



Modeling the Bight of Benin (Gulf of Guinea, West Africa) coastline response to natural and anthropogenic forcing

Gregoire O. Abessolo, Le Xuan Hoan, Magnus Larson, Rafael Almar

► To cite this version:

Gregoire O. Abessolo, Le Xuan Hoan, Magnus Larson, Rafael Almar. Modeling the Bight of Benin (Gulf of Guinea, West Africa) coastline response to natural and anthropogenic forcing. *Regional Studies in Marine Science*, 2021, <10.1016/j.rsma.2021.101995>. <hal-04720503>

HAL Id: hal-04720503

<https://hal.science/hal-04720503v1>

Submitted on 13 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License

Modeling the Bight of Benin (Gulf of Guinea, West Africa) coastline response to natural and anthropogenic forcing

G.O. Abessolo^{1,2}, L.X. Hoan^{3,4}, M. Larson³, R. Almar¹.

¹ LEGOS, OMP, UMR 5566 (CNES-CNRS-IRD-University of Toulouse), Toulouse, France.

² Ecosystems and Fishery Resources Laboratory, University of Douala, BP 2701 Douala, Cameroon.

³ Water Resources Engineering, Lund University, Box 118, 22100 Lund, Sweden.

⁴ Institute of Mechanics, Doi Can 264, 1000, Hanoi, Vietnam.

Abstract

The 400-km long coast of the Bight of Benin, formed by sand barriers and lagoons, is bordered to the east by the Niger River Delta and to the west by the Volta River Delta and is characterized by several coastal infrastructures, of which the most important are the deep water harbors of Lomé, Cotonou, and Lagos. In this study, an enhanced version of the CASCADE coastal evolution model was implemented in order to reproduce the evolution of the coast over the period 2000-2015, considering the presence of coastal infrastructure, inlets, and the reduced sediment influx from rivers. The model results showed simulated coastal response around the main coastal infrastructure in agreement with observed data. In addition, the validated model was used to estimate the amount of sediment needed to control erosion through beach nourishment downstream of the harbors. The impact of reducing sediment input on coastal evolution was investigated through model parameterization of the influx at the boundary. Overall, the model may be a useful tool for improving regional coastal policies in the Bight of Benin.

Keywords: Bight of Benin; sediment transport rate; harbor; inlet; shoreline evolution model; coastal management.

Corresponding Author: G.O. Abessolo (gregsolo55@yahoo.fr, LEGOS/IRD, 14 Avenue Edouard Belin, Toulouse, France).

Highlights:

- Shoreline evolution model validation over 15 years
- Well-resolved shoreline output in the vicinity of the harbors in agreement with data
- Model capabilities to derive the amount of sediment required to remedy downdrift erosion

1. Introduction

Decision-making for coastal development is still a challenge today due to multi-scale adjustments of the coast to changes in wave climate, sea level rise, and sediment supply (Ranasinghe 2016, Doody et al. 2004). Shoreline management and policies are increasingly concerned with adaptive responses to coastal change (Nicholls et al., 2012, 2013) and related plans are invariably framed by projections of climate change and their anticipated consequences for the coast (Zhang et al., 2004; Dickson et al., 2007; Nicholls and Cazenave, 2010).

Major barriers for sustainable coastal planning are therefore the limited understanding of the primary controls on coastal behavior over time scales relevant to management and the difficulty of implementing an integrated coastal management plan on a large scale across geographic boundaries, aiming at creating awareness between policy makers in different countries about current and future challenges (Giardino et al., 2018). For instance, in the Bight of Benin, which is a part of Gulf of Guinea, West Africa, disturbances to the stability of a 400-km long shoreline have been observed over the last few decades, mainly due to the three deep water harbors and their jetties together with the reduction in sediment supply from adjacent rivers (Anthony et al. 2019, Giardino et al. 2018, Almar et al. 2015; Laibi et al. 2014). However, there are few local indicators that enable the prediction of regional spatial scale impact of large settlements/infrastructure and changes in oceanic forcing, as the multi-scale interplay between natural and anthropogenic processes and influences is complex (Del Río et al., 2013; French and Burningham 2009). Sea-level rise, elevated storm-surge water levels, high-energy storm waves, depletion of sediment budgets from rivers, and the construction of sea walls are all capable of promoting large-scale beach change. In addition, Giardino et al. (2018) observed that the fragmentation of actors and responsibilities between West African countries, and even within the same country, have hampered the planning of effective and sustainable solutions for decades. Integrated large-scale spatial and temporal prediction of the evolution of this coastal system is therefore important to decision-makers in the concerned countries, which are low-income countries with 70% of the population in the coastal zone (Ndour et al., 2018). As shoreline evolution is the combined effect

of natural and human activities, which vary over space and time, numerical models are vital to understand shoreline change behavior that will eventually lead to large-scale integrated coastal zone management.

A wide variety of coastal evolution models have been developed for this purpose, each having attributes that reflect specific application areas. Until now, models, whether physics-based, process-based or empirical, inevitably rely on more or less extensive approximations of complex and multi-scale systems. Cross-shore and longshore processes have mostly been described separately in these models, where the latter is typically the largest contributor to coastal change. Thus, when considering coastline evolution at large spatial scales (1 to 100s km of coast), the representation of the cross-shore sediment exchange has been simplified, employing sources and sinks with schematized values in time and space (Larson, Kraus and Hanson, 2002a; Larson, Rosati, and Kraus, 2002b; Jiménez and Sánchez-Arcilla 2004; Hanson et al. 2008; Hoan et al. 2011a; Ranasinghe et al. 2013). To improve the predictive capability of these models from the time scales of hours (i.e. storm) to decades, longshore and cross-shore processes have been combined in a more rigorous manner, using physics-based formulations (Larson et al., 2016; Vitousek et al. 2017; Robinet et al. 2018). However, further simplifications are required to reduce the computational time since simulations are performed for large areas (more than 100 km of coast) over long time periods, i.e., decades to centuries (Larson et al., 2016).

In order to provide assistance to decision-makers regarding coastal development in West Africa, this study aims to model the observed evolution of a 400-km long coastal stretch (covering Togo, Benin and Nigeria) in the Bight of Benin from 2000 to 2015. Based on this modeling, the importance of anthropogenic influences on the coastal evolution in the Bight of Benin is investigated in a more rigorous manner. The validated model may be used to predict the evolution of the studied coast in the light of different scenarios and management policies. For this purpose, we used a regional coastal evolution model that can be applied to stretches of coastline covering hundreds of kilometers, encompassing several barrier islands separated by inlets, including such phenomena as inlet creation, ebb- and flood-tidal shoal development, bypassing bars between beaches and inlets, channel dredging, regional trends in the shape of the coast, and shore-protection structures and activities, for example groins, seawalls, and beach nourishment. Cross-shore related processes such as relative change in sea level, wind-blown sand, cliff erosion, and storms may be included as sources and sinks with strengths varying in time and space.

2. The Bight of Benin Coast

2.1 Location and general overview

The Bight of Benin, in the Gulf of Guinea, West Africa, is more than 400 km long, ranging between 1° to 5°E in longitude, and 5 to 7°N latitude and facing the South Atlantic Ocean (see Fig. 1). This embayment covers the coastal environments of four countries: Ghana, Togo, Benin, and Nigeria. It is a wave-dominated coast formed by sandy beach-ridge barriers and lagoons, bordered by the Niger River Delta in the east and the Volta River Delta in the west, and also fed by several small coastal rivers (e.g., Anthony and Blivi, 1999; Blivi, Anthony and Oyédé, 2002; Anthony, 2015). The historical evolution of this sand barrier and its associated lagoon and lacustrine system has been intensely investigated (e.g. Anthony, 1995; Anthony and Blivi, 1999; Blivi, Anthony and Oyédé, 2002). Barrier beach and shoreface deposits in prograded single or double sand barriers range in thickness from less than 5 m on their landward edges to 15-20 m offshore seaward. For the case of double sand barriers, Anthony (1995) showed that the segmented inner barrier was formed essentially from nearshore sand, while the outer barrier has been constructed from sand supplied by the Volta Delta. Deposits are essentially composed of medium to coarse (0.4–1 mm, $D_{50} = 0.6$ mm) quartz sand (>80%), with variable minor fractions of feldspars (up to 10%), shelly debris (5–15%), and heavy minerals (1–5%). Recent studies (Almar et al., 2014; Laibi et al., 2014) showed that beaches along this area are mostly in the ‘reflective-to-intermediate’ state classes and often exhibit an alongshore-uniform low-tide terrace and a steep reflective upper beach face. Anthony et al. (2019) observed that the continental shelf is narrow (widths ranging from 15 to 33 km). Therefore, the shoreface is fairly uniform and moderately steep with a gradient of between 1:120 and 1:150 down to 15 m, whereas seaward, the inner shelf forms a low-gradient (1:350–1:400) plain covered by relict transgressive sands (Anthony and Blivi, 1999).

