water

MDPI

Article

Shoreline Changes on the Wave-Influenced Senegal River Delta, West Africa: The Roles of Natural Processes and Human Interventions

Mamadou Sadio [1,2], Edward J. Anthony [1,*], Amadou Tahirou Diaw [2], Philippe Dussouillez [1], Jules T. Fleury [1], Alioune Kane [3], Rafael Almar [4] and Elodie Kestenare [4]

1. Aix-Marseille University, CEREGE UM 34, Europôle de l'Arbois, 13545 Aix en Provence Cedex 04, France; sadio@cerege.fr (M.S.); dussou@cerege.fr (P.D.); fleury@cerege.fr (J.T.F.)
2. Laboratoire d'Enseignement et de Recherche en Géomatique, Ecole Supérieure Polytechnique, Université Cheikh Anta Diop, Dakar, Sénégal; guede1914@gmail.com
3. Laboratoire de Morphologie et d'Hydrologie, Université Cheikh Anta Diop, Dakar, Sénégal; akane@ucad.sn
4. LEGOS (CNRS-IRD-CNES-University of Toulouse), 31400 Toulouse, France; rafael.almar@ird.fr (R.A.); Elodie.Kestenare@legos.obs-mip.fr (E.K.)

* Correspondence: anthony@cerege.fr

Academic Editors: Sylvain Ouillon and John W. Day
Received: 24 December 2016; Accepted: 12 May 2017; Published: 19 May 2017

Abstract: The Senegal River delta in West Africa, one of the finest examples of "wave-influenced" deltas, is bounded by a spit periodically breached by waves, each breach then acting as a shifting mouth of the Senegal River. Using European Re-Analysis (ERA) hindcast wave data from 1984 to 2015 generated by the Wave Atmospheric Model (WAM) of the European Centre for Medium-Range Weather Forecasts (ECMWF), we calculated longshore sediment transport rates along the spit. We also analysed spit width, spit migration rates, and changes in the position and width of the river mouth from aerial photographs and satellite images between 1954 and 2015. In 2003, an artificial breach was cut through the spit to prevent river flooding of the historic city of St. Louis. Analysis of past spit growth rates and of the breaching length scale associated with maximum spit elongation, and a reported increase in the frequency of high flood water levels between 1994 and 2003, suggest, together, that an impending natural breach was likely to have occurred close to the time frame of the artificial 2003 breach. Following this breach, the new river mouth was widened rapidly by flood discharge evacuation, but stabilised to its usual hydraulic width of <2 km. In 2012, severe erosion of the residual spit downdrift of the mouth may have been due to a significant drop (~15%) in the longshore sand transport volume and to a lower sediment bypassing fraction across the river mouth. This wave erosion of the residual spit led to rapid exceptional widening of the mouth to ~5 km that has not been compensated by updrift spit elongation. This wider mouth may now be acting as a large depocentre for sand transported alongshore from updrift, and has contributed to an increase in the tidal influence affecting the lower delta. Wave erosion of the residual spit has led to the destruction of villages, tourist facilities and infrastructure. This erosion of the spit has also exposed part of the delta plain directly to waves, and reinforced the saline intrusion within the Senegal delta. Understanding the mechanisms and processes behind these changes is important in planning of future shoreline management and decision-making regarding the articulations between coastal protection offered by the wave-built spit and flooding of the lower delta plain of the Senegal River.

Keywords: Senegal River delta; Langue de Barbarie spit; delta vulnerability; river-mouth migration; spit breaching; ERA hindcast waves; longshore sediment transport

1. Introduction

The impacts of human activities on coasts are often accompanied by a lack of understanding of the consequences of these activities on the hydrodynamic and sediment redistribution processes that shape coasts [1,2]. Alongshore sediment transport, gradients in transport, and interception of drifting sediment by natural or artificial (man-made) boundaries, including river mouths and inlets, are, from a coastal management point of view, very important, as these processes are significant drivers of short-term to medium-term (days to years) shoreline change. Much of the West African coast (Figure 1) is wave-dominated, and is classified as a cyclone- and storm-free "West Coast Swell Environment" in the global wave classification scheme of Davies [3], with a subsidiary contribution from shorter-period trade-wind waves from the Atlantic. In Figure 1, continental shelf width (clearer hue along the coast) is a fine indicator of the distribution of long stretches of wave-dominated coast (narrow shelf) and the much more limited, predominantly tidal, estuarine sector between Sierra Leone and Guinea-Bissau (broad, low-gradient shelf), subject to significant wave energy dissipation [4,5]. The West African coast is also characterised by a plethora of river deltas, the largest of which are those of the Niger, Senegal and Volta (Figure 1). Abundant sand supplies and strong wave-induced longshore drift have favoured the construction of numerous sand barriers, including at the mouths of these three deltas. These barriers are major settlement sites on the coast as they provide higher-lying areas above lagoons and wetlands, while acting as valuable aquifers. On the coast of Senegal, the barriers are generally elongate to curvilinear spits formed at the mouths of tidal or fluvial ria-like embayments. These spits are commonly capped by dunes, but individual beach ridges are visible in some of the more southern ones. These spits have a protective role on the back-barrier wetlands and lagoons by buffering wave energy. By forming alongshore barriers, they are also important in the regulation of the freshwater-saltwater balance and ecology of these lagoons and back-barrier wetlands, both of which can be considerably altered by breaches in the spits or by spit erosion [6,7]. This is particularly the case of the largest of the Senegal wetland systems, that of the lower Senegal River and delta plain (Figure 2).

The Senegal River delta is an iconic example of a delta subject to strong wave action [8–12]. This delta is often represented in the ternary (river-wave-tide) classification of Galloway [13] at the wave apex. Using a fluvial dominance ratio—defined as river sediment input versus the potential maximum alongshore sediment transport away from the delta mouth—to quantify the balance between river inputs and the ability of waves to spread sediments along the coast, Nienhuis et al. [12] computed a value of 0.04 for the Senegal, which highlights the strong role of wave-induced longshore transport along this delta's shoreline. A manifestation of this strong longshore transport potential is a long narrow sand spit presently fronting the delta plain, the Langue de Barbarie [10]. This spit has historically played an important role not only in the protection of the lower Senegal delta plain but also in regulating saltwater intrusion by diverting the mouth of the river several kilometres southwards. Of particular significance, in terms of long-term flood-risk and coastal management, is the historic and picturesque city of St. Louis (population in 2013: 300,000), a UNESCO world heritage site located in the proximal part of the delta (Figure 2). The cultural attractiveness of St. Louis, a French colonial city, and the biodiversity of the deltaic wetlands and lagoon bound by the Langue de Barbarie spit have also generated a substantial rise in tourism. Much of St. Louis, which has undergone a rapid growth in population over the last 50 years, lies at an elevation of less than 2.5 m above sea level [14], and the city has, therefore, been prone to the flooding that affects the lower Senegal valley in the rainy season (May to October).

In October 2003, to avoid flooding of St. Louis in the wake of a massive rise in the water discharge of the Senegal River, an artificial breach was hastily cut through the Langue de Barbarie, generating rapid reworking of the spit. In the present paper, we describe the recent dynamics of the spit within the framework of development of the Senegal delta and specifically aim at disentangling processes of natural forcing from those of the impact of this breach. Two approaches are used in the study: (1) clearly define the wave climate and longshore sediment transport potential along the Langue de Barbarie; and (2) compare spit behaviour patterns prior to, and following the October 2003 artificial breach. Both of these approaches are important in understanding the current dynamics prevailing along this deltaic coast. They should also be of use in planning of future shoreline management and decision-making regarding the articulations between coastal protection offered by the wave-built spit and flooding of the lower delta plain of the Senegal River.

