Chapter 2
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

Edward J. Anthony

Abstract The sand spits associated with the Volta and Senegal River deltas, the two largest river deltas in West Africa, after that of the Niger River, show complex patterns of morphodynamic development while also strongly reflecting the recent impacts of human activities. The large spit of the Volta delta seems to be a direct outgrowth of a natural change in the location of the mouth of the Volta and of a marked reduction in sand supply on the eastern coast of Ghana that largely predated the construction of the Akosombo dam, but which has been strongly aggravated since this dam was completed in 1961. Spit formation has led, in particular, to segmentation of the unique sand drift cell that prevailed on the Bight of Benin coast between the Volta delta mouth and the western confines of the Niger delta. These changes have been associated with strong gradients in longshore drift and fundamental modifications in the dynamics of sand barriers on the Bight of Benin coast and hitherto fed by sand supplied by the Volta River. The spit has prograded massively by the adjunction, in situ, of new individual beach ridges, rather than by undergoing elongation, a pattern of growth that has entailed sand sequestering within the confines of the delta. The distal tip of the spit has recently welded to the shoreline, creating a new barrier-lagoon system, and assuring the resumption of integral sand drift from the mouth of the Volta towards the rest of the hitherto sand-starved Bight of Benin coast. The process should also offer limited respite from erosion to the beleaguered town of Keta, located just downdrift of the former distal tip of the now welded spit.

The Langue de Barbarie spit at the mouth of the Senegal River delta is an outgrowth of strong longshore drift affecting one of the finest examples of a wave-dominated delta. The spit developed jointly with the delta and appears to have inexorably extended downdrift in conjunction with river-mouth diversion and

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migration southwards during the late Holocene, albeit with occasional breaches, the oldest of which are only preserved north of the city of St. Louis. The spit has had a downdrift migration range of about 30 km, beyond which alongshore sand drift and river discharge conditions led to stabilisation of the position of the river mouth. Numerous natural breaches have been identified on the Barbarie spit between 1800 and the present day, no doubt related to years of exceptionally high river discharge in an overall Sahel-influenced climatic context of rather irregular discharge. The recent evolution and potential future demise of the spit reflect the consequences of hasty and short-sighted artificial breaching to solve an impending flooding problem facing the historic city of St. Louis in 2003. An artificial breach through the spit created by engineers in just a few hours to counter a risk of flooding of St. Louis from exceptional river discharge in 2003 has had dramatic consequences on the integrity of the spit, notably by acting as a new river mouth that underwent rapid and significant widening. Part of the spit sand further downdrift of the new mouth is being recycled into river-mouth bars, while the rest of the eroded sand is transported downdrift by longshore currents, including beyond the sealed pre-2003 mouth. This dismantling of the spit has had dramatic consequences on recent settlements and tourist facilities and infrastructure. The erosion is probably a joint result of sequestering of part of the sand load transported by longshore currents in the new widened river mouth and a reinforced tidal prism through this new mouth. A new phase of spit dismantling and the formation of a second mouth a few kilometres downdrift of the new mouth occurred during high river discharge conditions in October 2012, thus illustrating the potential seasonal effect of high river outflow on spit reworking.

2.1 Introduction

Much of the coast of West Africa is characterised by essentially rectilinear wave-dominated sand barriers, with only a small proportion of muddy coast associated with open estuaries, relatively large tidal ranges and interspersed sandy and shelly cheniers between southern Senegal (south of the Gambia) and central Sierra Leone. The distribution of the long stretches of wave-dominated coast and the much more limited predominantly tidal estuarine sector is highlighted by continental shelf width in Fig. 2.1, the latter sector being subject to significant wave energy dissipation over a broad, low-gradient shelf (Anthony 2006). The two sandy sectors on either side of this muddy estuarine coast are under the influence of dominantly long and regular swell and/or shorter-fetch trade-wind waves. In conjunction with abundant fluvial sand supplies during the Late Pleistocene sea-level lowstand on the presently drowned inner shelf, this swell wave regime has resulted in the build-up of numerous sandy barrier systems. In Senegal, these barrier systems commonly consist of dune-decorated spits. Many of the barrier systems on the rest of the West African coast have been prograded ones and some are still progradational,