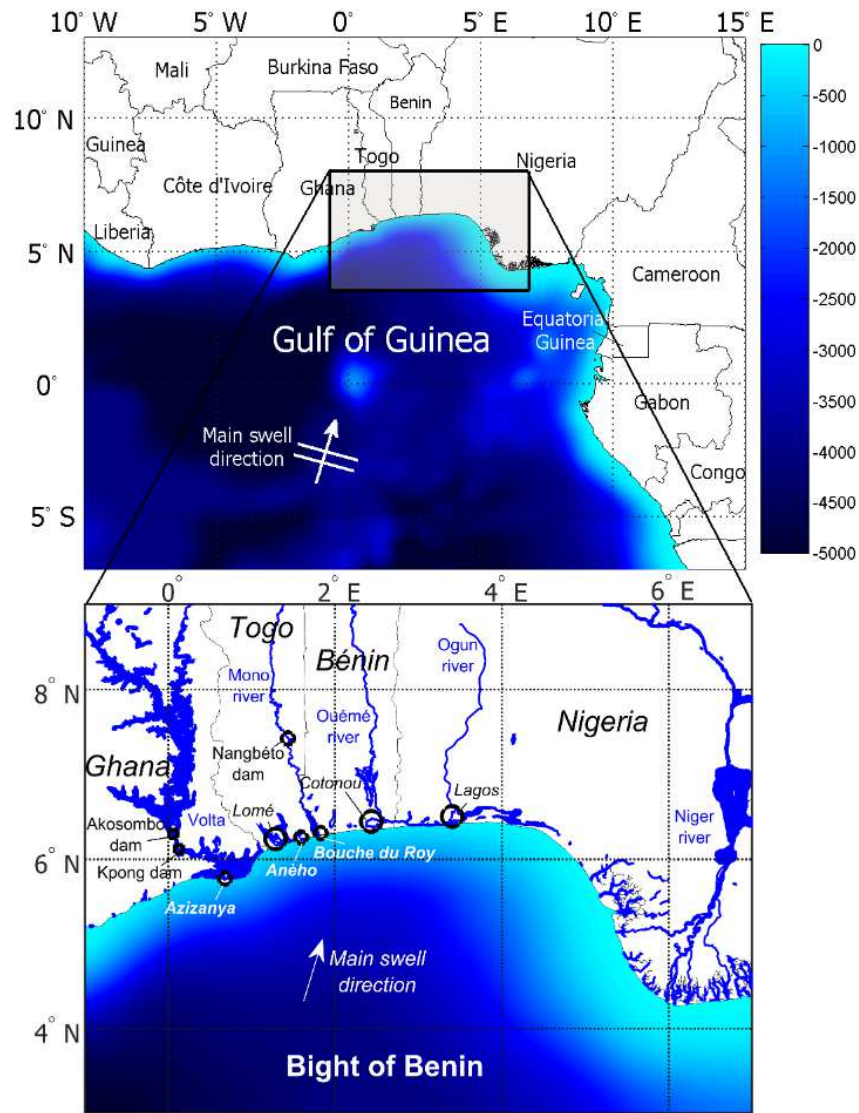


Fig. 1. The Bight of Benin in the Gulf of Guinea, West Africa. The largest circles stand for the three main coastal cities (Lomé, Cotonou and Lagos), each having deep water harbors and associated man-made structures. The smaller circles represent some small coastal towns. The black dots represent the location of river dams.

2.2 Oceanic forcing

The Bight of Benin is exposed to oceanic forcing, i.e., the action of waves and sea level oscillations. Wave forcing was shown to consist of two components with distinct origins and behaviour: locally generated wind waves in the Gulf of Guinea and long swell waves generated in subtropical regions (Almar et al., 2015). Long swell waves are dominantly generated by the mid- to high (45-60°) latitude westerlies, to which are superimposed, on a lesser extent, the effects of the south-easterly trade winds, blowing off the coast of Namibia (30–35°S). However, the southwesterly swells remain the most

dominant component compared to the others in this region (Almar et al., 2015), impinging slightly obliquely (at angles of 10–15°, between Lome and Lagos) with similar heights and periods on the nearly rectilinear west-east oriented Bight of Benin coast. Fig. 2 displays wave roses along the coast: averaged mean values $H_s = 1.29$ m, $T_p = 9.1$ s; averaged standard deviations 0.28 m and 1.17 s. This wave climate drives an easterly longshore sediment transport (one of the largest in the world) ranging between 0 up to 1.2 million m³/year, depending on the location (Allersma and Tilmans, 1993; Anthony and Blivi, 1999; Almar et al., 2015).

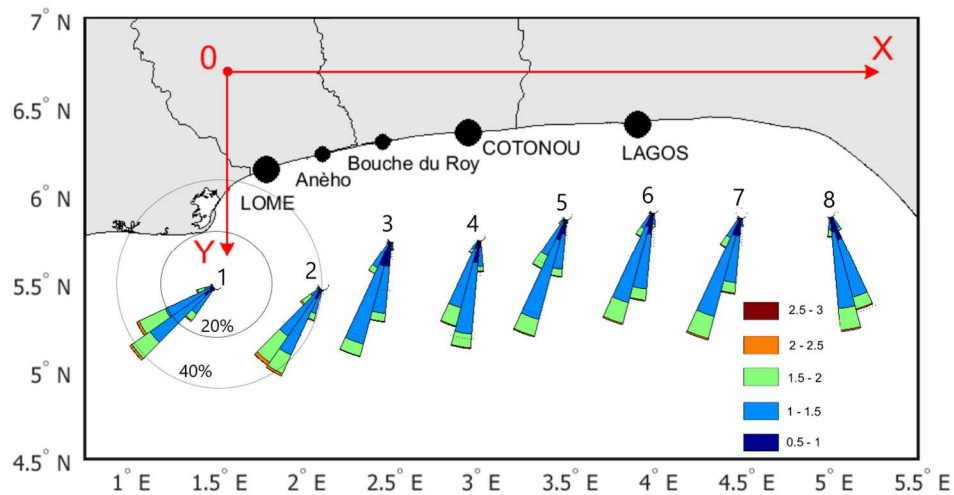


Fig. 2. Wave roses at locations of wave input stations (1 to 8), computed for the period from 1990 to 2015 in the Bight of Benin: the predominant directions of waves and their significant heights (H_s) are shown with color bands. The grid reference (0, X, Y) used to model the shoreline evolution in the Bight of Benin is shown with red axes.

Sea level variations in the Bight of Benin are characterized by several time scales. The shortest periods correspond to semi-diurnal tides, ranging from 0.3 m to 1.8 m for neap and spring tides, respectively. Polo et al. (2008) revealed intra-seasonal (20 to 90 days period) recurrent and continuous horizontal propagations of sea level fluctuations, triggered by coastally-trapped Kelvin and Rossby waves, distinguishable poleward along the coasts as far as about 10°N - 15°N, with peak-to-peak amplitudes of ~ 10 cm and phase speed range from 1.5 to 2.1 m/s along the West African coastline (Abessolo et al., 2020). South Atlantic climate variability modes in this tropical region result in ~ 25 cm seasonal and inter-annual variations in sea level. The regional trend in sea level rise is larger than the global rate that has doubled in the last two decades compared to the average rise in the 20th century (Melet et al., 2016).

2.3 Harbors and coastal infrastructure

Investigations carried out in the Bight of Benin (Anthony et al., 1995; Blivi et al., 2002) showed that before the years 1900, equilibrium was achieved between coastal morphology and the hydrodynamic regime. Recent studies (Laibi et al., 2014; Almar et al., 2015; Giardino et al., 2018; Anthony et al., 2019) have pointed out the disruption of this stability due to the construction of deep-water harbors in 1957 in Lagos, 1962 in Cotonou, and 1967 in Lomé. The three harbors have impacted alongshore sediment redistribution by segmenting the previously unrestrained longshore sand transport, resulting in long stretches with marked erosion that are endangering parts of the rapidly expanding port cities, coastal infrastructure, and numerous villages (Laibi et al., 2014; Anthony et al., 2019). Recently, coastal defense infrastructures have been planned along the coast to reduce erosion and limit the risks to human development and infrastructure. Downstream of the three harbors, a series of protective groins were built over a distance of about ten kilometers to limit the ongoing erosion. Between 2012 and 2016, near the city of Anèho (Togo), several groins have been constructed over a distance of about 10 km. Human activities, such as plantations and sand mining, have also destroyed the alignment of the multiple beach ridges characterizing the barriers, even though they can still be identified in certain places on aerial photographs (Anthony et al., 2019).

2.4 River discharges

The Volta River Delta and the Niger River Delta are among the three largest deltas in West Africa. The Volta Delta, situated entirely in Ghana, covers an area of about 5000 km² (Boateng et al., 2018), whereas the Niger Delta, much larger and situated in Nigeria, covers an area of 19,135 km² (Anthony et al., 2019). Anthony and Blivi, (1999) identified the Volta River as the single most important fluvial sediment source for much of the sand barrier system of the Bight of Benin. In contrast, the influence of the Niger delta has been limited essentially to the eastern confines of the Bight of Benin coast, as observed by Anthony et al. (2019). A few minor additional sediment inputs have been identified at the mouth of the Mono River.

According to Logah et al. (2017), the Volta sediment concentration at Azizanya station was recently measured to be 20 mg/l, which corresponds to a sediment discharge of ~320 000 m³/year for a mean water discharge of ~1200 m³/s (Anthony et al., 2019), assuming that the density of sediment is 2400 kg/m³. However, these discharges rates at the Volta delta recorded over the past decade have decreased by 70-90% compared to those recorded before the construction of the Akosombo and Kpong dams across the Volta river (Bollen et al., 2011; Boateng et al., 2012; Anthony et al., 2016; Anthony et al., 2019). The sand load supplied by the river to its delta has been estimated to be more

than 1 million m³ prior to the construction of the dam (Delft Hydraulics, 1990). The construction of Akosombo dam 100 km upstream from the sea between 1961 and 1965, and Kpong dam between 1977 and 1982, 24 km downstream of the Akosombo dam, have replaced the natural seasonal high and low flows of the river by an almost constant reduced flow throughout the year. Oguntunde et al. (2006) noted that the decrease in rainfall in the Sahel since 1975 also contributed to the reduction of river discharges. This reduction in Volta river sand supply could be a significant contributing factor to the observed disruption of shoreline stability.

Although sediment input from the Mono River was estimated to 100,000 m³ during the wet-season months, they have also been significantly reduced with the construction of the Nangbéto Dam, built 180 km upstream from the mouth of the Mono River in 1987 (Ago et al., 2005). The other smaller rivers (e.g. Ogun river) discharge into still infilling lagoons behind the coastal sand barriers, linked to the sea via inlets (Anèho, Cotonou and Lagos), which have all been stabilized by engineering structures.

3. Data employed

Wave characteristics were extracted and daily-averaged from ERAInterim ECMWF re-analyses (Sterl and Caires, 2005) at eight different stations along the coast (Fig. 2), at 6-hr interval.

In order to determine the coastline evolution over the 15 years, available 4-8 Landsat images were analyzed. The criteria for image selection focused on individual spatial coverage with minimal cloudiness, and on the robust and accurate determination of shoreline location. Twelve images were chosen and downloaded from the USGS data portal Earth Explorer, three for each of the years 2000, 2005, 2010, and 2015. The shoreline was derived with an accuracy of around 1 pixel (30 x 30m), using panchromatic at 10 m resolution and a customized combination of bands maximizing land-water contrast. Then, shorelines were digitized at 100-m alongshore spacing using the ArcMap extension module Digital Shoreline Analysis System (DSAS), version 4.3, coupled with ArcGIS®10. An error of $\pm 2.4\text{m/year}$ between 1990 and 2015 was obtained, considering image rectification, extraction of the shoreline, and operator digitization in delimiting the shoreline. Details can be found in Anthony et al. (2019).