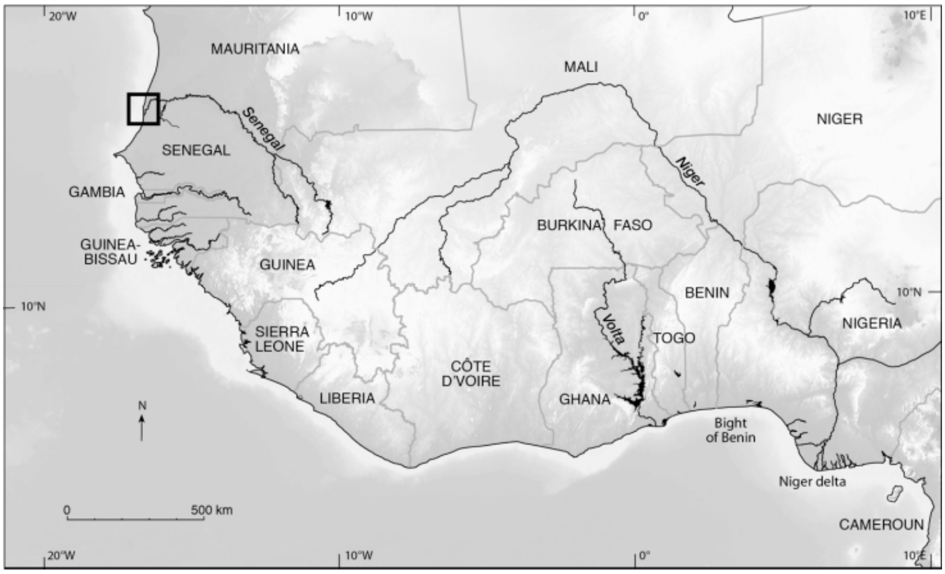

Figure 1. The coast of West Africa, showing the Senegal (box) and other major river deltas. Much of this coast is wave-dominated, and is characterised by beach-ridge sand barriers and spits.

Figure 2. The Senegal River delta, a fine example of a wave-dominated delta characterised by the Langue de Barbarie spit and a river-mouth system subject to strong north-south longshore drift.

2. The Senegal River and Delta

The Senegal River is about 1800 km long, and is the second longest river in West Africa after the Niger. The catchment size has been estimated at 345,000 km^2 [15], much of it covering the arid western Sahel. The river's discharge has been particularly affected by Sahelian droughts since the 1970s [16]. The mean annual water discharge at Bakel, the reference station of the Senegal River, situated 557 km upstream of St. Louis, is 676 m^3/s, and varies from a mean low dry season value of 10 m^3/s in May, to a mean maximum flood value of 3320 m^3/s in September at the height of the rainy season [17]. The interannual variability is extremely high, with a mean annual discharge ranging from 250 to

1400 m^3/s. Little is known of the solid discharge of the Senegal. This solid load has been estimated at 0.9 to 1 $\times$ 10^6 tonnes a year [18], a rather low figure when viewed against the size of the river's catchment and when compared to other tropical rivers. The solid discharge is largely dominated by suspended load transport [19]. The lower Senegal delta is characterised by high biological productivity and by rich agricultural and fishing sectors. In November 1985, the Diama dam (Figure 2) was built in the lower river valley 23 km upstream from St. Louis. The dam was commissioned with the twin aims of preventing saltwater intrusion, which, hitherto, penetrated up to 350 km upstream in the lower Senegal valley, and regulating the river's rainy season discharge in order to improve irrigation of agricultural lands [15]. The delta plain provides 8% of the arable land of Senegal [20].

The Senegal delta coast is fronted by a relatively narrow continental shelf only 15–20 km wide. The dominant waves are from the northwest, and this direction is especially prevalent during the dry season from November to June. One of the objectives of this study is to highlight the salient characteristics of this "West Coast" wave setting (see Results). The tidal regime along the Langue de Barbarie is semi-diurnal and the range microtidal, comprised between 0.5 m at neap tides and 1.6 m at spring tides. The relatively moderate river discharge, including during the flood season, the permanence of moderately energetic waves propagating across a relatively narrow shelf, and the microtidal regime, are three conditions that have been forwarded to explain the wave-dominated character of the Senegal River delta [10].

The stratigraphy and patterns of Holocene geomorphic development of the Senegal delta have been highlighted from borehole data, limited radiocarbon dating, and analysis of plan-view sand barrier and longshore drift patterns in relation to the courses of the river [21,22]. The delta plain prograded as a bayhead delta within a confined setting rich in Late Pleistocene aeolian deposits (Ogolian dunes) that extended as subaerial forms over the then exposed shelf during the last lowstand that peaked at 19,000 year B.P. [21,22]. Mud supplied by the river and fine sand derived from reworking of dunes inland by river-channel meandering have generated up to 8.5 km of essentially fine-grained delta-plain progradation within this bayhead setting. Although the delta plain does not protrude significantly into the Atlantic Ocean (Figure 2), probably because of the combination of this embayed setting and the relatively steep narrow shelf, the Senegal has, nevertheless, formed quite a large delta with an area of about 4254 km^2, much of which is subaerial, the ratio of the subaerial to subaqueous delta being 2:1 [9]. This mud-rich delta plain is bound by massive sandy barriers [21] built by waves propagating over loose aeolian deposits on the submerged narrow shelf. These coarse-grained barriers are separated by swales comprising abandoned river courses. Efficient trapping of river-borne sediments by the aggrading delta plain behind these wave-built sand barriers probably explains the high subaerial-subaqueous ratio of this delta, which is also consistent with the limited delta bulge compared to the more cuspate form commonly evinced by wave-dominated deltas. Remnants of these degraded barriers with beach ridges are discernible within the outer margins of the delta plain south of St. Louis. These spits are ancestral to the present Langue de Barbarie spit. Michel [21] dated the formation of these barriers at between 4000 and 1900 B.P. In essence, therefore, much of the Holocene development of the Senegal delta has consisted in embayment infilling behind the protection of these sand barriers, thus potentially giving rise to two distinct facies arrangements: wave-built sand bodies and back-barrier embayment facies represented by infilling fluvial deposits, including fine sands reworked from the Ogolian dunes by river meandering.

We used European Re-Analysis (ERA) hindcast wave data from 1984 to 2015 generated by the ECMWF Wave Atmospheric Model to characterise the wave climate affecting the Senegal River delta and to calculate longshore sediment transport rates along the spit. We then analysed changes in the position of the river mouth, rates of spit migration and spit width from aerial photographs and satellite images between 1954 and 2015 in order to characterise the shoreline morphodynamic context of the delta (see Materials and Methods).

3. Results

3.1. Wave Climate and Alongshore Sediment Transport

The wave climate of the Senegal delta shoreline is characterised by two components with strongly contrasting behaviour: wind waves generated locally and a dominant component of long swell waves from mid- to high latitudes (Figure 3). The region is not directly affected by major storms or cyclones but the influence of these distant high-energy events in the North Atlantic is materialised in the wave climate. Averaging over the 1984–2015 period gives annual significant swell and wind wave heights respectively of H_s = 1.52 m and 0.53, and peak swell and wind wave periods of T_p = 9.23 s and 3.06 s. The dominant swell waves originate from WNW to N and have a mean direction of 325°. The direction graph (bottom, Figure 3) shows a brief August swing dominated by swell waves from the south. Wind waves show a much wider directional window and a mean of 295°. There is a clear seasonal modulation, swell activity peaking during the northern hemisphere winter with strong storm activity at mid to high latitudes. Wind waves also show larger day-to-day and monthly variability. Contrary to swell waves, these wind waves are driven by local tropical winds and show peaks in spring and autumn that correspond to the passages of the Intertropical Convergence Zone over Senegal.

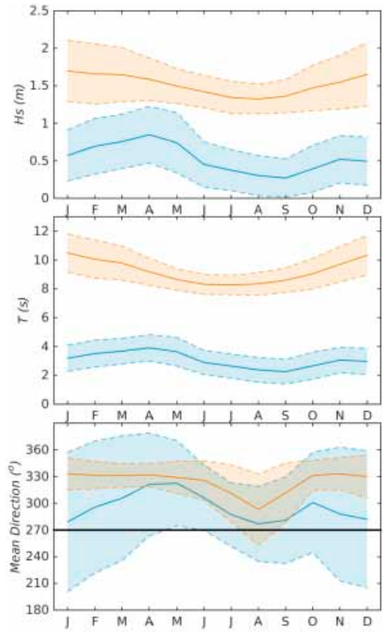

Figure 3. Mean wave characteristics (significant wave height (H_s), peak wave period (T), and incident direction (°)) along the Senegal River delta coast from 1984 to 2015 ERA hindcast data. Orange: swell waves, blue: wind waves.