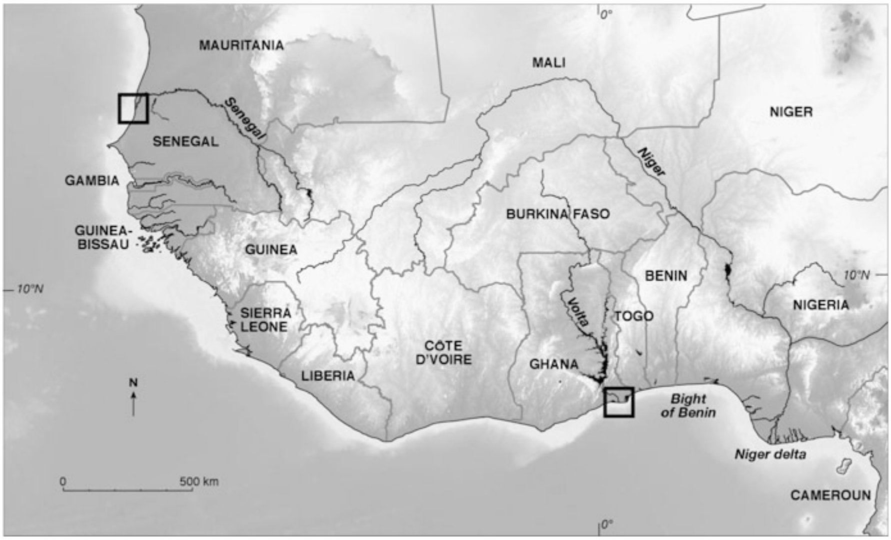

Fig. 2.1 The coast of West Africa. Continental shelf width (clearer hue along the coast) is a fine indicator of the distribution of long stretches of wave-dominated coast (narrow shelf) and the much more limited, predominantly tidal, estuarine sector between Sierra Leone and Guinea-Bissau (broad, low-gradient shelf), subject to significant wave energy dissipation. The two sandy sectors on either side of this muddy estuarine coast are under the influence of dominantly long and regular swell and shorter-fetch trade-wind waves. Abundant sand supplies and strong wave-induced longshore drift have favoured the construction of numerous sand spits, including at the mouths of the Niger, Volta and Senegal River deltas, the last two (*boxes*) of which are briefly described in this chapter

characterised by sequences of wave-formed beach ridges under dominantly 'drift-alignment' patterns (as defined by Davies 1980). Locally, 'swash-aligned' patterns have developed in embayed settings bounded by bedrock headlands, notably in Liberia. A hallmark of this constant wave regime is strong sustained longshore drift responsible for the commonality of spit formation. Some of the prograded barrier systems exhibit, in their distal sector (relative to drift direction), initial successive spit recurves reflecting mid-Holocene closures of a rather irregular coastline with a succession of bays and headlands inherited from the late Pleistocene sea-level lowstand. These spit recurves are succeeded by rectilinear successive beach-ridge extensions in the course of progradation under a high sand supply regime, although long stretches of the West African coast are also characterised by such rectilinear barrier systems with no evidence of spit recurves. This is especially so where a double barrier system exists, a common situation, comprising an inner barrier combining spits and rectilinear ridges, and an outer barrier of rectilinear ridges. In the vicinity of certain river mouths, however, the interaction between fluvial processes and longshore drift has generated more or less complex spit development. These spits are interesting in terms of manifestations of river-mouth morphodynamic patterns and from a coastal management perspective, especially where large deltas, such as those of the Volta and Senegal Rivers

(Fig. 2.1) are concerned. In this study, two examples concerning these two deltas, and illustrating variably complex patterns of sandy spit development in this strongly wave-dominated setting, are described and their morphodynamics analysed. The implications of the dynamics of these spit systems in terms of coastal management problems are also discussed.

2.2 The Volta River Delta Spit

2.2.1 Setting

The Volta River delta (Fig. 2.2) forms the proximal sector, on the Bight of Benin coast, of what was, until fairly recently (the 1960s), a single, very long sand drift cell stretching 500 km eastwards to the western confines of the Niger River delta in