4. Modeling regional coastal evolution

4.1 Background and theoretical formulations

The first approach to mathematically describe coastal evolution was made by Pelnard-Considère (1956) who characterized the response of the beach through the shoreline movement. The assumption was made that over longer time periods (i.e., years) the beach profile does not change its basic shape, but any local change due to gradients in longshore transport implies a horizontal translation of this profile, shoreward or seaward depending on whether accretion or erosion occurs, respectively. The response of the profile occurs over an active height that typically stretches from the depth of closure to the berm height (Hallermeier, 1981; Nicholls et al., 1998). Thus, to completely describe the movement of the beach only one contour line needs to be specified, which is often taken to be the shoreline; this approach is denoted one-line modeling. Pelnard-Considère (1956) linearized the governing equations and arrived at the equation for conduction of heat in solids for which many analytical solutions exist (e.g., Carslaw and Jaeger, 1959; Crank, 1975). Solutions were developed for the shoreline evolution updrift a groin, where comparisons were made with data from laboratory experiments, and the response of a sand source placed on a beach (i.e., nourishment).

The work by Pelnard-Considère (1956) was followed by a number of studies where new analytical solutions were proposed (Le Méhauté and Brebner, 1961; Walton and Chiu, 1979; Larson et al., 1987), the basic formulation extended (Bakker and Edelman, 1965; Bakker, 1969), and semi-analytical or numerical approaches taken (Le Méhauté and Soldate, 1978; Ozasa and Brampton, 1980; Kraus, 1983; Hanson, 1987). Subsequently, analytical and semi-analytical one-line models have been developed based on stability theory for open coasts subject to waves breaking at large angles towards the shoreline, initiating complex morphological features (Ashton et al., 2001; Reeve and Valsamidis, 2014).

The original one-line formulation has been the basis for developing comprehensive and general shoreline evolution models that simulate a wide range of engineering structures and activities, including groins, jetties, seawalls, detached breakwaters, beach nourishment, and dredging (Hanson, 1987). Although these models have been successful in reproducing shoreline evolution in a large number of engineering projects, they have their limitations in terms of scale, neglecting certain processes operating at the regional scale; for example, the impacts of inlets on sediment storage and transfer, jetties and harbor structures, and large-scale trends in shoreline orientation and alongshore wave conditions.

The CASCADE model (Larson, Kraus and Hanson, 2002a) was established to address time and space scales associated with regional coastal processes, providing predictions suitable in the planning and preliminary design phase of a project. As the first step towards modeling regional coastal evolution, CASCADE was developed to bridge the gap between a sediment budget approach and a shoreline evolution model. The dynamics of selected processes and controls of importance for the regional coastal evolution were modeled based on physical representations, whereas other processes were parameterized through time- and space-varying sources and sinks. CASCADE was calibrated and validated against high-quality data sets from three coasts that describe the regional coastal evolution after the creation of multiple inlets on open barrier-island coasts (Larson and Kraus, 2003, Larson et al., 2006). These successful long-term simulations were made for the opening of Moriches and Shinnecock Inlets on Long Island, and Ocean City and Indian River Inlets on the Delmarva Peninsula.

Hoan et al. (2011a) enhanced the capability of the CASCADE model to simulate inlet sediment transport and the evolution of morphological elements at an inlet. Also, the possibility to describe structures in the model was improved and a more general longshore sediment transport formula was implemented that is sensitive to grain size and includes currents that are not only wave-generated. The model was employed to reproduce the regional coastal evolution along the coast of Long Island as well as for predicting the progression of linear spits at several sites (Hoan et al., 2011a). An earlier version of this model was used to reproduce the observed evolution at Hai Hau Beach in Vietnam (Hoan et al., 2010).

The model by Hoan et al. (2011a), employed in this study, consists of the following main components:

- Nearshore wave transformation including breaking
- Longshore current and sediment transport
- Inlet sediment transport and morphological evolution
- Cross-shore sediment exchange through sources and sinks
- Impact from human intervention due to structures and activities
- Coastal evolution from sediment conservation

The wave conditions at breaking are computed based on linear wave theory assuming locally straight and parallel bottom contours, where an arbitrary number of wave input stations can be employed. Based on the breaking conditions, the longshore current and sediment transport are determined using the formula proposed by Bayram et al. (2007), expanded for tidal- and wind-induced currents

following Hanson et al. (2006). The inlet sediment transfer and storage, schematized through a number of morphological elements, are simulated using the reservoir model suggested by Kraus (2000), further refined by Hoan et al. (2011b). Cross-shore sediment exchange is handled through sources and sinks with strengths that may vary in time and space, including sediment supply from rivers.

Different structures and activities to control the sediment transport and coastal evolution are possible to include, for example jetties, groins, and beach nourishment. Structures require a set of properties to be specified, including the position, geometry (e.g., length), and permeability. The two latter quantities will determine the amount of sediment that may bypass or penetrate the structure, respectively, leading to downdrift transport. The evolution of the coastline is determined based on the sediment conservation equation after the longshore sediment transport has been computed together with contribution from sink and sources, and with application of the appropriate boundary conditions.

4.2 Model set-up

The evolution of a 400 km-long stretch of coastline along the Bight of Benin was simulated using a grid size of 100 m and a time step of 3 hr (equal to a half of the wave input time step). A grid was placed on land with the x -axis pointing in the eastern direction and the y -axis offshore. Fig. 2 displays the grid employed together with the input stations from the derived wave climates. The wave roses are shown at each station illustrating the bimodal wave climate, also indicating the prevalence for easterly sediment transport, except at the most easterly located station. The boundaries of the grid were placed at locations where the shoreline exhibited almost no change in the observed data, corresponding to boundary conditions with fixed shoreline positions, implying zero transport gradients. Thus, the longshore transport is free to move over the boundaries, attaining values that ensure no shoreline change.

In order to calibrate the model, the shoreline change between 2000 and 2010 was used, whereas the period from 2010 to 2015 was employed for validation. The main calibration parameters used to compute the total longshore sand transport and thus modelled shorelines, were the two transport coefficients K_1 and K_2 (see Hoan et al., 2011a). Coefficient K_2 represents the effects of wave height gradient alongshore and it might be taken as 50 % to 70 % of K_1 (Hanson, 1987); thus, in this study $K_2 = 0.7 \times K_1$. Coefficient K_1 was chosen based on the overall best fit between modelled and observed shorelines. In this comparison, only areas with significant evolution of the shoreline were taken into account (around tidal inlets, harbor areas, and structures). The model was run with different

values of K_1 and K_2 , and Fig. 3 shows the relative and absolute errors between modelled and observed values (%) for different K_1 -values. Values of K_1 and K_2 were chosen for minimum errors, where $K_1 = 0.15$ and $K_2 = 0.1$. Comparison shows that modeled results are not too sensitive for values on K_1 between 0.1 and 0.15. Errors used to estimate optimal parameter values were based on the root-mean-square deviations, and defined as follows:

$$RMS_{MM} = \sqrt{\frac{1}{N} \sum_{i=1}^N (Modelled - Observed)^2} \quad (1)$$

$$RMS_{IM} = \sqrt{\frac{1}{N} \sum_{i=1}^N (Initial - Observed)^2} \quad (2)$$

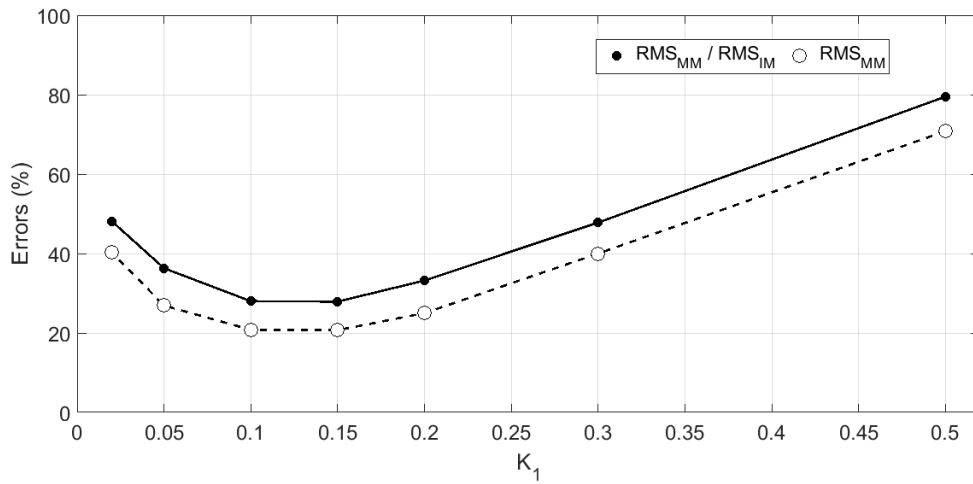


Fig. 3: Errors (%) between modelled and measured shorelines for different K_1 -values for the calibration period from 2000 to 2010. The solid line stands for the relative error ($\frac{RMS_{MM}}{RMS_{IM}}$) and the dashed line for the absolute error (RMS_{MM}).

The wave conditions between the stations were linearly interpolated at each time step and allowed to vary along the grid. The sediment supply from various rivers in the modelled stretch was added as continuous sources with a constant strength following the values reported by Allersma and Tilmans (1993). The supply from the Volta and Niger River was represented through the boundary values for the longshore sediment transport obtained at the right- (west) and left-hand (east) side of the grid, respectively.

The main structures along the coast, especially the jetties at the harbors, were described in the model employing their physical dimensions as determined from aerial photos, also including changes to

structural properties through time. The permeability of the structures was set to zero, whereas bypassing was allowed to occur, if the shoreline at the jetty were sufficiently close to the tip of the structure. Estimates of the bypassing ratio, that is, the portion of the longshore transport passing the tip of the jetty, is done based on the geometric blocking ratio with regard to an estimated cross-shore distribution of the longshore sediment transport (Larson et al., 2002a). This is a marked simplification, but seems to reproduce the main features of the bypassing as shown in comparisons with data from the US East Coast (Larson et al., 2002a; Larson and Kraus). However, the process of accretion at a jetty and possible bypassing is complex and difficult to adequately describe in a one-line model, where profile-related properties are highly schematized. Some of the minor groin fields were not included in the simulations, since they have limited influence on the evolution at the regional scale.

