Longshore drift cell development on the human-impacted Bight of Benin sand barrier coast, West Africa

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ABSTRACT

Laïbi, R. A., Anthony, E. J., Almar, N., Castelle, B., Senechal, and Kestenare, E., 2014. Longshore drift cell development on the human-impacted Bight of Benin sand barrier coast, West Africa. *In:* Green, A.N. and Cooper, J.A.G. (eds.), *Proceedings 13th International Coastal Symposium* (Durban, South Africa), *Journal of Coastal Research*, Special Issue No. 66, pp. xxx-xxx, ISSN 0749-0208.

The Bight of Benin is an open, microtidal, wave-dominated coast forming a 500 km-long mild embayment in the Gulf of Guinea, in West Africa, between the Volta River delta in Ghana, to the west, and the western confines of the Niger River delta in Nigeria to the east. The bight is exposed to energetic swells from the South Atlantic, and is characterised by Holocene sand barriers bounding lagoons. The barrier system has been sourced essentially by sand supplied through the Volta River delta, terminus of a large river catchment of 397,000 km2, although wave energy conditions and sand mineralogy also suggest inputs from the nearshore shelf. The long-term pattern of barrier progradation in the Bight of Benin culminated in a mildly embayed coast wherein incident wave behaviour, beachface gradient and the longshore sand transport system were intimately linked, generating what may be classified as an 'equilibrium drift-aligned' coast with a unique and homogeneous longshore drift cell stretching from the Volta River delta to the Niger River delta. This coast has, however, been significantly impacted over the last 50 years by the construction of three deepwater ports in Lomé (Togo), Cotonou (Benin) and Lagos (Nigeria) that have intercepted sand supply, as well as by a major dam on the Volta River, resulting in destabilization of the former single drift cell on this coast. The ensuing multi-cellular structure is characterised by long sectors of rampant coastal erosion that threatens parts of these cities, coastal villages and infrastructure.

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ADDITIONAL INDEX WORDS: *wave-dominated coast, drift-alignement, deepwater ports, coastal erosion.*

INTRODUCTION

One reason for the commonality of shoreline erosion induced by human activities on long open coasts is the lack of understanding of the spatial and temporal scales over which occur sediment redistribution processes that shape the coast. In many situations, small segments of coast, commonly of high value due to urbanisation, and with specific management preoccupations, are embedded in larger-scale aspects of coastal change that are not always well apprehended. From a coastal management point of view, a first step towards bridging the gap between these two scales of change has been the coastal cell concept, fundamentally hinged, on open beaches, as opposed to short embayed or pocket beaches, on alongshore wave gradients and longshore drift, the primary drivers of short-term (days to years) coastal change (Carter, 1988). The concept, has commonly been used in a purely sediment budgetary framework in which process gradients may be ignored, the emphasis being on definition of each cell and on the net gains and losses of sediment within each coastal cell (van Rijn, 2011). This approach is valid and useful on coasts where cell boundaries and their spatial and temporal changes are readily constrained, which is commonly the case of wave-dominated, microtidal coasts, such as in West Africa (fig. 1). The West African coast is characterised by two long stretches of wave-dominated coasts under the influence of long and regular swell and a minor component of shorter-fetch wind waves. A hallmark of this constant wave regime is strong sustained longshore drift that prevails along much of these two sectors of sandy coast. In conjunction with abundant fluvial sand supplies during the Late Pleistocene sea-level lowstand on the presently drowned inner shelf, this has resulted in the build-up of numerous barrier systems in the Gulf of Guinea and spit and aeolian dune systems on the Mauritania and Senegal coast.

Many of the barrier systems in the Gulf of Guinea are characterised by sequences of wave-formed beach ridges under dominantly 'drift-alignment' patterns (as defined by Davies, 1980), although locally, 'swash-aligned' patterns have developed in embayed settings bounded by bedrock headlands, notably in Liberia. Three sectors of sand barrier development with significant sequences of beach ridges bound by long, open beaches can be clearly distinguished: the coasts of southern Sierra Leone, Côte d'Ivoire, and the Bight of Benin (fig. 1). The long, open beaches of the last two sectors, subject to pronounced longshore drift, are also potentially highly susceptible to perturbations generated by anthropogenic activities.