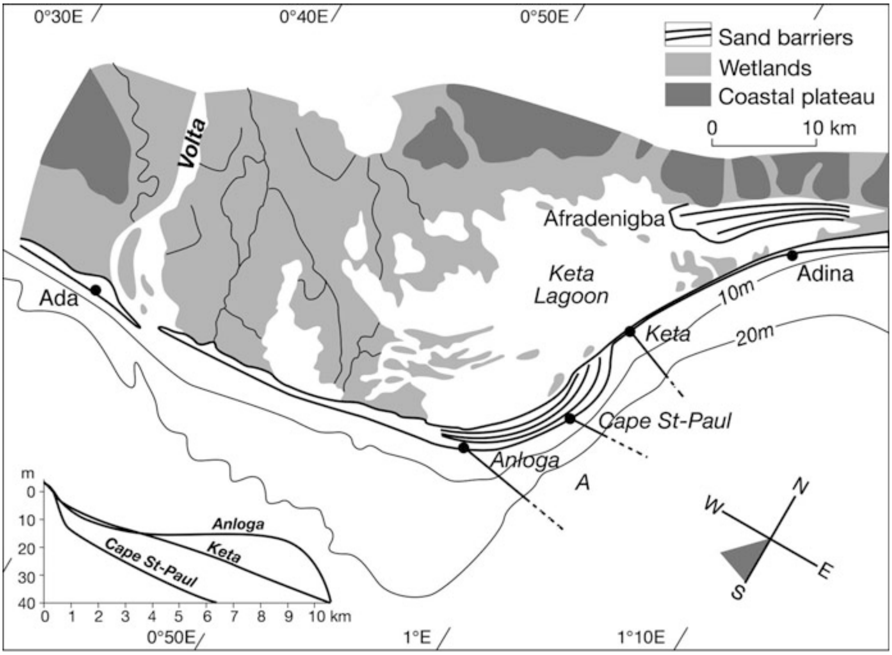

Fig. 2.2 Morphology of the Volta River delta and shoreface, showing the prograded river-mouth spit between Anloga and Keta. Massive spit growth appears to have occurred relatively recently, with regards to the post-mid-Holocene history of sand barriers in the Bight of Benin, in response to a westward shift in the river mouth and increased sequestering of sand by the Volta through enhanced wave refraction in the area south of Keta. This sand trapping has initiated a wave of important erosion of the narrower sand barrier linking the Volta delta to the Adina barrier system. Spit progradation has diminished considerably in response to a decreasing fluvial sand supply but, correlatively, the welding of the distal tip of the spit in the 1990s to the narrow Keta barrier has led to a reduction in erosion of the latter barrier, the southern part of which has been further consolidated by engineering works

Nigeria (Fig. 2.1). The Volta delta has developed in a large salient trap created by left-lateral offsetting on the coast of Ghana probably by the Romanche fracture zone (Kutu 2013), one of the many fracture zones that has offset the West African continental shelf and coast. The delta coast is bounded by a narrow shelf 15–33 km wide, and characterised by a fairly uniform, moderately steep shoreface with a gradient of between 1:120 and 1:150 up to −15 m, considered as the close-out depth for significant wave movements on this coast (Delft Hydraulics 1990; Rossi 1989), and beyond which the inner shelf levels out to a low-gradient (1:350–1:400) plain covered by relict transgressive sands. The wave setting is a cyclone- and storm-free West Coast Swell Environment as defined by Davies (1980), dominated by moderate to high energy (H = 0.5–4 m), long period (T = 10–15 s) southwesterly swells from the Atlantic. Waves break on the coast after refraction, with angles of 4–9°. Tides impinging on this coast are semi-diurnal, with a mean range of around 1 m. The mean spring tidal range is about 1.95 m. Overall, the constant wave regime of this coast, marked by long, moderate to high waves with low variation in directional approach, and a tendency for the prevalence of relatively steep, reflective beachfaces of medium to coarse sand, result in one of the highest rates of annual unidirectional longshore sand drift in the world, with values of up to 1 million m^3 (Blivi et al. 2002). These peak values are probably exceeded over short stretches of beach along the Volta delta. An important source of this sand has been the Volta River, one of the three largest river basins in West Africa, with the Niger and the Senegal. The Volta River drains a predominantly sandstone catchment that also includes a wide variety of lithologic terranes covering an area of 390,000 km^2, much of it located in the semi-arid Sahel zone of West Africa. The river's liquid discharge varied between a low of 1,000 m^3/s in the dry season and a high of over 6,000 m^3/s in the wet season before completion of the Akosombo Dam in 1961, only 60 km upstream from the sea. Discharge downstream of the dam has been strongly reduced by the decrease in rainfall over the Sahel since 1975 (Oguntunde et al. 2006). The Volta Delta covers an area of around 5,000 km^2. The sand load brought down annually by the river to its delta before dam construction has been estimated at about 1 million m^3 (Delft Hydraulics 1990). Much of this sand was injected into the longshore drift system via a single delta river mouth (Fig. 2.2). Sand supply from the shoreface has also been deemed to be important, especially in the early phases of barrier progradation as shoreface gradients in West Africa adjusted to sea level (Anthony 1995).

2.2.2 Barrier Dynamics in the Bight of Benin: Prelude to Volta Delta-Mouth Spit Development

The large spit at the mouth of the Volta delta is tentatively interpreted here, in the absence of absolute dates, to be a relatively recent feature resulting from adjustments between sediment supply from the river, delta dynamics and the strong longshore drift on this coast. The barrier systems that have developed in this sector of the Bight of Benin coast exhibit a relatively complex history, elements of which have been documented by Anthony and Blivi (1999). Much the bight coast exhibits a regressive single or double barrier. This barrier has been shown to be a 'hybrid' system in terms of internal facies composition and plan-view morphology, in that it has evolved from an essentially regressive to a stationary (synonymous with cessation of progradation) system. Once progradation of an inner barrier resulted in the regularisation of what was, hitherto, an indented shoreline, the succeeding phase of coastal development involved the emplacement of the more continuous outer barrier directly linked to the Volta river mouth, suggesting the establishment of a highly efficient drift alignment and transition to an economy of massive sediment sourcing by the Volta that predated the development of the Volta spit. Radiocarbon ages from parts of the barrier front show a phased pattern of progradation from the Volta delta to Benin. Ages of 5,000–6,000 years B.P. from Ada and Anloga near the sea (Fig. 2.2) in the proximal to central sectors of the Volta delta barrier (Streif 1983) suggest little net progradation of this part of the barrier over this period. The Volta delta-mouth barrier zone has thus essentially comprised a 'stationary' barrier sector of active through-drift of sand from the river up to Anloga, beyond which progradation of the distal Volta barrier continued, serving at the same time as a through-drift zone for the rest of the bight coast. This part of the barrier has not been dated. Old maps show that this delta-mouth barrier stretched continuously to Togo, with the zone between the old port of Keta and Adina acting as one of through-drift of sand between the Volta mouth and the barrier in Togo (Fig. 2.2). In spite of the massive sand supply from the Volta to the coast, the rest of the barrier front in neighbouring Togo shows no significant progradation since around 3,800 year B.P., and cessation of progradation occurred over 1,000 years later in Benin, further east (Anthony et al. 1996, 2002). These ages therefore suggest relatively rapid progradation over a fairly short time (5,000–3,000 year B.P.), especially in Togo, once longshore drift conditions became favourable to large-scale eastward advection of Volta sand. The ensuing phase of net long-term longshore stability in Togo and Benin probably stemmed from some sort of equilibrium among shoreline orientation, the nearshore profile and the hydrodynamic regime (Anthony 1995). The final sink for this sand is the eastern end of the Bight of Benin in Nigeria, near the western confines of the Niger delta.