4.3 Model calibration

Fig. 4 illustrates the calculated mean annual net longshore sediment transport rate (Q_{net}) in the study area for the calibration period, where eastward transport is taken as positive. In the figure are also results from other studies shown, derived through different means. Overall, the agreement between the present study and the previous investigations is good, although some deviations occur. The present modeling shows that Q_{net} decreases from more than a million $m^3/year$ in the eastward direction at the western end of the grid to Q_{net} about $0 m^3/year$ at the eastern end. The influence of the three harbors is clearly seen, where Lagos and Cotonou cause zero transport at their locations, whereas the influence of Lomé is more limited, although still pronounced.

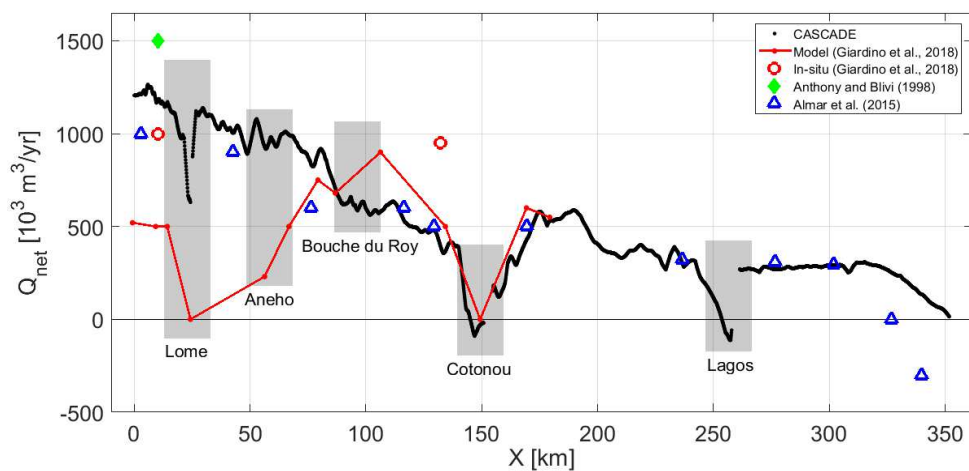


Fig. 4. Calculated mean annual net longshore sediment transport rate along the study area in the Bight of Benin for the calibration period from 2000 to 2010, together with estimated transport rates in previous investigations through various means.

Fig. 5 displays the initial shoreline at year 2000 together with the modelled and observed shorelines at 2010. The differences are hard to assess at the scale of the entire Bight, so detailed results are shown in Figs. 6a-6c for the three harbor areas. An important aspect of the modeling is the ability of the model to maintain the regional shape without any large-scale diffusion and shoreline smoothing. This lends credibility to the calculated large-scale alongshore sediment transport pattern based on the wave input station, since the transport gradients produce the correct regional shape of the shoreline. The harbor areas are clearly displayed as gaps in the shorelines with distinct offsets. For some of the harbors the updrift structure may experience bypassing, but typically this sediment is not transferred to the downdrift area because of the harbor configurations not promoting this.

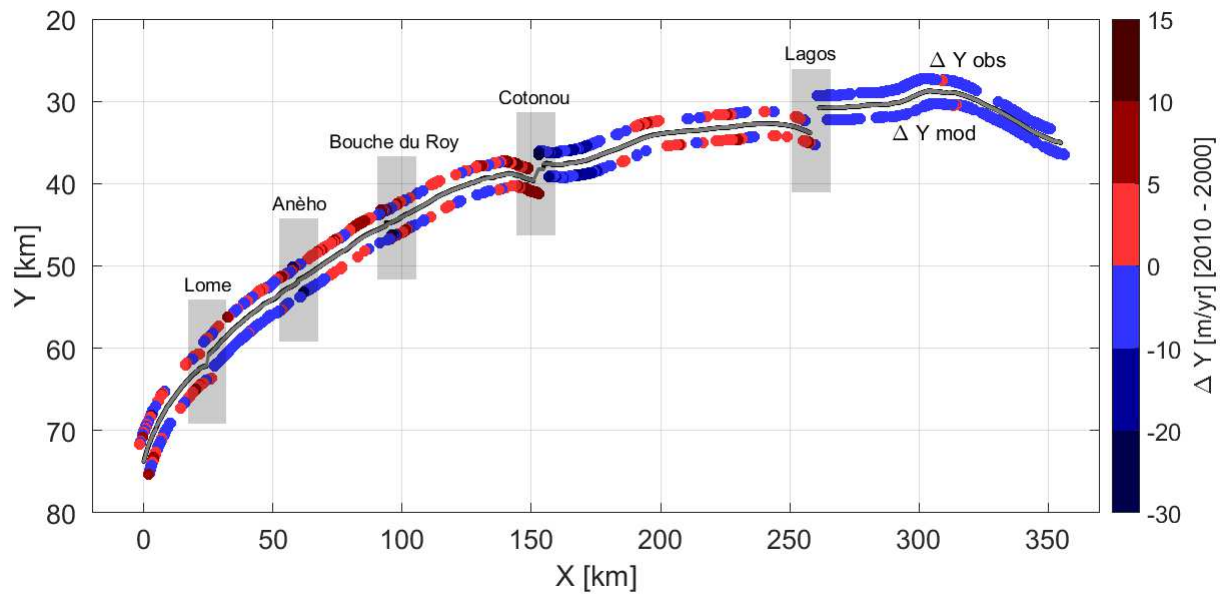


Fig. 5. The initial shoreline (black line) at year 2000 together with the modelled and observed shorelines at 2010 (grey lines, respectively), as well as the modelled and observed shoreline change represented with dots (ΔY_{mod} and ΔY_{obs} , respectively). Only changes greater than 20 m have been shown. Red indicates accretion, blue indicates erosion.

Fig. 6 display the shoreline evolution in the vicinity of the harbors at Lagos, Cotonou, and Lomé, respectively. The initial shoreline at year 2000 together with the modelled and observed shorelines at 2010, as well as the modelled and observed shoreline change, is shown in these figures. The focus is on the areas around the harbors since the largest changes occur here; it was difficult in some cases to exactly determine the harbor configuration and properly represent it in the model, especially on the downdrift side. It can be seen from the plots that the main features of the shoreline change is reproduced satisfactorily some distance away from the harbor area at Cotonou and Lagos ($r = 0.91$ and

$r = 0.96$ significant at 95% confidence level, respectively); however, this is not the case around Lomé harbor ($r = 0.09$).

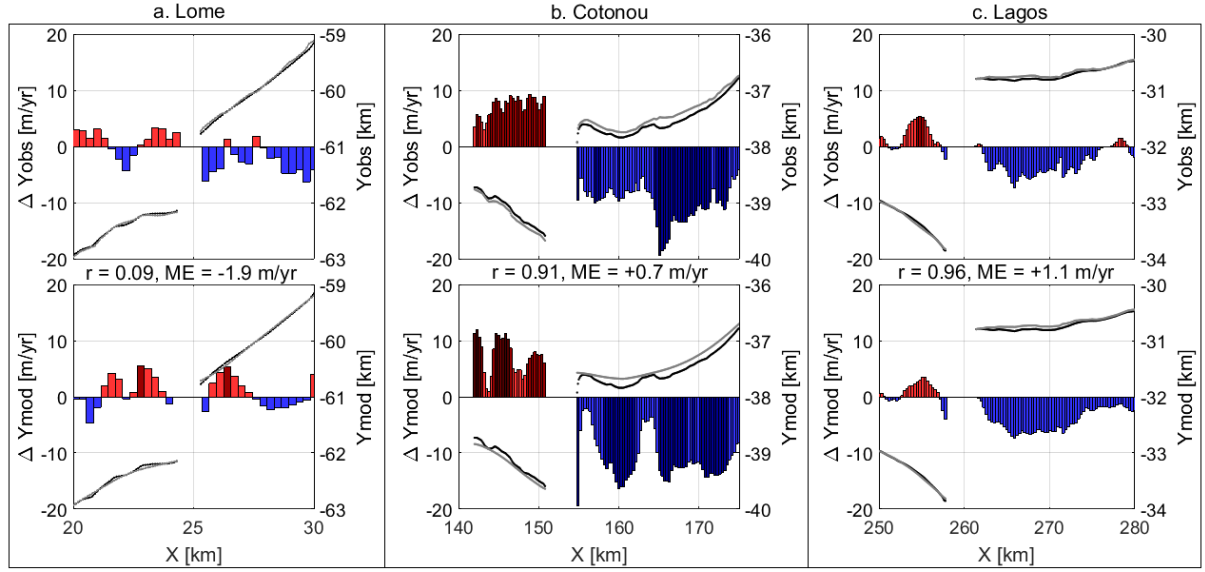


Fig. 6. Shoreline changes for the areas around the harbors of (a) Lome, (b) Cotonou, and (c) Lagos for the calibration period from 2000 to 2010. Left y-axis: observed and modelled shoreline changes (ΔY_{obs} and ΔY_{mod} , respectively) represented with bars. Red indicates accretion, blue indicates erosion. Right y-axis: the black line represents the initial shoreline at year 2000, the grey line represents the modelled or observed shorelines (Y_{mod} or Y_{obs} , respectively) at 2010. r and ME stand for the correlation and the difference between modelled and observed changes.

4.4 Model validation

The optimized model parameters based on the calibration period 2000-2010 were used to simulate the evolution 2010-2015 to validate the model. The agreement between the modelled and observed shoreline change during the validation period was somewhat less good ($r = 0.74$ significant at 95% confidence level), as the model shows a higher variance and seems to miss parts of the largest erosion ($\Delta Y_{obs} \leq -13$ m/yr), as displayed in the validation panel (2010 – 2015) in Fig. 7. Overall, the agreement remains similar to the calibration period, which gives confidence to the ability of the model to simulate shoreline evolution in the study area (Fig. 7). Furthermore, the main feature of the calculated annual net longshore transport rate for the validation period was identical to the calibration period, with only minor, local differences. One noteworthy difference was obtained; Q_{net} was negative at the eastern boundary, indicating some sediment influx from the Niger Delta during this time period (see Fig. 9; also, compare with the estimate in this region by Almar et al. (2015) shown in Fig. 4). The

transport on the western side, reflecting the supply of sediment from the Volta River side was similar to what is shown in Fig. 4.

