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Review

From Flood Mitigation to Environmental and Socioeconomic Disruption: A Case Study of the Langue de Barbarie Sand Spit Breach

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Abstract: In October 2003, an artificial canal was dug across the Langue de Barbarie sand spit at the mouth of the Senegal River to prevent the city of Saint-Louis (Senegal) from being submerged by floods. This study aimed to explore the multiple facets of this sudden environmental change to provide a holistic overview of the situation and a better understanding of man-made alterations of coastal features, a crucial step for implementing efficient management of such situations and developing appropriate mitigation and adaptation policies. Satellite imagery from the US Geological Survey was used to show the historical evolution of the breach, and a comprehensive overview of the existing literature was conducted to explore its hydrological, geomorphological, ecological, and socioeconomic impacts. Although the canal facilitated the rapid evacuation of floodwaters and saved the city from a major flooding event, the breach widened considerably, becoming the new river mouth and resulted in unforeseen adverse consequences. Environmental consequences included the partial dismantling of the spit, increased tidal range, salinization of land and water, and loss of habitat and local biodiversity. Socioeconomic consequences were severe, including the loss of agricultural land and reduced yields, declining fishing productivity, the destruction of villages, the displacement of entire communities, and the forced migration of many young people. Affected communities developed resilience strategies, with women playing a leading role in these adaptive responses. This study highlights the need for integrated coastal management and policies that consider both environmental and human factors, as well as for future research that will help improve the management of coastal ecosystem alterations.

Keywords: Senegal River delta; Langue de Barbarie spit; spit breaching; tidal amplification; coastal erosion; remittance; environmental migration

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1. Introduction

Human activities can significantly alter the Earth's landscapes and ecosystems, with the resulting changes often having detrimental effects on both natural environments and human well-being. These alterations can cause a variety of disturbances, including deforestation, modification of freshwater flows, habitat destruction, various types of pollution, soil and landscape degradations, the introduction of invasive species, and changes in climate patterns and ecosystem functions, all of which have the potential to lead to catastrophic consequences [1–4]. This study focuses on coastal regions where human-caused changes have a significant impact on fragile ecosystems and the communities that depend on them. Coastal regions constitute the interface between land and sea, and are among the world's most dynamic and biologically diverse ecosystems. They are more densely

populated than the hinterlands and provide a variety of social, economic, and ecological benefits [5–7]. However, they are extremely vulnerable and susceptible to perturbations caused by human activities, such as infrastructure development, urbanization, resource extraction, and climate change. Sand spits along coastal regions are particularly vulnerable to environmental factors, such as wave erosion, storm surges, and sea level rise, as well as alterations resulting from anthropogenic activities, including human settlements, infrastructure development, marine-related activities, and the installation of tourist facilities [8–10]. Such disturbances may hamper sand spits' ability to serve as a barrier and shield the mainland from different marine hazards.

That's why it is becoming increasingly important to have programs that continuously and effectively monitor coastal zones. Remote sensing has become a popular method for achieving this. Sensors mounted on various platforms (e.g., satellites, aircraft, Unmanned Aerial Vehicles) enable effective monitoring of coastal areas [11–13]. Multitemporal satellite imagery provides a time series covering several decades, thus allowing for effective monitoring of shoreline changes [14–18]. Remote sensing is also increasingly used for various coastal studies, including coastline extraction [19,20], the monitoring of coastal erosion [14,17], including sand spit breaches [21,22], coastal hazards [23], sand spits and other coastal landforms [20,21,24], and the study of estuarine systems [25,26]. Recently, the advent of unmanned aerial vehicles (UAVs, also known as drones) has led to the availability of new tools for coastal studies [27,28]. Drones are used in a wide range of applications, including the mapping of coastline evolution [29–31], the monitoring of coastal changes [32,33], coastal topography [34,35], coastal management [36,37], coastal ecosystems [38,39], the identification of coastal land use and land cover types using satellite image classification [40,41], and coastal pollution [42], to list a few applications.

One notable example of human-induced alteration of coastal morphology is the opening of a breach in the Langue de Barbarie sand spit. Located at the mouth of the River Senegal, this sand spit is a thin strip of land that has been shaped over the centuries by both natural and human interactions. The spit plays a key role in the coastal dynamics, biodiversity, and local livelihoods of this region. However, a single event, namely the opening of a breach across the sand spit, has significantly altered its form and function. Various aspects of this case have been studied separately in a large body of literature.

The objective of this paper is to provide a holistic view and a comprehensive understanding of the various aspects of this human alteration of the sand spit. As a case study, we describe the geographical setting of the study area and review and summarize the evolution of the Langue de Barbarie sand spit at the mouth of the Senegal River by combining satellite image analysis with the most up-to-date information from the literature. The expected outcomes of the study include advancing the understanding of coastal morphology and human-environment interactions to predict coastline behavior, assessing the impact on communities whose livelihoods depend on coastal resources, monitoring the effects of the breaching on local ecosystems and biodiversity, and providing the basis for developing sustainable coastal management plans.

2. The Study Area

2.1. Geographical Features of the River Senegal Estuary

The River Senegal Delta is located in the northwest region of Senegal and the southwest region of Mauritania (Figure 1).

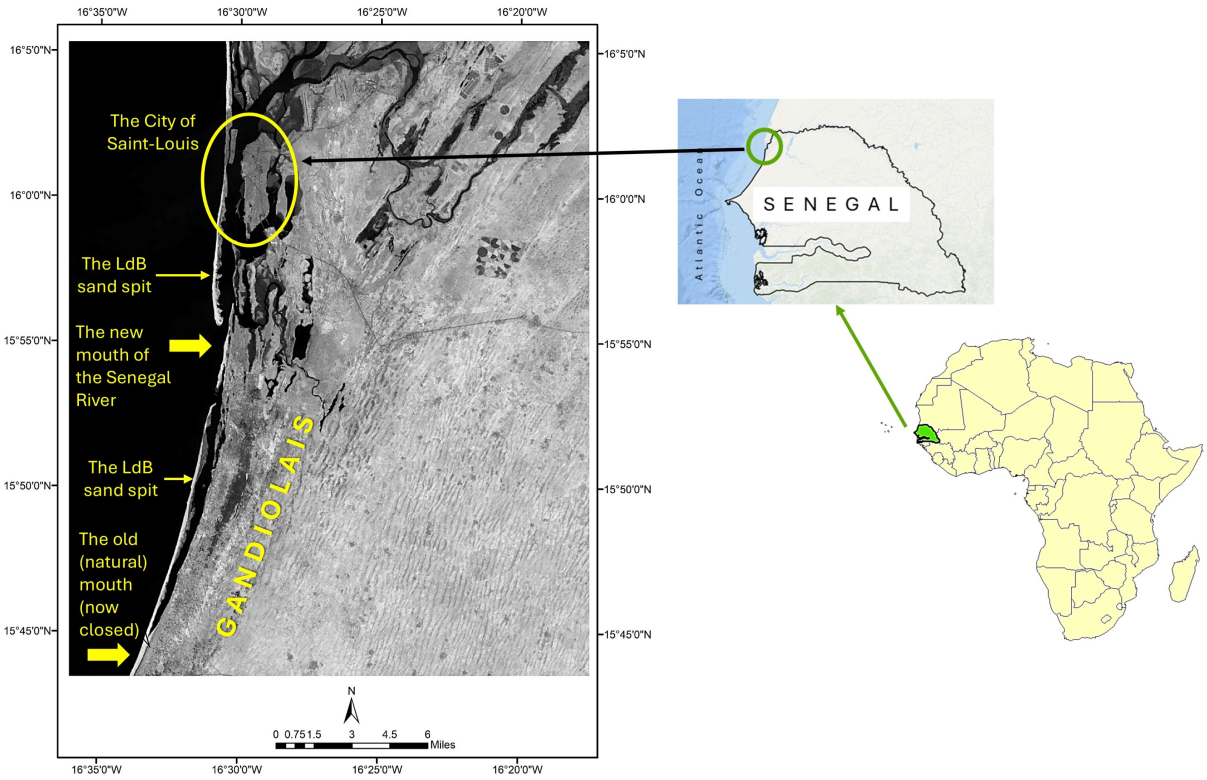


Figure 1. The study area: lower delta of the Senegal River (northwest of Senegal, in the Saint-Louis City area).