As both swell and wind waves originate dominantly from W to N, this results in an oblique approach to the coastline that generates a large longshore sediment transport (LST) towards the south. Figure 4 depicts the annual LST along the Senegal delta coast for swell waves and wind waves computed using the formula of Kaczmarek et al. [23] as described in the Methods Section. The mean annual net transport induced by swell waves over the 32-year period of the ERA dataset is of the order of 669 × 10^3 m^3/year, i.e., ~89% of the total transport, the total wind-wave-induced LST amounting to only 80 × 10^3 m^3/year. LST is very largely dominated by southwards swell-induced drift which amounts to an annual mean of 611 × 10^3 m^3/year, while net wind-wave-induced transport in the same direction is only 59 × 10^3 m^3/year. Counter LST towards the north is nearly an order of magnitude less: 58 × 10^3 m^3/year for swell waves and 21 × 10^3 m^3/year for wind waves, i.e., only ~14% of the total LST. These computed sediment transport volumes are remarkably similar to those provided by the French engineering firm [24] SOGREAH (1994) who calculated a drift volume that decreases from north to south along the spit from 700 to 600 $\times 10^3$ m^3/year.

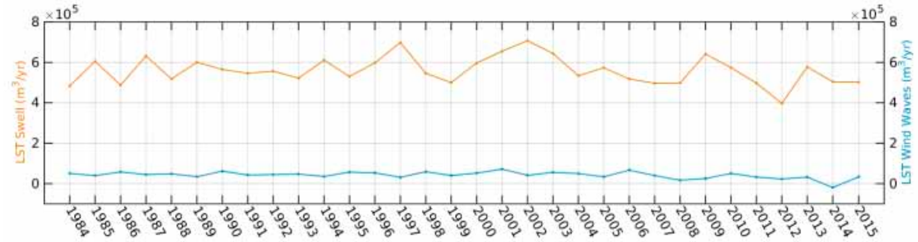

Figure 4. Gross annual longshore sediment transport (LST) along the Senegal River delta coast from 1984 to 2015. Orange: swell waves, blue: wind waves. Note the significant drop in swell-induced LST between 2009 and 2012, corresponding to a decrease of >35%, and the sharp rise the following year.

3.2. LST and Growth Dynamics of the Langue de Barbarie Spit

The Langue de Barbarie spit is a product of the strong wave action and high LST that have controlled the morphosedimentary development of the seaward fringe of the Senegal River delta (Figure 2). These observations and the satellite data also provide insight on the sand sourcing the seaward face of the Langue de Barbarie, which is derived from the coast and shoreface of Mauritania updrift of the historic mouth of the Senegal (Figure 1), in agreement with a conclusion also reached by Barusseau et al. [25]. The satellite data show that the Langue de Barbarie spit is a 100–400 m-wide feature. The spit is capped by aeolian dunes 5–10 m high. Widening of the spit and dune accretion occur through abstraction of the large alongshore sediment supply, especially in the distal section where bare, unvegetated dunes prevail, as well as through distal spit extension [26]. In contrast, the proximal sector, near St. Louis has been characterised by a much more stabilised dune system. Since 1900, a major coastal management preoccupation in the lower Senegal delta has been that of preventing natural breaches in the Langue de Barbarie in the vicinity of St. Louis, as this posed a threat for developing tourist facilities and infrastructure on the spit downdrift of every breach. Spit protection was achieved through the fixing and consolidation of the aeolian dunes via plantations of Filao (*Casuarina equisetifolia*) [27]. The alongshore transport volume would appear to undergo increasingly larger aeolian dune trapping of sand in the relatively poorly vegetated distal zone, compared to the relatively more urbanised and vegetated proximal sector of St. Louis. The former zone also represents one of active remigration following past natural breaches. The longshore gradient in sediment transport highlighted by SOGREAH [24] would appear to correspond to these morphological variations as one goes from the proximal to the distal sector of the spit.

The successive locations of the mouth of the Senegal River have been controlled by spit breaching followed by downdrift spit elongation. Spit breaching has generally been caused by increases in river water level, especially over the narrowest and lowest parts of the spit [26]. Once breaching occurs, the new breach is exploited by river discharge, tidal ingression, and waves, and forms a new river mouth. This leads to the older mouth becoming underfit and sealed by distal spit attachment to the shore. Natural breaching is attended by spit elongation through the classic formation of dune-capped beach ridges at the distal end, and this process has undoubtedly been favoured by the shallow overall depths of the mouth (2.5–3.5 m according to Bâ et al. [28]). The mouth is characterised by bars and spit recurves, remnants of which are identified in updrift locations on the spit. The mouth bars apparently serve as platforms for spit extension and eventual river-mouth diversion southwards.

3.3. Historical and Recent Changes of the Langue de Barbarie Spit Prior to the 2003 Artificial Breach

Joiré [29] and Tricart [30] situated the mouth of the river in the vicinity of St. Louis at about the mid-17th century, while a historical analysis of spit mobility and of the associated locations of mouth openings documented even earlier mouth scars north of St. Louis [27]. The Langue de Barbarie lengthened by 11 km between 1850 and 1900 (about 220 m a year), with a distal tip located 15 km south of St. Louis at the turn of the 20th century, and the spit was affected over this 50-year period by seven breaches [27]. Between 1900 and 1973, 13 other breaches occurred across the Langue de Barbarie [27], thus suggesting a breaching timescale (see Nienhuis et al. [31]) of ~6 years. There were no breaches between 1973 and 2003.

Following the 1973 breach, the Langue de Barbarie lengthened by 12.5 km (at a mean rate of ~400 m/year) before the spit was artificially breached in 2003. Spit elongation calculated from satellite images, aerial photographs and field measurements has, however, fluctuated widely from low values of nearly nil to <170 m/year (1985–1986, 1990–1991) to >1200 m/year (1987–1989, 2000–2002) (Figure 5). Gac et al. [27] showed that the farthest downdrift position of the mouth of the river, which corresponds to the maximal distal spit extension, did not exceed 30 km over the 80-year period covered by their observations, which is close to a value of 28 km reported in an earlier study [32]. The successive locations of the mouth of the Senegal River since 1973, which also correspond to those of the distal tip of the southward-extending spit, are shown in Figure 5, alongside the migration rates. The migration between 1973 and 2003 brought the distal tip of the spit close to the maximum spit length. The data from satellite images show a relatively narrow mouth (0.25–<1 km-wide) with the exception of the years 1968–1973 and 1988–1989 when the width exceeded 1.5 km (Figure 6).

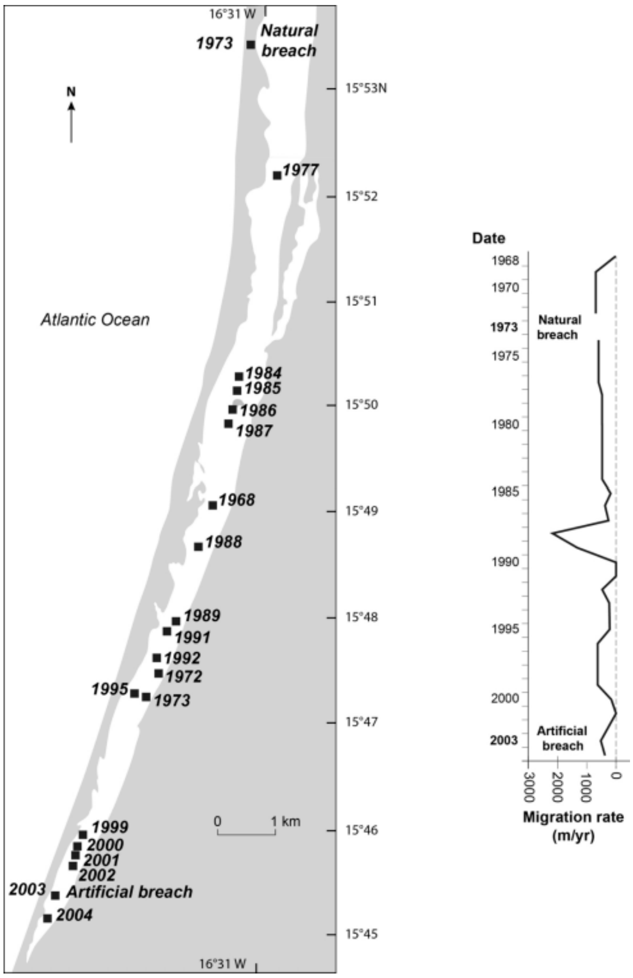

Figure 5. Successive dated locations of the mouth of the Senegal River delta materialised by the distal tip of the Langue de Barbarie spit (**left**); and spit migration rates in m/year from 1968 to 2004 (**right**).