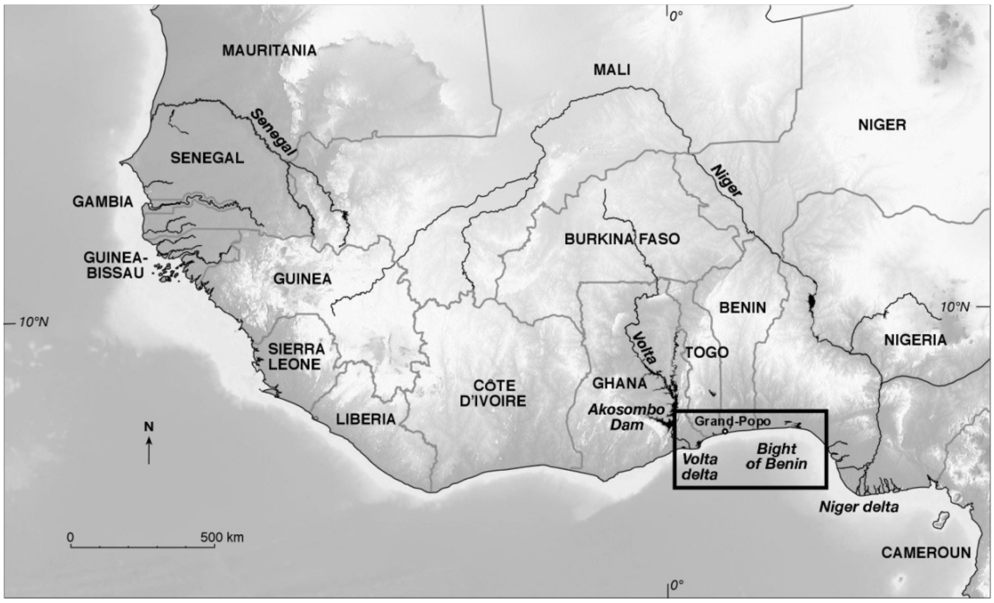

Figure 1. Wave-dominated sectors of the coast of West Africa characterized by moderate to strong longshore drift (Mauritania and Senegal, and from Sierra Leone to Cameroun), and the Bight of Benin coast between the deltas of the Volta and Niger Rivers

This paper focuses on the drift cell structure of the barrier system of the Bight of Benin, which like that of the Côte d'Ivoire coast has been significantly impacted by human activities, whereas the coast of southern Sierra Leone, characterized by moderate drift by virtue of its overall orientation to Atlantic waves (Anthony, 1995) has remained totally exempt from direct human modifications. We show that following progradation towards an equilibrium shoreline characterized by a single major drift cell, the Bight of Benin coast has been undergoing rapid destabilization over the last 50 years, resulting in breakdown into a less well-defined multi-cell structure. We also contend that disentangling the impacts of human activities on this coast from natural trends requires a grasp of the long-term morphodynamics.

STUDY AREA

The Bight of Benin is an open, microtidal, wave-dominated coast exposed to waves from the South Atlantic, and is characterised by Holocene sand barriers bounding lagoons. The bight is bounded by a narrow shelf 15 to 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). Beyond this depth, the inner shelf levels out to a low-gradient (1:350-1:400) plain covered by relict transgressive sands (Anthony and Blivi, 1999). The beaches bounding the sand barriers of the Bight of Benin coast are composed of relatively homogeneous medium to coarse (0.4–1 mm, *D*50: 0.6 mm), iron-coated quartz sand, except at a pronounced shore break (step), which also comprises rounded fine gravel. Tides affecting this coast are semi-diurnal, and have a mean spring tidal range of about 1.9 m. The wave setting is a cyclone- and storm-free West Coast Swell Environment as defined by Davies (1980).