The hydrography of the delta consists of a complex network of channels. The river splits into several streams, including the main channel (the River Senegal) and secondary streams such as the Lampsar and the Gorom. Upstream of the City of Saint-Louis, all streams converge into the main channel, and the river flows southward along the Langue de Barbarie sand spit before reaching the mouth [43,44]. In addition to the hydrologic network, the estuary comprises a variety of features, including brackish lagoons, sandbanks, mudflats, sandy shoals, tidal flats, various types of dunes, terraces, and mangroves [45–47]. This diversity is explained by the dynamic interaction between the river and the Atlantic Ocean [48,49]. High sediment loads prevail during the rainy season when stronger river flows occur (July to October), while there is reduced sediment transport during the longer dry season (November to June) due to lower flows [21,50].

The estuary is home to a wide variety of ecosystems and habitats. Wetlands, especially those surrounding mangroves, provide nesting areas for migratory birds, spawning grounds for fish and shrimp, as well as coastal freshwater lagoons, tidal marshes, seasonal swamps, and sandy beaches, which are important nesting ecosystems, particularly for sea turtles [51,52]. Nutrient-rich cold water upwelling increases fish diversity [52], and the Senegal River delta plain provides extensive arable land [24].

The hydrologic regime of the estuary is strongly influenced by seasonal variations and Sahelian climate variability, which are primarily driven by the dynamics of the West African monsoon. From 1960 to 1990, a drought severely affected the entire Senegal River basin [53,54], prompting the construction of the Diama Dam in Senegal and the Manantali Dam in Mali (in 1986 and 1988, respectively). In the 1990s, when wet conditions returned, these dams did not entirely prevent floods in the Senegal River valley [55]. Partial floods occurred in 1994, 1997, 1998, 1999, and 2003 [56,57].

Several other factors characterize the hydrology of the River Senegal estuary. Due to locally generated wind waves and a dominant component of long, medium to high-latitude

swell waves, the Senegal River mouth has a unique hydrodynamic environment [58]. Swell waves and tides affect the current hydrodynamics of this tidal river mouth. Swell waves refract across the continental shelf and approach the coast at an oblique angle, creating a north-south drift current [59,60].

Although the region is not directly impacted by major storms or cyclones, it is exposed to distant, oblique, and highly energetic waves originating from higher latitudes in the North Atlantic [9,52]. These waves contribute to one of the highest coastal drifts in the world [9,58]. In fact, the River Senegal Delta is a wave-dominated system in which the river's floods exceed the marine swells during only two to three months of the year [61,62].

The Diama Dam, built from 1981 to 1986, plays a crucial role in the estuary's hydrodynamics. The dam lies 23 km upstream from the City of Saint-Louis in the lower Senegal River valley. Currently, tidal waves and dam releases strongly influence the current hydrodynamics of the lower estuary [63,64]. The hydrological regime changes caused by the dam have influenced morphology, sedimentology, and ecology [65–67]. Reduced sediment output, especially near the river mouth, has destabilized the estuary system [51,56]. Regular water flow to the ocean has been hampered by the silting up of the riverbed caused by dysfunction in the river's hydrological regime and modifications to the morpho-sedimentary processes [66,68].

2.2. The Langue de Barbarie Sand Spit

The "Langue de Barbarie" is a 30-km-long coastal sand spit that diverts the lower Senegal River southward. The spit has a width of 100 to 400 m, a slope of 3 to 4%, and a height of just 2 m. Its length has varied throughout the previous century, ranging from 10 to 40 km [69]. The spit separates the terminal section of the Senegal River from the Atlantic Ocean (Figure 1) and serves as a natural barrier, protecting the City of Saint-Louis and the villages of the Gandiolais region [70]. It consists of three sectors: a coastal section swept by the swell, a wind-influenced dune region, and a fluvial sector or interior coastline susceptible to fluvial dynamics [47,51,69].

The development of the sand spit is attributed to beach nourishment and the transport of sediment caused by longshore drift from the north [71]. This drift is mainly influenced by the prevailing northwestern winds and high waves [69,71,72]. The waves advancing toward the Barbarie coast change direction due to refraction over the continental shelf and approach the coast at an oblique angle, creating a north-south drift current. The speed of this current ranges from 0.13 to 0.57 m/s, leading to the movement of a large amount of sediment towards the south [51]. It dumps sand on the beach along the Saint-Louis coast at a seasonal rate [48]. Multiple sediment transport estimations have been made. Many studies have shown that a significant amount of sand, ranging from 365,000 to 1,500,000 cubic meters per year, is continuously transported by marine drift and aeolian flows along the Langue de Barbarie, thereby fortifying the coastal dune that acts as a barrier between the Atlantic Ocean and the hinterland [73,74]. Kane (1985, 1997) estimated that 600,000 m^3 of sediment are carried to the Langue de Barbarie's forefront annually, based on topographical measurements and the annual average spit extending southward [66,75]. Previously, Barusseau provided estimates of the annual sediment transport amount, with values ranging from 223,000 to 495,000 m^3 for materials with dimensions varying between 0.1 and 0.5 mm [71].

A distinct feature of the Senegal River mouth is a turbid plume formed by the discharge of continental suspended sediments on the internal coast of the river sector. Michel et al. (1993) estimated that the sediment load varies between 106 tons in low flood and 2.8 106 tons in very high flood [65]. The suspended sediments consist primarily of clay, with smaller quantities of fine silt and coarse silt [46,66]. The evolution of the Langue de Barbarie

spit is driven by the simultaneous deposition of marine materials on its Atlantic side and river sediments on its opposite side. Both feeding mechanisms exhibit varying levels of activity, which are influenced by the tidal density and the condition of the river [64].

The Langue de Barbarie beach experiences both accretion and erosion processes [24,69,74]. The accumulation of sand along the shoreline can be attributed to marine dynamics that transport sandy sediments coming from the river mouth. An examination of shoreline changes between 1978 and 2018 indicated that erosion occurred along 65.04% of the coastline, whereas accretion occurred over 10.32% [69,76]. Between 2000 and 2018, the average erosion rate along the spit was estimated at 0.35 m per year, reaching up to 0.69 m per year in certain areas [57]. The maritime side of the spit has strengthened due to the intensification of accretion processes and the decrease of the fluvial water discharge caused by the construction of the Diama Dam [74]. Factors that have influenced the erosion and accretion processes include human activities (particularly the construction of river dams and coastal infrastructures) and changes in wave patterns [9,72,77].

Numerous breaches of the Langue de Barbarie spit have resulted from the interaction between fluvial and marine-induced sedimentary regimes (floods of the Senegal River, strong swells, and coastal erosion), which have significantly altered the characteristics of the estuarine zone [74,78]. The mechanism is described as a cycle by Gac et al. as follows: as the unstable and fragile sand spit lengthens, the river estuary migrates toward the south; the spit subsequently becomes vulnerable upstream and can be eroded and submerged by river flows in its most sensitive areas, or it can break under the pressure of the marine waves, causing the river mouth to shift back north; after each rupture, the spit reconstitutes itself and relentlessly resumes its southward progression [48]. Between 1850 and 1973, 24 natural breaches were documented, with 13 of these breaches occurring between 1900 and 1981 [48,74,79,80] 4. The frequency of intrusions has been 14 years, as indicated by historical documents and maps [46,48]. Nevertheless, the chronology of recent breaching occurrences indicates a reduced periodicity of six years between 1900 and 1973 [9]. The transient breaches, which occurred south of the City of Saint-Louis, were subsequently sealed by a substantial supply of sand from the littoral drift and contributions from the river sediments [64,74,81]. The breaches have been a significant factor in mitigating flood risk in Saint-Louis City, as they have enabled the rapid evacuation of river waters to the ocean until they were closed [81]. The sand spit breaches did not last long, and during such periods, the terminal mouth became narrower because of sand accumulation in shallows and banks, and the southernmost section of the lower reach transformed into a lagoon [74,82]. The absence of natural breaches since 1973 is mainly due to two factors: (i) there were no significant floods, and (ii) the servicing of the Diama dam since 1986 has resulted in the regulation of the river flows [9,51,83]. Consequently, the spit has extended towards the south following the littoral drift, along with the Senegal River mouth shifting farther away from Saint-Louis City [48,71,81]. In the past, the river mouth was situated close to the city, with distances ranging from 2.5 km in 1658 to 4.5 km in 1790, 3.4 km in 1850, and 4.5 km in 1854–1856 [48,49].

