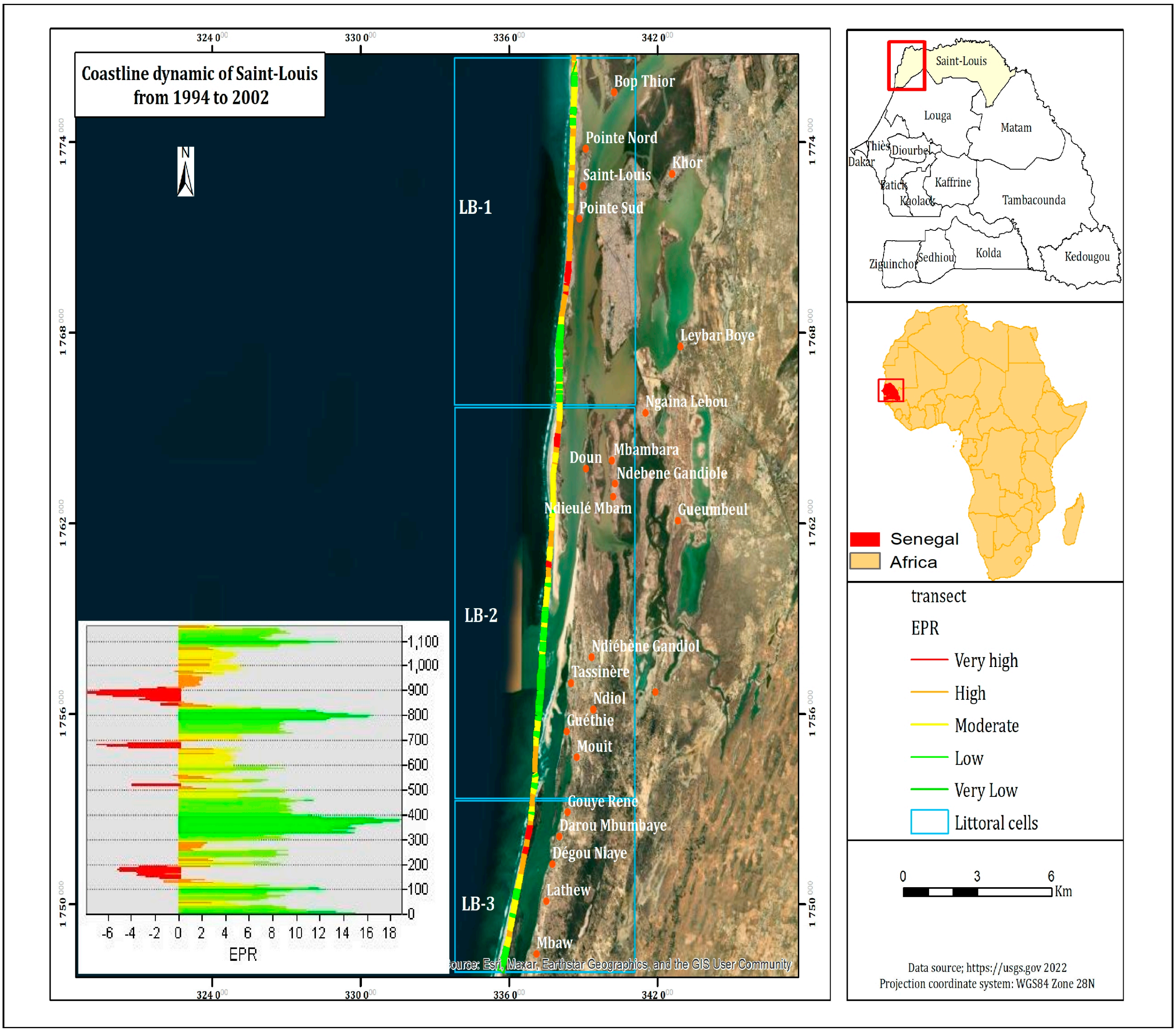

Figure 3. Coastline dynamic of Saint Louis from 1994 to 2002.