The Bight of Benin barrier system has been sourced essentially by sand supplied through the Volta River delta, which covers an area of about 5000 km^2 at the outlet of a large river catchment of 397,000 km^2. Minor additional inputs of sand come from the Mono River in Benin. Sand supply from the shoreface has been deemed to have been important in the early phases of barrier progradation as shoreface gradients in West Africa adjusted to sea level (Anthony, 1995). In the light of the cell dynamics discussed here, we surmise that this source may still be an important one. The Volta River discharge varied between a low of 1000 m^3/s in the dry season and a high of over 6000 m^3/s in the wet season before comissioning 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 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. 1). The only other river on this bight coast that supplies sand directly to the sea is the Mono (Anthony et al., 1996). The estimated 100,000 m^3 of sand supplied by this river during the wet season months supplements the massive sand load transported by longshore drift from the Ghana and Togo coasts but the commissioning of the Nangbéto dam on this river has also affected sand supply to the coast (Laïbi, 2011; Laïbi et al., 2012).

The Bight of Benin barrier systems exhibit a relatively complex history, aspects of which have been documented by Anthony and Blivi (1999), and Anthony et al. (1996, 2002). Much of the bight coast exhibits a regressive single or double barrier. Once progradation of an inner barrier resulted in the regularisation of what was a hitherto indented shoreline, the succeeding phase of coastal development involved the emplacement of a more continuous outer barrier directly linked to the Volta river mouth. This suggests the establishment of a highly efficient drift alignment and transition to an economy of massive sediment sourcing by the Volta. Following the complex phases of barrier construction highlighted by the afore-mentioned studies, 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). This equilibrium alignment implied long-term shoreline stability, despite the massive drift potential. This long-term stability is now threatened by anthropogenic activities that affect longshore drift, especially deepwater ports.

DATA AND METHODS

In order to estimate the longshore wave transport on the Bight of Benin coast, we had recourse to wave parameters (significant height, peak period and direction of both swell and wind waves) from hindcast data in the Atlantic Ocean between 1979 and 2012, generated by the ECMWF WAM wave model. The wave data are part of the ERAInterim dataset, which involves a reanalysis of global meteorological variables (Dee et al, 2011, Sterl and Caires, 2005). Wave data were extracted from the ECMWF data server (*www.ecmwf.int/research/era*) which are on 1°x1° grid, with a 6-hr temporal resolution. The ERAInterim reanalysis is 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) and Caires and Sterl (2005) demonstrated a very good correlation between the ERAInterim data and these sources, except for high waves (significant wave height, Hs >5 m) and low waves (Hs <1 m) which tend, respectively, to be under- and over-estimated. These critical wave conditions are not typical of the relatively constant wave regime of the Gulf of Guinea. Sand drift volumes for this coast were determined using the formula of Kaczmarek et al. (2005)

$$Q = 0.023(H_b^2 V) \qquad if\ (H^2 V) < 0.15, \qquad (1)$$

$$Q = 0.00225 + 0.008(H_b^2 V) \qquad if\ (H^2 V) > 0.15 \qquad (2)$$

where H_b is the breaking wave height and V and estimation of the longshore current within the surf zone given by

$$V = 0.25 k_v \sqrt{\gamma g H_b}\ sin 2\alpha \qquad (3)$$

where α is the breaking wave angle, $\gamma = H_b/h = 0.78$ is the constant breaker parameter according to Battjes and Janssen (1978), H_b the breaking wave height, h the local water depth and k_v an empirical constant. Here, we used $k_v = 2.9$ according to the values in Bertin et al. (2008) for wave-dominated environments with similar grain size characteristics.

Field observations on wave breaking and beach morphology were further carried out in an experimental site at Grand-Popo in Benin (fig. 1). Routine observations along much of the Bight of Benin coast show that the beach morphology and conditions at Grand-Popo are fairly representative of much of the bight coast, except in sectors undergoing massive accretion or erosion, which will be briefly evoked later.

Longshore drift cells were simply determined from morphological observations especially using Google Earth images coupled with empirical knowledge of long-term barrier morphodynamics as well as more recent patterns of barrier development documented by Anthony et al. (1996, 2002) in Benin, Anthony and Blivi (1999) in Togo, and, more recently Laïbi (2011) in Benin, and Anthony (2013) in the Volta River delta sector in Ghana.