The Langue de Barbarie spit stretches southward and narrows over a 30-to 35-year cycle [21,84]. The spit's extension rate varies seasonally. The spit swiftly grows southward during the dry season, corresponding to a period of low river water flow. During the rainy season, the spit's expansion slows or pauses due to increased beach erosion caused by higher river flows that carry sediments into the Atlantic Ocean [43,85]. Various stages of the coastal spit's elongation have been documented: a gradual lengthening from 1890 to 1913 at a rate of 350 m per year, followed by a more rapid growth rate from 1913 to 1950, and periods of very little change [64]. After the breach in 1973, the length of the spit increased by 12.5 km, with a growth rate of 400 m per year [9]. Between 1986 and 1990, with the

activation of the Diama Dam, the Senegal River mouth shifted southward by a distance exceeding 2.8 km [74]. In 2003, it was located approximately 30 km south of Saint-Louis. The gradual southward migration of the river mouth further exacerbated the effects of floods that resurfaced in the 1990s. Due to the growing challenge of water evacuation downstream, the floods lasted longer, resulting in Saint-Louis City being inundated for several consecutive days each time [81]. However, it is worth noting that following the opening of the artificial canal in 2003, coastal areas previously exposed to marine hazards due to this initiative were subsequently protected by the renewed lengthening of the sand spit and the associated southward migration of the new river mouth [57,86]. In 2011, this migration rate was estimated at 300 m/year on average [80].

The Langue de Barbarie is an unstable strip of land [9,20,72]. It has one of the country's highest population densities and is heavily urbanized with human settlements, artisanal landing ports, tourism amenities, and an environmentally valuable national park. Tourism, market gardening, and fishing are the primary economic activities [43,85]. The urbanization of the sand spit, resulting from intensive and unplanned settlement, has disrupted the natural sedimentary process and destroyed many dunes, thereby reducing the spit's protective barrier function. In addition, sand extraction by populations has caused beach imbalances when the sedimentary supply is insufficient [10,87]. The Langue de Barbarie spit is vulnerable to floods, storm surges, rising groundwater levels, and coastal erosion due to rising sea levels, which cause 5–6 m of beach loss per year [88]. With rising sea levels, waves have destroyed houses, cemeteries, and other buildings and undermined the fishing industry in this highly populated coastal area, affecting vulnerable populations. The natural fragility of the sand spit was exacerbated following the construction of the Diama and Manantali Dams, which strongly reduced the river sediment supply [79].

2.3. The City of Saint-Louis

The city of Saint-Louis is located in the estuary of the Senegal River, approximately 30 km from the former river mouth (Figure 2). Saint-Louis has a distinctive geographic location, surrounded by the Atlantic Ocean and the Senegal River. In 2000, Saint-Louis, which is commonly referred to as the "Venice of Africa" was designated a World Heritage site by the United Nations Educational, Scientific, and Cultural Organization (UNESCO).

The city is divided into three main components:

a. The Ndar island, also known as the colonial city, is a narrow strip of land surrounded by the Senegal River, measuring approximately 2.3 km in length and with a width that ranges from 450 to 200 m. The island barely rises above the average river level: more than 40% of the island's area is below 1.5 m, and very low areas along the river can easily allow water to flood within the city during significant floods. The flood alert level is at 1.20 m IGN, a threshold at which the colonial city begins to flood at its northwest and northeast ends. Note that alert level heights are determined based on the current Senegalese geodetic system established by the IGN (Institut Géographique National Français) in 2006 [81].
b. As described in the previous section, the Langue de Barbarie is a narrow sand spit oriented North-South, which stretches over roughly 40 km and has always served as a protective shield for the City of Saint-Louis and the entire lower Senegal delta plain.
c. The District of Sor, located in the eastern part of the city, is the mainland component, comprising low-lying lands with barely perceptible altitudes close to sea level, ranging from –0.3 m to 3.5 m, and surrounded by tidal marshes.



Figure 2. The City of Saint-Louis and a portion of the Langue de Barbarie sand spit. (Image source: consulmar.pt, accessed on 12 January 2024).

Surrounded by water, the City of Saint-Louis is vulnerable to various environmental hazards, including intense coastal erosion and recurrent flooding.

- Coastal erosion: A 2019 World Bank report estimated that coastal erosion costs the nation of Senegal more than half a billion dollars every year [89]. According to UN-Habitat, Saint-Louis is the city that is most threatened by rising sea levels in Africa. In recent years, the sand spit has been affected by sea level rise and intense coastal erosion, resulting in the shoreline's retreat. Over the past decade, ten meters of beach have disappeared in the urbanized section of the spit. This situation is exacerbated by rapid urban growth, leading to an intensive and unplanned settlement of populations along the coastal strip, which has eliminated many sand dunes, thus considerably reducing the protective barrier function of the sand spit [57].
- Recurrent flooding: Much of Saint-Louis lies at an elevation of less than 2.5 m above sea level [9,60,81]. Low areas represent 53%, of which 17% have altitudes between −1 and 0 m, and 36% emerge barely above sea level, with an elevation between 0 and 3 m [63]. Therefore, the city has always been prone to flooding that affects the lower Senegal River valley during the rainy season [66,90]. Other factors explaining the city's exposure to floods include the low speed of floodwater evacuation associated with the silting up of the riverbed and the lengthening of the Langue de Barbarie, the backflow of river waters by marine waters during high tides, the lack of river dredging, the absence of an appropriate drainage network, the spontaneous and unplanned urbanization in flood-prone areas, the limited resources and lack of technical competence, and the rising sea level [68,91,92].

The flood alarm level in Sor is set at 1.75 m and 1.20 m for the peripheral neighborhoods such as Diaminar, Pikine, and Khor [51]. Notable years of flooding in this district include 1950 (1.79 m), 1994 (1.27 m), 1995 (1.20 m), 1997 (1.28 m), 1999 (2.10 m), and 2003 (1.42 m) [66,93]. The latter flood episode (2003) prompted the digging of an artificial outlet

across the narrow coastal spit, resulting in a major disruption of the preexisting natural balance in the coastal zone with unforeseen environmental impacts.

3. The Breach of the Sand Spit

3.1. Events Leading to the Breach

Many studies have documented the circumstances leading to the artificial breaching of the Langue de Barbarie sand spit. During the period from May to September 2003, heavy precipitation was recorded over the Senegal River basin, resulting in extremely high water levels, particularly at the beginning of August. During this wet period, some gauges recorded a maximum flow rate exceeding 3500 m^3/s [56]. Throughout August 2003, the persistence of heavy precipitation resulted in water heights exceeding 1 m at the Saint-Louis station. By mid-September, the Senegal River level at Saint-Louis consistently remained between 1.27 and 1.42 m IGN [47]. Given that it continued to rain heavily upstream, several flood waves occurred in late August and early September [94]. Due to the sustained rains, the maximum reservoir level of the Diama dam (2.15 m) was reached, yet additional flood waves were still propagating toward the dam [47]. This situation resulted in gradually increasing discharges of excess water from the dam, with releases exceeding 1500 m^3/s from 22 August and growing to 1800 m^3/s on 20 September 2003. Meanwhile, (i) several Saint-Louis neighborhoods, both on the island and the mainland, had already experienced a significant level of flooding; (ii) additional releases were expected; and (iii) sustained precipitation over the river basin indicated that additional flooding would arrive at the Diama dam [51,93].