During the period spanning 2012 to 2022, dynamic rates were documented for LB-1 (−1.5 m/year), LB-2 (14 m/year), and LB-3 (1.3 m/year). In the northern region of LB-1 during this timeframe, a dynamic rate of approximately −0.11 m/year was recorded. Simultaneously, the southern region of LB-1 exhibited a buildup, with a dynamic rate of 3.64 m/year. Downstream of the Langue de Barbarie, evidence of a dynamic rate of 1.3 m/year was observed. Considering the entire studied region, the average dynamic rate is projected to be −2.7 m/year after the breach opens, emphasizing the sustained impact of the breach on the coastal dynamics across all examined locations (Figure 5). These findings underscore the ongoing and complex changes in coastal dynamics, particularly in response to the breach's continued influence.

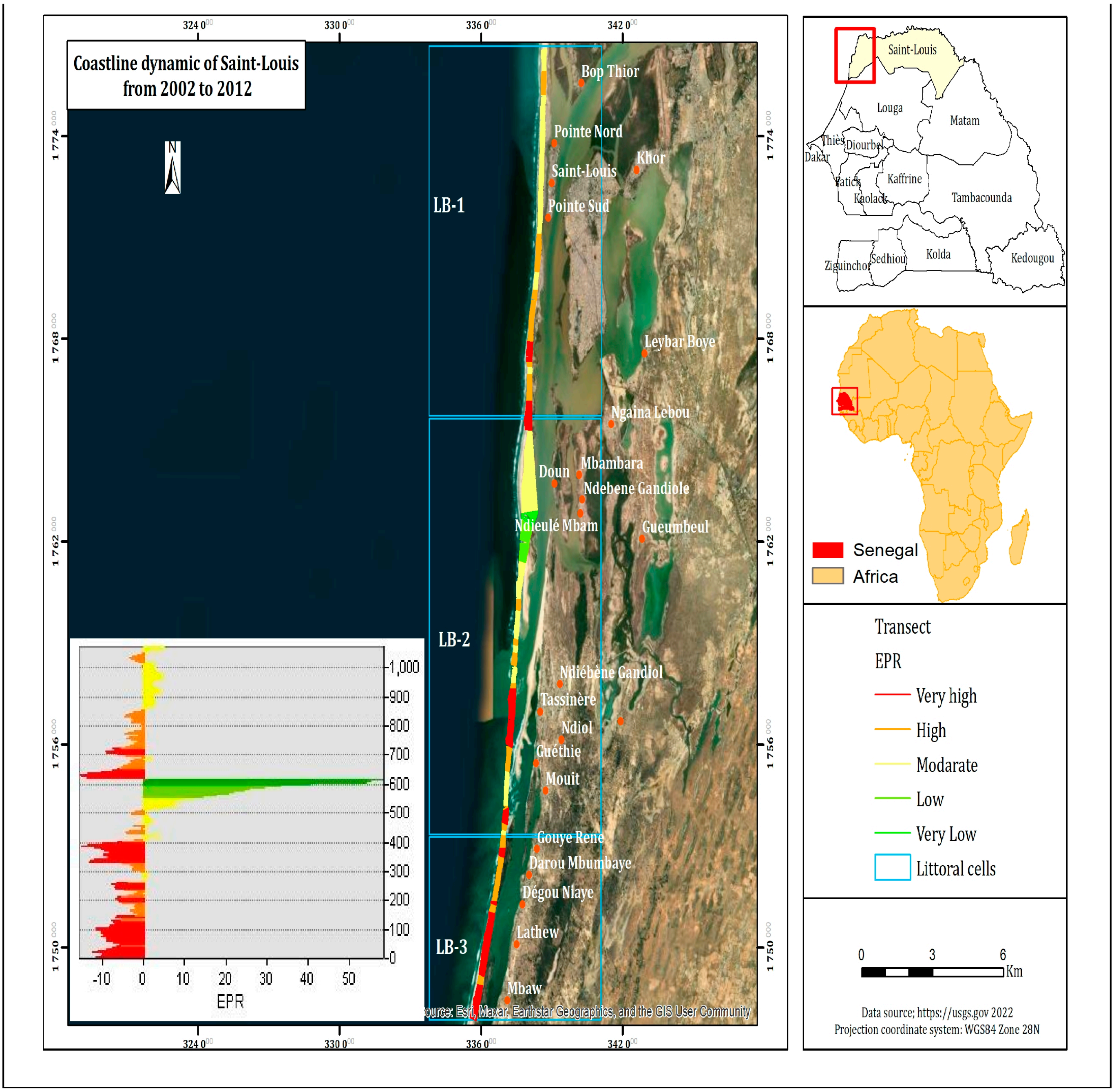

Figure 4. Coastline dynamic of Saint Louis from 2002 to 2012.