2.2.3 Inception, Development and Geomorphic Transformation of the Volta Spit

The inception of a distinct spit along the eastern sector of the Volta delta, in lieu of a former distally shore-attached barrier-lagoon system, is interpreted here as the result of increasing influence of the prograding distal Volta barrier on wave refraction patterns. This has been further compounded by a recent reduction in direct fluvial supply that has induced a wave of erosion of the downdrift barrier and shoreface deposits to fulfill the strong drift requirements. Although the construction of the Akosombo Dam in 1961 and the drastic reduction in sand supply to the Bight of Benin coast it caused (Ly 1980) readily come to mind as the trigger factor of such erosion and barrier readjustments, the evidence pleads for a more complicated scenario. There is clear evidence that coastal erosion antedated dam construction. The barrier sector of Keta, the hinge point between the distal Volta barrier and the Togo barrier, was a once flourishing colonial port, probably located in a sector of stationary barrier that served as a transit zone for Volta delta sand to Togo. Since the mid-1880s, net erosion of this area is probably close to 1 km (Kumapley 1989). The most likely reason for this dramatic erosion is that sand supply from the Volta delta area has progressively become insufficient to compensate for strong drift supply to the rest of the Bight of Benin, probably because the distal delta barrier, between Anloga and Keta had been increasingly sequestering a significant proportion of the river's sand supply to the coast, culminating in the formation and rapid growth of the present Volta delta spit. This may have occurred in conjunction with a shift in the river mouth from the distal barrier sector at about the present area of Anloga, where the shoreface bathymetry appears to suggest the presence of a deltaic lobe, to the present proximal position near Ada (Fig. 2.2). The estimated amount of sand captured annually in this prograding distal part of the barrier has been estimated, for the period 1968–1996, at about 750,000 m^3 a year (Anthony and Blivi 1999). In particular, the necessity to satisfy the strong longshore drift budget towards Togo has resulted in considerable reworking of the barrier downdrift of this prograding distal segment, including the nearshore zone, threatening coastal settlements such as Keta. As erosion around Keta has proceeded, this severely eroded drift acceleration zone (Fig. 2.3) became characterised, by the 1990s, by a narrow (<100 m wide) eroding transgressive barrier subject to overwash and breaching during the summer months of strong swell (Fig. 2.3). A shoreline stabilisation project completed in 2004 (Keta Sea Defence Project) and comprising several groynes and a seawall (Fig. 2.3) have reduced erosion in this sector, which is still estimated at about 5.5 m/year in a recent study (Boateng 2012). Downdrift of this sector erosion is even stronger (Addo et al. 2011), whereas the Volta spit has continued growing, increasingly with a concave seaward plan-view shape due to accretion of successive beach ridges, but with restricted longshore growth of the distal tip. Beach-ridge accretion occurs over subaqueous prograding of lobes of coarse to medium Volta sand over a silty shoreface at a depth of around 10 m (Rossi 1989), and this explains the relatively steep shoreface-to-shelf transition of the prograding sector off Cape St. Paul (Fig. 2.2). Once the initial through-drift configuration in this zone was altered by the sediment budget imbalance evoked above, accretion of the Volta spit forced further wave refraction, amplifying cell segmentation, and resulting in the instauration of a swash-alignment associated with sequestering of sand by this new spit complex. These changes have also induced new patterns of barrier behaviour that include transgressive and regressive dynamics at various locations alongshore. Drift requirements have been satisfied by substantial barrier retreat and shoreface erosion east of the Volta barrier.