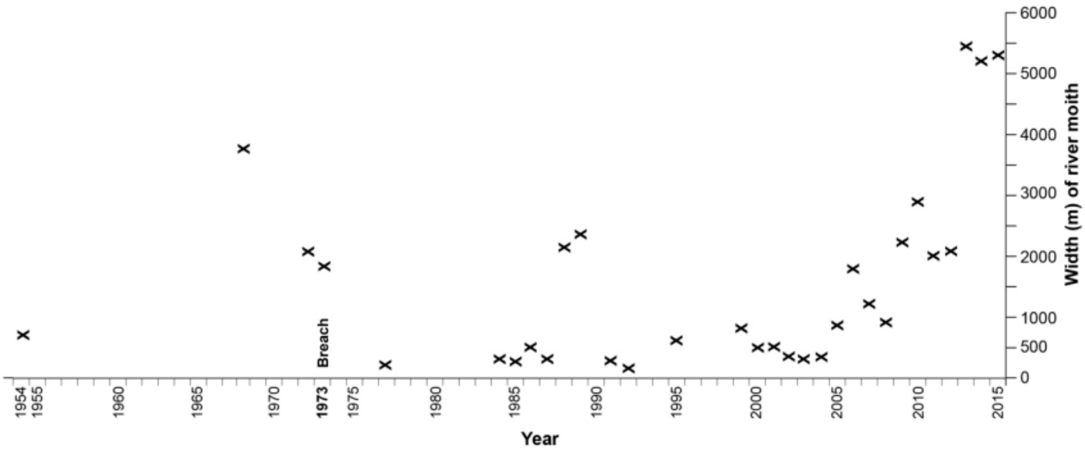

Figure 6. Width of the mouth of the Senegal River delta between 1954 and 2015. Except for the years 1968–1973 and 1987–1988, the width did not exceed 1 km, prior to the 2003 artificial breach. Following this breach, the width of the mouth fluctuated to attain ~1 km in 2008, which corresponds to the average width of the "fluvial" river mouth. A further rapid increase, not related to river-mouth hydraulics (see Discussion), occurred thereafter, peaking in 2013.

3.4. The Artificial Breach in 2003 and Post-Breach Spit and River-Mouth Evolution

An emergency water level in St. Louis prompted artificial breaching, on the night of 3 October 2003, of the Langue de Barbarie in the vicinity of the city to alleviate flooding. This high flood level had been preceded by several other episodes in the 1990s. One function of the Diama dam was to alleviate floods in the lower valley, notably in the deltaic sector. Mietton et al. [33] highlighted the rather mixed results from the flood-control function of the dam since the 1990s, and reported repeated episodes of severe flooding in St. Louis in 1994 (1.26 m above IGN datum), 1995 (1.21 m), 1997 (1.28 m), 1998 (1.43 m), 1999 (1.47 m), 2001 (1.2 m) and 2003 (1.38 m). The latter events preceding the artificial breach are depicted in Figure 7. The water level of 1.47 m above IGN datum attained at the height of the 1999 high-flow season exceeded the 1.2 m flooding threshold for 12 days, and the concern voiced by the population of St. Louis regarding this flooding progressively brought pressure to bear on the administrative authorities in their recourse to artificial breaching [34]. A 4 m-long and 1.5 m-deep trench was cut across a relatively narrow (100 m-wide) portion of the spit about 7 km south of St. Louis by engineers in the night of 3 October 2003. This induced a rapid overnight drop in water level of up to 1 m (Figure 7) that prevented further flooding [34]. Following this opening, the trench widened rapidly (Figure 8) and became the new river mouth, a case of inadvertent delta-mouth diversion generated by humans. The width of this artificial breach grew to 250 m 3–4 days after the opening. The depth of the breach increased to 6 m by 2007 [28], while the width increased to nearly 2 km in October 2006, three years after the breach (Figure 6), before decreasing once more to ~1 km in early 2008. Channelling of the Senegal River flow in the new enlarged mouth led to closure of the former natural mouth located further downdrift. An accelerated phase of widening ensued afterwards, peaking to nearly 5.5 km between October 2012 and June 2013 (Figure 6). Figure 9 summarises the dynamics of the spit and river mouth since the 2003 artificial breach. The rapid widening was related to an additional natural breach created in October 2012 by overwash 500 m south of the new mouth. Much of the remaining spit between this new opening and the mouth was eroded through several other washovers that tended to coalesce, widening the mouth and sea-intrusion pathways, as sand was transported southward by longshore drift.

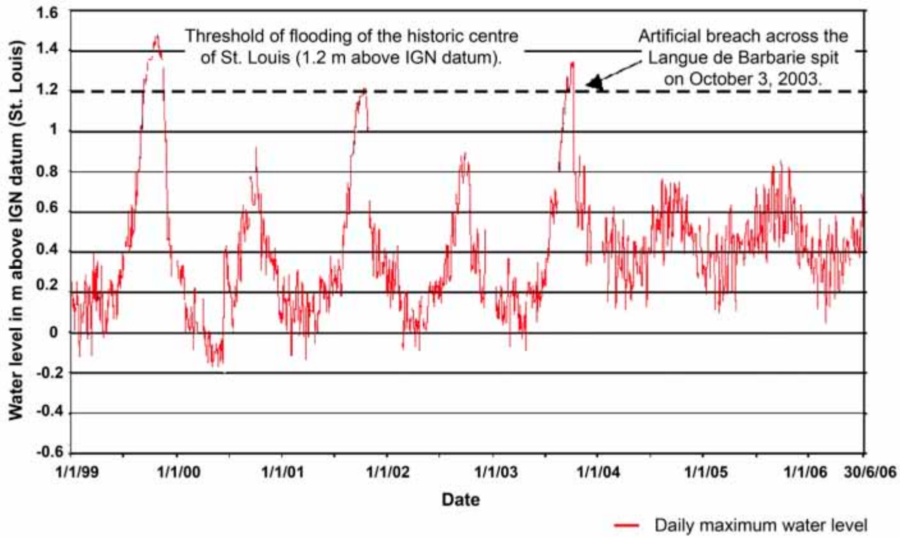

Figure 7. Maximum water levels in the Senegal River channel at St. Louis from 1999 to 2006. Adapted from [34].

Figure 8. Ground photographs showing the initial trench (4 October 2003), dug on the night of 3 October 2003, across the Langue de Barbarie to alleviate flooding of parts of St. Louis. The 5 October 2003 photograph shows the trench considerably widened by river and tidal flow (Photo credit: Service régional de l'Hydraulique, St. Louis du Sénégal).