In early October 2003, the water level reached 1.94 m in some of the city's mainland neighborhoods, significantly exceeding the flood alert level [44]. City managers feared that in addition to the damaging effects of further flooding, the rising river floods could breach the northern portion of the spit, thus resulting in the devastation of the highly urbanized sections located south of the natural opening. This dire situation sparked widespread discontent among the population and prompted the city managers to request urgent measures to alleviate the city's flooding [93,95].

On the night of 3 October, to avoid catastrophic flooding in the city, a 4 m-wide, 1.5 m-deep, and 100-m-long artificial canal was dug across a relatively narrow section of the sand spit. This relief channel was located in front of the Doune Baba Dieye island, about 7 km south of Saint-Louis City [47,92]. Improving river drainage by digging an artificial canal across the sand spit is not a new idea; it is a flood-protection strategy that has been previously proposed, often alongside accompanying measures such as dredging the river channel, installing floodgates, or building protective groynes next to the breach [51]. The opening of the artificial canal resulted in a rapid release of the floodwater, lowering the water level from 1.95 to 1 m IGN in 48 h, and 0.53 m IGN ten days later [21,51,87]. This man-made delta-mouth diversion prevented further flooding of Saint-Louis. However, the narrow artificial outlet widened rapidly [9,21].

3.2. Evolution of the Breach

As shown in Figure 3, the width of the artificial breach increased from 4 m on 3 October 2003 to 80 m two days later, 330 m 20 days later, and 800 m on 25 May 2004, while the canal's depth increased to 6 m.

The original narrow outlet had already become the new mouth of the Senegal River and will grow to more than 5.5 km between October 2012 and June 2013 after an additional natural breach caused by overwash occurred 500 m south of the new mouth, resulting in a rapid erosion of the portion of spit between this new opening and the new mouth [24,79,92]. Although the widening of the mouth has been a predominant trend, short episodes of

shortening (decrease in width) occurred in 2007, 2008, and 2009. The widening occurred mainly during the dry season when stronger NW and NNW swells resulted in intense erosion of the southern part of the mouth, while the mouth's width generally decreased during periods of high flows [81,96]. Topographic surveys revealed that between March and December 2011, the rate of retreat of the southern bank (830 m) was faster than the rate of advancement of the northern bank (550 m); the widening rate of the new mouth was 50 m per month, or approximately 1.6 m per day [97].



Figure 3. Evolution of the breach across the Langue de Barbarie sand spit from 3 October 2003 to 25 May 2004. The arrow displayed in the fourth panel (25 May 2004) indicates the direction to the offshore line. (Photos from Ibrahima Diop, Service Hydraulique de la Ville de Saint-Louis).

To illustrate the evolution of coastal changes that occurred following the opening of the artificial canal, we utilized satellite imagery obtained from the US Geological Survey. The satellite data comprised several Landsat scenes from 2003 to 2023 (Table 1).

Landsat 7 images collected after May 2003 have data gaps showing as stripes caused by the failure of the scan line corrector (SLC) [98]. The Landsat toolbox was loaded into ArcMap (a component of ArcGIS, the Geographic Information Systems software from the Environmental Systems Research Institute—ESRI), and the Fix SLC Error tool was used to remove the stripes. ArcMap's iso cluster unsupervised classification tool was used to classify Band 7 into two classes only. Landsat 7 and Landsat 8's shortwave infrared two band (Band 7) can clearly separate land and water because it has high soil and rock reflectance and a strong water absorption region. For each classified image, ArcMap's

measure tool was used to estimate the width of the Senegal River mouth. Figure 4 displays a subset of the classified Landsat images.

Table 1. Landsat satellite images used in the study.

Acquisition Date	Satellite
31 January 2003	Landsat 7 ETM
1 December 2003	Landsat 7 ETM
3 October 2005	Landsat 7 ETM
25 October 2007	Landsat 7 ETM
23 November 2009	Landsat 5 TM
13 November 2011	Landsat 5 TM
4 December 2013	Landsat 8
2 December 2015	Landsat 7 ETM
17 December 2017	Landsat 7 ETM
19 January 2019	Landsat 8
29 March 2021	Landsat 8
19 September 2023	Landsat 8
27 January 2025	Landsat 9

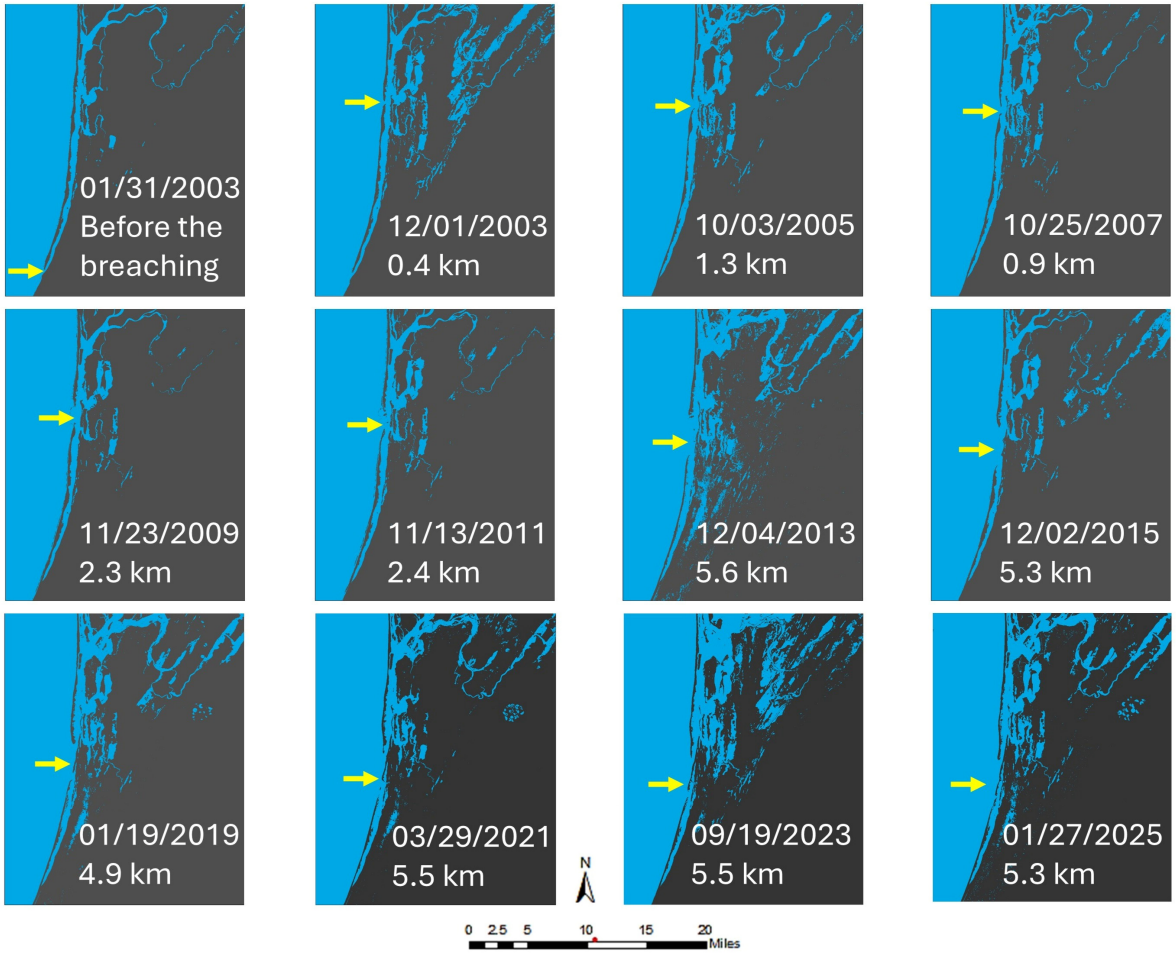


Figure 4. Evolution of the breach based on Landsat satellite imagery (2003–2025).