Fig. 8 display the shoreline evolution in the vicinity of the harbors at Lagos, Cotonou, and Lomé, respectively, for the validation period. The initial shoreline at year 2010 together with the modelled and observed shorelines at 2015, as well as the modelled and observed shoreline changes, is displayed in these figures. Again, the figures emphasize the areas in the vicinity of the harbors where the largest changes occurred. As for the calibration period (see Figs. 5a-5c) the main features of the shoreline change is reproduced satisfactorily.

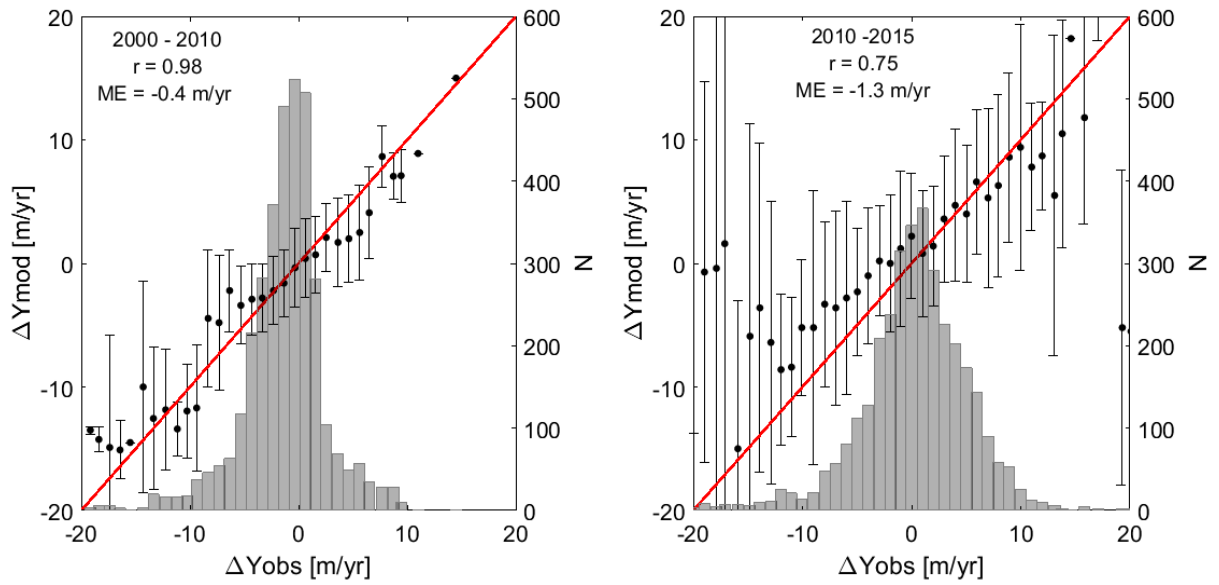


Fig. 7 : Comparison of observed (x-axis) and modelled (left y-axis) shoreline changes for the calibration (2000-2010) and validation (2010-2015) periods. Changes were averaged over a 1 m-window interval on the x-axis and the error bar gives the dispersion within the window. The number of samples (N) considered within the window is given on the right y-axis. Correlations were computed at 95% confidence level.

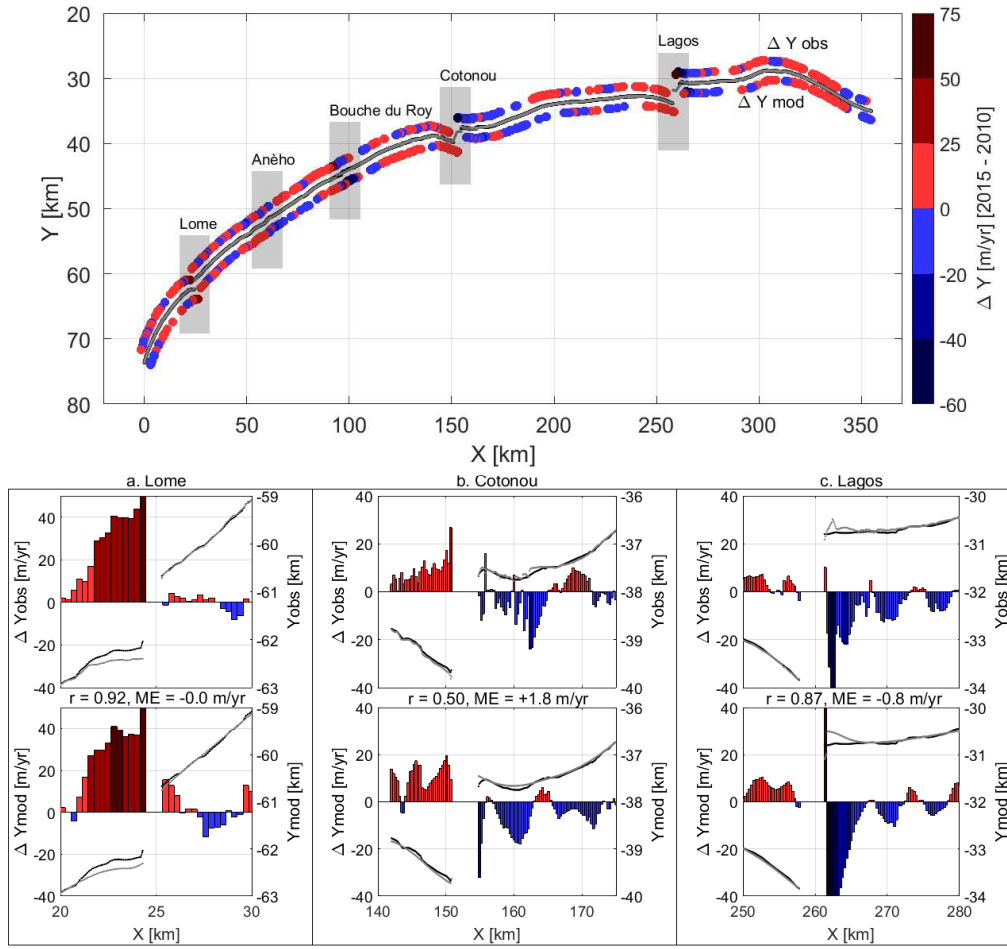


Fig. 8. Panel above: shoreline changes for the validation period from 2010 to 2015. Black and grey lines represent the initial shoreline at year 2010 together with the modelled and observed shorelines at 2010, respectively. Dots indicate the modelled and observed shoreline change (ΔY_{mod} and ΔY_{obs} , respectively). Red indicates accretion, blue indicates erosion. Panel below: corresponding shoreline changes for the areas around the harbors of (a) Lome, (b) Cotonou, and (c) Lagos. Left y-axis: observed and modelled shoreline changes (ΔY_{obs} and ΔY_{mod} , respectively) represented with bars. Right y-axis: the black line represents the initial shoreline at year 2000, the grey line represents the modelled or observed shorelines (Y_{mod} or Y_{obs} , respectively) at 2010. r and ME stand for the correlation and the difference between modelled and observed changes.

5. Simulation results for selected scenarios

5.1 Overview

In order to quantify the importance of anthropogenic influences on the coastal evolution in the Bight of Benin, different scenarios were simulated where the impact of man-made structure and activities were investigated. Three different scenarios are discussed here focusing on the impact of:

- Harbor structures
- Nourishment operations
- Reduced sediment influx due to dam construction

In the case of the harbor structures, the effects of Lagos, Cotonou, and Lomé harbors were investigated by removing the structures completely. The nourishment operations were employed to determine the amount needed to combat downdrift erosion at Lagos Harbor, where the most severe erosion was observed. Finally, the boundary condition for sediment influx on the western boundary was modified to mimic the effects of reduced sediment supply due to dam construction in the Volta River system. All simulations were made for the validation period 2010-2015.

It is recognized that the selected scenarios imply marked simplifications, especially for modeling the removal of the harbor structures and the reduced sediment influx at the boundary due to dam construction. For the beach nourishment more generally accepted model conditions are available, where the sediment input is described through a constant source. Since the influence of the harbor structures was of primary interest, in this case an effort was made to derive the pre-construction shoreline; the actual shoreline affected by the harbors was not used as the starting conditions in this scenario. The most difficult scenario to model was the reduced boundary inflow. If data were available, the entire Volta River Delta should have been included together with the river sediment transport. Instead, a highly schematized approach was taken, where the impact of different specified reductions in the transport magnitudes and their spatial influence was investigated.

5.2 Transport pattern without harbor structures

In this simulation, the three main harbors in the bight were removed as well as inlets at Anèho and Bouche du Roy. The input shoreline was smoothed in accordance with its natural shape. Fig. 9 shows Q_{net} for the cases with and without the harbors at Lagos, Cotonou, and Lomé. The plot clearly illustrates the influence of the harbors, in terms of magnitude, gradients, and spatial extent. The mean annual net transport rate without harbors and inlets influence represents the averaged net transport due to waves from 2010 to 2015. The difference between Q_{net} computed with and without harbors represents the transport fluctuations introduced by harbors and inlets. Using the implementation of a multiple linear regression, relative contributions to the variation in shoreline computed for the coast show that total shoreline changes are significantly influenced by harbors and inlets (60 %) with regard to direct effects from the waves (40 %). When analyzing the areas around the harbors, relative

contributions show that harbors (84 %) are dominant drivers of shoreline migration up and downstream in comparison to the waves (16 %).