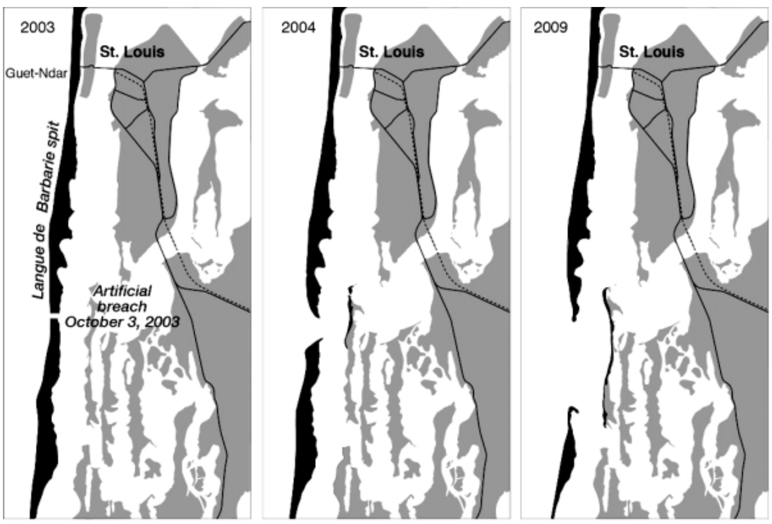

Figure 9. *Cont.*

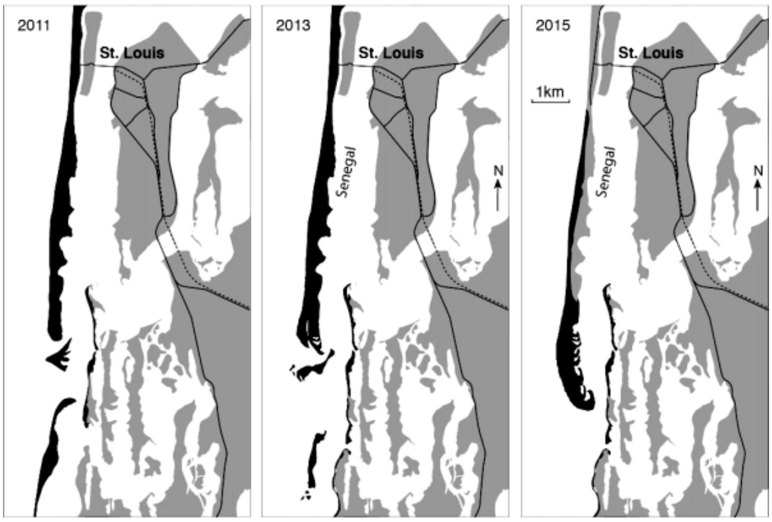

Figure 9. Assemblage from Google Earth images showing changes in the Langue de Barbarie spit and Senegal River mouth between March 2003, prior to the October 2003 artificial breach, and 2015. Black: Langue de Barbarie spit and beach sand; dark grey: subaerial lower delta plain potentially subject to river flooding (including St. Louis); light grey: delta plain seasonally flooded by the Senegal River. From 2012 to 2013, rapid wave-induced erosion of the residual spit downdrift of the mouth led to considerable mouth widening, an increase in tidal influence within the lower Senegal delta, and direct wave attack of parts of the delta plain hitherto protected by the residual spit.

4. Discussion

The shoreline of the Senegal delta offers an interesting example of strong wave influence on delta evolution. Two clear manifestations of this strong influence are the absence of a notable classic deltaic "bulge", and the presence of a persistent sand spit, the Langue de Barbarie, an extremely mobile feature that generates river-mouth diversion. This spit has been subject to repeated past breaches, and delta-mouth migration over a total distance of 28–30 km at least since the mid-17th century. The dominant natural mode of behaviour of the Senegal delta shoreline is thus one imprinted by strong longshore transport of sand generated by Atlantic waves from NW to N. The Senegal River mouth is thus a fine example of a wave-influenced delta illustrating the relationship between river-mouth migration, spit elongation and spit breaching by the river mouth [31], although a simple relationship between these processes cannot be expected because of the influence of fluctuations in river discharge and river-mouth bar dynamics [11]. Whereas high river discharge and the formation of river-mouth bars can lead to reduced sediment bypassing, which affects in turn the river-mouth migration rate and the size of the river-mouth spit [31], reduced discharge at the river mouth, tantamount to a decrease in hydraulic efficiency, can lead to bypassing of sediment around the mouth, thus reducing migration [31,35]. Natural breaches of spits barring river mouths and tidal inlets are a commonly cyclic process determined by a combination of spit lengthening, river discharge and river hydraulic efficiency, and also in many cases, storm wave action [31,36].

The absence of breaching between 1973 and 2003 associated with the lengthening of the Langue de Barbarie spit over this period constitutes a much longer timescale than past breaching timescales [27]. The reasons for this are not clear. They are unlikely to be related to the wave climate, which is devoid of storms, whereas breaching tends to be initiated by high river discharge during the flood season. The longshore transport volumes, of which the period 1984–2003 may be considered as representative, fluctuated but presumably were high enough to ensure spit elongation, without natural breaching updrift that could have been caused by a decrease in the alongshore budget. Spit morphometry (width, depth and migration range) as a criterion for determining the fraction of the LST sequestered in the spit, yields a value of 54%. This value is moderate relative to the relatively high hindcast and predicted values of the sediment bypassing fraction, β [31] (respectively, 0.83 and 0.74, 1 representing 100% bypassing) for the Senegal River mouth. These rates are, however, quite similar to those (0.8–0.9) calculated from our data on spit morphometry and LST using the sediment bypassing fraction equation and 50% of the river mouth depth as an estimate of the "updrift sediment spit depth" (see Materials and Methods). The mouth of the Senegal has thus been characterised by moderate to high bypassing that assured a degree of growth of the Langue de Barbarie but also the stability of the barrier and coast downdrift of the 2003 artificial breach. The absence of breaching over this long phase has been attributed to a decrease in river discharge [37]. Unfortunately, there are no available data on river water discharge to enable us to tie up natural breaches with the hydraulic efficiency of the river mouth. Mietton et al. [33] noted a total absence of critical floods between 1974 and 1993 associated with the Sahelian drought. This period also incorporates the construction of the Diama dam in 1986.

While the breaching timescale since 1973 appears exceptional compared to the pre-1973 conditions, the breaching length is also an important parameter in the onset of breaching [31]. The elevation of the water surface at the upstream boundary of a river channel is directly related to the channel length, such that an increase in the latter, as the river mouth migrates, results in a constant water surface slope, with the eventuality of breaching when a critical channel length is attained [31]. Guilcher [32] and Gac et al. [27] reported that the Langue de Barbarie spit generally did not exceed a maximum length of 28–30 km, beyond which breaching tended to occur. This length probably corresponds to the breaching length defined by Nienhuis et al. [31]. There is a probability, therefore, that a natural breach could have been imminent close to the time frame of the 2003 artificial breach. A reason for advancing this hypothesis is the increase in flooding (Figure 7), which suggests increasing impoundment of flood waters over the lower delta plain and decreasing hydraulic efficiency of the mouth. Whereas natural breaching has been a characteristic of the spit, spit instability since 2003 reflects, in part, the consequences of hasty artificial breaching to solve an impending flooding problem facing St. Louis. By protecting St. Louis and numerous smaller settlements and agricultural land within the delta plain from waves and marine influence, the spit is a major feature of the dynamics and management of the Senegal delta shoreline. Paradoxically, by impounding flood waters of the Senegal River, the spit also contributes to a flood risk that has grown apace with the urban extension of St. Louis. The long phase of absence of breaching between 1973 and 2003 coincided with a period of rapid tourism development in the Senegal delta associated with the emplacement of tourist infrastructure on the rectilinear spit that provided sandy grounds well above flood level. Although much of the lower delta is characterised by a population density of only about ten inhabitants/km^2, there are zones of very high population concentrations, as in St. Louis and certain areas of the Langue de Barbarie such as Guet-Ndar (Figure 9) where the 2013 census shows densities exceeding 80,000 inhabitants/km^2 [6]. The artificial breach annihilated the risk of flooding of St. Louis in 2003 and in the following years by enabling more rapid seaward drainage of river water during the high-flow season [34].

As in the pre-2003 period, the sediment bypassing fraction, β [31], across the mouth of the Senegal River has been quite high (0.8–0.9), although balancing spit morphometry against LST over the same period suggests up to 40% of sand locked up in spit growth, a value lower, however, than that of the pre-2003 breach. There have been marked fluctuations in spit growth, however, with even spit erosion in 2005–2006, 2008–2010 and 2012–2013. Under conditions of spit growth, sand has been incorporated in new recurves that mark the current form of elongation of the residual updrift spit sector, which is also characterised by an enlarged distal tip (Figure 9). The reasons for alternations between spit growth (including widening) and spit erosion are not clear. They may be related to variations in higher-energy waves, and potentially varying LST, as shown by the drop in the number of days with high-energy waves in 2012 (Figure 10) and the correlative drop in LST (Figure 4), but they could also be an outcome of variability in river discharge and sediment bypassing.