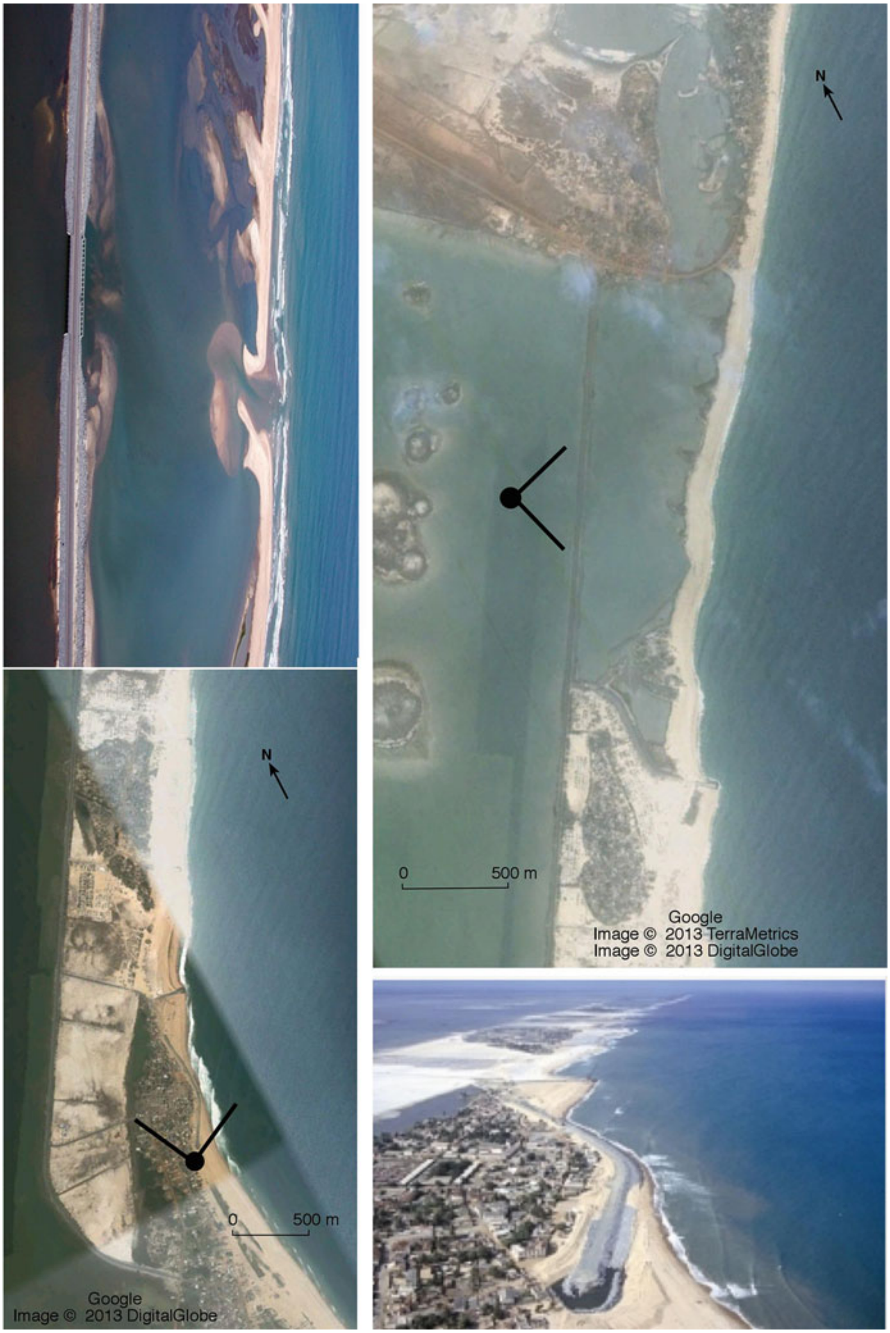

Fig. 2.3 Google earth images (*top right* and *bottom left*) and aerial views of the Volta spit hinge point with the shoreline, a particularly fragile drift-pulse sector that has been subject to important erosion in the past. *Top left* photograph taken in 2001 and *top right* 2013 Google extract show the narrow barrier and inlet system that connects the Volta delta spit to the Bight of Benin barrier system at Adina. The barrier is still subject to erosion, especially north of the sector shown here. *Bottom right* photograph (2001) and *bottom left* 2013 Google image show part of the town of Keta at the tip of the Volta spit and engineering works completed in 2004 (Keta Sea Defence Project) aimed at consolidating the spit hinge point and protecting the town. *Broad arrowheads* with dots show locations of photographs on the Google images (Photo credit: Great Lakes Dredge and Dock Company)

The situation has merely been aggravated since the 1960s by the construction of the Akosombo Dam. A recent feature of this spit growth is that the formerly highly eroded proximal zone of the drift acceleration zone, or drift 'pulse', is now being protected by this spit. Anthony and Blivi (1999) considered that this probably heralded a shift towards a less swash-aligned distal spit zone, and predicted eastward 'leakage' of some of the Volta sand, rather than quasi-total sequestering, thus alleviating erosion further downdrift. Recent images indeed show that the distal tip of the spit has now welded to the shoreline, thus resulting in the reconversion of spit to attached barrier, a process probably consolidated by the engineering works in this sector (Fig. 2.3).