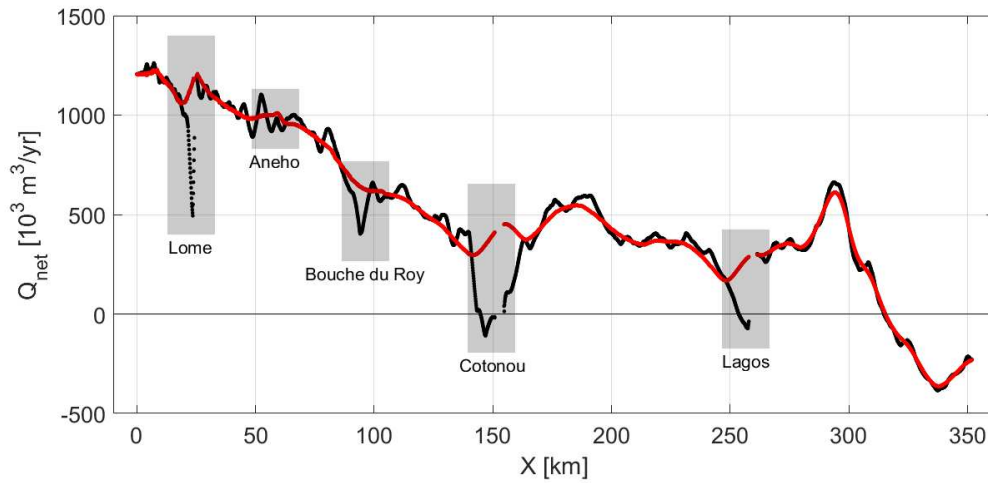


Fig. 9. Mean annual net transport rate for the validation period (2010 – 2015) for the cases with (black) and without (red) the harbors at Lagos, Cotonou, and Lomé and inlets.

5.3 Nourishment to remedy downdrift erosion

A common and popular method to remediate erosion is beach nourishment, where sand is added to the beach, typically to compensate for sand that is lost because of unfavorable gradients in the longshore sediment transport. The nourishment can be put in different parts of the beach and at different time intervals. Here, in order to estimate the amount of nourishment needed to compensate for downdrift erosion at Lagos Harbor, a constant source of sediment was added over a specific distance downdrift the harbor. The magnitude of the source was determined through calibration with the purpose to achieve a stable shoreline during the study period with limited erosion.

The model shows that the inlet jetty blocks the sediment transport to a large degree, producing downdrift erosion; thus, net sediment transport updrift the inlet is small (see Fig. 4), but net transport increases significantly along the erosion area (see Fig. 9, where $\Delta Y < -100$ m). The construction on the east side of the jetty, started from 2011 and modelled with a seawall condition, is another reason for the erosion. To maintain the beach, the total nourishment volume needed is about 3 300 000 m³ for the period from 2010 to 2015, as observed in Fig. 10. This corresponds to a nourishment of 650 000 m³/year.

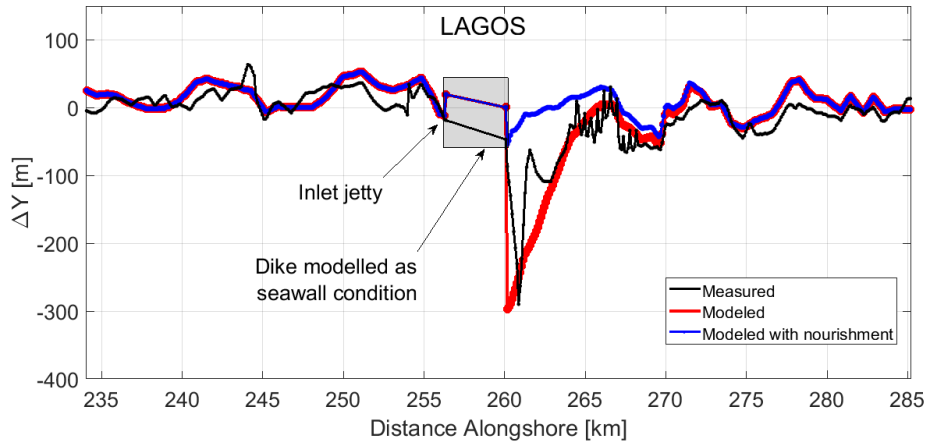


Fig. 10. Nourishment simulation at Lagos Harbor for the period from 2010 to 2015. ΔY represents the shoreline changes modelled and modelled in 2015 compared to the 2010 shoreline.

5.4 Influence of reduced boundary transport

A large amount of sediment enters into the study area from the western side, presumably originating from the Volta River Delta. The calculations showed varying input of sediment on the eastern side, related to the Niger River Delta, with a negligible net contribution during the calibration period, whereas the input was significant for the validation period. In order to evaluate the effects of a reduced boundary inflow of sediment, presumably replicating the case with less sediment being supplied from the Volta River Delta, a modified boundary condition was developed. Instead of allowing for a free inflow of sediment at the boundary, maintaining a stable shoreline, the inflow is restricted according to a specific function.

A specific multiplier (α) was employed to the transport rate obtained at the boundary with a fixed shoreline position, lowering the rate in order to represent a reduced inflow of sediment. To mimic the spatial influence of the reduced transport at the boundary, an exponential growth function was used from the boundary in towards the grid, where the influence on the local transport rate decayed from α to 0 (the latter implies no influence). The rate of the decay was determined by a coefficient κ having the units m^{-1} .

Fig. 11 illustrates the effect of different values on α and κ on the shoreline evolution. A larger α implies a larger reduction in the sediment influx and a smaller κ a larger spatial influence. For a given α , a smaller κ would expand the erosion area, but causing a smaller retreat at the boundary where the maximum effect occurs.

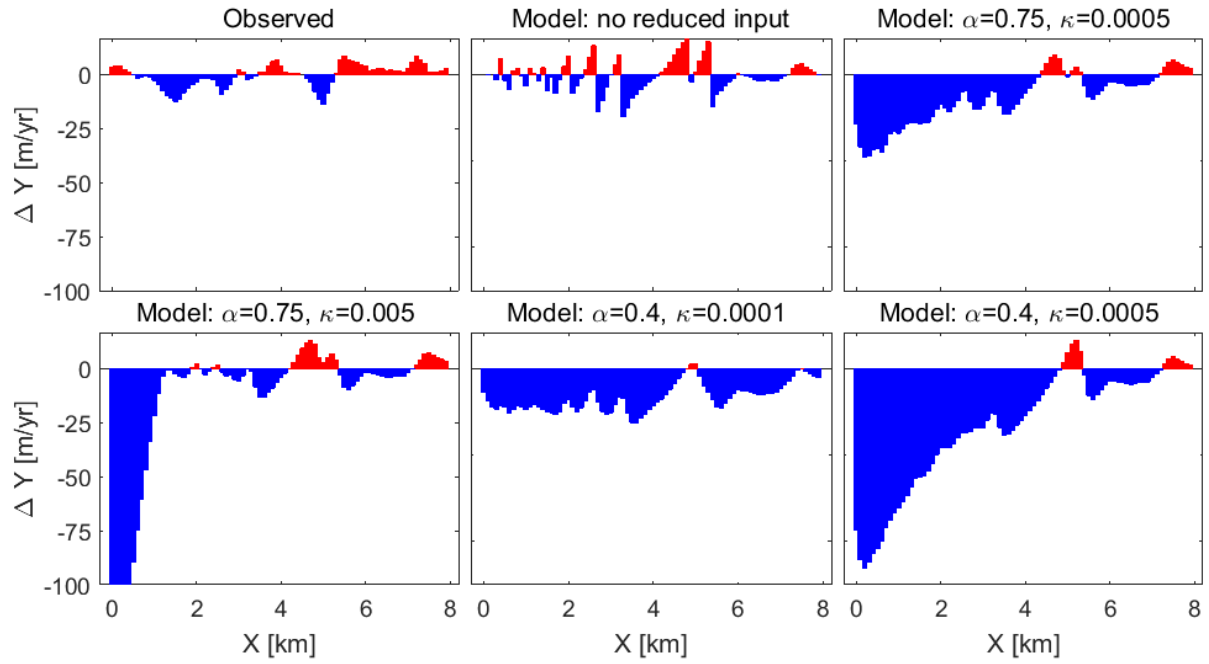


Fig. 11. The effect of reduced boundary influx on the shoreline evolution through a multiplier α with different spatial influence determined by a coefficient κ . Red indicates accretion, blue indicates erosion.

6. Discussion

In this study, the effects of the major man-made interventions (harbor dikes and river dams) on coastal evolution in the Bight of Benin were assessed using an enhanced version of the CASCADE model.

6.1 Capabilities of the CASCADE model to assess the impact of coastal infrastructures and sediment supply variability

The application of the model to the studied coast shows good overall performance in the vicinity of the harbors, reproducing well the erosion and accumulation areas (Laibi et al., 2014; Anthony et al., 2019) and showing robust behavior during the simulation period. The scenarios studied in this work were mainly used to assess the capability of the model to simulate coastal evolution in the Bight of Benin. The test performed in section 5.4 with the example of the Lagos harbor, shows that it is possible to estimate the amount of sediment that would be required to control erosion through beach nourishment. Since the massive landfill and the construction of the seawall at Lagos harbor (Fig. 10) in 2011, erosion has accelerated downstream and the model shows that nearly 650,000 m³/year of sediment would be required to keep the coastline stable. In section 5.2, the model was also used to assess the expected shoreline changes resulting from the removal of the major ports, providing an indicative net

transport anomaly induced by the harbors, as well as of the effects of the use of sediment by-pass systems at the harbor jetties.

The effects of a reduced boundary inflow of sediments from the Volta river delta were partly investigated in a simplistic manner from the test conducted in section 5.4. The results suggested that a reduced sediment input ratio by at least 40% can significantly affect shoreline with erosion rate higher than +20 m/yr over 8 km of coast. However, these results require further investigation for the choice of α and κ , two parameters introduced to describe the effects of reduced boundary inflow of sediment at the shoreline evolution. The model implementation also results in a well-resolved coastal response around inlets. Fig. 9 clearly shows the influence of sediment discharges from the Mono River at the Bouche du Roy, although this remains small compared to the influence induced by harbors.