5.3. Forecasted Coastline Position and Lost and Accreted Areas (2032–2042)

The summarized table encapsulates all results pertaining to the prediction of future coastline positions, including lost and gained areas, with forecasts for 2032 and 2042. Utilizing the merging technique in ArcGIS, predictions for future dynamic rates and eroded and accumulated areas were derived. The coastlines of 2022, 2032, and 2042 were amalgamated through the merging technique using the tool Arc Toolbox, and the resultant shapefile was converted into a polygon, facilitating the calculation of lost or gained areas along the beach [49].

In 2032, LB-1, LB-2, and LB-3 are anticipated to record dynamic rates of −11.5, 84.1, and −26.8 m/year, respectively. The estimated eroded areas are projected to reach 571,458 m^2, while the accumulated areas are predicted to be 76,191 m^2. Looking ahead to 2042, LB-1, LB-2, and LB-3 are projected to experience dynamic rates of −23, 168.2 and −53.6 m/year, respectively. The calculated eroded areas are expected to reach 1,021,963 m^2, while the accumulated areas are forecasted to be 94,930 m^2. These projections underscore the anticipated changes in coastal dynamics and the areas affected by erosion and accumulation in the specified timeframes.

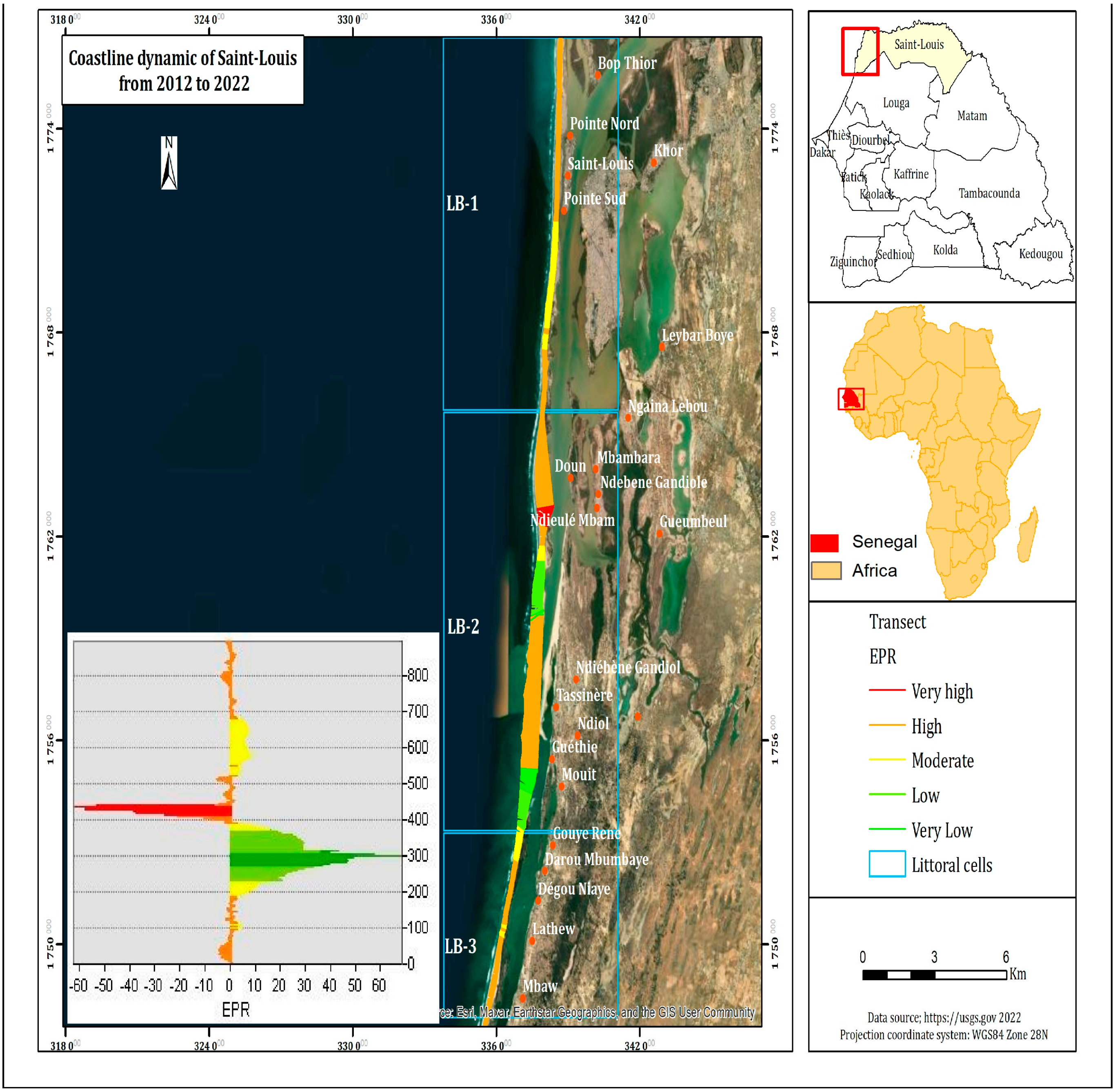

Figure 5. Coastline dynamic of Saint Louis from 2012 to 2022.

6. Discussion

In West Africa, abundant sand reserves and strong wave-induced coastal drift have favored the formation of numerous sand spits (Volta River Delta Spit). However, in the vicinity of certain river mouths, the interaction between fluvial processes and north–south coastal drift has resulted in a more or less complex formation [1].

Because of its estuary morphology, the Langue de Barbarie is one of the most exposed and vulnerable coastal zones to erosion in West Africa. It is undergoing profound changes to its hydrological and sedimentary balance [12]. Sediment dynamics are dominated by strong wind and marine erosion, leading to the silting up of basins and the reconfiguration of the river mouth. The