2.3 The Senegal River Delta Spit

2.3.1 Context

The Senegal River is about 1,800 km long, the second longest river in West Africa. Reports regarding the area of the Senegal catchment range widely from 288,000 to 450,000 km^2, which is quite surprising, given the modern possibilities of determination of river basin coverage from satellite imagery! The Senegal delta (Fig. 2.4) is a classical text-book example of a wave-dominated delta, characterised by strong longshore drift generated by Atlantic waves from the northwest. Two clear manifestations of such wave domination are the absence of a notable classic deltaic

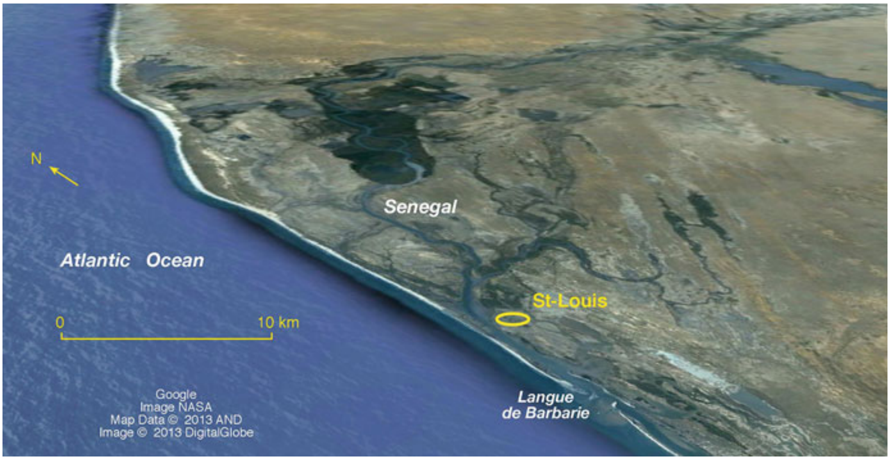

Fig. 2.4 The Senegal River delta, a fine example of a wave-dominated delta characterised by the Langue de Barbarie spit and river-mouth system subject to strong north-south longshore drift. This Google image shows a much widened river mouth in 2013 that developed very rapidly from an artificial breach created to prevent river flooding of St. Louis in October 2003. The former natural mouth much further south (sector not shown here) has been sealed by longshore drift

'bulge', and the presence of a persistent sand spit, the Langue de Barbarie, an extremely mobile feature, subject to repeated past breaches, associated with phases of delta-mouth migration over a total distance of about 30 km at least since the mid-seventeenth century. Of particular significance in terms of coastal management is the historic and picturesque city of St. Louis (population: 200,000), a UNESCO world heritage city at the proximal delta hinge point of the spit (Fig. 2.4), and protected from the ocean by the latter.

The lower Senegal delta is characterised by high biological productivity, rich agricultural and fishing sectors, a relatively high level of urbanisation and a recent strong bent towards tourism. St. Louis is frequently affected by flooding of the lower Senegal valley in the rainy season (May–October), as the discharge of the river rises dramatically, much of the city lying at an elevation of less than 2.5 m above sea level (Sall 2006). The mean annual liquid discharge of the Senegal River is 676 m^3/s. It varies from a low dry season value of 9 m^3/s in May, to an extreme flood value of 3,320 m^3/s in September. The wet season discharge is thus relatively moderate, given the size of the Senegal basin, and shows a slow rise, typical of large tropical river systems. Interannual variability is extremely high, however, with the mean annual discharge ranging from 250 to 1,400 m^3/s. The river drains a large area of the western Sahel, and its discharge has been particularly affected by droughts in the Sahel since the 1970s.

The Senegal delta coast is characterised by a relatively narrow continental shelf. The coast is dominated by waves that are predominantly from the northwest, and this direction is especially active during the dry season from November to June. Significant wave heights range from 1.5 to 2 m. NW waves impinge on the Langue de Barbarie at angles of 10–20°, thus generating active longshore drift to the south. Waves from the southwest and from the west account for the rest, and are only active during the rainy season between July and October. Wave periods range from 6 to 12 s, reflecting a mix of distant swell and wind waves (Anthony 2006). The tidal regime is semi-diurnal and the range microtidal, comprised between 0.5 m at neap tides and 1.6 m at spring tides.

2.3.2 The Migration Dynamics of the Langue de Barbarie Spit

The relatively moderate river discharge, including during the flood season, the permanence of moderate waves propagating across a relatively narrow shelf, and the microtidal regime are three conditions that explain the wave-dominated character of the Senegal River delta and quasi-permanent river-mouth diversion by the Langue de Barbarie. The Barbarie spit is a 100–400 m-wide feature that has fluctuated in length between 10 and 30 km over the last century. The spit is capped by a 5–10 m high dune. The river-mouth depths range from 2.5 m in the rainy season when sand deposition results from high river discharge, to 3.5 m in the dry season, when sediment flushing is assured essentially by tidal currents. A drift volume that decreases from north to south along the spit from 0.70 to 0.60 $\times$ 10^6 m^3 has been calculated by SOGREAH (1994), the gradient attributed to progressively more significant aeolian dune abstraction of sand between the relatively urbanised sector of St. Louis, where dunes have been fixed by vegetation, notably plantations of Filao (*Casuarina equisetifolia*), and the relatively poorly vegetated distal zone. Mild opposite drift towards the north occurs during the short summer period when waves from the southwest dominate.