At regional scale, the model maintains the shape of the bight well and reproduces the trend over the calibration (observed -0.9 m/year and modelled -0.7 m/year) and validation (observed +0.4 m/year and modelled +1.2 m/year) periods, which is consistent with previous observations (Anthony et al., 2019). However, some discrepancies were noted during model validation. In Fig. 7, for example, the model seemed to miss parts of the largest erosion ($\Delta Y_{\text{obs}} \leq -13$ m/yr). These discrepancies can be explained by factors that were not considered in this work. Giardino et al (2018) and Anthony et al (2019) investigated a list of factors to be taken into account, such as climate change, south atlantic climate dynamics, outer shoreface/inner shelf sand supply and localized sand mining reduced, all contributing at the same time to the total longshore transport and shoreline changes. As a consequence, a number of potentially interesting scenarios have not been considered, including effects due to sea level rise, despite its potential strong influence at long timescales (Le Cozannet et al., 2019; Vousdoukas et al., 2020). The observed discrepancies can also reveal deficiencies in the current model, knowing that models inevitably rely on more or less extensive approximations due to the simplification of cross-shore sediment exchange processes. On the one hand, it would be advisable to improve the consideration of these cross-shore processes by minimizing their simplification while taking into account the computational time since simulations are performed for large areas. On the other hand, consideration of other scenarios would require new model developments, fundamental understanding of the physical processes and much more input data on the coastal topography and its properties.

6.2 Using the CASCADE model to improve coastal policies

The CASCADE model therefore demonstrates its potential to assist decision makers in coastal development in West Africa, in evaluating the hazards that affect this region. The overall reduction of sand supplied by the Volta River, due to the decrease in rainfall (Mahe et al., 2001, Aguilar et al., 2009), is probably an important factor in coastline vulnerability in the Bight of Benin, as suggested by previous works (Boateng et al., 2012; Giardino et al., 2018; Anthony et al., 2016; Anthony et al., 2019). This decrease in sediment input at the coast, accentuated by the presence of harbors (Anthony et al., 2019), has already had devastating environmental and socio-economic consequences. The long-term prediction with the CASCADE model of possible scenarios related to this sediment depletion is therefore an asset for the region's policies in building adapted and ecological infrastructures. In addition to prediction, the model offers the possibility of erosion control by providing precisely where and how much sediment to inject to limit the impact on property and people.

Considering the severity of these coastal erosion problems, the model shows the capability to assess the long-term impact of building new coastal infrastructures (e.g., deepwater ports). This is all the more important at the regional scale as there is an interdependence between the various human interventions which do not pay heed to geographical boundaries, whether along the rivers or on the coast, on the overall sediment budget along the bight (Giardino et al., 2018). The implementation of a large-scale integrated sediment management and coastal development plan is therefore quite feasible based on the results obtained in this study. Such a plan should delimit and frame coastal development actions in order to preserve property and people without limiting the economic development of this booming region, although compliance with legal and regulatory frameworks is obviously a challenge that falls under the sovereignty of each state.

7. Conclusions

The work carried out in this paper aimed to provide assistance to decision makers regarding coastal development in the Bight of Benin, West Africa, by modeling the evolution of the 400 km long coastal stretch between 2000 and 2015. An improved version of the CASCADE numerical simulation model was used both to predict the effects of man-made infrastructures and inlets on the evolution of the coast and to limit the impact of the observed erosion on properties and persons. The model performance was tested by employing a 10-year calibration period (2000-2010) followed by a 5-year validation (2010-2015) period. The model results clearly show a well-captured shoreline behavior in the vicinity of the harbors in agreement with the observations. The model reproduces well the global trend and its capabilities were used to address the amount of sediment required to control erosion

downdrift Lagos harbor. In addition, the effect of a reduced discharge of sediment by the rivers was investigated. These results demonstrate the potential of the CASCADE model to assist decision makers in coastal development in West Africa in evaluating the hazards that affect this region both in prediction and in the search for local solutions. The implementation of a large-scale integrated sediment management and coastal development plan is therefore quite achievable in this region. Overall, the CASCADE model may be a useful tool for improving regional coastal policies.

Acknowledgements

This publication was made possible through the support provided by the IRD (French Institute of Research for Development). Thanks are due to J. Reyns and E.W. Anthony for providing shoreline data. Shorelines were derived from images downloaded from the USGS data portal EarthExplorer. We acknowledge use of the ECMWF ERA Interim dataset (www.ECMWF.Int/research/Era).

Author Contributions

G.O. Abessolo: Conceptualization, Methodology, Software, Formal analysis, Resources, Validation, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization.

L.X. Hoan: Conceptualization, Methodology, Software, Formal analysis, Validation, Data Curation.

M. Larson: Conceptualization, Methodology, Software, Writing - Review & Editing, Supervision.

R. Almar: Conceptualization, Investigation, Resources, Writing - Review & Editing, Supervision.

The authors declare no conflict of interest.

References

- Abessolo, O.G., Almar, R., Jouanno, J., Bonou, F., Castelle, B., Magnus, L., 2020. Beach Adaptation to Intraseasonal Sea Level Changes. Environmental Research Communications, in revision.
- Ago, E.E., Petit, F., Ozer, P., 2005. Analyse des inondations en aval du barrage de Nangbeto sur le fleuve mono (Togo et au Bénin). Geo-Eco-Trop. 29, 1–14.
- Aguilar E, Barry AA, Brunet M, Ekang L, Fernandes A, Massoukina M, Mbah J, Mhanda A, do Nascimento D, Peterson T, Umba OT, Tomou M, Zhang X (2009) Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955-2006. J Geophys Res Atmos 114:D02,115. <https://doi.org/10.1029/2008JD011010>
- Allersma, E., and Tilmans, W. M. K., 1993. Coastal conditions in West Africa - A review. Ocean & Coastal Management, 19(3), 199–240. [https://doi.org/10.1016/0964-5691\(93\)90043-X](https://doi.org/10.1016/0964-5691(93)90043-X).

Almar, R., and Coauthors, 2014: The Grand Popo beach 2013 experiment, Benin, West Africa: from short timescale processes to their integrated impact over long-term coastal evolution. *Journal of Coastal Research*, Special Issue 70, 651-656, <https://doi.org/10.2112/SI70-110.1>.

Almar, R., E. Kestenare, J. Reyns, J. Jouanno, E.J. Anthony, R. Laibi, M. Hemer, Y. Du Penhoat, and R. Ranasinghe, 2015: Response of the Bight of Benin (Gulf of Guinea, West Africa) coastline to anthropogenic and natural forcing, Part1: Wave climate variability and impacts on the longshore sediment transport. *Continental Shelf Research*, 110, 48-59, <https://doi.org/10.1016/j.csr.2015.09.020>.

Anthony, E. J., 1995. Beach-ridge progradation in response to sediment supply: examples from West Africa. *Marine Geology* 129: 175-186.

Anthony, E.J., 2015. 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: Randazzo, G., Jackson, D. W. T., Cooper, J.A.G. (Eds.), *Sand and Gravel Spits*. Coastal Research Library, Springer, vol 12, chap. 2, pp. 21–36.

Anthony, E. J., Almar, R., & Aagaard, T. (2016). Recent shoreline changes in the Volta River Delta, West Africa: The roles of natural processes and human impacts. *African Journal of Aquatic Science*, 41(1), 81–87. <https://doi.org/10.2989/16085914.2015.1115751>.

Anthony, E., Almar, R., Besset, M., Reyns, J., Laibi, R., Ranasinghe, R., Abessolo Ondo, G., Vacchi, M., 2019. Response of the Bight of Benin (Gulf of Guinea, West Africa) coastline to anthropogenic and natural forcing, Part 2: Sources and patterns of sediment supply, sediment cells, and recent shoreline change. *Continental Shelf Research*, 173, 93–103, <https://doi.org/10.1016/j.csr.2018.12.006>.

Anthony, E.J., Blivi, A.B., 1999. Morphosedimentary evolution of a delta-sourced, driftaligned sand barrier-lagoon complex, western Bight of Benin. *Mar. Geol.* 158, 161–176.

Bakker, W. T., 1969. The dynamics of a coast with a groin system. *Proceedings of the 11th Coastal Engineering Conference*, American Society of Civil Engineers, 492-517.

Bakker, W. T. and Edelman, T., 1965. The coastline of river deltas. *Proceedings of the 9th Coastal Engineering Conference*, American Society of Civil Engineers, 199-218.

Bayram, A., Larson, M., Hanson, H., 2007. A new formula for the total longshore sediment transport rate. *Coastal Engineering* 54, 700–710.

Blivi, A., Anthony, E. J., Oyédé, L. M., 2002. Sand barrier development in the Bight of Benin, West Africa. *Ocean and Coastal Management*, 45, 185-200.

- Boateng, I., Bray, M., and Hooke, J., 2012. Estimating the fluvial sediment input to the coastal sediment budget: A case study of Ghana. *Geomorphology*, 138(1), 100–110. <https://doi.org/10.1016/j.geomorph.2011.08.028>.
- Boateng, I., Addo, K. A., Nicholls, R. J., Codjoe, S. N. A., Mumuni, M., 2018. A biophysical and socio-economic review of the Volta Delta, Ghana. *J. Coast. Res.* 34, 1216–1226.
- Bollen, M., Trouw, K., Lerouge, F., Gruwez, V., Bolle, A., Hoffman, B., et al. (2011). Design of a coastal protection scheme for Ada at the Volta River mouth (Ghana). In *Proceedings of 32nd Conference on Coastal Engineering*, 2010. Shanghai, China: International Conference on Coastal Engineering (ICCE). <http://dx.doi.org/10.9753/icce.v32.management.36>.
- Carslaw, H. and Jaeger, J., 1959. *Conduction of heat in solids*. Clarendon Press, Oxford.
- Crank, J., 1975. *The mathematics of diffusion*. 2nd ed., Clarendon Press, Oxford.
- Delft Hydraulics, 1990. National and regional aspects of coastal erosion in the Bight of Benin. Project 6607.43.94.155, European Development Fund, Brussels.
- Del Río, L., Gracia, F.J., Benavente, J., 2013. Shoreline change patterns in sandy coasts. A case study in SW Spain. *Geomorphology* 196:252–266. <http://dx.doi.org/10.1016/j.geomorph.2012.07.027>.
- Dickson, M. E., Walkden, M. A., Hall, J. W., 2007. Systemic impacts of climatic change on an eroding coastal region over the twenty-first century. *Clim. Chang.* 84:141–166. <http://dx.doi.org/10.1007/s10584-006-9200-9>.
- Doody, P., Ferreira, M., Lombardo, S., Lucius, I., Misdorp, R., Niesing, H., Salman, A., Smallegange, M., (2004). “Living with Coastal Erosion in Europe: Sediment and Space for Sustainability: Results from the EUROSION Study,” European Commission, Luxembourg, p. 38.
- French, J.R. and Burningham, H., (2009). “Coastal geomorphology: trends and challenges,” *Prog. Phys. Geogr.* 33, 117-129.
- Giardino, Schrijvershof, A.R., Nederhoff, C.M., de Vroeg, H., Brière, C., Tonnon, P.-K., Caires, S., Walstra, D.J., Sosa, J., van Verseveld, W., Schellekens, J., Sloff, C.J., 2018. A quantitative assessment of human interventions and climate change on the West African sediment budget. *Ocean Coastal Management*, 156, 249-265.
- Hallermeier, R. J., 1981. A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering*, 4, 253-277.
- Hanson, H. (1987). *GENESIS: A generalized shoreline change numerical model for engineering use*. Lund, Sweden: Department of Water Resources Engineering, Lund University, Ph.D. thesis, 206p.
- Hanson, H., 1989. GENESIS - A generalized shoreline change numerical model. *Journal of Coastal Research*, 5(1), 1-27.