RESULTS AND DISCUSSION

Longshore transport potential

The Bight of Benin coast is exposed throughout the year to constant, moderate to high energy (ECMWF 1957-2012 Cotonou deep water closest node wave climatology: Hs=1.36 m, Tp=9.4 s) waves from the southwest (193.6°) (fig. 2). The wave spectrum is strongly dominated by swell. Waves break on the coast after refraction, with angles of 4 to 9°. Wave breaking is dominantly in the plunging regime, and the grain-size conditions result in relatively steep-faced (slope ~12-17°) reflective beaches year-round with milder gradients in summer when swell waves are higher, as a result of northward migration, by a few degrees, of the wave-generating zone in the high latitudes of the South Atlantic (~40° to 60°S). Beach gradients are highly reflective in sectors subject to erosion, and are more in the intermediate domain where sand is being sequestered by shore-normal structures.

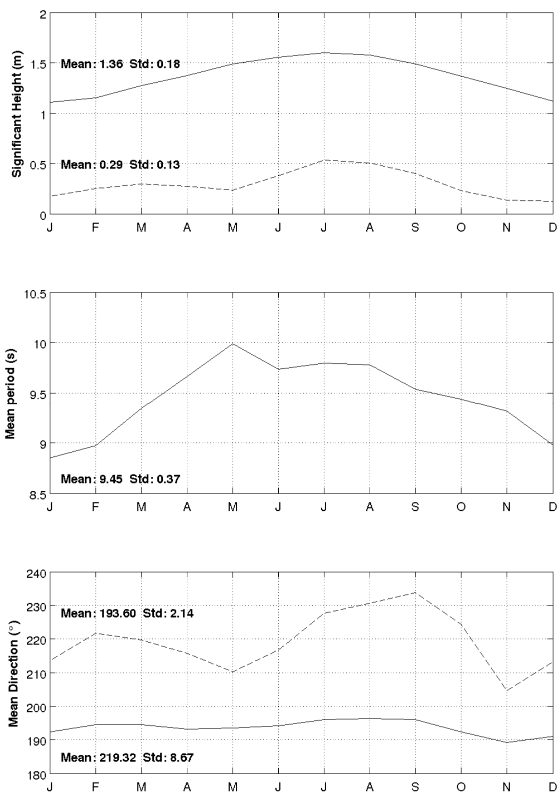

Figure 2. ERAInterim wave characteristics for the Bight of Benin, near Cotonou, showing the largely dominant moderate-energy southwesterly swell.The solid line shows the swell and the dashed line is the wind wave. Note that mean periods of wind waves, not shown, are below 2.5 s.

The regularity of the southwesterly swell throughout the year, the small tidal range, and the steep, dominantly reflective character of the beaches are three conditions that generate strong and persistent longshore drift from west to east. Past values estimated from intersection by harbour structures are 0.75-1.5 million m^3 a year (Delft Hydraulics, 1990). The transport value computed from the ERAInterim reanalysed data using the formulation by Kaczmarek et al. (2005) is 0.6-0.8 million m^3 a year (fig. 3), which is not too different from the lower range identified from harbour interception. This transport is mostly driven by swell waves, rather than wind waves, and presents a large seasonal and interranual variability. Much of the sand is transported as bedload and in suspension in a narrow (30-50 m-wide) zone between the wave breaker line and the swash-dominated beachface.

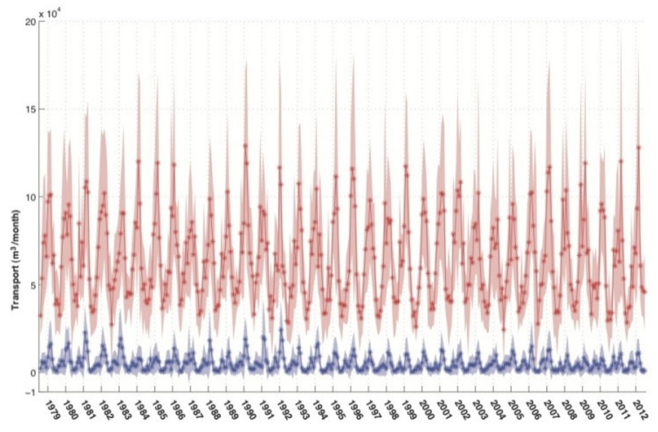

Figure 3. Potential monthly-integrated longshore drift on the Bight of Benin coast computed from ERAInterim wave statistics for the shoreface integrating refraction. Longshore drift, almost exclusively to the east (positive values) is very largely dominated by swell (red spikes), with a minor component associated with wind waves (blue spikes).