intertidal zone is expanding rapidly. As a result, the dynamics of the Saint Louis coastline are markedly different from those observed on other Senegalese coasts [12]. The sandy spit has acted as a natural protection for the beach against hydrodynamic agents and has prevented the rapid evacuation of water from the river during periods of flooding [6].

Coastal development in the Saint Louis region is closely linked to the complexity of the Senegal River estuary, with a river regime closely linked to the seasonal distribution of rainfall in the upper basin. Two opposing forces are at work: the flow of the river and the amplitude of the tide, which attempt to dominate most of the year [13]. Consequently, from 1994 to 2022, two periods can be considered: before (1994–2002) and after (2002–2022) the opening of the breach. Before 2003, the dynamics were directed by hydrodynamic, climatic, and geomorphological agents. These hydrodynamic agents play an essential function in coastal dynamics. For example, wave, tide, storm surge, and nearshore currents combine and interact with coastal land. These hydrodynamic agents contribute to coastal erosion [50].

Waves redistribute sediments, create erosional structures like sea cliffs, and form depositional features like beaches and spits [51]. Ocean currents have a considerable impact on sediment movement, erosion, and deposition along coastlines. They can damage shorelines or aid in beach nourishment by transporting sediments [52]. Tidal changes affect water levels, sediment transport, and erosion patterns. High tides can cause coastal flooding, and low tides expose intertidal zones [53]. The LB sand spit is mostly the consequence of continual sedimentation from the subsurface to the present. The formation of the various geomorphological and geological units follow multiple sequences, including subsidence tectonics, eustatic movements, and quaternary climatic oscillations, as evidenced by the delta's continual sinking. As a result, the lower delta of the Senegal River has been sculpted by several eustatic motions and climatic cycles [43].