Rates of spit growth proposed in the literature from the analysis of satellite images and aerial photographs and from field measurements vary widely, from 94 to 700 m a year. It is likely that rates actually vary interannually depending on variations in wave characteristics, river discharge and mouth dynamics coupled with breaching. Spit growth occurs through the classic adjunction of ridges at the distal end, and the process is undoubtedly favoured by the shallow overall depths of the mouth. Gac et al. (1982) conducted a historical analysis of the mobility of the spit and of the corresponding locations of mouth openings. They showed that the spit has varied neither in elevation nor in width since 1800, and that the farthest downdrift position of the mouth of the river, which corresponds to the maximal distal spit extension, did not exceed 30 km, no doubt constrained beyond this point by the conjunction of sand supply taken up by dunes along the spit and river-mouth discharge supplemented by drainage of the southern part of the delta which comprises a shallow infilling basin. Joiré (1947) and Tricart (1961) situated the mouth in the vicinity of St. Louis at about the mid-seventeenth century, but Gac et al. (1982) have identified even earlier mouth scars north of St. Louis. Michel (1980) dated the formation of the spit at between 4000 and 1900 BP. The spit lengthened by 11 km between 1850 and 1900, and its distal tip was located at the turn of the twentieth century 15 km south of St. Louis. It was affected over this period by seven breaches, of which the most important, in 1884, resulted in a new mouth opening that rapidly attained a width of 4 km (Gac et al. 1982). Since 1900, a major coastal management preoccupation has been that of preventing breaches in the vicinity of St. Louis, achieved through dune reinforcement via Filao planting. Between 1900 and the date of their study, Gac et al. (1982) enumerated 13 breaches, 8 of which occurred between 1954 and 1973. The 1973 breach was also the last natural breach of the twentieth century. The absence of breaches over the last quarter of the twentieth century may be explained by the absence of major floods over this period, characterised by the Sahel drought, and by the flow regulatory effects of dams constructed in the lower Senegal valley. The mean reduction in river discharge in Bakel, a hydrographic station located 550 km upstream of St. Louis, attained 25 % between 1970 and 1990, and even diminished by half between 1980 and 1990 (Mahé and Olivry 1995). An anti-salt dam, the Diama dam, was constructed 54 km upstream of St. Louis in 1987, and a hydropower dam, the Manantali dam, constructed in 1987 in the upper basin in Mali, thus resulting in modification of the hydrological regime and in sediment trapping upstream.

2.3.3 Impending Demise of the Spit?

One ancillary function of the two dams constructed on the Senegal River was to alleviate floods in the lower valley, notably in the deltaic sector of St. Louis. The flood control function of these dams has yielded rather mixed results (Mietton et al. 2006), with flooding still being persistent in the critical area of St. Louis, as a result of rainfall anomalies and the potential blocking of freshwater outflow at the Langue de Barbarie inlet by strong wave activity. One such rainfall anomaly occurred in October 2003, resulting in a rapid rise in water level around St. Louis that led to the drastic decision, by the local authorities, to create an artificial breach near the city to alleviate the flooding. In urgency, on the night of October 3, 2003, a 4 m-long, and 1.5 m-deep trench was opened up by engineers in a relatively narrow (100 m-wide) portion of the spit about 7 km south of St. Louis (Durand et al. 2010), enabling a rapid overnight drop in water level of up to 1 m, thus preventing flooding. Following this opening, the tips of the two opposed spits were rapidly eroded, the breach acting as the new river mouth, and attaining a width of 250 m 3–4 days after the opening (Fig. 2.5a), and 800 m 6 months later. The depth of the

Fig. 2.5 Ground photographs showing the initial trench (*top left*) that preceded the artificial breach of the Langue de Barbarie created in October 2003 in order to alleviate flooding of parts of St. Louis. *Top right* photograph shows the breach considerably widened by river and tidal flow a few days later (Photo credit: Service régional de l'Hydraulique, St. Louis du Sénégal). *Bottom* photographs taken in January 2013 show a natural breach that occurred in October 2012 500 m downstream of the artificial breach (Photo credit: Bertil Wilmotte)