Recent destabilization and drift cell structure

The present bight coast shows four identified erosional sectors, three of which are matched by downdrift, and one by updrift, accretion (fig. 4). The first of these erosional sectors corresponds to the sector of the coastal town of Keta, which constitutes a hinge point linking the Volta River sand supply to the rest of the Bight of Benin coast. Keta was once flourishing colonial port, probably located in a sector of stationary barrier in the transit zone for Volta delta sand to the Bight of Benin. Erosion has prevailed in this area since the mid-1880s (Kumapley, 1989), which largely predates the construction of the Akosombo dam (Ly, 1980), whereas the large Volta spit has accreted considerably over the last few decades. Anthony and Blivi (1999) estimated the amount of sand captured in this spit for the period 1968 to 1996 at about 750,000 m^3 a year, which accounts for nearly all the drift potential on the Bight of Benin coast (fig. 3). As erosion around Keta has proceeded, this erosional sector became characterised by the 1990s by a narrow (<100 m wide) eroding transgressive barrier subject to overwash during the summer months of strong swell. A shoreline stabilisation project completed in 2002 and comprising several groynes and a seawall have reduced erosion in this sector, which is still nevertheless appreciable and estimated at about 5.5 m/yr in a recent study (Boateng, 2012). Downdrift of this sector erosion is even stronger (Addo et al., 2011). Updrift of this sector, 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.

The other three erosional sectors are clearly associated with the construction of the three deepwater ports (fig. 4) of Lagos (1957), Cotonou (1962) and Lomé (1967). These major offshore-protruding port breakwaters have significantly impacted the hitherto unidirectional drift, breaking down the equilibrium shoreline alignment that prevailed prior to port construction, especially in the more updrift sectors of Togo and Benin. These structures have also generated accretion sand updrift, and several hundreds of metres of beach progradation over a shoreline distance of up to 5 km. The erosional sectors downdrift of the ports are longer (up to 20 km), and their erosion ensures continuity of the strong drift potential (fig. 4). The most massive accumulation and corresponding erosion has been that of Lagos harbour. The erosional sector in Cotonou has been further complicated by a canal cut through the beach-ridge barrier in 1888 to alleviate river flooding of Lake Nokoué, the wide, circular lagoon in this sector.

The erosion downdrift of these ports is a threat to large areas of the cities of Cotonou, Lomé, and Lagos, and to numerous villages, as well as coastal infrastructure. Apart from the cell segmentation induced by the port breakwaters, highy localized drift reversal (counter-drift to the west) appears to operate in the immediate lee of these structures, as a result of strong wave refraction and diffraction.

The large accretion spit at the mouth of the Volta delta appears 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 (Anthony, 2013). The most likely reason for the dramatic erosion in the Keta sector 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. This is probably because the distal delta barrier, between Anloga and Keta, had been increasingly sequestering a significant proportion of the river's sand suply to the coast, culminating in the inception of the Volta delta spit (Anthony, 2013). Under these conditions, the necessity to satisfy the strong longshore drift budget towards the rest of the bight coast has resulted in considerable reworking of the barrier, threatening coastal settlements such as Keta. In this sector, coastal erosion largely antedated dam construction. The situation has merely been aggravated since the 1960s by the construction of the Akosombo Dam.

CONCLUSIONS

The morphology of the Bight of Benin coast is an outgrowth of beach-ridge progradation that generated a mildly embayed coast wherein incident wave behaviour, beachface gradient and the longshore sand transport system were intimately linked, generating what may be classified as an 'equilibrium drift-aligned' coast. The patterns of current beach shoreline orientation along much of this bight coast strongly reflect, however, the overarching impacts of human activities. The construction of three deepwater ports on one of the earth's coast exhibiting one of the highest rates of longshore sand drift has resulted in destabilisation of such drift, generating a multiple drift cell system characterised by short updrift sectors of important accretion but longer downdrift sectors of erosion. Such erosion has rendered large areas of the strongly growing cities of Lomé, Cotonou and Lagos increasingly vulnerable to erosion that is set to continue in the coming decades. The general overview of longshore drift cell destabilization given here is a prelude to an ongoing study of the morphodynamics and longshore and cross-shore sediment dynamics of the beaches bounding this bight coast, initiated in February 2013 (see project overview in Almar et al., this issue, as well as related studies by Castelle et al., this issue, and Senechal et al., this issue).