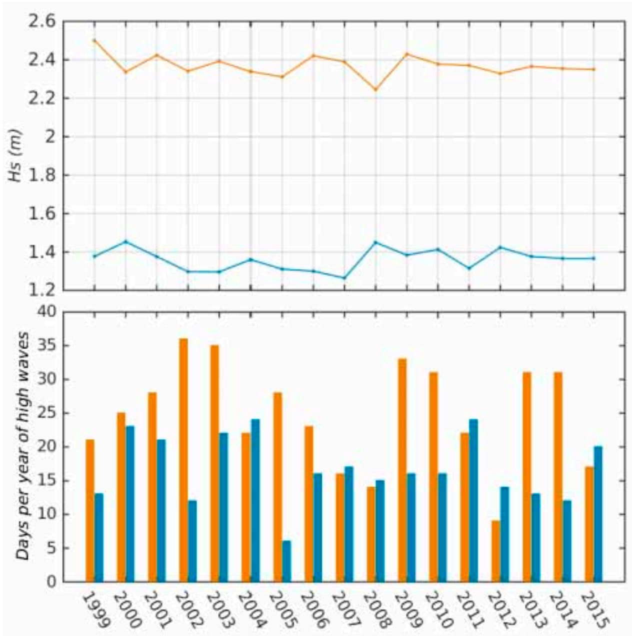

Figure 10. Significant heights (*Hs*) of high-energy waves (±1.6 standard deviations around mean *Hs*) from 1999 to 2015 (**top**); and number of days per year with high-energy waves along the Senegal River delta coast, derived from ERA hindcast data (**bottom**). Orange: swell waves ($Hs \geq 2.37$ m), blue: wind waves ($Hs \geq 1.36$ m). Note the significant drop in high-energy swell waves in 2012 (see also Figure 4).

Over this post-2003 period, fluctuations of the width of the river mouth (Figure 6) are presumably a function of the balance between the river's hydraulic efficiency, including the tidal discharge, and incident wave energy and sediment bypassing [11]. The width of the "fluvial" mouth of the river is very likely in the range of ~0.5–1 km, which is the "usual" mouth width (Figure 6) and the stabilised width attained shortly after the artificial breach. The rapid widening between October 2012 and June 2013 occurred following wave overwash and erosion of the remaining spit downdrift of the mouth. This rapid erosion would appear to result from a combination of the most significant drop in LST recorded (2010–2012) over the period 1984–2015 (Figure 4), with a lag effect in time, and possible sequestering of sand in the river mouth. Lower bypassing (due to higher river discharge?) and a sharp increase in LST from 2012 to 2013 (an increase of about ~45% relative to the 2010–2012 LST (Figure 4)) could explain the ensuing exceptionally rapid elongation of the Langue de Barbarie spit between June 2013 and May 2015 (~2 km) (Figure 9). A review of conceptual advances in wave-river-mouth interactions [11] and modelling of alongshore sediment bypassing at river mouths [31] have shown that waves refracting over the river-mouth bar create a zone of low alongshore sediment transport updrift which reduces sediment bypassing. These observations imply that the LST potential south of the new mouth is being assured by a degree of "cannibalisation" of the rest of the spit, as sand transported from the north has been increasingly trapped updrift of the wider mouth, presumably leading to lower bypassing. Except for 2007–2009, and 2010–2011, this sector has been in erosion. This demise of the spit downdrift of the new mouth has led to the destruction of villages, campsites and other tourist structures. The delta plain in this eroding sector is now directly exposed to ocean waves and erosion that are threatening numerous villages.

Much of the lower delta plain and the main river channel are now situated over 20 km upstream of the former mouth, between the new mouth and the anti-salt intrusion Diama dam that confines the tidal prism to the lower delta plain. In consequence, the much wider mouth appears to have become favourable to a larger tidal prism, manifested by an increase in the tidal range in St. Louis, and confirmed by recent studies [33,34]. Durand et al. [34] showed that the maximum semi-diurnal tidal range downstream of the Diama dam has increased three-fold, from a mean of 0.30 m in 2001–2002 to

0.93 m in 2004–2005, whereas the mean maximum spring tide range attained 1.18 m, for a predicted value of 1.29 m, along the Langue de Barbarie spit. These authors have also noted that the semi-diurnal tidal effects are now more clearly expressed even during the high river flood waters. The impacts of these changes are still to be studied, but it may be expected that they are leading to increasing soil salinization in the lower delta plain, to the extension of bare saline flats, and to modifications in biodiversity.

The extent to which accelerated subsidence, one of the two major causes of delta vulnerability (together with rapid and chronic erosion), affects the delta is not known, although it may be inferred that a decreasing sediment load and damming may be contributing to more exacerbated flooding in the delta plain. However, the problem seems to have more to do with accelerated urbanisation of St. Louis over the last few decades, bringing new populations to encroach on areas of the delta that are susceptible to flooding during exceptionally wet years. Durand et al. [34] have highlighted the potential vulnerability of the city and the surrounding low delta plain to sea-level rise. Their model simulating flood propagation in the city, and based on various sea-level scenarios, shows the susceptibility of St. Louis to flooding during the highest annual water levels in the course of the 21st century.

5. Materials and Methods

5.1. Waves and Wave-Induced Longshore Transport

In order to estimate the wave-induced alongshore transport on the Langue de Barbarie, we extracted bulk wave parameters (significant height H_s, peak period T_p and direction of both swell and wind waves) from hindcast data in the Atlantic Ocean between 1984 and 2015, generated by the ECMWF Wave Atmospheric Model (WAM) model [38]. The wave data are part of the ERA-Interim dataset, which involves a reanalysis of global meteorological variables [39,40]. Wave data were extracted from the ECMWF data server on a 0.5° × 0.5° grid, with a 6-h temporal resolution and covering the sector 16.5° N/17° W. The ERA-40 and the following ERA-Interim reanalysis are the first in which an ocean wind–wave model is coupled to the atmosphere, and the quality of the wave data has been extensively validated against buoy and altimeter data. Sterl and Caires (2005) [40] demonstrated a very good correlation between the ERA-40 data and these sources, except for high waves ($H_s > 5$ m) and low waves ($H_s < 1$ m), which tend, respectively, to be under- and over-estimated [41]. These critical wave conditions are not typical of the relatively constant wave regime affecting the Senegal delta coast, and extreme wave condition issues reported for ERA-40 are partially resolved for higher resolution ERA-Interim. However, the Senegal coast has scarce observations, and this affects the hindcast quality. ERA-40 and -Interim results in this region should be taken with caution.

Several alongshore sediment transport formulae exist and are widely applied by coastal engineers and dynamicists. However, there is still an important research effort on the improvement of alongshore sediment transport parameters and no large consensus on the choice of a formulation, as dispersion between predictors is often substantial [42], and validation dataset at the regional scale scarce. Here, we chose the formula of Kaczmarek et al. [23] because of its straightforward implementation for remote sites such as the Langue de Barbarie where only limited observations exist and because it has been applied to similar environments [43,44]. The amount of sediment drifting alongshore was computed as follows:

$$Q = 0.023 \left(H_b^2 V\right) \quad if \left(d_b^2 V\right) < 0.15 \tag{1}$$

$$Q = 0.00225 + 0.008 \left(H_b^2 V\right) \quad if \left(d_b^2 V\right) > 0.15 \tag{2}$$

where H_b is the breaking wave height and V an estimation of the alongshore current within the surf zone derived from the commonly used formula of Longuet-Higgins [45]:

$$V = 0.25 k_v \sqrt{\gamma g d_b}\, sin 2\alpha_b \tag{3}$$

where α_b is the local breaking wave angle, $\gamma = H_b/d_b = 0.78$ is the breaker parameter constant [46], g the gravitational acceleration (m/s^2), H_b the breaking wave height, d_b the local water depth and k_v an empirical constant. Here, we used $k_v = 2.9$ based on the values of Bertin et al. [43] for wave-dominated environments with similar grain-size characteristics. A separate computation for sediment transport induced, respectively, by wind waves and swell waves was conducted.