Before the opening of the breach, the dynamic rate averaged 4.9 m/year, with a margin of error of 1.9 m/year. At 4.4 m/year, LB-1 had the highest erosion rate, followed by 5.9 m/year for LB-2 and 4.4 m/year for LB-3. These dynamic rates are comparable to those reported in studies assessing the dynamic coastline of the LB. Ndour et al. (2018) [54], for example, calculated that the average dynamic rate in the LB was −4.2 m/year in the upstream segment and −3.7 m/year, −2.7 m/year, and −4.4 m/year in the downstream segment at these locations [54].

Sand spits are elongated landforms formed by the deposition of sediments carried by longshore currents. They generally extend from the coast towards the sea. If the breach causes an increase in sediment discharge downstream, it can lead to the growth of the spit by adding sediment to the spit. Conversely, if the breach causes erosion and loss of sediment, the spit may shrink or degrade [55].

In terms of hydrographic implications, the breach helped to prevent flooding by allowing the river to reach the ocean more easily. However, due to the breach, marine currents have significantly altered the hydrological regime. Because of the tide's strong rising effect, water levels are now determined by its rhythm [16]. Significant changes in coastal hydrodynamics, including tidal patterns, have been observed. During high tides, ocean levels rise dramatically, whereas river flows are significantly evacuated during low tides. The area is under jeopardy from increased coastal erosion [17].

The breach has increased salinity in the water table, rendering gardens unusable. Furthermore, the loss of mangrove stands, an environment that provided fish breeding grounds, as well as the change in water pH have had an impact on fishing activities [18]. Furthermore, the Senegalese lower estuary is at a crucial juncture in its history as a result of the accumulation of various risk factors, including the development of a marine dynamic and over-salinization of both the land and the water. Extreme coastal erosion has rapidly altered the morphology of the LB sand spit [19].

Following the opening of the breach in 2003, the hydrography of the region changed. In addition, the Langue de Barbarie sand spit is currently undergoing insularization following the opening of a breach. As a result, in some parts of the coast, the dynamics of the coastline have become faster than before the breach [39]. The breach is posing a threat to agriculture and freshwater drinking water resources as it continues to spread and migrate southward, exposing numerous settlements to wave erosion, marine submersion, and saltwater intrusion [56]. The average rate of change over all the zones is −1.5 m/year (Figure 4). This rate is also in agreement with the rates found in certain studies [57] (−1.9 m/year), [58] (−1 m/year), [34] (−0.6 m/year) [59].

This situation can be explained by the absence of protective infrastructures, such as walls and vegetation cover, which were in place several decades ago. In addition, it can also be explained by changes in the sand supply along the coast and the growing urbanization of the shore. Since the artificial breach first opened, its gradual enlargement has been connected to the instability in the downdrift zone [54]. A study shows that the advancing sea has gradually caused large areas of land in the Langue de Barbarie to disappear [36]. The sea has now invaded some houses in Goxu Mbathie, Get Ndar, and Santhiaba. As a result, some protective structures have been affected. At Guet Ndar, for example, the protective wall had been completely buried for more than 30 years. In addition, economic activities such as fisheries and processing plants located on the maritime fringe have been affected. The vegetation that protected the Langue de Barbarie beach has also declined significantly [59].

In addition, with the impacts of dredging activities in the management of breaches, a moderation of the coastline dynamics was observed from 2012 to 2022. The average dynamic rate over this period was around 1.5 m/year instead of 4.9 m/year for the period 1994–2002, which indicates that the coastline has been eroding rather than accreting. However, there is considerable variability between sites. LB-2 records an estimated accretion rate of 2.8 and 14 m/year for the periods 2002–2012 and 2012–2022, respectively. These rates are similar to those found in a study by Ref. [60]. Shoreline dynamics were estimated at 12 m/year in the LB-2 zone. LB-1 experienced some erosion of −0.8 m/year, and LB-3 recorded the highest erosion rate, estimated at −6.6 m/year. The uncertainty associated with the average erosion rate over this period is ±1.4 m/year. With such uncertainty, the average dynamic rate from 2012 to 2022 was approximately 4.59 m/year. Estimated accretion rates for LB-2 are the highest at 14 m/year, followed by LB-3 at 1.3 m/year, and some erosion for LB-1 at −1.5 m/year.