- Hanson, H., Larson, M., Kraus, N. C., Gravens, M. B., 2006. Shoreline response to detached breakwaters and tidal current: comparison of numerical and physical models. *Proceedings of the 30th Coastal Engineering Conference*. World Scientific, pp. 3630–3642.
- Hanson, H., Bocamazo, L., Larson, M., Kraus, N.C., 2008. Calculation of beach change under interacting cross-shore and longshore processes. *Coast. Eng.* 57, 610–619.
- Hoan, L.X., Hanson, H., Larson, M., Donnelly, C., and Nam, P.T. 2010. Modeling shoreline evolution at Hai Hau Beach, Vietnam. *Journal of Coastal Research*, 26(1), 31-43.
- Hoan, L. X., Hanson, H., Larson, M., and Nam, P. T., 2011a. Modeling regional sediment transport and shoreline response in the vicinity of tidal inlets on the Long Island coast, United States. *Coastal Engineering*, 58, 554-561.
- Hoan, L. X., Hanson, H., Larson, M., 2011b. A mathematical model of spit growth and barrier elongation. *Estuar. Coast. Shelf Sci.* 93 (4), 468–477.
- Jiménez, J., Sánchez-Arcilla, A., 2004. A long-term (decadal scale) evolution model for microtidal barrier systems. *Coast. Eng.* 51 (8–9), 749–764.
- Kraus, N.C., 1983. Applications of a shoreline prediction model. *Proceedings of Coastal Structures '83*, American Society of Civil Engineers, 632-645.
- Kraus, N. C., 2000. Reservoir model of ebb-tidal shoal evolution and sand bypassing. *Journal of Waterway, Port, Coastal and Ocean Engineering* 126 (3), 305–313.
- Laibi, R. A., Anthony, E. J., Almar, N., Castelle, B., Sénéchal, Kestenare, E., 2014. Longshore drift cell development on the human-impacted Bight of Benin sand barrier coast, West Africa. *J. Coast. Res. (Special 70)*, 78–83.
- Larson, M. and Kraus, N. C., 2003. Modeling regional sediment transport and coastal evolution along the Delmarva Peninsula. *Proceedings Coastal Sediments '03*. ASCE (on CD).
- Larson, M., Hanson, H., and Kraus, N.C., 1987. Analytical solutions of the one-line model of shoreline change. Technical Report CERC-87-15, US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.
- Larson, M., Kraus, N. C., and Hanson, H., 2002a. Simulation of regional longshore sediment transport and coastal evolution – The CASCADE model. *Proc. 28th Coastal Eng Conf.*, World Scientific Press.
- Larson, M., Palalane, J., Fredriksson, C., Hanson, H., 2016. Simulating cross-shore material exchange at decadal scale. Theory and model component validation, *Coastal Engineering*, 116, 57-66.

- Larson, M., Rosati, J. D., and Kraus, N. C., 2002. Overview of regional coastal processes and controls. Coastal and Hydraulics Engineering Technical Note CHETN XIV-4, U.S. Army Engineer Research and Development Center, Vicksburg, MS. <http://chl.wes.army.mil/library/publications/chetn/pdf/chetn-xiv4.pdf>.
- Larson, M., Kraus, N.C., Connell, K.L., 2006. Modeling sediment storage and transfer for simulating regional coastal evolution. Proceedings of the 30th Coastal Engineering Conference. World Scientific, pp. 3924–3936.
- Le Cozannet, G., Bulteau, T., Castelle, B., Ranasinghe, R., Woppelmann, G., Rohmer, J., Bernon, N., Idier, D., Louisor, J., Salas-y-Mélia, D., 2019. Quantify uncertainties of sandy shoreline change projections as sea level rises. Scientific Reports, 9:42. Doi: 10.1038/s41598-018-37017-4.
- Le Méhauté, B. and Brebner, A., 1961. An introduction to coastal morphology and littoral processes. Report No. 14, Civil Engineering Department, Queens University at Kingston, Ontario, Canada.
- Le Méhauté, B. and Soldate, M. 1977. Mathematical modeling of shoreline evolution. CERC Miscellaneous Report No. 77-10, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.
- Logah, F. Y., Amisigo, A. B., Obuobie, E. and Kankam-Yeboah, K., 2017. Floodplain hydrodynamic modelling of the Lower Volta River in Ghana. Journal of Hydrology: Regional Studies, 14, 1-9, <http://dx.doi.org/10.1016/j.ejrh.2017.09.002>
- Mahe, G., L'hote, Y., Olivry, J. C., and Wotling, G., 2001. Trends and discontinuities in regional rainfall of West and Central Africa: 1951-1989. Hydrological Sciences Journal, 46(2), 211-226. <http://doi:10.1080/02626660109492817>
- Melet, A., R. Almar, and B. Meyssignac, 2016: What dominates sea level at the coast: A case study for the Gulf of Guinea. Ocean Dynamics, 66, 623–636, <https://doi.org/10.1007/s10236-016-0942-2>.
- Nicholls, R.J., Birkemeier, W.A., and Lee, G.-H., 1998. Evaluation of depth of closure using data from Duck, NC, USA. Marine Geology, 148, 179-201.
- Nicholls, R. J., Bradbury, A., Burningham, H., Dix, J. K., Ellis, M., French, J., Hall, J. W., Karunaratna, H. U., Lawn, J., Pan, S., Reeve, D. E., Rogers, B., Souza, A., Stansby, P. K., Sutherland, J., Tarrant, O., Walkden, M. J. A., Whitehouse, R., 2012. iCOASST - integrating coastal sediment systems. ICCE2012 International Conference on Coastal Engineering, Santander, ES, 01–06 Jul 2012 (15 pp.).
- Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328:1517–1520. <http://dx.doi.org/10.1126/science.1185782>.
- Nicholls, R.J., Townend, I., Bradbury, A.P., Ramsbottom, D., Day, S.A., 2013. Planning for long-term coastal change: experiences from England and Wales. Ocean Engineering 71, 3–16. <http://dx.doi.org/10.1016/j.oceaneng.2013.01.025>.

- Ndour, A., Laïbi, R. A., Sadio, M., Degbe, C. G. E., Diaw, A. T., Oyédé, L. M., Anthony, E. J., Dussouillez, P., Sambou, H., Dièye, E. h. B., 2018. Management strategies for coastal erosion problems in West Africa: Analysis, issues, and constraints drawn from the examples of Senegal and Benin. *Ocean and Coastal Management*, 156, 92-106. <https://doi.org/10.1016/j.ocecoaman.2017.09.001>.
- Oguntunde, P.G., Friesen, J., van de Giesen, N., Savenije, H.H.G., 2006. Hydroclimatology of the Volta River Basin in West Africa: trends and variability from 1901 to 2002. *Phys. Chem. Earth* 31, 1180–1188.
- Ozasa, H., and Brampton, A.H., 1980. Mathematical modeling of beaches backed by seawalls. *Coastal Engineering*, 4(1), 47-64.
- Pelnard-Considère, R., 1956. Essai de théorie de l'évolution des formes de rivages en plage de sable et de galets," 4th Journées de l'Hydraulique, les Energies de la Mer, Question III, Rapport No. 1, 289-298.
- Polo, I., A. Lazar, B. Rodriguez-Fonseca, and S. Arnault, 2008: Oceanic Kelvin waves and tropical Atlantic intraseasonal variability: 1. Kelvin wave characterization. *Journal of Geophysical Research*, 113, C07009, <https://doi.org/10.1029/2007JC004495>.
- Ranasinghe, R., (2016). Assessing climate change impacts on open sandy coasts: a review. *Earth-Sci. Rev.*, 160, 320–332.
- Ranasinghe, R., Duong, T., Uhlenbrook, S., Roelvink, D., Stive, M., 2013. Climate change impact assessment for inlet-interrupted coastlines. *Nat. Clim. Chang.* 3, 83–87.
- Reeve, D.E. and Valsamidis, A. 2014. On the stability of a class of shoreline planform models. *Coastal Engineering*, 91, 76-83.
- Robinet, A., Idiera, D., Castelle, B. and Marieu, V., 2018. A reduced-complexity shoreline change model combining longshore and cross-shore processes: The LX-Shore model. *Environmental Modelling and Software* 109, 1–16, <https://doi.org/10.1016/j.envsoft.2018.08.010>.
- Sterl, A. and Caires, S., 2005. Climatology, variability and extrema of ocean waves- the web-based KNMI/ERA-40 Wave Atlas. *Int. J. Climatol.* 25, 963–977.
- Vitousek, S., Barnard, P.L., Limber, P., Li Erikson and Cole, B. (2017). "A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change: CoSMoS-COAST," *Journal of Geophysical Research*, doi:10.1002/2016JF004065.
- Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M. and Feyen, L., 2017. Extreme sea levels on the rise along Europe's coasts, *Earth's Future*, 5, doi:10.1002/2016EF000505.
- Walton, T. and Chiu, T., 1979. A review of analytical techniques to solve the sand transport equation and some simplified solutions. *Proceedings of Coastal Structures '79*, American Society of Civil Engineers, 809-837.

Zhang, K., Douglas, B.C., Leatherman, S.P., 2004. Global warming and coastal erosion. *Clim. Chang.* 64:41–58.
<http://dx.doi.org/10.1023/B:CLIM.0000024690.32682.48>.