The evolution of the artificial canal and associated mouthwidth are consistent with the changes reported in the large body of studies dealing with the dramatic coastal changes that followed the breach event. The widening trend is evident, only disrupted by short episodes of shortening.

The coordinates of the northern and southern banks of the river mouth, collected from satellite imagery and plotted as a graph, further illustrate the widening and southward migration of the river mouth (Figure 5).

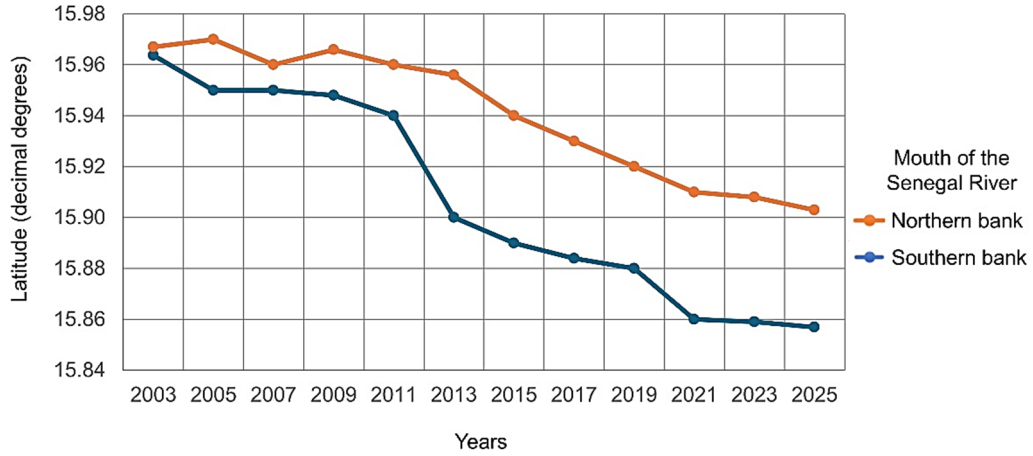


Figure 5. Widening and southward migration of the breach (the new mouth) based on Landsat imagery.

4. The Consequences

The opening of the breach across the Langue de Barbarie sand spit was a well-intended effort to reduce flood risk for the City of Saint-Louis. However, it resulted in unforeseen environmental and socioeconomic consequences.

4.1. Environmental Consequences

4.1.1. Hydrological Consequences

- Reduction in flood risk: The objective for digging the channel across the spit was reached: the new mouth, which is much closer to the City of Saint-Louis, allowed for faster evacuation of floodwaters, reducing the risk of flooding in the town. Since the opening of the channel, the maximum level of the river's floods has remained consistently below the flood level alert [81]. Moreover, the new mouth will not threaten Saint-Louis since it migrates southward, away from the city [80]. However, this came at the cost of other environmental consequences.
- Tidal amplification: The opening and subsequent widening of the breach resulted in a significant change in coastal hydrodynamics, the most notable being a substantial increase in the tidal range between the new mouth and the Diama Dam [9,63,81]. For example, the daily maximum tidal fluctuations tripled in some areas. Significant drops in river level occurred to the extent that, at low tide, it was sometimes possible to walk to the middle of the river on foot [60]. Tides now affect the lower estuary year-round, even during the rainy season, which typically coincides with the high river flow period. In the long term, such tidal patterns may undermine the wharves of Saint-Louis, the piers of Faidherbe Bridge, and the foundations of the Diama Dam [67,93].
- Salinization of water and land: Following the opening of the breach, salinity levels in both surface and groundwater rose significantly. A 77% increase in marine salinity values was observed in Saint-Louis between 2003 and 2006 [99]. The widening of the breach has exposed the lower delta directly to marine influences, considerably reducing the seasonal differences in salinity [100]. The river, now heavily influenced by marine tides, experiences saline intrusion for most of the year [51]. Samplings of water from wells in the Gandiolais indicated a significant increase in groundwater salinity between 2005 and 2012, while plots located near the Senegal River recorded

salt concentrations up to 2 g/L [51,67]. This sharp increase in salinity levels in the Gandiolais is enabled by a highly porous environment that facilitates exchanges between freshwater and saltwater [101]. The salinization of land and water has contaminated the thin layer of freshwater, made most of the western Gandiolais unsuitable for agriculture, and considerably reduced access to freshwater [80,101].

4.1.2. Geomorphological Changes

By altering the tidal dynamics and shifting the balance between riverine and marine forces, the opening of the breach led to a significant transformation of coastal and estuarine characteristics.

- Changes to river mouths
  There were two notable changes:
  - Creation and widening of the new mouth: The opening of the breach constituted a substantial alteration in the Langue de Barbarie's configuration. In a brief period, the river's mouth had relocated 30 km northward and was now situated only 7 km south of Saint Louis. The 4-m-wide canal, which was opened in October 2003, widened rapidly due to heavy flood discharge and sediment erosion, reaching 800 m in May 2004 and becoming the new mouth [9,102]. The breach further widened to more than 5 km in 2013 following an intense wave erosion of the southern section of the spit [9,84]. The new mouth has been widening and migrating southward as the northern portion of the spit is elongating while the southern part is being eroded at a much higher rate. For example, from March 2011 to August 2012, the northern part of the spit elongated at an average rate of 1.3 m per day, while the southern part retreated at an average rate of 1.9 m per day [86,103,104].
  - Closure of the old river mouth: With the rapid widening of the breach, the downriver section of the river was deprived of freshwater, and materials transported by the north-south coastal drift were no longer cleared by the ebb currents, which now flow through the new mouth. The old mouth gradually silted up and narrowed from 500 m in 2003 to 5 m in 2005, eventually closing by 2006. As a result, the terminal section of the river between the old and new mouths became a lagoon with high salinity [22,101,105]. Recent satellite imagery has shown that this southern section is now almost completely sealed, thanks to the extension of a flying spit (Figure 6).

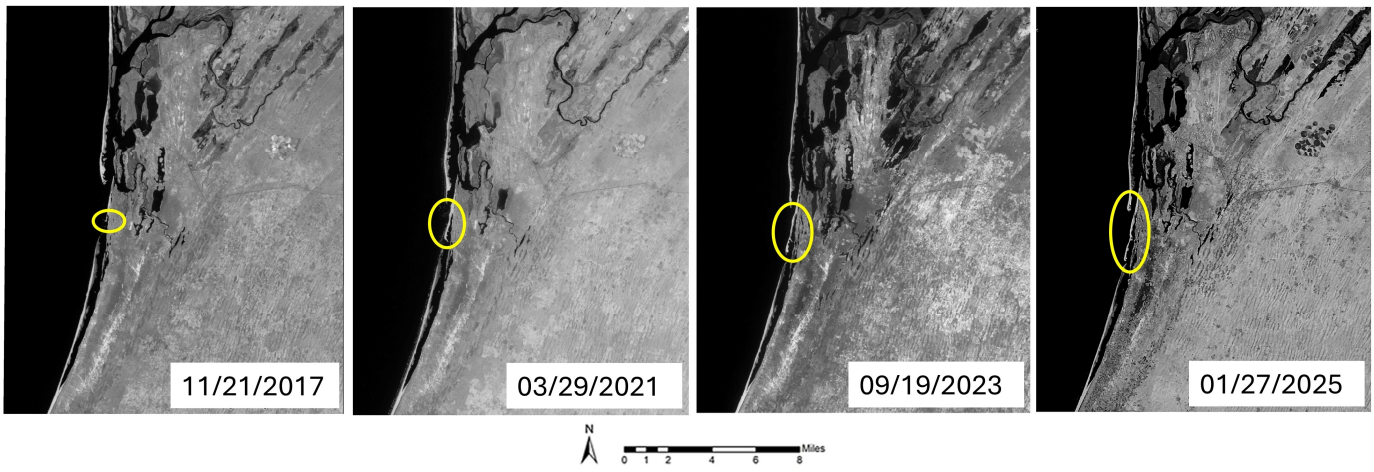


Figure 6. Evolution of a secondary spit (flying spit) at the mouth of the Senegal River based on Landsat imagery. The yellow circles indicate the location of the secondary spit.