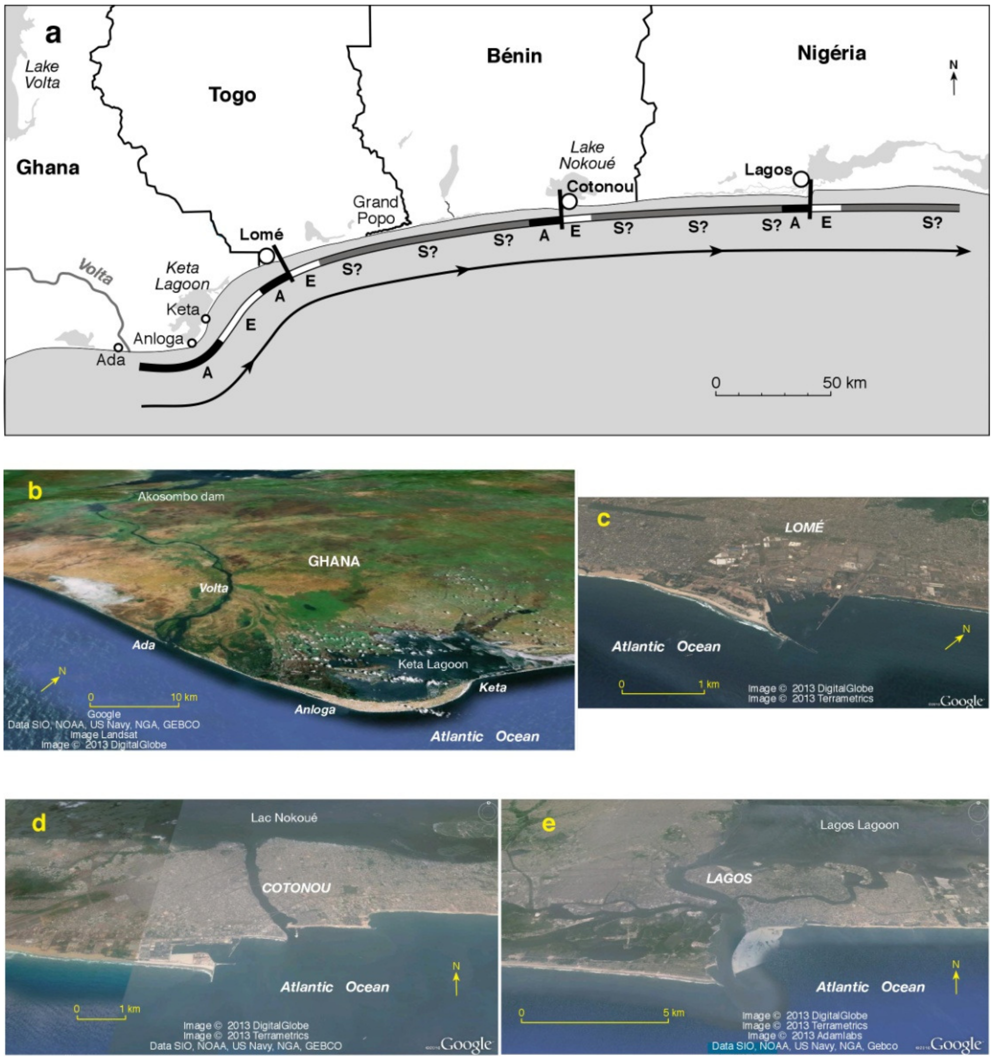

Figure 4. Current longshore drift cells and erosion and accretion associated with port breakwaters in the Bight of Benin. (a) Drift cell structure: a = accretion, e = erosion, s? = presumed stability; (b) the Volta delta; (c) port of Lomé; (d) port of Cotonou; (e) port of Lagos.

ACKNOWLEDGEMENT

This study was funded by the French INSU LEFE and EC2CO programmes and the IRD (Action Incitative programme). This study was funded by the French INSU LEFE and EC2CO programmes and the IRD (Action Incitative programme). We benefited the ECMWF ERA Interim dataset (*www.ecmwf.int/research/era*), made freely available.

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