Alongshore sediment transport formulae necessitate breaking wave parameters as inputs, but global wave hindcast only provide deepwater characteristics. While a nested model (e.g., SWAN or WW3) to propagate waves from deepwater to the breakpoint would be ideal for a short-term study, the present analysis focuses on seasonal to inter-annual wave variations covering a long period of 32 years. We chose therefore to use the direct breaking wave predictor proposed by Larson et al. [47]. This formula provides breaking wave height H_b and angle α_b from deepwater wave height H_o, period T and incidence angle α_0:

$$H_b = \lambda C^2/g \tag{4}$$

$$\alpha_b = \text{asin}\left(\sin(\alpha_0)\sqrt{\lambda}\right) \tag{5}$$

with a correction factor λ computed as:

$$\lambda = \Delta\lambda_a \tag{6}$$

considering

$$\Delta = 1 + 0.1649\,\xi + 0.5948\,\xi^2 - 1.6787\xi^3 + 2.8573\,\xi^4 \tag{7}$$

$$\xi = \lambda_a sin\theta_0{}^2,\ \lambda_a = [\cos(\alpha_0)/\theta]^{2/5}, \theta = \left(\frac{C}{\sqrt{gH}}\right)^4\left(\frac{C}{C_g}\right)\gamma^2 \tag{8}$$

where deep water phase celerity is given by $C = 1.56T$, wavelength $L = 1.56T^2$, and group celerity $C_g = C/2$.

5.2. Shoreline Change and Spit and River-Mouth Dynamics

In order to highlight recent deltaic shoreline changes, we resorted to available aerial photographs (1954), a CORONA satellite image (1968) and LANDSAT (1984–1988, 1992, 1999–2004, 2006–2011, 2013, 2015–2016) and SPOT satellite images (2005) with moderate pixel size resolution (30 to 60 m) made available by the USGS and the French IGN. The main items analysed were spit length and corresponding migration rates, spit width, and river-mouth width and the underlying dynamics. The spatial data were chosen to cover the entire "delta-influenced" shoreline for each year of analysis and with a cloud cover not exceeding 10%. We limited our choice to images taken at low tide and systematically in January of every year to minimise seasonal and tidal distortions (tides induce very little variability in the microtidal context of the Senegal River delta). The results on shoreline change were completed by a literature review on the past dynamics of the Langue de Barbarie and by field observations of this spit conducted in 2005, 2007 and 2016.

Based on data from the satellite images and aerial photographs on spit and river-mouth characteristics, the fraction of sediment bypassing the mouth, β, assuming conservation of mass, was inferred from the following relationship [31]:

$$\nu = Qs(1-\beta)/Ab \tag{9}$$

where ν is the migration rate of the mouth (m·s^{-1}), Qs is the volumetric alongshore sediment transport rate (m^3·s^{-1}), and $Ab = Ws{\cdot}Ds$ which is the cross-sectional area of the river mouth spit (m^2) composed of blocked littoral sediment from the updrift coast, Ws the width of the spit, and Ds spit updrift sediment depth.

Acknowledgments: This work benefited from the ECMWF ERA Interim dataset (www.ECMWF.Int/research/Era), and from Landsat satellite images provided by the United States Geological Survey, and Spot satellite images provided by Centre National d'Etudes Spatiales. We acknowledge funding from the Belmont Forum Project: *BF-Deltas: Catalyzing Action Towards Sustainability of Deltaic Systems with an Integrated Modeling Framework for Risk Assessment*. Mamadou Sadio benefited from a partial PhD grant provided by the Embassy of France in Senegal. We thank the anonymous reviewers for their salient suggestions for improvement.

Author Contributions: Mamadou Sadio, Edward J. Anthony, Amadou Tahirou Diaw and Alioune Kane designed the project. Mamadou Sadio, Amadou Tahirou Diaw, Philippe Dussouillez and Jules T. Fleury analysed the satellite images. Mamadou Sadio., Edward J. Anthony, Amadou Tahirou Diaw, and Alioune Kane conducted field reconnaissance. Rafael Almar and Elodie Kestenare analysed the E.R.A. data and longshore transport products. All authors wrote the paper.

Conflicts of Interest: We declare no conflicts of interests.

References

1. Crossland, C.J.; Kremer, H.H.; Lindeboom, H.J.; Marshall Crossland, J.I.; Le Tissier, M.D.A. *Coastal Fluxes in the Anthropocene*; Springer: Berlin, Germany, 2007; p. 231.
2. Van Rijn, L.C. Coastal erosion and control. *Ocean Coast. Manag.* **2011**, *54*, 867–887. [CrossRef]
3. Davies, J.L. *Geographical Variation in Coastal Development*, 2nd ed.; Longman: London, UK, 1980; p. 212.
4. Anthony, E.J. Coastal progradation in response to variations in sediment supply, wave energy and tidal range: Examples from Sierra Leone, West Africa. *Géodynamique* **1991**, *6*, 57–70.
5. Anthony, E.J. The muddy tropical coast of West Africa from Sierra Leone to Guinea-Bissau: Geological heritage, geomorphology and sediment dynamics. *Afr. Geosci. Rev.* **2006**, *13*, 227–237.
6. Diatta, I. L'ouverture d'une Brèche à Travers la Langue de Barbarie (Saint-Louis du Sénégal). Les Autorités Publiques et les Conséquences de la Rupture. Master's Thesis, Université Gaston Berger, St Louis, Senegal, 2004.; p. 116.
7. Sy, B.A. L'ouverture de la brèche sur la Langue de Barbarie et ses conséquences. Approche géomorphologique. *Revue de Géographie de Saint-Louis* **2004**, *4*, 50–60. (In French)
8. Bhattacharya, J.P.; Giosan, L. Wave-influenced deltas: Geomorphological implications for facies reconstruction. *Sedimentology* **2003**, *50*, 187–210. [CrossRef]
9. Coleman, J.M.; Huh, O.K. *Major Deltas of the World: A Perspective from Space*; Coastal Studies Institute, Louisiana State University: Baton Rouge, LA, USA, 2004.
10. Anthony, E.J. Patterns of sand spit development and their management implications on deltaic, drift-aligned coasts: The cases of the Senegal and Volta River delta spits, West Africa. In *Sand and Gravel Spits*; Randazzo, G., Cooper, J.A.G., Eds.; Springer: Berlin, Germany, 2015; Volume 12, pp. 21–36.
11. Anthony, E.J. Wave influence in the construction, shaping and destruction of river deltas: A review. *Mar. Geol.* **2015**, *361*, 53–78. [CrossRef]
12. Nienhuis, J.H.; Ashton, A.D.; Giosan, L. What makes a delta wave-dominated? *Geology* **2015**, *43*, 511–514. [CrossRef]
13. Galloway, W.E. Process framework for describing the morphologic and stratigraphic evolution of delta depositional systems. In *Deltas: Models for Exploration*; Broussard, M.L., Ed.; Texas Geological Society: Houston, TX, USA, 1975; pp. 87–98.
14. Sall, M. Crue et Elévation du Niveau Marin à Saint-Louis du Sénégal: Impacts Potentiels et Mesures D'adaptation. Ph.D. Thesis, Université du Maine, Le Mans, France, 2006.
15. Kamara, S.; Martin, Ph.; Coly, A. Organisation traditionnelle du bas delta du Sénégal et nouvelles régulations hydrauliques. Dimension anthropospatiale d'un développement. *Revue Espaces et Sociétés en Mutation* **2015**, *2015*, 127–144. (In French).
16. Mahé, G.; Olivry, J.C. Variations des précipitations et des écoulements en Afrique de l'Ouest et central de 1951 à 1989. *Sécheresse* **1995**, *6*, 109–117. (In French).
17. Kane, A.; Niang-Fall, A. *Hydrologie du Sénégal*; Atlas Jeune Afrique: Dakar, Sénégal, 2007; p. 14. (In French)
18. Ostenfeld, C.; Jonson, N. *Etude de la Navigabilité et des Ports du Fleuve Sénégal; Études Portuaires à Saint-Louis, Kayes et Ambidebi. Vol. 1: Travaux Préliminaires; Vol. 2, Annexe 2: Rapport Sur les Enquêtes Hydrauliques*; Surveyer-Nenninger et Chevenert Inc.: Montréal, QC, Canada, 1972. (In French)