- Coastal erosion and shoreline retreat:
  Erosion increased dramatically after the spit breaching, leading to accelerated shoreline retreat. Ba et al. (2007) [22] cited previous studies showing that before the opening of the relief breach, shoreline retreat along the Langue de Barbarie spit varied from 1 to 2 m per year [70,75,105]. Accelerated erosion occurred after the opening of the breach, with shorelines retreating rapidly. From 2003 to 2006, the erosion rate ranged from 13 to 97 m per year [22]. Coastal erosion is sectorized and more pronounced near the new mouth. For example, from 2009 to 2012, the village island Doune Baba Dieye directly facing the new mouth experienced severe erosion as riverbanks in this area had become coastlines [80,97]. From the opening of the breach to 2010, approximately 70% of the island's area was lost due to coastal erosion. During this period, the average erosion rates in this sector reached 18.6 m per year, compared to lower rates of 0.5 to 1.4 m per year in sectors farther from the new river mouth [103,104]. As the southern portion of the spit was being eroded and the new mouth migrated southward, new sectors of the Gandiolais would be directly exposed to waves and intense coastal erosion, hence experiencing problems like those ongoing at the current mouth location [80]. With the southward extension of the spit, the Doune Baba Dieye sector became less vulnerable to marine hazards. Between 2012 and 2016, its beaches experienced accretion at a rate of 12.5 m per year, thus demonstrating self-organization and coastal resilience [57,86]. Since the opening of the new inlet, accelerated erosion, and increased marine influence have threatened "l'Ilot aux Oiseaux" (Birds Island), a small Senegal River island that is a critical habitat for birds nesting located in the Langue de Barbarie National Park. Strong tidal currents have eroded the island's banks, resulting in the loss of 20% of its area between 2003 and 2007 [47]. In addition, at low tide, the island's current extent represents only 39% of its area before the breaching of the spit. This surface is reduced to 16% at high tide [106].
- Erosion of dunes:
  Entire dunes along the Langue de Barbarie have disappeared due to the combined effects of waves, wind, and a reduced sediment supply. A substantial retreat of the vegetated dunes occurred between September 2008 and May 2010 [92]. The degradation of this coastal vegetation has resulted in increased exposure of the dune system to marine hazards [47,92].
- Accretion dynamics, sediment transport, and deposition
  - Accretion: The sand transported southward by longshore currents significantly contributed to the elongation of the spit, the emergence of localized accretion zones, and the reconfiguration of coastal regions [9,20]. Accretion is particularly noticeable at the northern tip of the sand spit. Taveneau et al. (2021) found that from 2015 to 2020, the average rate of sand volume transported alongshore and captured by the sand spit was approximately 230,000 m^3 per year [21]. As the new mouth extended southward, areas previously exposed became more stable and experienced new accretion. For example, in the Doune Baba Dieye sector, accretion rates were estimated to be 12.5 m per year between 2012 and 2016 [86]. Accretion also occurred toward the ocean, resulting in a widening of the spit of roughly 100 m from March to December 2011, at an average rate of 10 m per month [97].
  - Sediment transport and deposition: The opening of the relief canal resulted in increased erosion near the breach. With the widening of the mouth, the increased energy of swells, waves, and floodwater from the Senegal River disrupted hydro-sedimentation patterns [102]. Significant alterations in sediment transport and deposition occurred because of the opening and subsequent widening of the

breach. Part of the sand from the eroded spit was carried by high water flows in the seaward direction and deposited offshore in the shallow coastal areas of the outer delta [80]. Energetic waves near the breach had a major influence on the recycling of eroded sand into river-mouth bars [20,21]. The opening and subsequent widening of the breach caused substantial alterations in sediment transport and deposition. Part of the sand from the eroded spit was carried by high water flows in the seaward direction and deposited offshore in the shallow coastal areas of the outer delta [80]. Another portion of eroded sand was transported southward by longshore currents [84]. Energetic waves near the breach had a significant influence on the conversion of a portion of the eroded sand into river-mouth bars and islets [84]. As the breach migrated southward, sandbanks were formed within the channel, expanded considerably in 2011, and became barriers, reducing the impacts of incoming marine swells and allowing the Doune Baba Dieye sector to recover progressively [96,97]. Overall, the widening of the breach had turned the new mouth into a large hub for sedimentary deposits and recycling [9].

4.1.3. Ecological Impacts

- Degradation of estuarine ecosystems and loss of biodiversity: The opening and subsequent widening of the breach caused a sudden and drastic alteration of the hydrological regime. Freshwater ecosystems declined, and marine waters became more prevalent. Estuarine ecosystems were transformed into lagoon-like systems and new saline ecosystems [51,80]. The resulting increases in salinity levels have caused modifications to the amphibian environment and estuarine ecosystems, transforming habitats, disrupting the flora and fauna of several local sites in the Gandiolais region, and affecting biodiversity. These various changes have threatened the region's biodiversity and ecosystem services [102].
- Impacts on flora
  Plant species generally suited to marine environments, such as coconut and palm trees, withered and/or died because they could not sustain the increased salinity [104]. This situation was exacerbated by the intensification of coastal erosion, which significantly degraded the vegetated dunes and the spit's coastal barrier vegetation, uprooting trees along the banks, including the "filao" trees that were planted in the early 1900s to stabilize the coastal barrier [47,104]. Increased salinity and erosion have also led to substantial mangrove degradation, negatively affecting the associated ecosystems [47]. However, some salt-tolerant plant species rapidly prospered, leading to the emergence of floristic uniformity in certain areas, which resulted in a reduction of habitat diversity and undermined the resilience of the region's ecosystem [104].
- Impacts on fauna
  The region's fauna also suffered, especially in areas that constitute wildlife sanctuaries, including the Parc National des Oiseaux (Djoudj Parc, for birds), l'Ilot aux Oiseaux (The Birds Island), and the Gueumbeul Faunal Reserve. Some freshwater species, such as fish and tortoises, have declined considerably due to the disappearance of critical habitats [102,104]. As the mouth migrates southward, Birds Island, which is a critical nesting habitat for migrating birds, is now shrinking due to erosion and may even disappear if directly exposed to ocean waves [47,102]. Conversely, the presence of marine turtles, shellfish, and oysters grew after the opening and widening of the breach [103,104].

As biodiversity in wildlife sanctuaries declines, the region's position as a protected area and its value as a tourist attraction are now at risk [104].

4.1.4. Microbial and Water Quality Changes

Microbial communities have been significantly impacted by changes in hydrological conditions. Surveys conducted in 2002 (pre-breach) and 2006 showed that increased salinity and nutrient input from marine waters resulted in a significant shift from picophytoplankton dominance to nanophytoplankton, accompanied by a sharp decrease in the abundance of heterotrophic nanoflagellate (HNF), which constitute a large fraction of the zooplankton biomass in rivers. Another significant change following the breach opening was the increase in concentrations of fecal indicator bacteria (FIB), indicating a decline in water quality and a higher health risk for nearby communities [99].

4.2. Socioeconomic Consequences

Before the opening of the breach, market gardening and fishing were the primary economic activities in Gandiolais, supporting approximately 80% of the working population. Locals not only used to cultivate various crops (such as onions, tomatoes, cabbage, potatoes, and eggplants) but also practiced freshwater and sea fishing [102]. However, the opening of the breach resulted in changes to the hydrologic regime and intense coastal erosion, which have significantly affected local communities that primarily rely on freshwater resources for consumption, fishing, and agriculture.