Fig. 2.6 Assemblage of sketches showing changes in the Langue de Barbarie spit and inlet system between March 2003, prior to the October 2003 artificial breach, and 2013. The artificial breach has been followed by significant destabilisation of the spit and by widening of the new river mouth that has exploited this breach. Parts of the eroded spit are being reworked by waves and currents into river-mouth bars and islets. Mouth widening has also led to an increase in tidal influence within the lower Senegal delta and in direct wave attack of parts of the delta plain hitherto protected by the spit

breach had also increased to 6 m, and its width by 1.5 km by 2007 (Bâ et al. 2007). Similar artificial breaches of an extremely mobile spit in Benin, with migration rates of up to 700 m, are commonly operated in order to alleviate flooding, without major consequences on the morphodynamic functioning of the river mouth (Laïbi et al. 2011). In the case of the Senegal River delta spit, the implications of this breach, operated without a consideration of the consequences of subsequent behaviour of the spit and of river-mouth dynamics, has turned out to be dramatic for the numerous villages in the lower delta plain south of St. Louis, and the tourism-based structures that have developed on the Langue de Barbarie in the decade preceding the opening. The spit may also have been lastingly destabilised by this artificial breach, this new mouth characterised by in situ widening rather than migration (Fig. 2.6). Channeling of the Senegal river flow in this new mouth led to closure of the former natural mouth located downdrift. A natural breach 500 m south of the artificial 2003 breach occurred in October 2012, thus creating a new additional mouth (Fig. 2.5b). Following this breach, much of the remaining spit is now being eroded, resulting in several washovers that tend to coalesce, widening sea intrusion pathways, as the sand is transported downdrift by the strong longshore drift. This has led to the dismantling of campsites and other tourist structures. The delta in this eroding sector is now directly exposed to erosion, threatening numerous villages.

2.4 Discussion and Conclusion

The patterns of spit development of the two largest river deltas in West Africa, after the Niger delta, strongly reflect the recent impacts of human activities and, in at least the case of the Senegal delta spit, lack of foresight in engineering practice aimed at delta-plain flood control behind the Langue de Barbarie spit. The Volta delta spit seems to be an outgrowth of a change in river-mouth location and of a marked reduction in sand supply on the eastern coast of Ghana that largely predated the construction of the Akosombo dam. The resulting strong gradients in longshore drift have been responsible for changes in sand barrier morphology and, most likely, in the initiation of the Volta delta spit. Spit formation led, in turn, to segmentation of the unique sand drift cell that prevailed on the Bight of Benin coast between the Volta delta mouth and the western confines of the Niger delta. This unique drift cell has been further segmented in the 1960s by the construction of deepwater ports in Togo, Benin, and Nigeria (Laïbi et al. 2014). The formation of the spit is a manifestation of sand sequestering within the confines of the delta, under a delta morphodynamic regime of joint river and wave-domination, assuring its future integrity in a context of sand deficit. The Volta delta spit has behaved essentially as one of restricted longshore growth, prograding massively instead by the adjunction, in situ, of new individual beach ridges. This pattern of growth has ultimately led to the welding of the distal tip of the spit to the Bight of Benin shoreline, thus creating a new barrier-lagoon system in replacement of the spit. This change should be synonymous with the reestablishment of a single drift cell on the western Bight of Benin coast between Ghana and Togo, thus assuring resumption of integral sand drift from the mouth of the Volta. The process should also offer limited respite from erosion to the hitherto beleaguered town of Keta.

The Langue de Barbarie spit at the mouth of the Senegal delta is altogether different in its inception, dynamics and future evolution. The spit is an outgrowth of strong longshore drift affecting one of the finest examples of a wave-dominated delta. Its recent evolution and potential future demise reflect, however, the consequences of hasty and short-sighted artificial breaching to solve an impending flooding problem facing the historic city of St. Louis. The Barbarie spit developed jointly with the delta and appears to have inexorably extended downdrift in conjunction with river-mouth diversion and migration southwards during the late Holocene, albeit with occasional breaches, the oldest of which are only preserved north of the city of St. Louis. The spit has had a downdrift migration range of about 30 km, beyond which alongshore sand drift and river discharge conditions led to stabilisation of the position of the river mouth. Over time, breaching appears to have been essentially influenced by river discharge spates. Numerous natural breaches have been indentified on the Barbarie spit between 1800 and the present day, no doubt related to years of exceptionally high river discharge in an overall Sahel-influenced climatic context of rather irregular discharge. In contrast, the long phase of river-mouth stability between 1973 and 2003 was associated with a decrease in river discharge related to the Sahel drought, and this phase of stability was marked by the development of tourism-based activities on the spit. The artificial breach through the spit created by engineers in just a few hours to counter a risk of flooding of St. Louis from one such exceptional river discharge season in 2003 has had dramatic consequences on the integrity of the spit, notably by acting as a new river mouth that underwent rapid and significant widening (Fig. 2.6).

It is not clear why the spit is being progressively dismantled. One important question relative to this is that of the net sediment budget. There are no reasons to believe that sand supply from updrift, along the coast of Mauritania, and hitherto feeding the spit, may have diminished, and this does not seem to be a likely explanation for spit demise. A more likely reason may reside in sequestering of sand drifting alongshore from the north within the confines of the new, wide river mouth, a process that may be reinforced by a now larger tidal prism associated with this new mouth. 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 enlarged mouth and the anti-salt intrusion Diama dam that confines the tidal prism to the lower delta plain. It is interesting to note that the latest phase of spit dismantling occurred during high river discharge conditions in October 2012, thus illustrating the potential seasonal effect of high river outflow on spit reworking. As sand is being sequestered within the confines of the new mouth, the spit downdrift is being eroded to balance the strong requirements in longshore drift.

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