19. Gac, J.Y.; Kane, A. Le fleuve Sénégal. Bilan hydrique et flux continentaux de matières particulaires à l'embouchure. *Sci. Geol.* **1986**, *39*, 99–130 & 151–172. (In French).
20. Food and Agriculture Organization of the United Nations (FAO). *Caractérisation Des Systèmes de Production Agricole au Senegal*; Document de Synthese; FAO: Rome, Italy, 2007. (In French)
21. Michel, P. The southwestern Sahara margin: Sediments and climate change during the recent Quaternary. *Palaeoecol. Afr. Surround. Isl.* **1980**, *12*, 297–306.
22. Monteillet, J. *Environnements Sédimentaires et Paléohcologie du Delta du Sénégal au Quaternaire*; Lmprimerie des Tilleuls: Millau, France, 1986; p. 267. (In French)
23. Kaczmarek, L.M.; Ostrowski, R.; Pruszak, Z.; Rozynski, G. Selected problems of sediment transport and morphodynamics of a multi-bar nearshore zone. *Estuar. Coast. Shelf Sci.* **2005**, *62*, 415–425. [CrossRef]
24. SOGREAH. *Etudes de Faisabilité et D'avant Projet Sommaire de L'émissaire Delta*; Rapport Final: Grenoble, France, 1994; p. 70. (In French)
25. Barusseau, J.P.; Bâ, M.; Descamps, C.; Diop, E.S.; Diouf, B.; Kane, A.; Saos, J.L.; Soumaré, A. Morphological and sedimentological changes in the Senegal River estuary after the constuction of the Diama dam. *J. Afr. Earth Sci.* **1998**, *26*, 317–326. [CrossRef]
26. Sall, M.M. Dynamique et Morphogenèse Actuelles au Sénégal Occidental. Ph.D. Thesis, Université Louis Pasteur-Strasbourg I, Strasbourg, France, 1982.
27. Gac, J.Y.; Kane, A.; Monteillet, J. Migrations de l'embouchure du fleuve Sénégal depuis 1850. *Cahiers ORSTOM Série Géologie* **1982**, *12*, 73–76. (In French).
28. Bâ, K.; Wade, S.; Niang, I.; Trébossen, H.; Rudant, J.P. Cartographie radar en zone côtière à l'aide d'images multidates RSO d'Ers-2: Application au suivi environnemental de la Langue de Barbarie et de l'estuaire du fleuve Sénégal. *Télédétection* **2007**, *7*, 129–141. (In French).
29. Joiré, J. Amas de coquillages du littoral sénégalais dans la banlieu de Saint-Louis. *Bulletin de l'Institut Français de l'Afrique Noire* **1947**, *9*, 170–340. (In French).
30. Tricart, J. *Notice Explicative de la Carte Géomorphologique du Delta du Sénégal*; Mémoires, B.R.G.M., Ed.; Bureau de Recherches Geologiques et Minieres: Orléans, France, 1961; Volume 8, p. 137. (In French)
31. Nienhuis, J.H.; Ashton, A.D.; Nardin, W.; Fagherazzi, S.; Giosan, L. Alongshore sediment bypassing as a control on river mouth morphodynamics. *J. Geophys. Res. Earth Surf.* **2016**, *121*, 664–683. [CrossRef]
32. Guilcher, A.; Nicholas, J.P. Observation sur la Langue de Barbarie et les bras du Sénégal aux environs de Saint-Louis. *Bulletin d'Information du Comité Océanographique pour les Etudes Côtières* **1954**, *6*, 227–242. (In French)
33. Mietton, M.; Dumas, D.; Hamerlynck, O.; Kane, A.; Coly, A.; Duvail, S.; Baba, M.L.O.; Daddah, M. Le delta du fleuve Sénégal. Une gestion de l'eau dans l'incertitude chronique. In *Incertitudes et Environnement—Mesures, Modèles, Gestion*; d'Allard, P., Denis, F., Picon, B., Eds.; Ecologie Humaine/Edisud: Arles, France, 2006; pp. 321–336. (In French)
34. Durand, P.; Anselme, B.; Thomas, Y.F. L'impact de l'ouverture de la brèche dans la langue de Barbarie à Saint-Louis du Sénégal en 2003: Un changement de nature de l'aléa inondation? *Cybergeo* **2010**, *496*. (In French) [CrossRef]
35. Balouin, Y.; Ciavola, P.; Michel, D. Support of subtidal tracer studies to quantify the complex morphodynamics of a river outlet: The Bevano, NE Italy. *J. Coast. Res.* **2006**, *39*, 602–606.
36. Cooper, J.A.G. Ephemeral stream-mouth bars at flood-breach river mouths on a wave dominated coast: Comparison with ebb-tidal deltas at barrier inlets. *Mar. Geol.* **1990**, *95*, 57–70.
37. Niang, A.J. Les Processus Morphodynamiques, Indicateurs de L'état de la Désertification Dans le Sud-Ouest de la MAURITANIE. Approche Par Analyse Multisource. Ph.D. Thesis, Université de Liège, Liège, Belgium, 2008.
38. The Wamdi Group. The WAM model—A third generation ocean wave prediction model. *J. Phys. Oceanogr.* **1988**, *18*, 1775–1810.
39. Dee, D.P.; Uppala, S.M.; Simmons, A.J.; Berrisford, P.; Poli, P.; Kobayashi, S.; Andrae, U.; Balmaseda, M.A.; Balsamo, G.; Bauer, P.; et al. The ERA-interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc. Bull.* **2011**, *137*, 553–597. [CrossRef]
40. Sterl, A.; Caires, S. Climatology, variability and extrema of ocean waves—The web-based KNMI/ERA-40 Wave Atlas. *Int. J. Climatol.* **2005**, *25*, 963–977. [CrossRef]

41. Caires, S.; Swail, V.R.; Wang, X.L. Projection and analysis of extreme wave climate. *J. Clim.* **2006**, *19*, 5581–5605. [CrossRef]
42. Pinto, L.; Fortunato, A.B.; Freire, P. Sensitivity analysis of non-cohesive sediment transport formulae. *Cont. Shelf Res.* **2006**, *26*, 1826–1839. [CrossRef]
43. Bertin, X.; Castelle, B.; Chaumillon, E.; Butel, R.; Quique, R. Alongshore drift estimation and inter-annual variability at a high-energy dissipative beach: St. Trojan Beach, SW Oleron Island, France. *Cont. Shelf Res.* **2008**, *28*, 1316–1332. [CrossRef]
44. Almar, R.; Kestenare, E.; Reyns, J.; Jouanno, J.; Anthony, E.J.; Laibi, R.; Hemer, M.; Du Penhoat, Y.; Ranasinghe, R. Part 1. Wave climate variability and trends in the Gulf of Guinea, West Africa, and consequences for longshore sediment transport. *Cont. Shelf Res.* **2015**, *110*, 48–59. [CrossRef]
45. Longuet-Higgins, M.S. Alongshore currents generated by obliquely incident sea waves. *J. Geophys. Res.* **1970**, *75*, 6788–6801.
46. Battjes, J.A.; Janssen, J.P.F.M. Energy loss and setup due to breaking of random waves. In Proceedings of the ASCE International Conference on Coastal Engineering, Hamburg, Germany, 27 August–3 September 1978; pp. 569–587.
47. Larson, M.; Hoan, L.X.; Hanson, H. A direct formula to compute wave properties at incipient breaking. *J. Waterw. Port Coast. Ocean Eng.* **2010**, *136*, 119–122. [CrossRef]