4.2.1. Impact on Livelihoods and Economic Activities

- Destruction of villages

  The widening of the new Senegal River mouth at the Langue de Barbarie triggered a rapid coastal erosion of the spit that previously protected the Gandiolais, directly exposing the local villages to intense marine swells. The village of Doune Baba Dieye exemplifies the catastrophic social, economic, and environmental consequences of the breach. Figure 7 shows the evolution of the Doune Baba Dieye area following the artificial breaching of the Barabarie spit. Between 2003 and 2007, the village's area decreased by 8%, with significant habitat loss and damage to community buildings. By 2012, the last inhabitants had relocated, leaving behind only remnants of walls and foundations [57,80].

  The destruction of the village forced its inhabitants to relocate to new places. However, administrative delays, lack of suitable lands for settlement, and insufficient resources for rehousing plagued the relocation process. Since resettlement locations were further inland, fishermen had to travel longer distances to access the ocean, making fishing more challenging [104,107]. However, as accretion allowed the southward elongation of the spit and associated migration of the new river mouth, the direct impact of ocean waves on the area was significantly reduced.

  This change allowed sediment to accumulate, and the Doune Baba Dieye area experienced beach accretion at a rate of 12.5 m/year between 2012 and 2016. This decreased vulnerability to marine hazards demonstrated some natural resilience, and some former residents returned to the site for vegetable farming [86]. Other nearby villages were also destroyed, severely impacted, or threatened as the new mouth widened and migrated southward, including Keur Bernard, Pilote Barre, and Tassinère. As a result, many lives were disrupted, and the region's social and economic potential was significantly undermined [103,106].

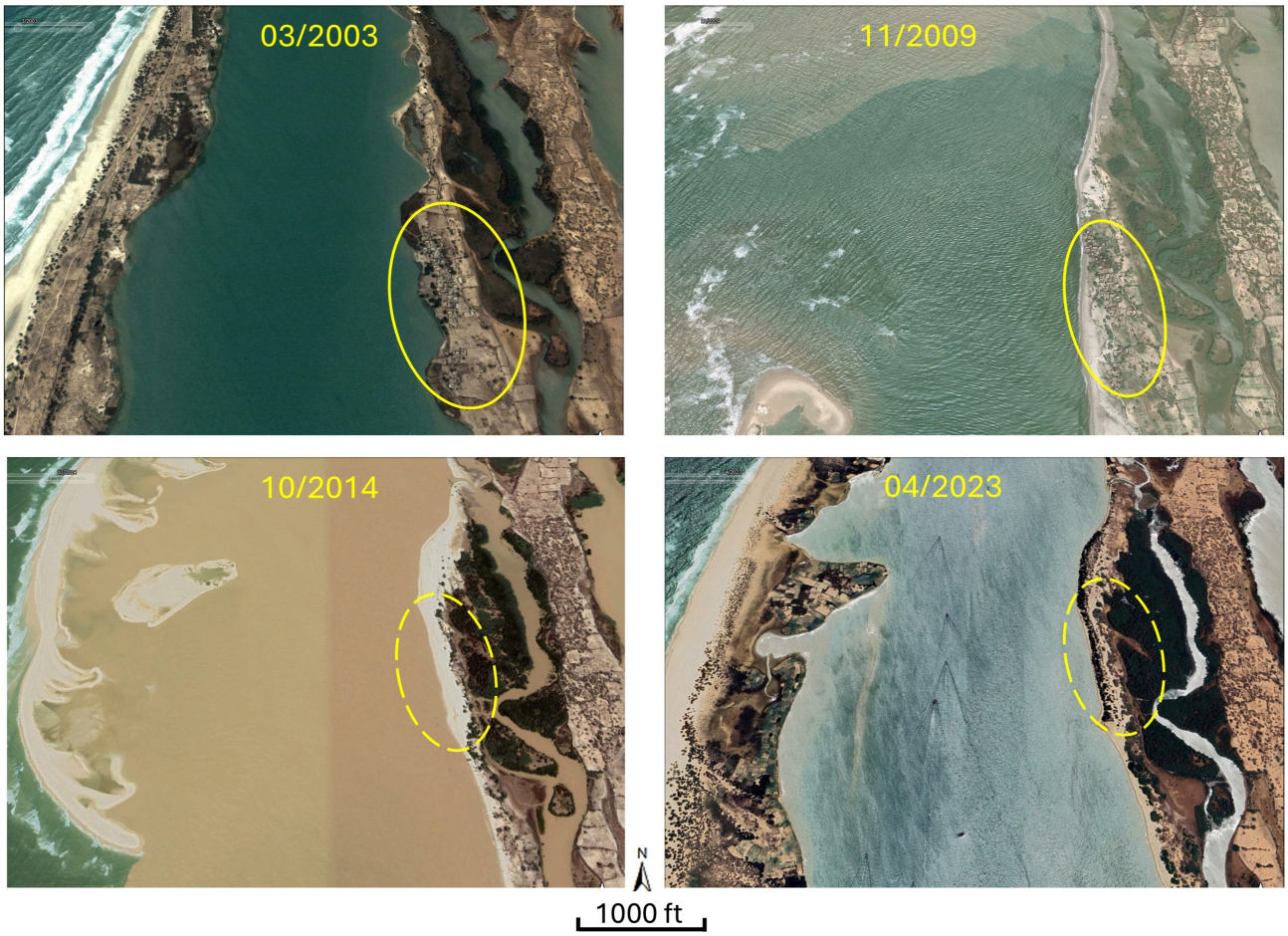


Figure 7. Evolution of the coast and Senegal River banks in the Doune Baba Dieye village area from 2003 to 2023, based on historical Google Map images. This sequence shows how the entire village was wiped out after the opening of the artificial breach across the sand spit. The yellow ellipses indicate the location of the village (solid line: the village's structure are still standing; dotted line: the structures have been destroyed).

- Fishing sector decline

  Although some instances of increasing fish production immediately following the opening of the breach have been mentioned [108], the consequences of this drastic environmental change have been generally devastating for the fishing sector. The opening of the breach caused the shrinking of mangroves, which constitute vital fish breeding grounds for many fish species [109]. This loss of habitat, combined with the salinization of the Senegal River's freshwater ecosystem, caused a sharp decline in freshwater and brackish fish species, including economically important ones like mullet, catfish, and tilapia [102,104]. As a result, the productivity of inland fishing was significantly reduced. For example, surveys conducted in the Gandiolais area showed that the daily catch per fisherman dropped from an average of 40 kg to 10 kg [47,110]. However, it is worth noting that maritime fishing experienced some growth. Data from the Saint-Louis Fisheries Service (2007) showed that from 2001 to 2006, there was a 20,000-ton increase in catches in the Gandiolais area [110].

  Turbulent waters at the level of the breach made its crossing dangerous for fishermen who sail daily across the new mouth to access the ocean, resulting in boat capsizing and tragic losses of life [103,104]. The disruption of fishing activities has forced families to turn to other activities, relocate, or take loans to compensate for lost income [107,109]. Given that local catches are insufficient, Gandiolais women must travel to Saint-Louis

to purchase fish for salting and drying, while young fishermen migrate to other fishing centers of the country [104,110]. Aquaculture was introduced as an alternative, but its progress remains slow due to limited technical expertise [109].

- Agricultural and livestock damage

  The salinization of soil and water, combined with erosion and loss of freshwater sources, adversely impacted agriculture in Gandiolais, a sector that employed 70% of the local population, according to the 2010 Local Development Plan [104].