Forecasts have been made of future coastline positions and areas eroded and accumulated in 2032 and 2042. According to the data, areas LB-1, LB-2, and LB-3 will record −11.5, 84.1, and −26.8 m/year, respectively, in 2032. On the other hand, in 2042, LB-1, LB-2, and LB-3 will record −23, 168.2, and −53.6 m/year (Table 3). Eroded areas have been calculated to be 571,458 m^2 in 2032 and 1,021,963 m^2 in 2042, and accumulated areas should be 67,191 m^2 in 2032 and 94,930 m^2 in 2042 (Table 3). These future positions of the coastline and eroded areas will have an impact on socio-economic activities such as fishing and tourism and will result in a number of economic losses. Human settlements along the coast, particularly at Goxu Mbathie, Santhiaba, and Guet Ndar, will be affected, causing considerable damage, especially as relocation will be difficult, if not impossible.

Table 3. Future coastline positions, accretion, and lost areas of Saint Louis's region in 2032 and 2042.

Future Coastline Position in 2032 (m/Year)			**Future Coastline Position in 2042 (m/Year)**			**Forecasted Accretion (m^2)**		**Forecasted Erosion (m^2)**	
LB-1	**LB-2**	**LB-3**	**LB-1**	**LB-2**	**LB-3**	**2032**	**2042**	**2032**	**2042**
−11.5	84.1	−26.8	−23	168.2	−53.6	67,191	94,930	571,458	1,021,963

In response to the genuine threat of coastal erosion in West Africa, particularly in estuarine regions where rivers meet the sea, there is a pressing need for enhanced protective measures [51,61]. Traditional approaches focused on the "stabilization" of the shoreline's cross-shore position and shape have proven to be insufficient for comprehensive coastal management due to the intricate dynamics at play [62]. For instance, in Saint Louis, local communities residing along the Langue de Barbarie's coast have resorted to using sandbags as a makeshift defense against coastal erosion. In 2012, the Senegalese government, through its Ministry of Environment, initiated the installation of aligned tires as another protective measure. However, these interventions have demonstrated inefficiency in addressing the long-term challenges posed by coastal erosion. Recognizing the heightened risks associated with human densification and the rapid retreat of coastlines in West Africa, some planned relocation activities have been reported [56].

In the aftermath of disasters, communities often form councils and district committees to plan the relocation of exposed communities, along with providing emergency aid and adaptation measures. Such relocations involve the more or less permanent abandonment of high-risk areas in favor of newly established, safer locations [63]. The Saint Louis Emergency Recovery and Resilience Project, backed by the World Bank, exemplifies a proactive approach. By facilitating the relocation of thousands of people residing in high-risk coastal erosion zones, the project aims to enable them to prepare for the escalating and more intense impacts of climate change. This initiative not only supports planned relocations but also contributes to enhancing urban and coastal resilience across the broader Saint Louis area [64].

7. Conclusions

In conclusion, the coastal dynamics of the Saint Louis region, particularly the Langue de Barbarie, present a distinctive vulnerability to erosion influenced by a complex interplay of natural factors. The region has experienced significant changes in hydrological and sedimentary balance, with two distinct periods observed before and after the opening of a breach in 2003. Prior to the opening of the breach, natural agents stimulated the dynamics, resulting in an estimated accretion rate of 4.9 m/year. Post-breach, accelerated erosion, exacerbated by factors like urbanization and the absence, of protective infrastructure, has been observed, with an average dynamic rate of -1.5 m/year across all zones. This difference in terms of dynamic rates is due to human activities, through the opening up of the gap, the modification of the river flow, and the impacts of climate change through the modification of hydrodynamic agents. Projections for 2032 and 2042 indicate substantial challenges, with eroded areas reaching significant magnitudes, impacting socio-economic activities and human settlements along the coast. Recognizing the urgency to address coastal erosion, traditional stabilization methods have proven insufficient. Current local interventions fall short in addressing long-term challenges. Planned relocation activities and the Saint Louis Emergency Recovery and Resilience Project, supported by the World Bank, exemplify proactive measures. By facilitating community relocations and enhancing resilience, these initiatives represent crucial steps in mitigating the detrimental effects of coastal erosion in the Saint Louis region and serve as models for addressing similar challenges in vulnerable coastal areas.

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