  - The effects of salinization and coastal erosion: The intrusion of seawater into the Senegal River and surrounding aquifers has increased soil and groundwater salinity. As a result, the productivity and viability of agricultural lands were considerably reduced. Farmers abandoned many vegetable plots, especially those near the river, because of the high salt content in the soil and irrigation water that caused the withering or death of vegetable plants [93,109,111]. Even villages located 2–3 km inland experienced high salinity levels and associated dwindling farming opportunities. In addition, the salinization of ponds and small streams caused further freshwater shortages, reducing drinking water sources and making farming increasingly challenging [51,86,107]. The availability of arable land and fertile plots was substantially reduced because of the intensification of coastal erosion and salinization following the opening of the breach. While plots located within or near villages were not viable anymore, the nearest arable lands were now situated several kilometers away from dwellings [109]. The abandonment of agricultural land had a cascading effect on food security and the economic viability of farming [93,101].
  - Decline in market gardening: The opening and widening of the breach had adverse impacts on market gardening, which used to be a major source of employment and income [104,109,112]. Before the breach, farmers grew a wide variety of crops, including onions, tomatoes, potatoes, eggplants, and cabbage. As market gardening declined rapidly due to degraded land and financial constraints, many vegetable plots were no longer usable and were abandoned, as many farmers shifted to other income-generating activities, such as trading, weaving, or dyeing [104].
  - Reduction in crop diversity and yields: Historically, Gandiolais supported diverse agricultural production with year-round harvests of fruits and vegetables. However, after the opening of the breach, most crops could no longer tolerate the saline conditions. As a result, fruit production and annual harvests dropped significantly [102,104]. Farmers had to travel further distances to find cultivable land, increasing costs and effort [107,109]. Many farmers unable to maintain sustainable crop yields were obliged to take out loans or abandon farming altogether [101,107].
  - Livestock sector decline: Decreasing freshwater resources and grazing lands led to a sharp increase in the cost of maintaining livestock and forced herders to reduce herd sizes or abandon livestock farming [104,111].
  - Adaptation efforts: To address the challenges caused by environmental changes, some farmers have adopted new techniques, including drilling deeper wells to access fresh groundwater and installing drip irrigation systems. These investments are often funded by remittances and allow for limited diversification of crops and increased harvests. However, for many farmers, adapting to these drastic changes is difficult because they cannot afford such efforts [112].

- Tourism sector losses

  Tourism is an important sector of the economy in the Langue de Barbarie and the adja-

cent Gandiolais region. It helps diversify the local economy, constitutes a commercial advantage for local communities, and helps promote the local culture [110,113]. However, since the opening of the breach, hotels and other tourist facilities in this region have been damaged or destroyed by coastal erosion. This disruption has harmed the local economy and further contributed to population displacement [104,106].

4.2.2. Migration and Demographic Shifts

- Environmental migration: Environmental change and disasters have long been significant drivers of migration [114]. Faced with the disruption of livelihoods based on fishing, agriculture, and livestock, the Gandiolais people turned to migration as a solution to their growing problems [109,112]. Initially, migration in the Gandiolais region was circular and seasonal, as it was primarily driven by the movement of fish shoals [109]. However, the environmental and socioeconomic degradation caused by the breach changed this tradition. Many men now consider that permanent migration to support families remaining in their villages is a necessary adaptation to the decline of the region's economy. This type of migration mainly involves young people, particularly those aged 15 to 27. Roughly 80% of this demographic group leave their villages to seek better opportunities in other Senegalese fishing centers, such as Mbour, Joal, and Kayar, or even abroad in countries like Mauritania and The Gambia [110].
- Role of remittances: Migrants often send to their families remittances that are used to improve living conditions, support farm labor, and fund income-generating activities such as crafts, transport, and building services [115,116]. In the Gandiolais region, remittances have played a major role in improving recipients' adaptive capacity. Financial contributions sent by Gandiolais migrants have helped maintain subsistence, pay off loans, hire day laborers, purchase agricultural equipment, support daily needs, and contribute to the development of local infrastructure, such as health centers and places of worship [109,112]. Agricultural practices have particularly benefited from remittances used by local farmers to enhance their techniques by installing drip irrigation systems or drilling deeper wells to access the still-fresh groundwater. Since local insurance and credit systems have limited capacity and few farmers can access them, monetary transfers have become critical for helping reduce family risks and adapt to environmental stress [112].

4.2.3. Social and Gender Dynamics and Adaptive Strategies

As many men migrated in response to environmental and economic challenges, women who were traditionally involved in the private sector have engaged in new economic responsibilities to maintain the survival of their families and have become the primary providers for their households [104,107,109]. The increased salinity in the Gandiolais has led to new opportunities and contributed to the growth of economic activities predominantly managed by women. These activities include shellfish and oyster processing, as well as salt extraction, which has become a cornerstone of the local economy [102,109].

In addition to new activities that constitute an important source of income, Gandiolais women have gained increased access to financial capital through remittances sent by migrants and have access to micro-credit through women's groups. This steady income has allowed them to hire farm laborers, sell seafood to inland regions of Senegal and neighboring countries, and invest in market gardening, seafood processing, and trading [102].

Despite the challenges posed by environmental degradation and the departure of male family members, women have diversified the region's economic activities and reshaped traditional gender dynamics by engaging in activities traditionally dominated by men. They

have demonstrated remarkable resilience and significantly contributed to the mitigation of the breach's impacts [102,107].

In response to the challenges posed by the breach, local communities have demonstrated community resilience by implementing various adaptive strategies to mitigate the socioeconomic and environmental impacts. These include:

- Salt mining: Gandiolais villages have switched to salt extraction due to rising salinity levels. This occupation, which is primarily carried out by women, has become an important source of income, although it is considered an adaptation to the decline of agricultural output [51,80].
- The use of remittances for agricultural innovation: Remittances sent by migrants have allowed local farmers to adopt new agricultural techniques, such as drilling deeper wells and installing drip irrigation systems, thus maintaining their activities despite the adverse impacts of the breach [112].
- The re-emergence of vegetable farming: in areas previously devastated but now recovering, like the former village of Doune Baba Dièye, families have replanted vegetables, signaling early recovery and adaptation [86].

5. Conclusions

The opening of an artificial canal across the Langue de Barbarie sand spit was executed as a flood mitigation measure to protect the city of Saint-Louis, at the lower estuary of the Senegal River. This man-made alteration of a natural setting resulted in rapid and unexpected changes that modified the Gandiolais environment and significantly affected the local communities. This study, which combined satellite imagery and a comprehensive overview of existing literature, reveals the following key findings:

- The dramatic evolution of the spit: The breach, initially created in 2003 for flood mitigation, resulted in a significant widening of the river mouth and a modification of the area's geomorphology over time. This study summarizes the timeline and process of these changes based on satellite imagery and other studies.
- Severe environmental consequences: This review identified significant environmental changes resulting from the breach, including increased tidal ranges, salinization, and accelerated coastal erosion. These alterations were associated with the degradation of key ecosystems and shifts in biodiversity.
- Significant socioeconomic effects: The breach caused profound changes in local agriculture, fishing productivity, community displacement, and significantly altered the livelihoods of affected communities and migration patterns.
- Resourceful, adaptive responses: Despite the negative impacts, local communities, particularly women, have developed adaptation strategies by diversifying their economic activities, and remittances have played an important role in supporting these adaptations.

This study utilized satellite imagery from Landsat and scientific inquiry to assess the environmental impacts of the artificial canal across the Langue de Barbarie spit over time. Using historical imagery, it is possible to monitor coastal dynamics and track changes in shoreline morphology and river mouths. By combining these images with scientific inquiry, this study has established a clearer understanding of the impacts of artificial alterations on the environment and local communities, which is a crucial consideration for mitigating future challenges.

The findings underscore the importance of conducting socioeconomic assessments to gain a deeper understanding of the broader impacts of human interventions on communities in affected areas. For example, understanding adaptation strategies, environmental

migrations, and the role of remittances can help decision-makers develop more effective support systems for affected communities.

It is likely that environmental changes caused by both natural and human activities will continue to impact coastal ecosystems and the communities that depend on them. Therefore, management strategies should address (i) the protection of the environment, (ii) people's well-being, (iii) the potential for unforeseen consequences such as intense salinization and habitat loss, and (iv) more research on adaptive strategies such as the exploitation of new resources made available by the environmental changes (e.g., salt mining, shellfish, and oyster processing) and the use of remittances for local adaptation.

While the artificial breach of the Langue de Barbarie successfully prevented a severe flooding event in Saint-Louis, it also led to unanticipated environmental and socioeconomic consequences. A better understanding of these outcomes can help decision-makers manage similar interventions and support long-term recovery in the region.

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